Feasibility Study of using an Electric Vehicle in the Actual Infrastructure of a Small City in Spain

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Abstract: This study simulates certain conditions in Cuenca, a small city located in the centre of Spain, between Madrid and Valencia, which uses electric mobility. The objective is to conduct an appraisal of the use of electric mobility in order to ascertain possible improvements or developments that will be required in a green, ecological and smart city in the future. In order to facilitate this experiment, an electric vehicle will be driven from Cuenca to Madrid. Battery charging will take place at designated charging stations along the way, if required. Four commercial vehicles with different characteristics have been chosen for the simulations. In case there are any vehicles which cannot reach the destination, likely causes will be reviewed, and solutions will be suggested.

1 INTRODUCTION

Until recently, the electric vehicle was an unknown and unfamiliar phenomenon. However, there was a disposition to replace private vehicles propelled by Internal Combustion Engines (ICE) with vehicles that are propelled by electric motors and powered by batteries (Kiyakli and Solmaz, 2019; Besselink et al., 2010). According to experts, the key motivation for this change is the technological revolution that the electric vehicle represents. Changes in automotive policies and a commitment to environmental protection are additional strong reasons, with the environment being the most pressing and pervasive concern (Evtimov et al., 2017). Considering how burning of fossil fuels contributes to climate change, replacing the millions of cars propelled by ICE with electrical vehicles should significantly alleviate this problem for the Earth (I.N. Laboratory). Spain has made good progress in deploying electric vehicles compared to other European countries (Hedge et al., 2016). Registered electric vehicles represent 0.32% of the market share compared with 1.7 % which is the average in other European countries (Valsera-Naranjo et al., 2009; Yan et al., 2014). Yearly improvements are visible, both in perception and thinking of the Spanish people, as well as in sales and governmental policies regarding electric vehicles. A limitation to the use of electric vehicles in Spain is the relatively small number of charging stations. In spite of widespread availability of charging equipment, in 2017 Spain was only fifth place in Europe with 5000 points (4.26% of European charging stations), while the United Kingdom (UK) was fourth place with 12.2%, signifying a huge gap between them. The situation is more deplorable when reviewing fast charging stations. Only 12% of charging stations are configured for fast charge. The geographical distribution of charging stations is irregular (He and Hou, 2017; Mehmet Cem Catalbas et al., 2017). They are principally located only in the biggest cities such as Madrid, Barcelona, Valencia, Bilbao and Seville. They are also installed along major roads and highways and close to the coast for tourism. This study is focused in checking if people can move from Cuenca to Madrid and come back using an electric vehicle, charging the batteries during the trip if is required. Battery charging will take place at designated charging stations along the way, if required. Four commercial vehicles with different characteristics have been chosen for the simulations. In case there are any vehicles which cannot reach the

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destination, likely causes will be reviewed, and solutions will be suggested.

The paper is divided into the following sections: Section 3 describes the model of an EV with a real driving cycle. In Sections 4 and 5, details of the case study and simulation results using Matlab-Simulink are provided, followed by discussions. Finally, the last section provides the main conclusions of this study.

2 PERFORMANCE MODEL OF AN ELECTRIC VEHICLE DRIVEN IN A REAL PATH

In order to understand the dynamics of a vehicle, electric or fuel powered car, train or trucks, it is necessary first to evaluate the forces involved in their movement (Di Giorgio et al. 2017; Zhongjing et al. 2013). Those principal forces are determined using the physic laws that are used to model and simulate the motion of the electric vehicle (Hosseini et al, 2020; Tan and Osama, 2013). The typical problem is to identify the forces of a vehicle in a ramp as represented in figure 1.

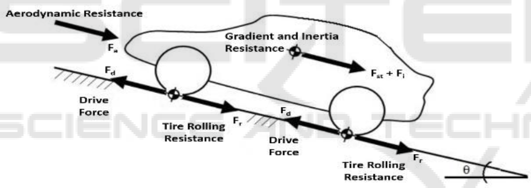

Figure 1: Forces of a vehicle located in a ramp.

During driving, the resistance forces which act on the vehicles are determined with the following governing equations:

- Aerodynamic resistance:

$$F_a = \frac{1}{2}\rho C_d A_f v^2 \quad (1)$$

where ρ is the air density, whose typical value is 1.225 kg/m^3; C_d is the aerodynamic coefficient; A_f is the frontal area of the vehicle (m^2) and v is the speed of the vehicle (m/s).

- Tire rolling resistance:

$$F_r = mgC_r cos(\theta) \quad (2)$$

where m is the vehicle mass (kg); g is the gravity acceleration. Its value is 9.81 m/s^2; θ is the slope of the ramp and C_r is the tire rolling resistance coefficient and it varies according to the road surface (0.013 for concrete or asphalt).

- Gradient resistance:

$$F_{st} = mgsin(\theta) \quad (3)$$

where m is the vehicle mass (kg); g is the gravity acceleration. Its value is 9.81 m/s^2 and θ is the slope of the ramp.

- Inertia resistance:

$$F_i = ma \quad (4)$$

where m is the vehicle mass (kg) and a is the acceleration or deceleration of the vehicle (m/s^2).

Finally, the total resistance force is the sum of all them:

$$F_{res} = F_a + F_r + F_{st} + F_i \quad (5)$$

Manufacturers do not give the data of each of the component of the vehicle. For this reason, it will be not accurate to model a whole vehicle by taking into account the energy flows from the battery to the wheels including the electronic converter, electric motor and the transmission system. However, the EV battery capacity is known. Normally, the EV tries recharging the battery before spending the 80% of its capacity. That is known like battery utilisation factor. Moreover, the efficiency of the power train is also around 80%. That is known as the 80% rule of thumb for BEV power train efficiency and battery utilisation. Therefore, knowing the battery capacity and the parameters of the vehicle per Eqs. (1–5), which allow to calculate the resistant forces, the required energy for moving the vehicle can then be computed.

The required power which has to be delivered by the battery is:

$$P_{DC} = \frac{1}{\eta_d} \cdot F_{res} \cdot v + P_{aux} \quad (6)$$

where η_d is a constant overall efficiency of the power train and P_{aux} is the power usage for auxiliary systems. In the following, a procedure is provided for modelling the behaviour of an electric vehicle driven in a path according to the parameters given in the manufactures' specifications and the known position and characteristics of the actual charging stations.

2.1 Inputs Definition

It is important to know all needed parameters for characterizing both the vehicles and routes. For vehicles, the principal parameters are the mass of vehicle, dimensions, the capacity of the battery of the vehicle and its aerodynamic coefficient. For more precision, knowing their maximum acceleration and speed could be an advantage. Those data are detailed in technical data of vehicles given by manufacturers. Referring to the parameters of the routes, these are principally the total distance, slope in different intervals, the referent speed in each part of the path and the location of the charging station where it is possible to charge the vehicle. Google Earth is a free software which allows getting those parameters by means of obtaining the altitude, longitude and latitude of several points which draw the route. After that, data could be extracted in an Excel file.

2.2 Speed, Acceleration and Slope Profiles in Simulink

In order to get a better precision, Simulink computes the speed, acceleration and slope profiles. Input data in Simulink are the maximum speed of the ways, which will be the reference speed of the vehicle, and the slope which have been imported from Excel. Those data are introduced in "Lookup tables" whose input is the distance from the starting point. A PID (Proportional–Integral–Derivative) controller allows to reach the reference speed of the vehicle when slope and/or the speed of the way change. The design of the PID have been done using Ziegler-Nichols method for each vehicle knowing its acceleration.

2.3 Energy and SOC Calculation

Once acceleration, speed and slope in each stretch of the paths are known, required power can be calculated using Equation 6.

It is worth noting that, due to the fact inertial force is only required in transients, it has not been taken into account. For calculating the required energy and the State of Charge (SOC) in each point of the path, the algorithm has been computed calculating the consumed energy from the starting until a certain point as the sum of the consumed energy in little intervals of 50-100 metres of length.

Taking from Simulink the input data from calculating the required power and the time between two intervals of discretization of the path, energy consumption in that interval is calculated. Finally, the SOC is calculated.

2.4 Checking if Charging is Required

The last part of the algorithm is to check if charging the battery of the vehicle is required in order to not reach a SOC lower than 20% which could damage the battery. It will also say where the vehicle should be charged. If there are points which SOC becomes lower than 20% and there is not any charging station before, a charging station will be necessary. Multiplying that power delivered by the battery times the spending time of the journey, the energy supplied by the battery can be known.

Finally, the SOC of the battery, that is, the level of charge of a battery relative to its capacity, is calculated:

$$\mathrm{SOC} = \frac{Battery\ capacity - Energy\ consume}{Battery\ capacity} \quad (7)$$

3 CASE STUDY

Cuenca is a city in central Spain, and is the capital of the Cuenca province, in the region of Castile – La Mancha. Cuenca city is located 168 km from Madrid, 199 km from Valencia and 179 km from Toledo; these are the surrounding principal Spanish cities. In 2019, the Spanish Statistical Office (Instituto Nacional de Estadística - INE), recorded the total population of Cuenca city as 54,690 people while the province of Cuenca has 196,323 people. This means that 27.28% of the province's population live in the capital city. Cuenca province is one of the most affected by depopulation in Spain. Depopulation happened for many reasons: Cuenca is an area with a large proportion of aged people; there are few big industries and the economy is principally reliant on farming, agriculture and forestry activities; and there is minimal investment in new industries or in infrastructure. For these reasons, young people seek employment in the capital city or other city outside the province, principally in Madrid or Valencia due to their proximity. In respect of Electric Vehicles, Castile – La Mancha represents only 3% of the vehicles registered in Spain, what shows that its deployment there is insignificant.

Moreover, in the city of Cuenca, amidst the 11 charging stations, only one is public, and is managed by Iberdrola. The others are either private or are located in hostels, supermarkets or in car dealerships, or are out of service. The objective is to determine whether an electric vehicle can get to Madrid, which is the city closest to Cuenca. Achieving this feat could be a motivation for Cuenca residents to purchase electric vehicles. This is because that route is popular since many of them currently work or study in the two cities. It is also commonly traversed for tourism and leisure.

Four different commercial vehicles have been selected according to parameters including battery capacity, and price, and number of sales in past years. The vehicles are: Citröen C-Zero, Nissan Leaf, BMW i3 and Tesla model S. The required parameters for the model can be easily obtained in their specifications. The assumption will be that the vehicle is driven with daily lighting and heating or air conditioning turned on during the trip. So, the term P_{aux} of Equation 6 is equal to 540 W. Regarding the travel route, it is important to know its parameters such as total length, the slopes at different intervals of the route, the reference speed of the vehicle at each point of the route, location of the actual charging stations and their number, and the types and capacity (power) of the connectors. The chosen travel route is the fastest and most commonly used route to Madrid. Reference speed will be the maximum allowed by the Spanish traffic law, which is: 50 km/h inside the urban and industrial areas, 90 km/h on conventional roads and 120 km/h on highways.

Figure 2 presents the altitude profile of both routes. It allows the taking of data for calculating the slope profile. Red points indicate the location of the actual charging station that can be found during the trip.

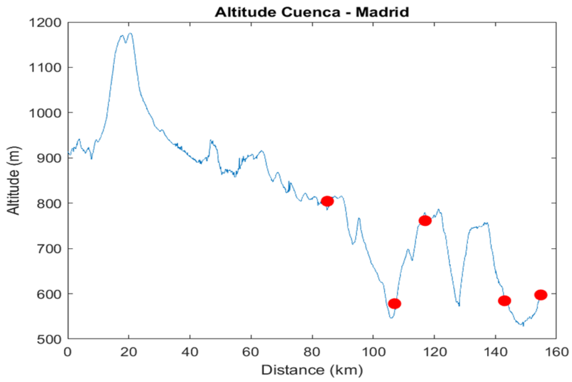

Figure 2: Altitude profile from Cuenca to Madrid.

Table 1 presents the features of those charging stations.

Table 1: Actual charging stations in the route Cuenca-Madrid.

No	Location Type	Use	Connector Type	Power (kW)
1	Car dealer	Charging allowed	Schuko (EU Plug)	2.3
			CEE 3P+N+E	11.0
2	Street charging	Public (managed by Iberdrola)	TYPE 2	43.0
			TYPE 2	43.0
			CCS2 (x2)	50.0
			CHAdeMO (x2)	50.0
3	Hotel - restaurant	Charging allowed	CHAdeMO	50.0
			CCS2	50.0
			TYPE 2	43.0
			Tesla Dest. Charger	7.5
4	Private		Tesla Dest. Charger	16.0
5	Supermarket	Only for clients	TYPE 2 (x2)	7.0
6	Hotel	Only for clients	Tesla Dest. Charger (x2)	11.0
			TYPE 2	11.0
7	Hotel - restaurant	Only for clients	Schuko (EU Plug)	22.0
8	Street charging	Public	TYPE 2	22.0
9	Street charging	Public	TYPE 2	22.0
10	Street charging	Public	Schuko (EU Plug)	3.7
			TYPE 2	22.0
11	Street charging	Public	TYPE 2 (x2)	22.0
12	Street charging	Public (managed by Iberdrola)	TYPE 2	43.0
			CCS2	50.0
			CHAdeMO	50.0
13	Car dealer	Charging allowed	CHAdeMO	50.0
14	Supermarket	Only for clients	TYPE 2 (x2)	7.0

4 RESULTS AND DISCUSSION

The procedure adopts for this work is reported in figure 3. The result of the simulation is indicated in a graph in which remaining battery life is represented as the SOC of the battery for each kilometre from the starting point. It can show the desired results in this way:

- If there is at least one point of the graph with SOC lower than 20%, then theoretically this means that the vehicle cannot reach the destination.
- The graph indicates the points where the last charging station that is compatible with the vehicle is located for charging before SOC becomes lower than 20%. Those points are represented in the graph as a step upwards until SOC is equal to 100% by which time the battery is fully charged.
- If SOC drops to 0%, the vehicle will stop. It is possible that a graph could indicate that, after SOC equals to 0, there is subsequently a movement upwards until it reaches 100%. In such case it represented that way in order to observe the charging range afterwards at that charging station if the vehicle's battery is completely depleted but is later recharged at the same station.
- If SOC never reaches 20%, it means that the vehicle can reach the destination without charging its battery during the trip.

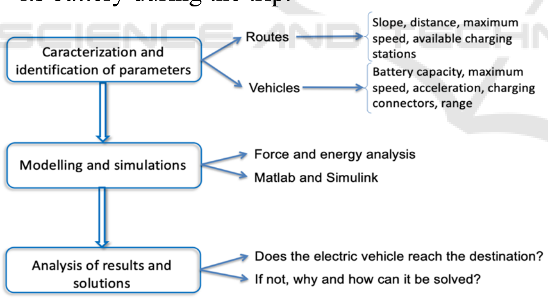

Figure 3: Logical algorithm applied to the case study.

Figure 4 presents the simulation results for the four vehicles in the trip from Cuenca to Madrid.

It is possible to charge a Citröen C-Zero' battery both in Cuenca and in Madrid's commercial centre because there are CHAdeMO connectors in both cities. Thus, for a trip from Cuenca to Madrid and then back to Cuenca, the battery will start with a full charge both ways. The same is true for the remaining vehicles because both locations have charging stations with connectors TYPE 2. It is worth noting that the return trip is undertaken on the assumption that the vehicle came from Cuenca.

Once simulations have been done, the feasibility study reaches the important part: analysis of results and taking of decisions. Simulations indicate whether or not electric vehicles can reach their destinations and return again to Cuenca. If that is not possible, some measures will be undertaken to resolve the problems and assist the city of Cuenca to become green and sustainable in the foreseeable future. For the Citröen C-Zero, driving it to Madrid's commercial centre is not feasible because there are points where SOC is lower than 20% and charging stations are unavailable during the trip to charge the battery. This presents the risk of battery depletion and the vehicle would stop where SOC becomes 0%. For the same reason when the trip initiates from Madrid, it is also not possible to return to Cuenca.

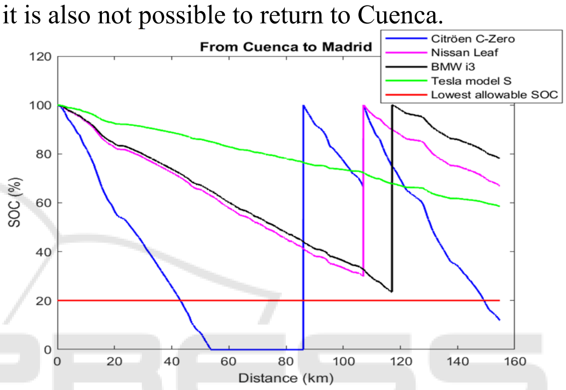

Figure 4: Altitude profile from Cuenca to Madrid. Simulation results from Cuenca to Madrid in the actual driving conditions for different vehicles.

In the case of the Nissan Leaf, it is possible to get to the commercial centre of Madrid and also return to Cuenca. However, one stop is required halfway through the journey to charge the battery. Going to Madrid, the last compatible charging station before SOC drops lower than 20% is located in the hotel-restaurant of Fuentidueña de Tajo (point 3 of table 1). For the return trip, the stop is recommended to be located at the public charging station of Tarancón (Point 2 of table 1).

The BMW i3 can similarly get to the destination in Madrid but it will have to stop once on the way for charging. The last compatible charging station is in the supermarket of villarejo de Sabanés (Point 5 of table 1). The same applies when returning to Cuenca and the stop is recommended to be in Tarancón (Point 2 of table 1). Driving a Tesla model S, it is possible reach the destination without any charging being necessary. The same is the case when returning to Cuenca. Table 2 is a summary of features of the trip to Madrid.

Table 2: Characteristics of the trip to Madrid in electric vehicle in the actual environment case study.

	Charging Station	**Arrival SOC [%]**	**Energy to charge [kWh]**	**Cost [€]**	**Connector type**	**Power [kW]**	**Time [min]**
Nissan Leaf	Fuentidueña de Tajo	29.96	25.214	3.409	TYPE 2	7	216.123
	Tarancón*	35.99	23.044	3.115	CHAdeMO	50	27.652
	Madrid	67.23	11.797	1.595	CHAdeMO	50	14.157
	Tarancón	48.10	18.684	2.526	CHAdeMO	50	22.421
	Cuenca	39.33	21.841	2.953	CHAdeMO	50	26.209
			Total Cost (€)	10,482			
BWM i3	Villarejo de Sabanés	24.47	28.626	3.870	TYPE 2	7	245.365
	Tarancón*	40.09	22.706	3.069	CHAdeMO	50	27.247
	Madrid	78.18	8.270	1.118	CCS2	50	9.924
	Tarancón	51.54	18.366	2.483	TYPE 2	43	25.627
	Cuenca	42.63	21.743	2.939	CCS2	50	26.092
			Total Cost (€)	10.410			
Tesla model S	Madrid	58.55	39.3775	5.323	TYPE 2	43	54.945
	Cuenca	53.56	44.118	5.964	TYPE 2	43	61.560
			Total Cost (€)	11.287			

*Alternative stop in Tarancón in order to spend less time charging the battery.

The problem that occurred during the simulation with Citröen C-Zero happened because it could not reach Madrid. SOC of battery of Citröen C-Zero drops to 20% after 42 km from Cuenca. Assuming that it could get to the following charging stations at Tarancón and Fuentidueña del Tajo, the Citröen C-Zero would still not have reached Madrid without another stop. It can thus be concluded that it is impossible to travel from Cuenca to Madrid driving a Citröen C-Zero. This limitation arises because there are inadequate charging stations along the travel route.

Two options are available to resolve it: add new connectors to charging stations that are already installed and functioning; or build new charging stations. This is on the assumption that all the new charging stations will be equipped with CHAdeMO connectors with power 50 kW which is typical of Iberdrola charging infrastructure. New charging stations should be constructed at strategic points for many reasons. Good locations would have service centres such as restaurants, cafes, canteens and hotels where drivers and other travellers can wait, refresh themselves, eat or rest comfortably while the vehicle is charging in a safe environment without the discomfort of standing up throughout. Other possible good locations will ideally be close to villages or industrial areas where cheaper electrical equipment and spares can easily be sourced since electrical outlets are already installed, and also for staffing. To avoid the vehicle's SOC dropping lower than 20%, a charging point is required before 42 km from Cuenca. A village known as Naharros is located 35 km from Cuenca, with a fuel station and a bar at its entrance. This could be a good location for the first charging station.

It will be impossible to reach Tarancón where two additional charging stations can be found, without charging once again. Carrascosa del Campo located 57 km from Cuenca, can be an ideal spot for this, especially since it also has restaurants, hotels, a medical centre and a service station.

The charging stations of Tarancón and Fuentidueña del Tajo can be used. It is necessary to add one more charging station before getting to Madrid. If the charging station at the supermarket in Villarejo de Sabanés has the capacity to charge with Type 1 or CHAdeMO connectors, the problem will be solved, and it would be possible to get to Madrid driving a Citröen C-Zero (table 3).

Table 3: Characteristics of the trip to Madrid for driving a Citröen C-Zero with new charging stations.

Charging Station	**Arrival SOC [%]**	**Energy to charge [kWh]**	**Cost [€]**	**Time [min]**
Naharros	34.52	9.494	1.28	11.393
Carracosa del Campo	59.81	5.827	0.787	6.992
Tarancón	47.39	7.628	1.031	9.154
Villarejo de Sabanés	41.34	8.505	1.149	10.206
Madrid	37.05	9.127	1.233	10.952
Villarejo de Sabanés	24.19	10.992	1.486	13.190
Tarancón	39.30	8.801	1.189	10.561
Carrascosa del Campo	43.14	8.244	1.114	9.893
Naharros	56.06	6.371	0.861	7.645
Cuenca	38.22	8.958	1.210	10.750
		Total Cost (€)	11.348	

5 CONCLUSIONS

The scope of this work was to simulate certain conditions in Cuenca, between Madrid and Valencia, which uses electric mobility. The objective is to conduct an appraisal of the use of electric mobility in order to ascertain possible improvements or developments that will be required in a green, ecological and smart city in the future. In order to facilitate this experiment, an electric vehicle was driven from Cuenca to Madrid. Four commercial vehicles with different characteristics have been chosen for the simulations. The following considerations can be drawn from the present study:

- It is not possible to travel to Madrid, the big city closest to Cuenca, if the electric vehicle is similar to the Citröen C-Zero, because of its weak battery capacity. Sadly, this vehicle is economically affordable by most people.
- It is possible to make a direct trip to Madrid with powerful and expensive vehicles like Tesla model S. Smaller, less powerful vehicles like Nissan Leaf or BWM i3 can also make the trip if they stop just once for charging. The problem however is that most people cannot afford those vehicles.
- Province of Cuenca does not have many charging stations. Most of the proposed new charging stations which will enable driving the Citröen C-Zero to destination are located in this area, where, in spite of poor industry and depopulation, this kind of infrastructure will be necessary in the future.
- In the city of Cuenca there are different types of connectors in charging stations, and these can charge all types of vehicles. The problem is that only one charging station is public whereas there is an increasing number of electric vehicles being sold.
- The use of electric vehicle and its infrastructure is increasing in the larger cities in Spain such as Madrid, Barcelona, Valencia and Bilbao, but not in poorer and less populated areas. Government at all levels should give incentives to electric vehicle manufacturing companies to increase the number of charging stations in areas similar to Cuenca before encouraging people to buy electric vehicles.
- Costs of driving an electric vehicle are much lower than a conventional car that is powered by fossil fuels.

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