ANALYSIS OF AN AUTONOMOUS DRIVING MODULAR BUS SYSTEM

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ABSTRACT

One of the main complaints about the performance of the bus systems is the time lost at recurrent stops along the route, that results in a low bus speed service. Among the potential measures to speed up the bus service, the introduction of the Autonomous Driving Modular Bus, able to adjust the transport unit by coupling or decoupled pods, will represent a new paradigm in the provision of service. This concept is able to maintain high stable cruising speeds to the transport unit, decoupling only one pod with passengers that may alight at the next stop. This paper analyze the potentialities of this concept in terms of user travel times and operationg cost. This work also features the formulation and analytical models to calculate the performance and oeprational variables, implementing them into two existing bus lines in Barcelona.

1. INTRODUCTION

The current commercial speed of buses in crowded areas (8-15 km/h, Vuchic, 2013) is significantly lower than other public transportation modes in competition (15-40 km/h in tramways, 24-55 km/h in subways). There are several strategies to speed up buses along the routes based on segregated lanes, double lanes, multiple boarding platforms at stops, traffic light synchronization, etc (see Kittelson and associates, 2013). Nevertheless, the travel time savings obtained are still marginal and require huge investments to deploy right of way measures or technological devices. In fact, these measures do not dramatically change the operation of buses: every transit vehicle, with passing passenger onboard, is still obliged to loose cruising speeds before and after a stop location, and is held at the stop facility during dwell time. The major challenge for bus operation would be whether the time lost performing these processes at intermediate stops can be removed from the bus motion. It means that bus services may resemble taxi systems, offering a direct door-to-door service from origins to destinations without intermediate stops. However, one of the innovation concepts that is gaining momentum and could meet this goal is the Autonomous Driving Modular Bus. With this new concept, travel times could be reduced considerably while the service quality could be upgraded. This paper is aimed at analyzing the potentialities of this concept by means of an analytical model. This model consists of several compact formulas to estimate both the user performance (travel time) and operational cost of the service. The model developed is applied to low and high demanded routes in the current Barcelona Bus Network, so the implementation of this new system will be analyzed. The less demanded line corresponds to the V5 (Zona Franca-Avinguda Pearson), while the crowded one to the H10 (Plaça de Sants-Olímpic de Badalona).

2. CONCEPT OF AUTONOMOUS DRIVING MODULAR BUS

Buses are still conceived as a classical configuration of one driver leading the bus and slowing at every stop that passengers request. In order to understand the meaning of this new technology, we must see beyond the concept of bus that we own. This new system is developed with the idea of not stopping at traffic lights neither at bus stops, with totally electric vehicles and, as its name suggest, driverless.

First, no-stopping at traffic lights is not anything new. Many on-streets public transport, like the Barcelona, Zaragoza, or Granada's tramways, rarely stop at them since activated traffic light priority measures are deployed (Estrada et al., 2009). This idea should be tested in buses with the aim to ease bus circulation in detriment of the private vehicle. Of course, this requests a complete restructuration of the current traffic lights configuration.

Second, this technology changes drastically our conception of buses. Nowadays, the word "bus" makes us thing about a large and indivisible vehicle to convey people. But the "modular" bus suggests something different; the current bus will be transformed into a convoy made of n-pods that will be able to couple and uncouple freely, like a train with its wagons. The key idea in this conception is that pods will be detached from the convoy to give service at the bus stop, while the other part of the convoy continues its journey. A brief scheme of the concept is shown in Figure 1.

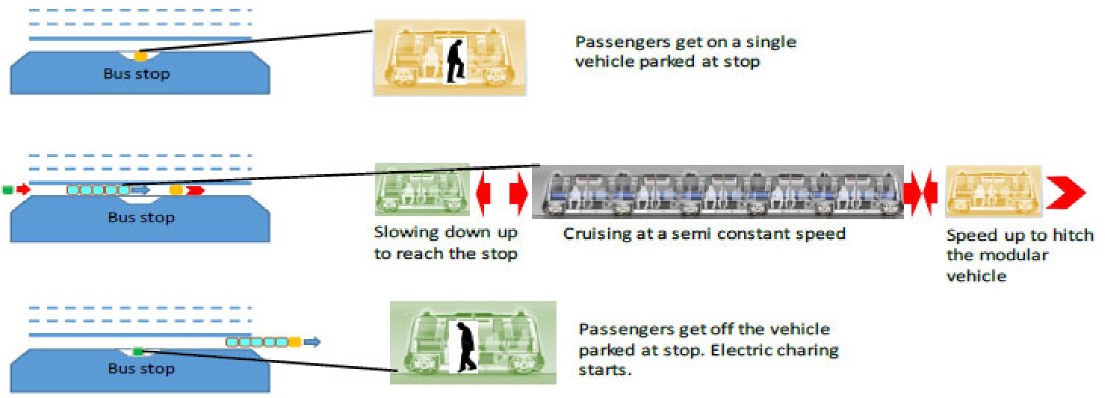

Figure 1: Operational scheme.

On the other side, there will always be a pod ready at the bus stop to depart when it detects that the convoy is approaching.This new pod will be attached to the front of the set, and the procedure will be repeated at the next bus stop. This ability of coupling and uncoupling gives passengers the chance of not stopping at every bus stop, as they will be able to move freely between pods when the convoy is running. In addition, it will be possible to couple and uncouple n-pods per stop depending on the demand that needs to be satisfied, and this ability will also ease the job when it comes to deploy more pods when the service requires it. Finally, these pods will be driverless and their traction will be based in electric batteries.

3. METHODOLOGY

The model proposed has some simplifications to make the estimation of performance variable easier to reproduce and understand. Despite this, the results obtained are not far from the real ones (Daganzo, 2009), and can therefore be taken as valid. These simplifications are to assume a uniform demand through all the line, and an equidistance spacing between stops. The model presented aims to reduce the total cost of the system (Z_T), as the sum of the agency's (Z_A) and users' (Z_U) costs (Eq. 1).

$$Z_T = Z_A + Z_U \tag{1}$$

3.1 Agency's Costs

The formula to determine all the cost incurred by the agency (Equation 2) is a combination of different factors that are introduced along the following subsections.

$$Z_A = €_L \cdot L_T + €_V \cdot V + €_M \cdot M + €_{ER} \cdot M + €_B \cdot C \cdot M \tag{2}$$

3.1.1 Infrastructure Cost (€L) and Route Length (LT)

These firsts terms of the equation do not vary regardless of the bus type: diesel, hybrid or electrical. The proxy $€_L$ represents de infrastructure deterioration, expressed in [€/km-h], and the variable L_T is the route length expressed in [km].

2.1.2 Unit Vehicle Distance Cost (€V) and Distance Covered by the Fleet (V)

The unit vehicle distance cost represents the energy cost per kilometer to run each pod plus its maintenance cost. It is expressed in [€/veh-km] and its values are (Estrada et al, 2021).

Concept	Value
Energy Cost	0,036
Pod Maintenance	0,66
$€_V$ Total	**0,696**

Table 1: Estimation of the unit distance cost, €V [EUR/veh-km].

It has been estimated that the pod's energy consumption will fall between the consumption of an electric car and bus. Considering a Tesla Model S (5 meters long) with an average consumption of 0,20 kWh/km (Motorpasion, 2019), and a 1,00-1,40 kWh/km as an average current standard bus (12 meters) consumption (Estrada et al, 2021), a pod energy consumption of 0,30 kWh/km will be considered. Then, multiplying this number by the electricity price (0,1199 €/kWh Spain average in April 2020) the energy cost is obtained. Regarding the maintenance cost, the value has been taken directly from Estrada et al (2021). On the other side, the distance covered by the fleet per hour (*V*) [veh-km/h] is calculated with the following equation.

$$V = L_T/H \cdot \#_{pods/convoy} \tag{3}$$

where H represents the headway [hours].

3.1.3 Unit Vehicle Temporal Cost (€M) and Number Vehicles (M)

The third term of the sum corresponds to the agency expenses related to temporal units, expressed in [€/veh-h], and the number of pods serving the line (*M*). These temporal expenses are determined in the following table.

Concept	Value
Driver Salary	0,00
Vehicle Amortization	1,587
Insurances, Technicians and Engineers	11,83
$€_M$ Total	**13,417**

Table 2: Estimation of the unit temporal cost, €M [EUR/veh-h].

The driver salary disappears because of the autonomous vehicles. Regarding the vehicle amortization, easymile (pod manufacturer) builds 4 meters long pods. So, considering the average acquisition price per meter of electric, hybrid and diesels buses according to Estrada et al (2021), an acquisition price of 100.000 €/vehicle will be approximated. If each pod runs for 15 years, 300 days/year and 14 hours/day, the value is obtained. The insurances and other salaries are also taken directly from Estrada et al (2021). On the other side, the number of pods needed per line are found with Eq. (4).

$$M = [V/v_{Net} + n \cdot L_T/s] \tag{4}$$

where n represents the number of pods stopped at each bus stop, v_{Net} stands for the commercial speed [km/h], and s is the separation between two bus stops [km]. Through all this model, "n" will be considered 1. Please, note that the second quotient represents the total number of stops thanks to the simplification of equidistance spacing between stops.

3.1.4 Unit Vehicle Charging Facility Cost (€ER)

The charging of pods will be performed during the 10 hours per day that they do not run. Because obtaining a reference value is quite complex, it has been taken the one from Estrada et al (2021) for electric buses with a slight modification. Now, it will be considered that each charger can supply energy to two pods simultaneously, and its lifespan should be 30 years, 300 days/year and 10 hours/day. This parameter is expressed in [€/veh-h].

Concept	Value
Facility Amortization (€/day)	9,60
Facility Maintenance (€/day)	10,00
Pods per Charger	2
€$_{ER}$ Total (€/veh-h)	**0,98**

Table 3: Cost of the Charging Facility, €ER.

3.1.5 Unit Temporal Battery Cost (€B) and Battery Capacity (C)

This new technology must satisfy that the battery endures for all day run without charging. Of course, a different charging scheme must be implemented with charging points along the road, but to simplify the model, it will be considered that pods can only be recharged at depots.

First, the term €$_B$ represents the battery cost expressed in [€/kWh-h] considering a battery lifespan of 4 years (Estrada et al, 2021). What is more, Estrada et al (2021) also suggests recommends using a battery price of 400$/kWh. So, if the pod runs 300 days/year and 14 hours/day, "€B" stands for a value of 0,021 €/kWh-h. The Battery Capacity, expressed in [kWh], is something to be determined with the results shown at the end, as it is totally related to the headway (H), stop spacing (s) and the number of pods per convoy. However, the pod's energy consumption per day is found in Eq. (5), and it satisfy the Battery Capacity (C) requirement.

$$Consump. = v_{Net}[\mathrm{km/h}] \cdot f_{consump}[\mathrm{kWh/km}] \cdot 14[h/day] \cdot (1 + S_{Factor}) < C \quad (5)$$

The consumption factor is 0,30 kWh/km, the pod runs 14 hours/day, and a 20% safety factor has been taken, which is enough to cover extra consumptions like accelerations, air cooling and slopes. Finally, the commercial speed (or net speed) is approximated with the following equation.

$$v_{Net} \approx L_T/((L_T/v_{Cr}) + (H + \tau) \cdot (L_T/s \cdot \#_{pods/convoy} + 1)) \quad (6)$$

where v_{Cr} represents de cruising speed of the pod [km/h], and "τ" the time lost by each pod for breaking and accelerating at a bus stop in comparison with a non-stopping one [hours].

3.2 Users' Costs

When users travel, they spend time and money. The money side is fully covered with the ticket price, but one way to transform this time into monetary units is using the so-called Value of Time, which takes into account the user salary. The formula used to determine the user's cost is the following one, where Λ represents the hourly demand expressed in [pax/h], β the value of time and the term into brackets is the expected door-to-door travel time of a single passenger.

$$Z_U = \Lambda \cdot \beta \cdot (A + W + IVTT) \tag{7}$$

3.2.1 Value of Time (β)

This first parameter of the equation is crucial because it translates the time spend on public transport into monetary terms. It is estimated to be 12,50 €/pax-h. This average value comes from considering a salary of 2.000 €/month and working 40 hours per week.

3.2.2 Access and Exit Time (A)

The first and last part of every journey by public transport corresponds to the walking time to the bus stop and to our destination once we get off the transport. Because one of the simplifications is to consider an evenly distributed demand, the expected access and exit time are the same, so the term "A", [hours], represents the sum of both.

$$A = ((s/4)/v_w + (s/4)/v_w = s/(2 \cdot v_w \tag{8}$$

where v_w is the walking speed of the pedestrian [km/h].

3.2.3 Waiting Time (W)

The waiting time includes factors like service regularity, traffic jams, and even smartphones applications that tells the remaining time for the vehicle to come. Nevertheless, to simplify the calculous, considering a perfect regularity and no use of mobile phones, and with the aid of the same simplification used in 3.2.2., the expected waiting time is half the headway.

$$W = H/2 \tag{9}$$

3.2.4 In-Vehicle Travel Time (IVTT)

This is usually the bigger time when travelling by public transport. So, if an improvement of the service offered needs to be done, it is imperative to reduce the time spend by the user inside the bus. In this particular case of the autonomous and modular bus, the user will only perceive an acceleration, travelling at constant speed, and breaking time. So, the equation used is shown hereunder.

$$IVTT = (l/v_{Cr}) + \tau) \tag{10}$$

where l represents the length travelled by the user inside the pod (which has been considered as $L_T/4$ to be conservative) in [km], and "τ" the time lost by a pod to accelerate and brake in comparison with a non-stopping one.

4. RESULTS AND DISCUSSION

The Autonomous Driving Modular Bus has not been implemented yet in any city as a conventional mode of transport. Thus, these chapter will not study any real configuration but to give the optimal parameters to obtain the best configuration and minimize the total cost of the system (Z_T). These "key" parameters are the headway (*H*), the stop spacing (*s*), and number of pods per convoy. In addition, it will be also possible to determine the battery capacity (C).

Besides the battery capacity requirement, any public transport service must also satisfy the occupancy (O) one. It means that the service provided must be enough to cover the whole demand, otherwise there would be users that will not be able to go aboard. The occupancy is found with Eq. (11).

$$O = l/L_T \cdot \Lambda \cdot H \ \leq C_p \tag{11}$$

where Cp represents de pod capacity [pax/veh], with a value of 15 pax/pod according to Easymile. Finally, and before getting into detail with the results, it must be stated that a minimum and maximum threshold on those key parameters have been adopted to simulate a real solution, and not letting the optimization fall into an unfeasible one.

Concept	V5 Line	H10 Line
Headway (minutes)	5-15	1-7
Stop spacing (km)	0,30-0,75	0,30-0,75
Minimum pods/convoy	2	3

Table 4: Optimization thresholds.

4.1 Input parameters

The set of parameters (Guida et al., 2018; Estrada et al., 2021) used are presented below.

Parameter		V5 Line	H10 Line
Line Length (L_{Total})	km	15,20	23,70
Demand (Λ)	pax/h	396	6.247
Length covered by Users (l)	km	3,80	5,93
Free Speed (v_{Cr})	km/h	40,00	
Maximum Speed (v_{Max})	km/h	50,00	
Acceleration (a)	m/s^2	1,30	
Value of Time (β)	€/h	12,50	
Pedestrian Walking Speed (v_{walk})	km/h	4,00	
Infrastructure Cost (€$_L$)	€/km-h	7,61	
Unit Vehicle Distance Cost (€$_V$)	€/veh-km	0,696	
Unit Vehicle Temporal Cost (€$_M$)	€/veh-h	13,417	
Unit Vehicle Charging Facility Cost (€$_{ER}$)	€/veh-h	0,98	
Unit Temporal Battery Cost (€$_B$)	€/kWh-h	0,021	

Table 5: Input parameters.

4.2 Results

After combining all the equations and numbers seen up to now, and doing an optimization process with the main aim to reduce the total cost of the system (Eq. 1), the following optimal variables are found.

Parameter		V5	H10
Headway (H)	min	8,00	1,50
Stop spacing (s)	km	0,73	0,30
Battery Capacity (C)	kWh	63,96	118,03
Pods/Convoy	-	2	4
Total Pods (M)	veh	39	243
Occupancy (O)	pax/veh	13,20	39,04
Agency's Costs (Z_A)	€/h	888,40	6.922,44
Users' Costs (Z_U)	€/h	1.266,63	15.702,83
Travel Time per Trip	min	15,35	12,07

Table 6: Optimization results.

It can be clearly seen that the occupancy is always below the convoy capacity. What is more, all convoys have one extra pod in case any user wants to get off at the next bus stop.

4.3 Comparison with Current Configuration

If the optimal results obtained are compared with the current bus configuration in those lines (run by diesel, hybrid, and electric buses), the user's and total costs suffers a huge downfall. It must be clarified that the V5 is served with standard buses (12 meters), while H10 with articulated ones (18 meters).

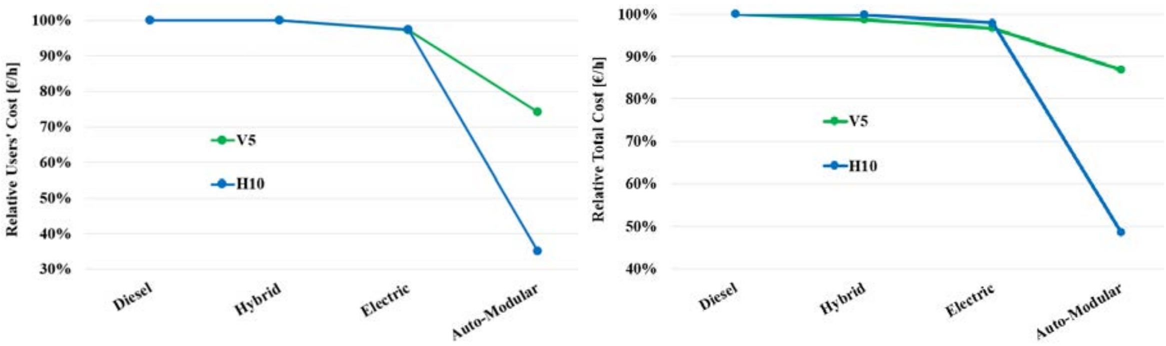

Figure 3: a) Relative Users' Cost to Diesel vehicles, b) Relative Total Cost to Diesel vehicles

As reflected in both figures, user and total costs are reduced when technology evolves to greener vehicles. In addition, one must notice the tremendous reduction the Autonomous Driving Modular Bus could bring to the system if it is implemented. However, it has been seen that the agency cost would increase considerably. In this sense, the current configuration for the H10 line run by electric buses, produces expenses up to 2.228 €/h, while the optimal one for the autonomous driving modular bus provides an agency cost of 6.922 €/h. This occurs due to the large number of pods needed in comparison with the number of buses deployed today.

5. CONCLUSION

It is inevitable to express the necessity for developing a more efficient and sustainable public transport. The results express it themself; as technology upgrades, the reduction in users' and total costs is significant. And not only that, but in environmental and health terms too.

The results also demonstrate that low-demanded lines do not perceive that change in the technology as much as the high-demanded ones. This means that for the low ones, the improvement in technology is not a key factor when it comes to determine the optimal type of bus (diesel, hybrid…). Nevertheless, the high-demanded lines experience a contrary effect; the need for a better and sustainable bus type rises in effigy while the total costs are more than halved. Thus, a first conclusion is the good behavior this new technology would have in high-demanded lines.

Although the results displayed demonstrate the high efficiency it presents, the model has been applied to a very particular case. So, it needs further study in other environments and situations, as well as an exhaust research in different operational schemes and charging itineraries within the lines, which will come in handy to reduce costs even more.

Finally, this further study also needs to focus on the elongation of these lines through the suburbs, which will improve the territorial cohesion with the peripherical neighborhoods and will connect them in a fast and efficient way.

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