OPPORTUNITY CHARGING OF BUSES. EFFECTS ON BUS OPERATOR COSTS AND USER PERFORMANCE

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1. INTRODUCTION

Transit systems are a key strategy to reduce the use of private cars and mitigate congestion episodes in major cities. Transit networks can be operated by different kinds of transit technology (Bus, BRT, LRT or Subways). In recent years, the deployment of high performance bus systems (HPB) has provided competitive user travel times, comparable to Light Rail Transit Systems, at reasonable capital expenditures. However, there is already a pending issue to be addressed. As Subways and Light rail transit systems take the energy to move the rolling stock from electric power plants, the vast majority of HPB vehicles are powered by internal combustion or hybrid engines. Therefore, these bus systems are responsible for the emission of a huge quantity of pollutants that contributed to the global warming problem (GHG) or worsened the health of the citizens in metropolitan areas. In order to tackle this problem, the European Union are fostering the deployment of electric bus vehicles in the operation of European cities. Hence, the implementation of these electric buses, will contribute to the reduction of the fossil fuel consumption, carbon dioxide (CO_2) emissions and local air pollution, by improving energy efficiency.

Those standard buses (12 meters long) operating routes during a daily shift of 12 hours or less can be charged at bus garage (depot) at the end of the service. This slow charging operation takes 2-5 hours and does not have any effect on the user performance and does not imply further vehicles. However, for those bus routes requiring articulated buses or 12 hours or more of continuous service, the bus batteries should be charged during the service. This operation is known as opportunity charging. It consists of an on-street fast-charging operation of bus batteries and present two available schemes: (i) charging at ending / starting bus stops in each line direction and (ii) charging at intermediate stops of the bus route. The former scheme will maintain the in-vehicle travel time, but the time spent at ending stops (lay-over time plus slacks) is usually higher than the conventional diesel-engine powered vehicles. This fact causes that bus operator would need additional vehicles to operate the bus route at the desired headway. Additionally, when the required charging time is greater than the target headway, we would perform charging operations with multiple charging points in tandem or in parallel at the end of the route. This operating requirement is usually incompatible with the limited public space in urban areas. The latter scheme may increase both in-vehicle travel time and fleet size if the charging operation is made at stops with low passenger boarding rates.

The aim of this paper is to analyse the effect of the opportunity charging constraints on the operation of bus services. The total number of resources (vehicles and chargers) is assessed by an analytical model that resembles the bus operation for each electric charging scheme. This model is also able to estimate the corresponding operating variables for diesel buses. The effects of opportunity charging have been estimated on the bus route H6 and H16 in Barcelona.

2. ESTIMATION OF OPERATING VARIABLES

The usage of electric vehicles will imply new operating schemes and kinematic characteristics (acceleration, deceleration, commercial speed) that may vary both the number and type of resources to be deployed in the bus route. In this section, the operating issues to analyze the performance and agency cost of BEB electric buses in comparison to ICE vehicles are presented on a given single route. This analysis is based on the models explained embraced in Piccioni, C. and A. Musso (2017), where the authors contributed in estimating the effects of opportunity charging in the operation of urban bus lines.

For the sake of simplicity, we consider the route of Figure 1 that presents 2N bus stops located along the whole length, where the position of each stop is denoted by s. Stops s=1 and s=N denote the starting points for each route direction trip.

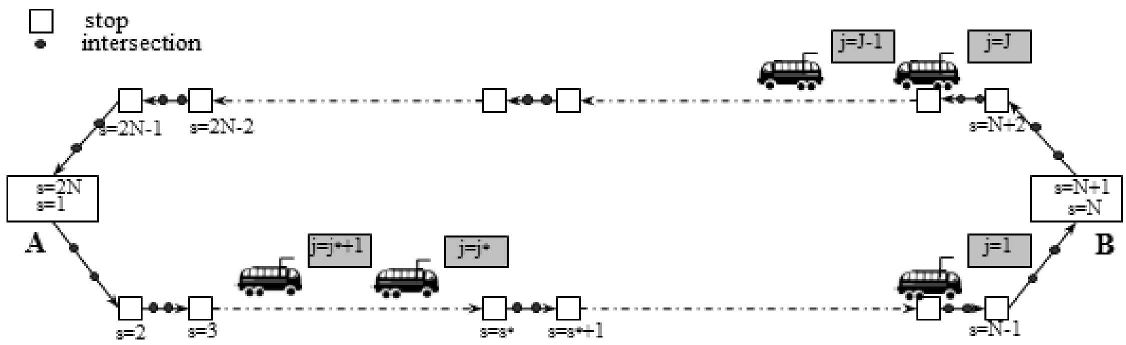

Figure 1. Schematic illustration of a bus route. Source: Estrada et al. 2016

Let M be the total number of buses operating the whole roundtrip. The gross commercial speed of this bus route is estimated as the quotient of the route length (L) over the vehicle travel time in each direction (R), excluding the time spent at the ending stops of each direction. The total average travel time of a single bus (R) in both directions can be estimated by Equation (1):

$$R = \sum_{s=1}^{N} (T_{r,s} + T_{p,s} + T_s) + \sum_{s=\mathrm{N}+1}^{2N} (T_{r,s} + T_{p,s} + T_s) \quad (1)$$

The expression of equation (1) is the sum of three time components in each segment between stop s and s+1 for both route directions: the average running time ($T_{r,s}$), the average time spent at intersections ($T_{p,s}$) and the average time spent at stop s (T_s).

Nevertheless, disruptions make it difficult to maintain the time-headway adherence of buses and control the transit system performance. A traditional way to reduce this effect is to introduce slack times in bus schedules at determined stops (holding points) along the route, which affects the roundtrip travel time; and consequently the fleet size M. In Estrada et al (2016) the slack time strategy is explained as the inclusion of an additional amount of time in the bus schedule at certain stops.

Therefore, in Equation (2) the potential holding time (φ_s) is introduced in schedule at stop s in order to compensate potential service disruptions (if it exists). Although slacks could have been implemented at any stop s (s=1, …, 2N), bus agencies prefer that holding times be performed only at the ending stop of each direction of service (also called headers) to maintain time-headway adherence (s=N and s=2N). The reason is that, at these ending stops all onboard passengers must alight, so the term does not infer any additional travel time for passengers. Therefore, holding times are usually $\varphi_s=0$ for s=1,..;N-1; N+1,..,2N-1.

$$R' = R + \sum_{s=1}^{N} (\varphi_s) + \sum_{s=\mathrm{N}+1}^{2N} (\varphi_s) \quad (2)$$

When we are wondering to estimate the fleet size needed, the roundtrip travel time should consider the time spent by buses at the ending stop of each route direction AB and BA (see Figure 1). At these ending stops s= 2N (A) and s=N (B) the bus schedule usually encompasses the lay-over times θ_A and θ_B to let drivers rest for an amount of time. This extra time is defined by a mandatory labour rule for each agency and it is independent of the slack time devoted at holding points.

Finally, the total travel time (T) including those time spent at ending stops is determined in Equation (3). The net commercial speed v_c to be considered to estimate the fleet size is defined by Equation (4).

$$T = R' + (\varphi_A + \theta_A) + (\varphi_B + \theta_B) \quad (3)$$

$$v_c = \frac{L}{T} = \frac{L}{\sum_{s=1}^{N}(T_{r,s} + T_{p,s} + T_s + \varphi_s) + \sum_{s=\mathrm{N}+1}^{2N}\left(T_{r,s} + T_{p,s} + T_s + \varphi_s\right) + (\varphi_A + \theta_A) + (\varphi_A + \theta_A)} \quad (4)$$

Therefore, the estimation of the fleet size (M) provided in Equation (5) will be composed by a term that represents the minimal number of vehicles needed to provide a time-headway (*R/H*), and an additional number of vehicles (B/H) to ensure the resting time for the drivers at the ending stops and the holding times to perform the system coordination by slacks along the route, where $B = \left[\theta_A + \theta_B + \phi_A + \phi_B + \sum_{s=1}^{N} \phi_s + \sum_{s=N}^{2N} \phi_s\right]$.

$$M = \frac{T}{H} = \frac{R+B}{H} \quad (5)$$

In fact, the term B captures the sum of all unproductive times and should present a number as low as possible to minimize inefficiencies.

2.1. OPERATING CONSTRAINTS CAUSED BY THE BATTERY CHARGING SCHEMES

The average unit distance energy consumption of a bus depends on the weather conditions, slope of the route, congestion, density of stops. It ranges between 1-2.5 kWh/km (12 meters long standard bus) and 2-4 kWh/km (18 meter long articulated bus). In addition to that, BEB need to maintain the State of Charge (SOC) of their batteries in a given domain of operation defined by the manufacturer (for example 0.2<SOC<0.8) to ensure the guaranteed cycle life (number of discharge-charge cycles that the battery can handle). This fact, introduces more constraints in the operation scheme of the electric route. Although there is enough room in the roof or base of the bus chassis to accommodate the battery pack, the main limitation it’s the maximal weight. Due to this fact, BEB vehicles cannot be in service during the whole daily shift. It can be stated that there is not any fully- electric articulated bus of 18 meters of length in the market (or even an articulated bus prototype) able to provide continuous service (15-16 hours per day) with an initial charge at the bus garage. All of them need on-route charging operations at charging stations located along the route to maintain the actual SOC under the target domain.

Generally, there are three types of charging operation of the bus batteries depending on the range of the vehicles:

Bus garage charging. This charging operation usually takes 2-5 hours (slow charging) and is performed during the night period at bus garage, once the BEB has finished the service.

Opportunity charging. This charging scheme is undertaken when the available SOC range of the batteries does not allow the provision of the required daily vehicle mileage between two consecutive charging operations at bus garage. In those cases, fast charging stations should be deployed along the route to provide enough energy to maintain the SOC level at the recommended values. Therefore, the charging operation is made on-street during the service. There are two operations schemes known as opportunity charging depending on the location of the charger points:

Opportunity charging at the ending stop of each route direction. The charging operation can be made at the ending stops of the route direction, taking 3-8 minutes.

Opportunity charging at intermediate stops of a route direction. This option reduces the battery weight and size. As there are several charging points along the route, the

SOC can be more frequently rebalanced with fast charging operation at bus stops. It allows the usage of super capacitors in vehicles, elements of higher energy power and lower energy capacity. In that situation, each charging operation can be done in 10-30 seconds.

The charging time at depot or, specially, at on-street charging stations, is the new crucial decision variable in an electric operation system. This variable encompasses one component needed to provide the target amount of electricity according to the planned range between two consecutive charging operations. This electric charging time $T_{ch,x}$ is proportional to the length L_x travelled between two consecutive charging points, to the vehicle energy consumption f_c and to the inverse value of the recharging speed of the station, S . Additionally, the initiation of the charging operation needs that bus driver has parked the vehicle properly in the on-street charging platform and the pantograph equipped in the vehicle (or other substitutive device) is fully spread out to connect to the charging voltage arch. This operation takes an additional prepositioning time T_{po}. Therefore, the total time devoted to the charging operation ($T_{co,x}$) is defined by the sum of the electric charging time and prepositioning time (Equation 6)

$$T_{co,x} = \frac{L_x fc}{S} + T_{po} \tag{6}$$

Depending on the value of this charging time estimated by Equation (6), the agency cost might rise because more vehicles might be needed. Moreover, the total charging time at the header stops will determine whether one or more charging points at these stops are needed. We identified three different situations in which the number of resources or the sequence of the charging operation may differ. The following conditions have been analyzed considering a tough assumption: vehicles arrive regularly at bus stops and the time headway adherence is excellent.

Case 1. The charging operation time needed at each ending stop A or B is lower than the corresponding lay-over time $T_{co,A} \leq \theta_A$, $T_{co,B} \leq \theta_B$, . In these cases, there is enough time at bus headers to complete the charging time without introducing more idle time in the schedule. The roundtrip travel time T is maintained by the expression $T = R' + (\varphi_A + \theta_A) + (\varphi_A + \theta_A)$. Note that the slack time introduced in the target bus schedule is not considered in this evaluation. Delayed buses can recover the headway adherence with the vehicle ahead at the expenses of being held a time t at the ending stop A, where $+\theta_A < t < \varphi_A + \theta_A$. A similar condition can be provided at bus header B replacing the variables $(\theta_A; \varphi_A)$ by $(\theta_B; \varphi_B)$.

Case 2. The charging operation time is higher than the lay-over time but still lower than the headway, H (i.e. $\theta_A < T_{co,A} \leq H$ or $\theta_B < T_{co,B} \leq H$). In these situations, buses need to spend an additional time at charging or header stations to perform the charging operation. The term of lay-over time, θ_A at bus header A should be replaced by the charging operation time, $T_{co,A}$ (in bus header B we need to replace lay-over times by the corresponding charging operation time $T_{co,B}$). Consequently, the new roundtrip time considering the time spent at bus headers (T') is now defined by Equation (7).

$$T' = R' + (\varphi_A + \varphi_B) + \max(\theta_A; T_{co,A}) + \max(\theta_B; T_{co,B}) \quad (7)$$

Additionally, the additional number of vehicles needed to provide service is estimated by means of Equation (8) with regard to a regular bus that only spent lay-over and holding times at ending stops:

$$\Delta M = \frac{T' - T}{H} \quad (8)$$

Case 3. The charging operation time is higher than the target headway. In these situations, we need to increment the number of charging positions or platforms at ending stops and allow bus charging operations in parallel or tandem servers. Parallel charging layout is not usually feasible in urban streets. Moreover, the deployment of the tandem servers is also affected by the distance between two consecutive intersections in a common block. Therefore, the maximal number of tandem servers would be limited to 2-3 servers. In that way, if we refer the number of servers as N_s at each ending stop, the necessary condition to allow the dispatching of vehicles at each H time period is stated by Equation (9).

$$T_{co,x} \leq N_s \cdot H \quad (9)$$

3. DISCUSSION

In this section, we will focus on specific bus route planning examples to quantify the effects of electric operation. In fact, we will analyze the H6 and H16 bus routes of the new bus system in Barcelona. To do so, we will consider the operation in perfect headway-adherence.

H6 is a straight-shaped route that connects several university campus (Zona Universitaria) and new business areas to residential districts (Fabra i Puig), running along quite congested streets and avenues. The line presents a target time headway of H= 4.72 min, with 23 buses operating the roundtrip service, and a total passenger flow of 1400 pax/h in the period of study. The line has a mandatory layover time of 3 minutes and an additional slack time of ϕs= 3 minutes for tackling bus bunching at each ending stop of each route direction. The capacity of these buses is 134 pax/veh. The line is 19.3 km long with 49 bus stops.

Additionally, we have also analyzed the H16 bus route that connects Zona Franca to the Forum district along the sea front of Barcelona city. This line is 24.2 km long and presents 67 bus stops. We consider the same layover time (3 minutes) at each bus direction however the slack time is now higher (4 minutes). The layout and lengths of each direction of service in both bus routes H6 and H16 are characterized in Figure 2 and Table 1.

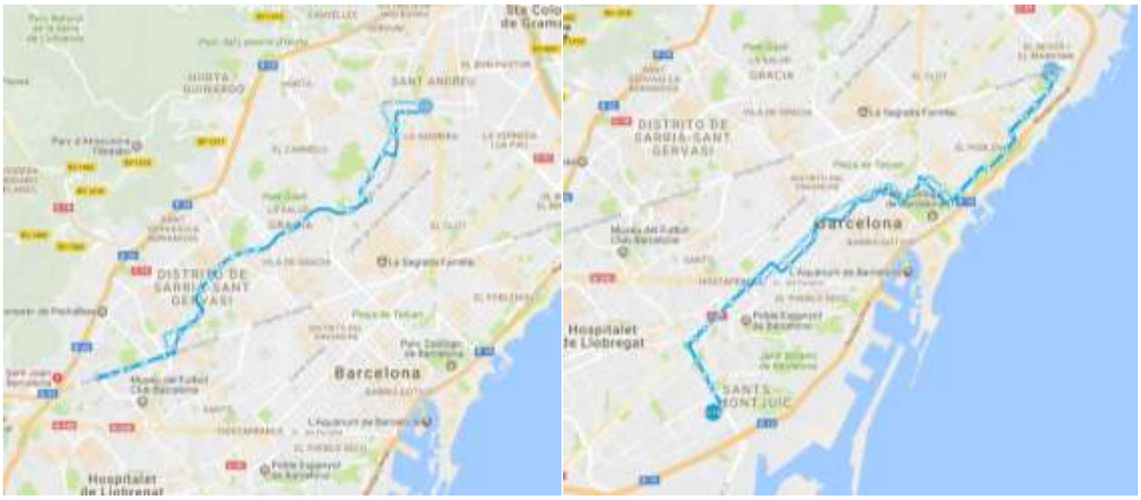

Figure 2. Layout of the bus route H6 (left) and H16 (right) operated by TMB (major bus agency in Barcelona city).

Table 1. Length of the direction trips in route H6 and H16.

Trip	H6 route	H16 route
Garage to origin A	15.86 km	4.11 km
One way trip, A-B	9.59 km	12.21 km
Return trip, B-A	9.74 km	11.99 km
Destination B to Garage	4.08 km	12.88 km

We consider that these bus routes will be fully operated with the vehicle tested in the Barcelona demonstration in the framework of ZeEUS project. This is a fully electric bus of 18 meters of length manufactured by Solaris. Once the pilot test will have been completed, it is supposed that the whole fleet in route H16 and H6 will consist of this vehicle typology. The most important electric attributes of these vehicles will be the following: a) the nominal capacity of the battery pack is 125kWh, b) the speed of the charging station is 6.67kWh/min and c) the available SOC can be always kept equal or higher than 40% (conservative value considered by the bus operator in the pilot test). We will consider only charging points at the header stops. For the analysis we consider six different alternatives of charging point layout:

- Deployment of 1 charging point at route origin A – 0 charging points at route origin B .
- Deployment of 0 charging points at route origin A – 1 charging point at route origin B.

- Deployment of 1 charging point at route origin A – 1 charging point at route origin B.
- Deployment of 2 charging points at route origin A –0 charging points at route origin B.
- Deployment of 0 charging points at route origin A –2 charging points at route origin B.
- Deployment of 2 charging points at route origin A –2 charging points at route origin B.

Additionally, we consider a given range of the energy consumption factor of (2.5; 3.5) kWh/km. This range has been estimated considering the information provided by the bus manufacturer from its in-house tests and the weather conditions in Barcelona. Therefore, the electric feasibility range of the batteries has been verified for an energy consumption variation of 0.1KWh/km. This range is supposed to encompass the real consumption that these vehicles will have in real operation. Table 2 and Table 3 summarize the final results obtained in this energy consumption range for the proposed charging schemes in route H6 and H16 respectively. The columns determine whether the solution is feasible or not in terms of headway adherence (🕓), and the SOC consumption (🔋, lower than 60%). The temporal suitability for charging the battery and the maintenance of a convenient headway, depends on the charging and manoeuvre or prepositioning time. This time should be lower or equal to the headway of the line. If the scenario is time- feasible, the column will have a green "V", otherwise it will have a red "X". The battery scheme is feasible (green "V") in the scenario, as long as the battery consumption in the trip under analysis does not exceed the 60% of the nominal battery capacity. If this constraint is violated, a red "X" will be displayed in the column. We also consider the integer number of vehicles needed to provide the service. In those cases when the charging time is greater than the lay-over time, the number of vehicles can be increased.

Table 2. Feasibility analysis of electric charging schemes in route H6 (Barcelona).

	Charging points distribution scheme																	
Unit Consumption (kWh/km)	1-1			1-0			0-1			2-0			0-2			2-2		
	🕓	🔋	M (veh)	🕓	🔋	M (veh)	🕓	🔋	M (veh)	🕓	🔋	M (veh)	🕓	🔋	M (veh)	🕓	🔋	M (veh)
2.5	V	V	24	X	V	24	X	V	24	V	V	24	V	V	24	V	V	24
2.6	V	V	24	X	V	25	X	V	25	V	V	25	V	V	25	V	V	24
2.7	V	V	24	X	V	25	X	V	25	V	V	25	V	V	25	V	V	24
2.8	X	V	24	X	V	25	X	V	25	V	V	25	V	V	25	V	V	24
2.9	X	V	24	X	V	25	X	V	25	V	V	25	V	V	25	V	V	24
3	X	V	24	X	V	25	X	X	25	X	V	25	X	X	25	V	V	24
3.1	X	V	24	X	V	25	X	X	25	X	V	25	X	X	25	V	V	24
3.2	X	V	24	X	V	25	X	X	25	X	V	25	X	X	25	V	V	24
3.3	X	V	24	X	V	25	X	X	25	X	V	25	X	X	25	V	V	24
3.4	X	V	25	X	V	25	X	X	25	X	V	25	X	X	25	V	V	25
3.5	X	V	25	X	V	25	X	X	25	X	V	25	X	X	25	V	V	25

Table 3. Feasibility analysis of electric charging schemes in route H16 (Barcelona).

	Charging points distribution scheme																	
Unit Consumption (kWh/km)	1-1			1-0			0-1			2-0			0-2			2-2		
	◷	▬	M (veh)	◷	▬	M (veh)	◷	▬	M (veh)	◷	▬	M (veh)	◷	▬	M (veh)	◷	▬	M (veh)
2.5	V	V	20	X	V	21	X	V	21	V	V	21	V	V	21	V	V	20
2.6	V	V	21	X	V	21	X	V	21	V	V	21	V	V	21	V	V	21
2.7	V	V	21	X	V	21	X	V	21	V	V	21	V	V	21	V	V	21
2.8	V	V	21	X	V	21	X	V	21	V	V	21	V	V	21	V	V	21
2.9	V	V	21	X	V	21	X	V	21	V	V	21	V	V	21	V	V	21
3	V	V	21	X	X	21	X	V	21	V	X	21	V	V	21	V	V	21
3.1	V	V	21	X	X	21	X	X	21	V	X	21	V	X	21	V	V	21
3.2	V	V	21	X	X	21	X	X	21	V	X	21	V	X	21	V	V	21
3.3	V	V	21	X	X	21	X	X	21	V	X	21	V	X	21	V	V	21
3.4	V	V	21	X	X	21	X	X	21	V	X	21	V	X	21	V	V	21
3.5	V	V	21	X	X	21	X	X	21	V	X	21	V	X	21	V	V	21

From the results of route H6 presented in Table 2, there are critical unit consumption factors that define three different charging schemes. For low energy consumption (<2.8 kWh/km), the best charging point distribution scheme is the deployment of 1 charging station at both ending bus stops (scheme 1-1 with chargers at Zona Universitària A and Fabra i Puig B). This scheme only needs 24 vehicles to operate the service and fulfil the dispatching of vehicles at the desired time headway as well as the sufficient range of the batteries. When the energy consumption ranges between 2.8-3kWh/km, there are two potential charging distributions: the 2-0 (or 0-2) and 2-2 scheme. The former scheme has just 2 charging stations but needs an extra vehicle (25 operating vehicles). The latter implies 2 extra charging stations but maintains the fleet size at 24 vehicles. Generally, for costs purposes, we will prefer the scheme 2-2 that reduces one operating vehicle than reducing charging stations. This statement is also justified by safety deployment reasons.

However, for unit energy consumption factors higher than 3 kWh/km, the only feasible scheme is the deployment 2 charging stations at each origin and destination (A and B) of the route. In that case, for energy consumption factors higher than 3.4kWh/km, the route will need an extra vehicle (25 vehicles in service). The reason is that vehicles must spend more time charging at ending stops and this fact increases the roundtrip travel time.

The most restrictive constraint to ensure the feasibility of the service from the results is the headway adherence (◷). In fact, 0-1 and 1-0 schemes never allow dispatching bus vehicles at the desired headway. In those cases, the charging time at the bus header is greater than the headway. However, all six charging schemes guarantee a sufficient range for operating the two route directions. Some of them are not able to guarantee the minimal available 40% of SOC in the trip between the more distant stop with regard to the bus garage (schemes 0-1 and 0-2). In those cases, the origin of the route without charging point (point A) is 15.96 km away from the bus garage, and the bus had previously run the distance between points B-A in service (9.74 km).

The results in route H16 (Table 3) are more homogeneous since lay-over times at bus headers and time headway are higher. These facts allows that charging operation can be done simultaneously with the rest of drivers and vehicles are dispatched less often. In that route, the most efficient charging scheme is the 1-1 for all energy consumption factor domain considered. Schemes 1-0 or 0-1 can never maintain the target headway.

4. CONCLUSION

The deployment of battery electric buses (BEB) will have an important effect on the route operational planning. Some buses can provide 12-14hours of continuous service between two consecutive charging operations. However, articulated buses or standard buses operating long daily shifts (higher than 14 hours) currently need opportunity charging to maintain the daily mileage.

The provision of BEB in busy bus routes with low time headways (headway less than 6 minutes) is a challenge. In case they need opportunity charging, the necessary charging time at the ending stop of one route direction will require higher holding times at final stops than in diesel buses. Indeed, this charging time would be usually higher than the target headway. This fact would imply that multiple charging platforms at the ending stop need to be deployed to perform charging operations simultaniously at different vehicles. Although parallel charging servers would be preferable, the limitations of urban layout only admit tandem charging points, distributed along the right lane. On the other hand, if this charging operation is made at intermediate stops, the dwell time at stops would be increased, causing higher passenger in-vehicle travel times. In both opportunity charging alternatives (ending or intermediate stops), the number of vehicles required to provide the service at the target headway can be higher than diesel vehicles.

The effects of opportunity charging have been estimated on the bus route H6 and H16 in Barcelona. The opportunity charging at the ending stops results to be the optimal charging scheme. This opportunity charging implies one additional vehicle due to the additional time spent at ending stops. Under perfect regularity, if the unit consumption rate is lower than 2.5kWh/km, the deployment of 1 charging station at each ending stop (1-1) is enough to guarantee the operation at the desired headway. However, if the energy consumption factor is greater than this threshold, the bus operator will need the 2-2 configuration (two servers at each stop). Nevertheless, if we consider the real time headway adherence of buses, the 1-1 configuration is not able to guarantee the dispatching of buses at the target time headway. In those cases, we need to deploy 2 chargers at each ending stop. The main conclusion is that bus regularity should be controlled in order to minimize the extra-cost caused by the electrification of buses.

REFERENCES

Estrada, M.,Mensión, J.,Aymamí, J.M., Torres, L. (2016). Bus control strategies in corridors with signalized intersections. *Transportation Research Part C* 71, 500-520.

Piccioni, C. and A. Musso (2017). Deliverable 42.6. Training material for University workshops. ZeEUS. Zero Emission Urban Bus System Project. European Commission