AGENT-BASED SIMULATION MODEL OF BUS EVACUATION EVENTS

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ABSTRACT

The time required for the evacuation of the occupants of buses and coaches, that is, Large-Dimension Passenger Transport Vehicles (V.G.D.T.P.) is a fundamental safety parameter for these vehicles. Starting from the fact that they are a mode of transport with very high levels of security, when events with collision and subsequent fire occur, or in cases of fire exclusively, it is when these events generate injuries or even deaths. Additionally, part of the UN CEPE regulations that affect these vehicles (e.g. R107) are defined in such a way as to reduce this evacuation time. Others, R118, are aimed at reducing the severity of the fire and, therefore, increasing the time available before suffering serious consequences.

Therefore, the need to know which are the fundamental aspects that can improve these two time intervals, evacuation and available, is concluded.

In the present work, a coach is modelled, and simulated by means of an agent-based model, both the boarding process, and the disembarkation or evacuation process. Some relevant characteristics of the model are that it allows to analyse the influence of the mobility of each agent (occupant) as well as that of the vehicle's configuration. Among others, some of the characteristics of the occupants are their average speed of movement and associated with a probability function, their size, the probability of using emergency exits (e.g. jumping through an emergency window), etc. Regarding the vehicle, the fundamental aspects contemplated in the model are those relating to accessibility to the interior of the vehicle and, once inside it in the corridors, access to the seats. Among other parameters, the width of the gangway, the distances between seats, the characteristics of the entrances, stairs, etc.

The model is used to analyse the influence of the variability of each of the occupant and vehicle parameters described, and the probabilities of complete and partial evacuation times are deduced. Based on these results, it is concluded that the exits locations, and the age (mobility) of the passengers are the main parameters influencing the probability of a high evacuation time,

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1. INTRODUCTION

Transportation by bus or coach is a means that has proven to be very safe for its occupants. However, given that they are a means of collective transport, and on many occasions public, the agents involved in the design, approval and use of these vehicles continue to seek to reduce the consequences of their accidents.

One type of accident that occurs with some frequency is fire. These accidents, in which the total or partial fire of the vehicle takes place, normally only have material consequences.

Fundamentally, the vehicle is damaged or partially destroyed. The absence of injuries to the occupants is mainly due to the design of the vehicles that is defined for a fast enough evacuation. The characteristics that buses and coaches must meet to ensure that they are safe in the event of an incident are defined in United Nations Regulation R107. UNECE. WP29. (2018). This regulation defines the maximum and minimum dimensions of each of the parameters that affect safety, including those related to evacuation, dimensions of service doors, emergency exits, etc.

However, and despite the measures ensured in the vehicle type-approval process, from time to time, an incident with fire in a bus, or coach, has as a consequence a significant number of victims. Often these incidents, with fire and serious consequences for the occupants, are the consequence of a collision prior to the fire and a, for different reasons, defective faulty evacuation. This was the case of the accidents that occurred in Bailen Spain (1996) and in Puisseguin, France (2015) with 28 and 43 deaths respectively.

The importance of evacuation, or more specifically of the speed of evacuation of the vehicle, lies in the need to minimize the risk of loss of consciousness due to the inhalation of gases from combustion. There are many studies that analyse the evacuation times of infrastructures, and also some of means of transport including coaches. Some of these studies are carried out by means of evacuation tests, one of the most relevant is the one carried out by JK Poland and SH Markos (2009) where they measure times of passage through different types of emergency exits, service doors, windows, hatches, and used different lighting conditions.

However, all these studies cannot be exhaustive in terms of the profile of the passengers involved in the drill, or the variety of vehicle models based on their interior configuration, entrances and exits. That is why it was decided to approach the study by simulation with a stochastic model that allows to obtain with fidelity an interval of evacuation times associated with a probability of occurrence.

2. OBJECTIVE

Through this WORK, it is intended to carry out an evacuation model for vehicles of class M2 and M3, commonly known as buses or coaches, using the service doors and, also, analysing the probability of using the windows as an emergency exit. This objective has been raised by observing that in certain accidents, in which the vehicle

For this, some partial objectives have been met, which are:

1.- The characterization of the mobility of people, so that the analytical model allows determining the interval of evacuation times of the vehicles, based on the characteristics of the travellers, and the probability associated with each value of evacuation time of the vehicle. model.
2.- The characterization of the vehicle, so that by introducing the plan of the vehicle and the characteristics of the accesses, the evacuation time can be determined.
3.- By using the vehicle model, and the mobility of the agents (passengers), obtain valid results and conclusions on the following factors:

- Evacuation times and uncertainty in their determination.
- Influence of the characteristics of the passengers on the evacuation time.
- Influence of the plant and the distribution of the vehicle.

Finally, the model can be used to obtain an optimal configuration and determine possible improvements to reduce evacuation times, referring to both passenger education and vehicle layout.

3. METHODOLOGY

The model has been developed using the AnyLogic software. This code uses agent-based simulation algorithms and is supported by the Java language. An advantage of this software is that it allows to perform dynamic simulations, discrete events simulations and combined models applying a stateflow to a continuous dynamic model. This type of models allows assigning individual characteristics to each passenger (and vehicle), modify these characteristics during the simulation process, as well as defining the interactions passenger-passenger and passenger vehicle. It is taken the advantage of the fact that AnyLogic already has implemented the internal algorithms for the movement of individuals and the interactions between them.

To analyse the evacuation, the coach layout is modelled based on the requirements reflected in Regulation R107 of the UNECE. In this model, three dimensions are chosen as critical: distance between seats, aisle width and door width. In the standard coach used to determine passenger influence, the aisle is 530 mm wide, the seats are 720 mm apart, and the front and rear doors are 800 and 700 mm wide, respectively. The rear door is located in front of the rear axle, as is common in many M3 Class III vehicle configurations. Stairs are defined as an area in which passengers see their speed reduced to 50%.

The movement of passengers has only been defined by the maximum speed they can reach and by their size. For this, and because the achievable speed is not determined by the size of the vehicle aisle, for values from 40 cm as demonstrated by Huang, S. et al. (2018), various studies on achievable speed according to age are analyzed (Bohnannon 1996 and 1997; Capote 2011; Chiu, 2007; hoogendoom, 2005 and Spearpoint, 2012) and it is decided to use normal speed distributions for each group decreasing with the age, and increasing fixed sizes. This variation is very marked when reaching the third age.

The movement of passengers has been defined considering the maximum speed that they can reach in a corridor (Huang, 2018), and by their size, which determines their mobility. The maximum velocity has been characterized by an approximation to a normal probability distribution assigning the value of the mean and the standard deviation.

To analyse the influence of passengers, simulations are carried out by varying the age distribution within the vehicle. Evacuation is designed as a process in which passengers initially go to the nearest door, since they do not know if it is possible to open that door. Subsequently, and after checking whether it is possible to open the doors, the passengers head towards the available doors following the same principle of proximity. During the entire evacuation time, passengers periodically check if the condition of the doors has changed and after 60 seconds, they begin to consider using the windows as exits (Aparicio, et al 1996).

3.1 Vehicle plant model

This plant of the vehicle is defined by several wall-type elements (Wall). The strange shape of both doors is due to the fact that the entire simulation must take place within a closed wall and because we want to consider that the passenger has left the vehicle once they have managed to cross the line that runs along the side of the coach. Striped areas are areas where passengers cannot enter.

Next, the lines (Target Line) that act as doors are drawn and also another, continuous, on the entire left side that simulates the emergency window. It is decided to simplify the window in this way since it is not used as the main exit in a real evacuation. The hatches are not included and are not used in the case of no overturning.

Lastly, the seats are modelled. The seats are represented by their positions. These positions are fixed by Attractor elements. As the Attractor elements are linked to an area, the area areaAreasSeats is defined and the points are marked on it. The Final model of the vehicle is shown at Fig. 1.

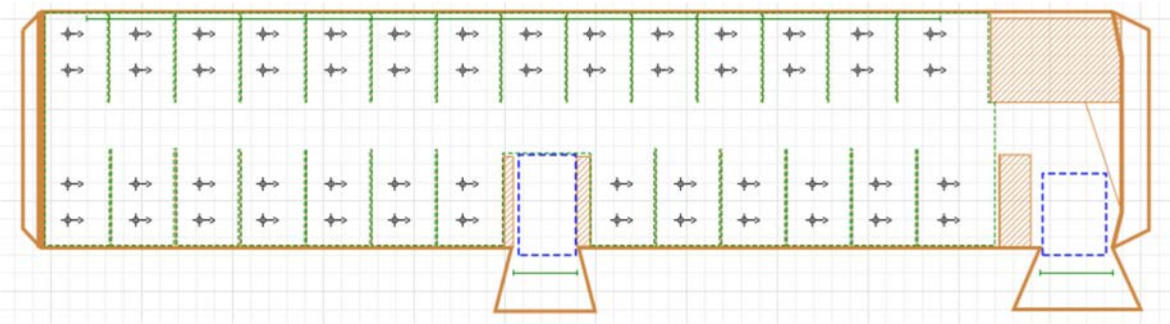

Fig. 1. Complete model of the vehicle plant.

3.2 Passenger model

Before modelling the passengers, it is useful to know the limitations that AnyLogic has when it comes to simulating a Pedestrian-type agent. Passengers are created in a block Ped Source has three mandatory parameters: size, initial speed and maximum speed. The latter, called Comfortable Speed, is the maximum speed at which it travels if there are no obstacles on the road.

Other internal variables of the passengers are also created, which are explained after the three that are indispensable.

3.2.1 Passenger Size

The main limitation in the size of the agents is the size of the coach aisle itself, which is the smallest dimension of the vehicle. Because the agents are represented as circles, it is necessary to check the appropriate size not to create agents that cannot access into the vehicle.

Through test simulations, it has been found that passenger diameters greater than 0.30 meters pose serious problems during evacuation and, therefore, prevent passengers from approaching this size in any evacuation. The lower diameter limit is less critical, but is set at 0.15 meters for very agile passengers or children. This size allows one passenger to outrun another down the aisle.

Therefore, a standard population distribution will contain passengers between 0.15 and 0.25 meters, indicating greater and less mobility and agility, respectively. Each population group will have a fixed size.

3.2.2 Confortable Speed

AnyLogic defines this speed as the speed at which the agent moves in the absence of external factors. In the simulation it will be the maximum speed at which the passengers can move inside the bus. In the simulation, it cannot be considered that there is an absence of external factors.

The backs of the seats act as walls that make the officers stop and they can never move at the speed that is chosen as comfortable. For this reason, the speed values that are finally applied are slightly lower than the movement of a person in an aisle.

The speed of the passengers depends mainly on the age since the gender barely has an influence of between 10 and 15%, which is considered negligible in order to simplify the model. The dependence of speed with respect to age is decreasing, with a more pronounced influence after 60 years of age, and as age increases, the uncertainty in determining said speed also increases.

Group	Reference	Avg speed (m/s)	Standar dev. (m/s)	Size Φ (m)
< 30 yo	G1	2	0,1	0,17
[30 yo: 50 yo]	G2	1,8	0,1	0,2
[50 yo: 65 yo]	G3	1,7	0,2	0,2
[65 yo: 80 yo]	G4	1,3	0,15	0,23
> 80 yo	G5	0,8	0,1	0,25

Table 1 – Passengers study groups

In this way, only the percentage of passengers belonging to each group will have to be established to run the model.

3.2.3 Initial velocity

The initial speed of an agent is the speed with which it is generated in the Ped Source block. It is verified that changes in this value have no influence on the results obtained, since, in the evacuation, the agents start at zero speed from their seats. Therefore, it is set at 0.5 meters per second, the value that AnyLogic assigns by default.

3.4 Validation

Once the construction of the model is finished, four experiments of a thousand test simulations are carried out to analyze if values similar to those found in the literature in simulations and in models are achieved based on the following factors: times used, standard deviations of the times, trends with the variation of passengers and trends when locking the doors.

When carrying out the four experiments and checking the influence of the erroneous simulations, between 1 and 2%, it is decided that the evacuation time taken as a reference will be the time95, since on certain occasions the last two passengers take illogically high times in get out of the vehicle.

When the time95 is excessively high and goes outside the range of times determined by the other simulations, this data is eliminated from the analysis. The loss of 1% of the data is considered acceptable for the statistical analysis.

This is verified by ordering the results from highest to lowest and eliminating those that are 2 seconds or more apart from the next.

The four experiments carried out for the validation, with their results, are shown at table 2:

Run	Available exits	Age	AVG (s)	Standard Deviation (s)
1	Front + Rear	100% Young	*53,5*	*5,9*
2	Front + Rear	100% Above 65	*74,4*	*7,5*
3	Front	100% Young	*68,7*	*12,6*
4	Rear	100% Young	*101,0*	*7,1*

Table 2 – Validation Runs

The values obtained, although they differ slightly from other models, are close and follow the same trends as them. So, the model is considered correct as an explanatory method and as a correct estimate of evacuation times for the following reasons:

- Times when evacuating in similar conditions are similar, although slightly higher than in drills. This increase in time is followed by all the models studied and is considered to correct the preparation and learning of the participants in a drill.
- The standard deviation is in the existing values in other models and correctly corresponds to what is expected and found in other stochastic models.
- Locking a door produces time increases of the same order as in drills and models. In this case, the blockage may involve increases between 30 and 90%.

3.5 Evacuation study

Once considered that the model represents the best state of art of evacuation simulations it was used to perform three independent analysis: Analysis of the standard evacuation, Analysis of the influence of the passengers' characteristics and Analysis of the influence of the vehicle configuration

3.5.1 Standard evacuation analysis

The standard evacuation process study employs a population distribution similar to that of aerial evacuation. For the standard evacuation, passengers are chosen from the first four groups, in such a way that it is considered a worse situation than that assumed by the air regulations. G5 passengers, who are very elderly, are not included, because the usual drills do not use people with reduced mobility or who could be injured.

POPULATION GROUP	PERCENTAJE
Jóvenes – G1	30%
Media edad – G2	40%
Mayores de 50 – G3	20%
Mayores de 65 – G4	10%

Table 3 – Vehicle passengers distribution configuration

Regarding standard evacuation, the following parameters are studied:

- Normal development of the evacuation and shape of the time-passengers graph
- Development of evacuation with only one available door
- Door Blocked during the evacuation.

3.5.2 Passengers characteristics influence analysis

To study the influence of passengers, the distribution of speeds and sizes will be varied, separating them from the previously defined as standard distribution. The following experiments are performed with the following distributions:

NÚMERO EXPERIMENTO	JÓVENES	MEDIA EDAD	MAYORE S DE 50	MAYORES DE 65	MUY ANCIANOS
1	100%	-	-	-	-
2	80%	20%	-	-	-
3	-	100%	-	-	-
4	20%	40%	20%	20%	-
5	-	-	100%	-	-
6	-	20%	40%	40%	-
7	-	-	-	100%	-
8	-	-	10%	70%	20%
9	-	-	-	50%	50%

Table 4. – Experiments to study the influence of passengers

The evacuation times and the standard deviations in each case will be analysed, checking how they vary when the distribution of passengers in the coach changes and trying to obtain an estimate of the evacuation time through linear regression.

3.5.3 Vehicle characteristics influence analysis

Considering the standard passenger distribution – defined at para 2.5.1. –, relevant parameters of the coach seat layout are modified to see how they influence the evacuation.

The 54 seats of the coach are maintained at all times. There are three parameters that are analysed to evaluate the coach:

- Width of the doors
- Aisle width
- Rear door position

In this base approach, the two doors are the same width as opposed to the standard evacuation and the corridor is reduced up to 500 mm in its narrowest configuration. The experiments to be performed are shown below.

The increase of the aisle to 600mm is unrealistic and exceeds the legal limit, even taking into account the adaptations of the model, but it is included when considered interesting.

Experiment number	Door width	Aisle Width	Door location
1	700 mm	500 mm	Middle
2	700 mm	500 mm	Rear
3	700 mm	550 mm	Middle
4	700 mm	550 mm	Rear
5	800 mm	500 mm	Middle
6	800 mm	500 mm	Rear
7	800 mm	550 mm	Middle
8	800 mm	550 mm	Rear
9	700 mm	600 mm	Middle
10	700 mm	600 mm	Rear
11	800 mm	600 mm	Middle
12	800 mm	600 mm	Rear

Table 5– Experiments to study the influence of the vehicle

4 EXPERIMENT RESULTS AND DISCUSSION

4.1 Standard evacuation analysis

As it was presented in the paragraph dedicated to the methodology the objective was to characterise de variability of the evacuation process. To perform this characterisation, it the corridor average $\pm 2 \cdot \sigma$ was represented considering each percentage of the passengers evacuated.

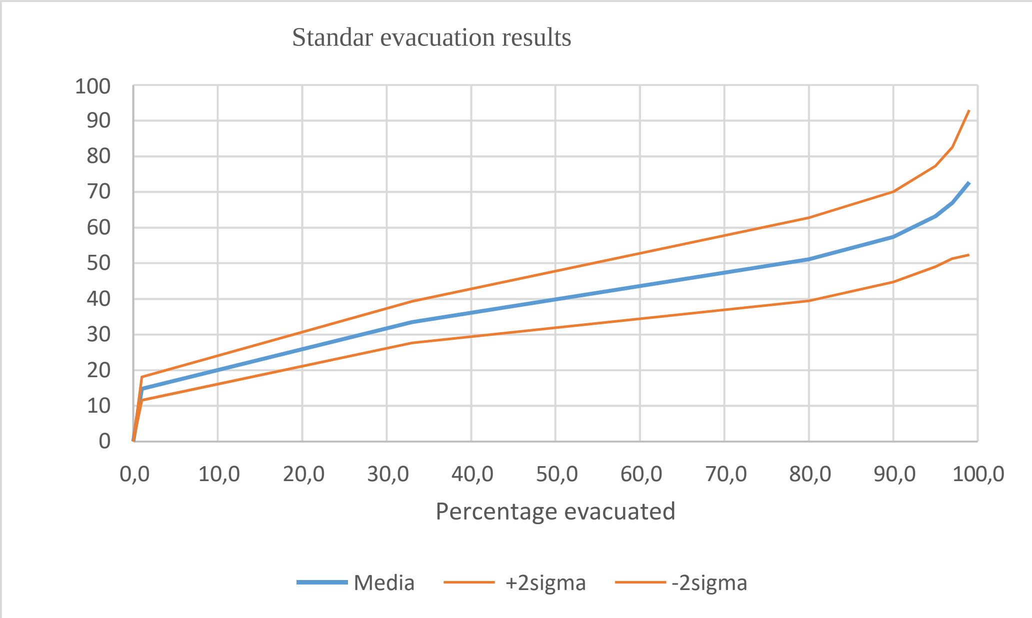

Fig. 2 Standard evacuation Charaterisation

From this standard evacuation and the filtered graphs, the histogram of the value time95 is obtained, the one chosen as the representative time of the evacuation, which is used as a reference to compare other experiments.

The distribution followed by the results of each time has also been studied using the SPC extension for Microsoft Excel. Despite the fact that sometimes follow the Beta4 distribution, it is chosen to define them by means of a log-normal distribution, since this is better adapted to all cases on average.

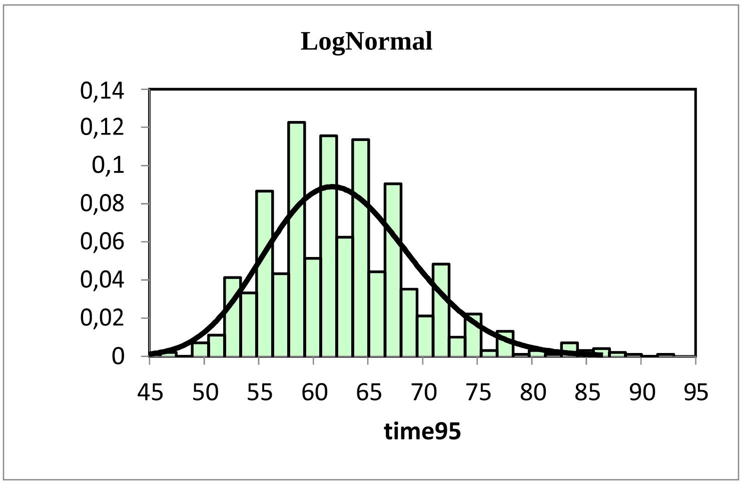

Fig. 3. Time 95 evacuation distribution

4.1.1 Standard evacuation with on door Blocked before the evacuation start

Studies with only one available door are carried out with the standard passenger distribution, obtaining the results shown in the table. During the obtaining of results, it is observed that when evacuating through the rear door there are an average of 12.2

passengers who use the emergency window. For this reason, another experiment is carried out in which the emergency windows are not used. The standard evacuation process through the two doors is included for comparison.

Experiment	Averrage Evacuation Time (s)	Standard deviation (s)
Standard, two exit doors	*62,7*	*6,8*
Front door	*78,4*	*13,6*
Rear door	*109,5*	*10,5*
Rear door and windows	*104,8*	*6,9*

Table 6. – Experiments with only one door available

A clear increase in evacuation times is observed when evacuating with a single door compared to when evacuating through both. This increase is 25% when the door is locked at the back and 75% when the front door is locked. This second case is more common when it comes to frontal crashes or when the fire starts in the front, for example, in the tank or in the front brakes.

The use of the emergency windows in the case of evacuating only from the rear does not significantly affect the times.

The standard deviation also increases with increasing evacuation time: it doubles with the rear locked and 55% more when the front is locked. The fourth experiment shows atypical results, since the standard deviation does not increase with respect to the standard evacuation, something that can only be explained assuming that the people that abandon the vehicle through the windows have less variability and the number of the passengers that exit through the doors is reduced by the same amount.

4.1.2 Standard evacuation with on door Blocked during the evacuation

This experiment considers the situation where some passengers start the evacuation through both available doors, and at some point – e.g. Bailén accident – one of the doors is blocked.

It is decided that the door block occurs when 40% of the passengers have evacuated, in order to observe its influence from time to time50.

Two experiments are performed, the first blocking the front door and the second blocking the back door. In this case, the use of emergency windows is allowed, which are used by a variable number of passengers between 0 and 8, considered reasonable in the face of the panic situation that would be generated.

Below are the evacuation times when the front door is blocked and when the rear door is locked:

% Evacuated	T1 (s)	T25 (s)	T50 (s)	T80 (s)	T95 (s)
Media	*14,3*	*23,6*	*38,0*	*63,9*	*81,5*
Desviación típica	*1,7*	*1,9*	*3,6*	*4,1*	*13,8*

Tabla 7. - Results with blocking the front door during evacuation

% Evacuated	T1 (s)	T25 (s)	T50 (s)	T80 (s)	T95 (s)
Media	*14,3*	*23,6*	*35,3*	*54,7*	*65,7*
Desviación típica	*1,7*	*2,0*	*3,7*	*4,6*	*7,4*

Table 8. - Results with blocking the rear door during evacuation

The development of both evacuations is identical until any of the doors is blocked. From that moment on, all passengers head towards the only one available, or towards the emergency windows if the conditions are met. This difference is observed from time50.

From then on you can consider a situation such as where only one door is available. The same trends are observed as in the previous case: a substantial increase in time when the available door is the rear and this is in an intermediate position of the vehicle.

Rear lockout assumes an average of 16 more seconds of evacuation for the last 30 occupants, or 50% more time since lockout occurs.

The drift of the data also increases with the elapsed time due to the same reasons as in the previous cases: an increase in time implies a greater probability of a blockage in the continuous flow of passengers. This blocking is favoured if two flows mix, as happens when evacuation is through the back door.

4.2 Passengers characteristics influence analysis

As has been performed in the previous analyses, the reference value considered as the evacuation time is the value time95. The results of erroneous simulations are eliminated and the means and standard deviations of the experiments carried out are found.

Finally, a linear regression is carried out in order to estimate the evacuation time of the vehicle as a function of the distribution of passengers. To carry out the study, the results of means and standard deviations of the standard evacuation and the other nine experiments carried out were used.

Young	Mid age	Above 50	Above 65	Above85	avg (s)	SD (s)
1	0	0	0	0	*55,8*	*5,5*
0,8	0,2	0	0	0	*57,3*	*5,6*
0	1	0	0	0	*62,9*	*6,6*
0,2	0,4	0,2	0,2	0	*66,1*	*7,7*
0	0	1	0	0	*65,2*	*7,1*
0	0,2	0,4	0,4	0	*72,4*	*8,8*
0	0	0	1	0	*82,9*	*9,4*
0	0	0,1	0,7	0,2	*101,2*	*16*
0	0	0	0,5	0,5	*128,2*	*18,2*
0,3	0,4	0,2	0,1	0	*62,7*	*6,8*

Table 9 - Percentage of passengers and evacuation results obtained

If a qualitative analysis of the results is carried out, it is observed that, indeed and as expected, the evacuation time grows with the presence of older passengers and therefore slower and less agile.

The big differences in evacuation times occur when dealing with very elderly passengers and with reduced mobility due to age. The presence of these passengers significantly increases the time required to evacuate the vehicle. While the presence of passengers over 65 in good physical condition increases the time by 49% compared to young people, the fact that half of these passengers have mobility problems increases the time by 150% compared to the initial proposals.

In turn, it is observed that the standard deviation increases when the mean evacuation time increases. This indicates that the results of each simulation are more different from each other the slower the entire evacuation process is carried out.

4.3 Vehicle characteristics influence analysis

The results of the experiments defined at paragraph 2.5.3 are collected in the table below:

Experiment number	Door width (mm)	Aisle width (mm)	Door location	Average (s)	SD (s)
1	700	500	Middle	*66,5*	*15,0*
2	700	500	Rear	*53,3*	*6,0*
3	700	550	Middle	*69,3*	*15,0*
4	700	550	Rear	*53,6*	*5,9*
5	800	500	Middle	*66,0*	*12,9*
6	800	500	Rear	*49,9*	*5,0*
7	800	550	Middle	*67,4*	*11,6*
8	800	550	Rear	*51,1*	*5,6*
9	700	600	Middle	*74,6*	*16,5*
10	700	600	Rear	*54,2*	*6,2*
11	800	600	Middle	*71,5*	*12,5*
12	800	600	Rear	*51,0*	*5,0*

Table 10 - Results of the experiments on the influence of the vehicle

In the results it is observed at a glance that the constructive parameter that has the most influence is the position of the rear door. An increase in standard deviations is also observed, linked to the increase in evacuation time. The slower the output, the more difficult it is to predict.

Focusing first the analysis on the average evacuation time a 100 mm increase in the width of the doors causes a minor decrease of 2.4 seconds in the evacuation time. This is due to a greater ease of leaving the vehicle for passengers.

The increase in the width of the corridor causes an increase of 3.9 seconds in said time.

This result is inexplicable and needs further experimentation. If correct, it could be because, with a wider corridor, several people could try to move through it simultaneously, impairing the normal flow of people towards the door.

Placing the rear door at the end of the seats is the factor that most influences the evacuation time. When the door is located in the back of the bus, the passengers are distributed more or less evenly between the two doors and, in addition, the flows towards both doors are unidirectional so that traffic jams are not created either. Placing the door at the back of the coach reduces the estimated evacuation times by 17 seconds and the standard deviation of the simulations by 8.3 seconds.

Broadly speaking, the position of the door has seven times more influence than its width and four times more than the width of the corridor.

5 CONCLUSIONS

It has been developed a bus and coach evacuation model that allows a stochastical analysis of the influence of vehicle and passengers variables.

The model has a good behaviour compared with evacuation drills performed by relevant transport safety institutions as INSIA in SPAIN and RISE in Sweden. The S shape behaviour of the evacuation percentage vs time curve is also coherent with the drill results.

The passengers profile may lead to double the time needed for a full evacuation of the vehicle in case of emergency, this value, even being significantly high is a result that can been used to define the burning behaviour of the materials used for vehicle interiors.

Considering the vehicle design a door blocked can slow down the process by 25-65%. The consequences are much more severe if the blocked door is the front one, which is usually the most common due to a frontal collision. These trends are also observed when the blockage occurs with the evacuation in progress.

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