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Energy and environmental impacts of potential application of fully or partially electric propulsion vehicles: application to Lisbon and São Miguel, Portugal

Patrícia Baptista[a,*], José Tavares[a], Gonçalo Gonçalves[a]

[a]*IDMEC - Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1 - 1049-001 Lisboa – Portugal*

Abstract

The transportation sector has been one of the fastest growing sectors resulting in a high final energy consumption in Portugal (40% in 2011), with road transportation sector being responsible for 82% of that energy consumption. As a result, alternative vehicle technologies such as electric vehicles are becoming increasingly important since they may contribute to greater energy efficiency. However, their electric autonomy limitations influence the mobility paradigm, making their acceptance dependent on the location and context of driving. Thus, the objective of this study was to characterize mobility patterns and compare the potential application of fully or partially electric propulsion vehicles in two different Portuguese contexts: the Lisbon region (city pattern) and the Island of São Miguel, Azores, Portugal (rural pattern). This characterization was performed by on road monitoring of 9 drivers in Lisbon and 17 drivers in Sao Miguel. São Miguel drivers are those which have a more suitable pattern for using alternative vehicles comparably to the Lisbon region, since they travel about 47% less than the Lisbon population (33 km daily compared to 62 km per day) and, consequently, having a charging time availability about 30% higher. The São Miguel population also has greater presence in lower vehicle specific power (VSP) modes, with an average speed 25% lower than the Lisbon population. São Miguel drivers present greater efficiency in electricity consumption per kilometer (25% more efficient) than the Lisbon sample. Finally, the impacts of using alternative vehicles were quantified, concluding that the alternative technologies would reduce the Well-to-Wheel (WTW) energy consumption per kilometer between 37% and 68%.

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Keywords: Driving patterns; VSP methodology; Electric mobility; Technology adequacy; Energy and environmental impacts

* Corresponding author.
E-mail address: patricia.baptista@tecnico.ulisboa.pt

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1. Introduction

The high flexibility and accessibility are the main advantages of using the private car for short and medium distances. The use of private car h[1]as allowed a greater distance between the residential and work areas, leading to increased globalization and expansion of cities and enabling cars as the main transportation mode (IEA, 2012). Therefore, the transportation sector has been one of the fastest growing sectors in the recent decades which results, nowadays, in a high final energy consumption in Portugal (40% in 2011), with the road transportation sector being responsible for 82% of that energy consumption, as well as in many other countries. Besides the high energy consumption, the transportation sector is the major source of emissions (responsible for about 70% of the CO_2 equivalent emissions) (EUROSTAT, 2013). Similarly, the road transportation sector represents 90% of the total emissions in the transportation sector. As a result, the road transportation sector faces increasing challenges and issues, forcing the sector to re-think the current concept of private car and to consider alternative energy sources and powertrains but maintaining the same mobility level. The development and market availability of hybrid vehicles (HEV), plug-in hybrid vehicles (PHEV) and electric vehicles (EV) are examples of possible alternatives. EV were created more than a century ago, but have never been applied on a large scale in the transportation sector. The operational competitiveness of electric technologies in comparison with conventional ones is still not allowing its adoption in a generalized way (Duin et al., 2013). The running costs of electric vehicles are actually lower, but these do not stand out sufficiently on a total cost basis (Thiel et al., 2010), also associated with the high recharging infrastructure costs (Faria et al., 2014). Studies show that assuming a scenario without electric vehicles, energy consumption in the transport sector will increase in 58% by 2050 compared to 2009 (Pina et al., 2014, Baptista et al., 2013). On the other hand, a 70% penetration of electric vehicles would reduce energy consumption by 34% and CO_2 emissions by 39% in 2050 (Pina et al., 2014, Baptista et al., 2013). Karabasoglu et al. (Karabasoglu and Michalek, 2013) also concluded that PHEV and EV could reduce 60% in emissions and 20% in costs according to the New York mobility pattern.

However, pollutant emissions and energy consumption does not depend only on vehicle technical specifications, but are also strongly influenced by the characteristics of each driver and road environment. Similarly, the efficiency of the alternative vehicle technologies is also dependent on the conditions referred. For example, in the case of PHEV, the point in time when the internal combustion engine starts running (due to the lack of electricity for propulsion of the vehicle) is variable and depends on the driving mode and the road environment. For example, a smoother ride and a flat zone could lead to a reduced consumption of electricity and, thus, delay the start time of the internal combustion engine, allowing lower fuel consumption and emissions. As a result, the mobility pattern may influence the type of vehicle that suits different situations, in order to take full advantage of alternative technologies in the automotive market. Note that the use of the charging infrastructure also depends on the driving pattern, because it affects the charging frequency of the vehicle. Moreover, driver behavior may be influenced by feedback to the driver (Beusen, 2009, Barth and Boriboonsomsin, 2009). A study by Rolim et al. shows that a group of drivers reduce fuel consumption in 4.8% (l/100km) and 6.56 g CO_2/km, after receiving a training session on eco-driving, showing the importance of drivers behavior (Rolim et al., 2013). Besides fuel reduction, the size of a battery in a PHEV or in an EV can be optimized according to a typical mobility pattern, allowing lower costs in acquiring the vehicle (Smith et al., 2011).

Moreover, when considering electric mobility, the Well-to-Tank (stage of the WTW methodology, which evaluates the impacts of the necessary steps to turn a resource into a fuel and bring that fuel to a vehicle) must be accounted for, because it influences the final WTW impacts of these technologies, since the time and location of recharging influence the final result (Baptista et al., 2013).

Taking into account this framework, the main objective for this work was to characterize the mobility patterns in two different contexts: in the Lisbon region coincident with a city pattern; and in the island of São Miguel corresponding to a more rural pattern. This characterization was achieved through the on-road monitoring of 9 drivers in the Lisbon Metropolitan Area and 17 drivers in São Miguel, for a minimum period of one month. Moreover, this characterization allowed the development of a methodology to evaluate the potential of introducing total or partial electric propulsion technologies in the two contexts according to their mobility pattern estimating the possible time of recharging and resulting energy requirements. As a result of the possible use of these alternative vehicle technologies, the quantification of fuel life cycle impacts in the two contexts was also performed, in order to understand the real impact of the technologies considered.

2. Methodology

2.1. Description of the drivers

A total of 25 drivers and approximately 1285 hours (and 57000 km) of monitoring where measured in periods with an average duration of 2 month between January 2012 and March 2013. The total sample of drivers is subdivided into two populations according to each different location: Lisbon – Population A; and São Miguel – Population B. The characterization of the populations can be seen in Table 1. The fact that this was a small sample did not allow performing a detailed analysis in terms of socioeconomic profiles of the drivers', taking into account variables as age, sex, among others. However, that analysis will be performed in the future with a sample enlarging and implementation of surveys.

Table 1 – Populations characterization.

	Number of drivers	Average age	Total monitoring	
			Time (h)	Distance (km)
Population A	9	38	842	41147
Population B	17	38	443	15883

2.2. Data collection

On-road data was collected with a CarChip device (Davis Instruments Company). CarChip is an engine performance and driving data logger that collects data from the vehicles on-board computer and gathers information such as trip duration, mileage, vehicle speed, engine speed, throttle position, engine load, intake air flow rate, manifold air pressure and temperature, coolant temperature, as well as number of events such as hard and extreme brakes and accelerations. This data is provided from the OBD II (On-board Diagnostic) Port, which gives access and monitoring information from various vehicle sub-systems, and is usually found around the dashboard or the steering wheel area. However, although OBD II port provides various parameters, only five variables can be collected with a frequency of 0.2 Hz (5 seconds), except for the vehicle speed that used a 1 Hz frequency. The five chosen parameters were: vehicle speed, engine speed, engine load, intake air flow rate (or manifold air pressure) and manifold air temperature. The data collected was then downloaded to a computer and processed by a Matlab code.

2.3. Methodology for data analysis

The VSP (Vehicle Specific Power) methodology enables to study the vehicle's environmental performance, assigning fuel consumption and CO_2 emissions according to the driving power requirements. The VSP concept is defined as the ratio between the instantaneous power and the weight of the vehicle (W/kg). VSP is a function of speed and acceleration of the vehicle, road grade and depends on the drag coefficient and rolling resistance coefficient of the vehicle. In a simplified form, VSP is the instantaneous power that the motor must produce to overcome the increase in kinetic energy (acceleration) and potential (slope), and the forces imposed by friction and aerodynamics. VSP is a very useful parameter when it comes to real measurements, since it allows grouping different driving situations that require the same engine power. In other words, given the enormous variability of driving conditions, VSP is able to group situations that require the same power, thus enabling to correlate events with specific emissions and fuel consumption. The VSP equation is then defined as follows:

$$VSP = v \times \left(1{,}1 \times a + g \times \sin\varphi + rolling\,resistance\right) + \text{drag coefficient} \times v^2 \tag{1}$$

where VSP is vehicle specific power (m^2/s^3 or W/kg); v is the instantaneous vehicle speed (m/s); a is the instantaneous acceleration (m^2/s) and φ the road slope. Since the Carchip is not equipped with a GPS receiver, road slope was not included. Substituting the coefficients for light-duty vehicles the equation used is present below:

$$VSP = v\times\left(1{,}1\times a + 0{,}132\right) + 0{,}000302\times v^3 \qquad (2)$$

As presented in Table 2, VSP is divided in 14 modes in the case of light-duty vehicles. Modes 1 and 2 present negative values of VSP and concern deceleration or negative road slopes (which in EV allows recharging the battery due to regenerative braking). Idling is represented in mode 3. Beyond this mode, the higher the speed and accelerations the vehicle reaches, and consequently the power demand, the higher the mode. Even though each mode presents statistically different fuel consumption, none is dominant in the estimation of the trip's fuel consumption.

Table 2 – VSP binning and ranges of W/kg for each mode.

VSP Mode	Definition	VSP Mode	Definition	VSP Mode	Definition
1	VSP < -2	6	7 ≤ VSP < 10	11	23 ≤ VSP < 28
2	-2 ≤ VSP < 0	7	10 ≤ VSP < 13	12	28 ≤ VSP < 33
3	0 ≤ VSP <1	8	13 ≤ VSP <16	13	33 ≤ VSP < 39
4	1 ≤ VSP < 4	9	16 ≤ VSP < 19	14	VSP ≥ 39
5	4 ≤ VSP < 7	10	19 ≤ VSP < 23		

The driving patterns and mobility characterization, besides the VSP methodology, was defined by a group of events that are presented on Table 3. Given the small number of extreme brake and extreme acceleration occurrences, those were included in the analysis groups of hard brakes and hard accelerations, respectively. Besides the events presented, the populations were also characterized by average trips per day, kilometers traveled per day, fuel consumption (l/100 km), power per weight, hourly distribution of kilometers and emissions of CO_2 per kilometer.

Table 3 – Events definition for characterization of the driving patterns.

Events	Description	Events	Description
Speed Bands	0 km/h (Idle) 0-50 km/h 51-00 km/h 91-120 km/h >120 km/h	Hard brake	0.34G ≤ Brake force ≤ 0.51G
		Extreme brake	Brake force > 0.51G
		Hard acceleration	0.31G ≤ Acceleration force ≥ 0.45G
		Extreme acceleration	Acceleration force > 0.45G
		Excessive engine speed	Diesel - RPM>2500 and Speed <120 km/h Gasoline - RPM>3500 and Speed<120km/h
		Fuel cut off	RPM=0 or Eng. Load =0 or Eng. Load < 20 and RPM >1200(Diesel) or 1500 (gasoline) and VSP <0

Two electric (EV) and plug-in hybrid electric (PHEV) representative vehicles were chosen to simulate their adequacy in the driving patterns. The EV has a 80 kW electric motor, a 24 kWh Li-ion battery and a total weight of 1493 kg, while the PHEV has a 55 kW electric motor, an 111 kW internal combustion engine, a 16 kW Li-ion battery and a total weight of 1715 kg. The possible performance of these vehicles for each population on an hourly basis for a typical day was simulated using a developed algorithm. The simulation was done in an hourly basis and considers electricity and fuel (only for the PHEV) consumption, availability for charging and state of charge (SOC) of the battery in the end of the day. Real world monitored data from the vehicles (such as battery capacity and energy use by VSP mode) was used to calibrate the model (Lopes, 2013). Additionally, the charging is assumed as standard charging (at 3.68 kW) which represents the domestic charge in Portugal.

Each driver average electricity and fuel consumption if driving the EV and PHEV were establish according to their percentage of time in each VSP mode and the consumption of fuel and electricity in each VSP mode (independent of the driver) for the two cars. The disaggregation of energy use by VSP mode can be seen in previous studies (Lopes, 2013, Alves, 2013). The simulations were done considering day periods (daytime and nightly period) and two types of day (week and weekend day), but only the week day results will be presented in this study.

The environmental impacts and benefits of using this technology were assessed in a life cycle approach, in particular, a Well-To-Wheel (WTW) approach. The WTW is sub-divided into two analysis named Well-To-Tank (WTT) and Tank-To-Wheel (TTW), which represents the impact cycle of extraction/production of primary energy to the storage of power source in the vehicle, and the impacts resulting of using the vehicle, respectively. This methodology accounts primary energy consumption and emissions of CO_2 along the two stages. For the TTW stages, the impacts were calculated based on each driver's hourly energy consumption of fuel and electricity demands. The impact of the WTT cycle for the electricity was established by using the WTT energy source factors (Concawe, 2011), the Portuguese electricity mix for Lisbon drivers (population A and B) and the São Miguel Island mix for population C (Electricidade dos Açores, 2012), using 2012 as a reference year. For fossil fuels reference factors were considered (Baptista et al., 2012, Concawe, 2011).

3. Results

3.1. Drivers' mobility patterns

The following section focus on the results obtained to characterize the drivers mobility pattern. As can be seen on Table 4, Population A and B drivers' spend most of their driving time on lower speed bands, driving on average 50% and 57% of time, respectively, below 50 km/h and spend 16% and 14% of the time in idling. The highest value for idling occurs for population A since the Lisbon urban area haves more traffic. Also note that the percentage of the last speed band is practically negligible for population B, due to few highways availability and hilly topography. Hard brakes and accelerations per 100 km are higher in population B than in population A.

Table 4 – Events characterization.

Population	Fuel Cut of (%)	Excessive RPM (%)	Hard Brakes /100km	Hard accelerations /100km	Idling (%)	0-50 km/h (%)	50-90 km/h (%)	90-120 km/h (%)	>120km/h (%)
A	9.0	1.1	0.07	2.2	16	51	18	8	7
B	7.4	2.0	0.09	2.9	14	57	25	4	0.2

Table 5 shows a general mobility view (trips/day and km/day) and the specifications of the conventional vehicles used in monitoring. The trips/day are practically the same but the km/day are very distinct between the populations, with population A having a much higher value (+88% higher). The power to weight ratio is also very similar meaning that the sample is consistent, which means that the vehicles have the same power and, consequently, are comparable. Fuel consumption is slightly higher in population B, which may be a result of the higher percentage of time in low VSP modes.

Table 5 – General mobility and specifications of the population's vehicles.

Population	Trip/day	km/day	Power/ Weight (W/kg)	Fuel consumption (l/100km)	CO_2 emissions (g/km)
A	6	62	59	5,6	136
B	7	33	56	5,8	147

The population's percentage of time spent in each VSP mode can be seen in Figure 1. The figure shows that population B has higher percentage of time spent in the lowest VSP modes (until mode 5) except for mode 3 that represents idling. The maximum value in idling corresponds to population A (Lisbon urban area), which means they spent more time in traffic.

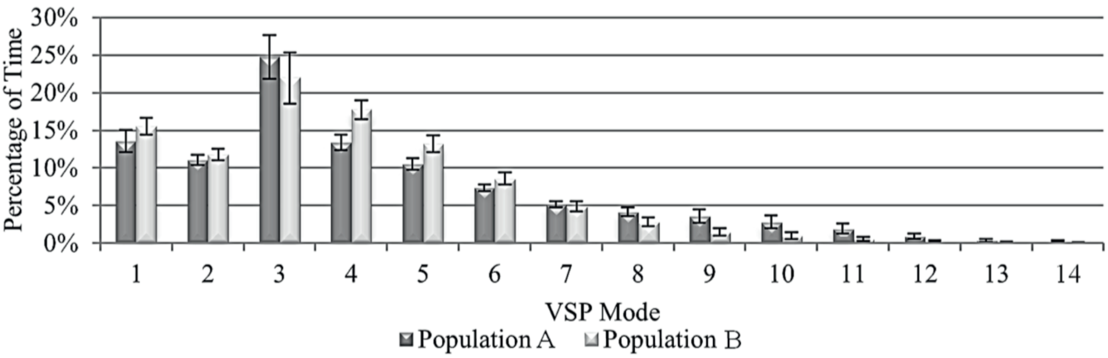

Figure 1 – Time distribution (%) per VSP mode for the two populations.

The kilometers distribution is a very important parameter, since it determines the possibility of charging the vehicle. Figure 2 shows the percentage distribution of kilometers in a typical week day. The figure shows the existence of two moments with high percentage of kilometers made. The first moment is located between 8 and 9 o'clock, which represents people's quotidian of going to work. The second moment, coming back from work, is not uniform in the three populations, with population A having a delay of 1h (18h-19h).

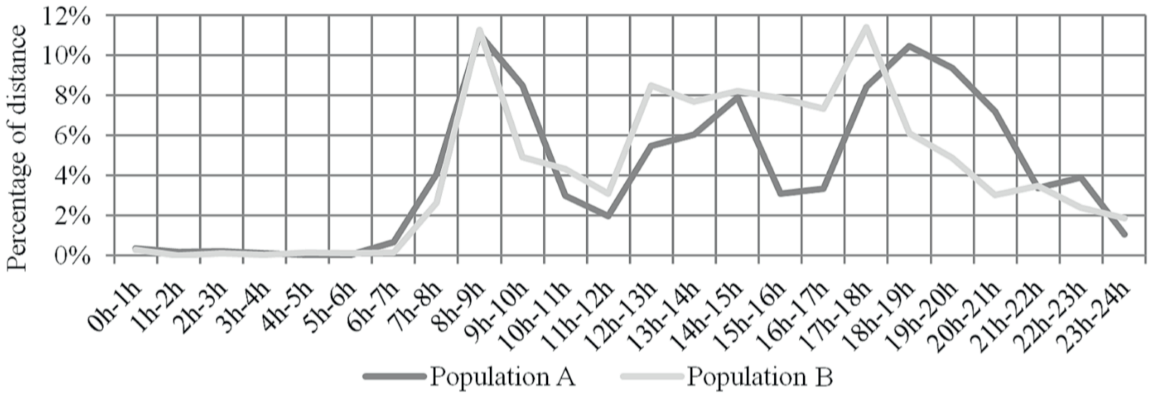

Figure 2 – Average distance distribution per hour in a week day.

According to each population driving distribution, it was possible to draw their daily availability of charging in an hourly basis, considering negligible the kilometers made below 1 km (Figure 3). Population A and B present a daily average charging availability of 46% and 65%, respectively.

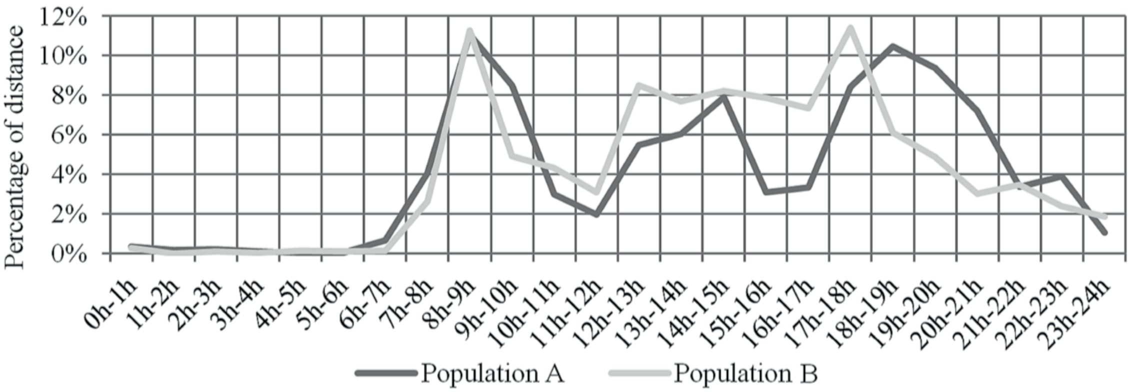

Figure 3 – Hourly charging availability in a week day.

Also the charging availability was studied according to the consecutive hours that drivers have for charging, as can be seen in Figure 4. All populations have more consecutive time of charging during the night and population B has more available time in each day period.

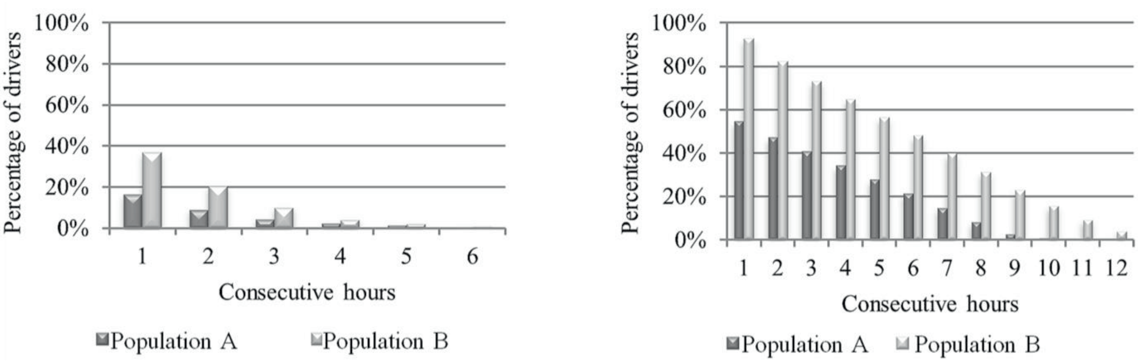

Figure 4 – Charging availability in consecutive hours (daytime period on the left and nighttime period on the right) in a week day.

3.2. Adequacy of the EV and PHEV vehicles to the driving patterns and resulting WTW impacts

The developed methodology was applied to study the adequacy of the alternative vehicle technologies according to the populations' driving profile. If these populations used alternative technologies their energy consumption behavior would be as presented in Table 6. The electricity consumption per kilometer is lower in both vehicles of population B, meaning that São Miguel drivers are more efficient according to their mobility pattern. Since they have higher efficiency, their electric autonomy is also higher. However, the situation is different for the PHEV fuel consumption per 100 kilometers, with population B having a higher fuel consumption value, which is observed when the electric autonomy does not cover the daily kilometers travelled, forcing the PHEV to use the internal combustion engine.

Table 6 – Main results from the adequacy methodology.

Population	PHEV			EV	
	Electricity consumption (kWh/km)	Electric autonomy (km)	Fuel consumption (l/100km)	Electricity consumption (kWh/km)	Electric autonomy (km)
A	0.222	66	5.3	0.152	139
B	0.153	94	5.8	0.118	173

The daily evolution of the battery state of charge (SOC) in a week day, considering that no charging is performed during the day, is portrayed in Figure 5. Both populations are able to end the day with the battery partially charged, with population A having an higher energy consumption and presenting a lower SOC at the end of the day due to the higher number of kilometers travelled.

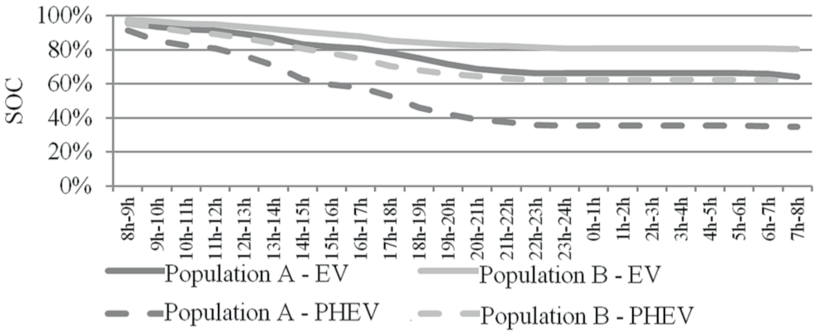

Figure 5 – SOC by vehicle in a week day.

Figure 6 presents the WTW energy consumption per kilometer, reflecting the different energy mixes in 2012 for the two regions. The conventional vehicle presents an higher energy consumption per kilometer than the remaining vehicles (on average 37% higher than in the case of PHEV and 59% higher for the EV). Comparing the two alternative vehicles, the PHEV has a higher energy consumption than the EV (on average 34% higher), mainly due to the existence of fuel consumption resulting for his lower electric range. Population B drivers have lower energy consumption than Population A, except for the conventional vehicle case. Quantitatively, in the PHEV case, population A has a 11% higher WTW energy consumption than population B, while for the EV case a 6% difference is observed.

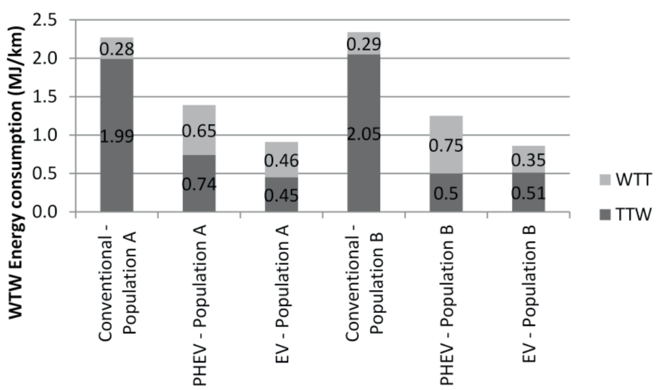

Figure 6 – Primary energy consumption by vehicle in WTW methodology.

The WTW methodology also evaluates CO_2 emissions, which are presented in Figure 7. The conventional vehicle has on average 41% and 68% higher CO_2 emissions than the PHEV and the EV, respectively, having the PHEV 44% higher emissions than the EV. Contrary to the WTW energy consumption, population B emits more than A (8% higher) due to the WTT phase. As for the EV, CO_2 emissions are also higher in population B, about 18% higher relatively to Population A.

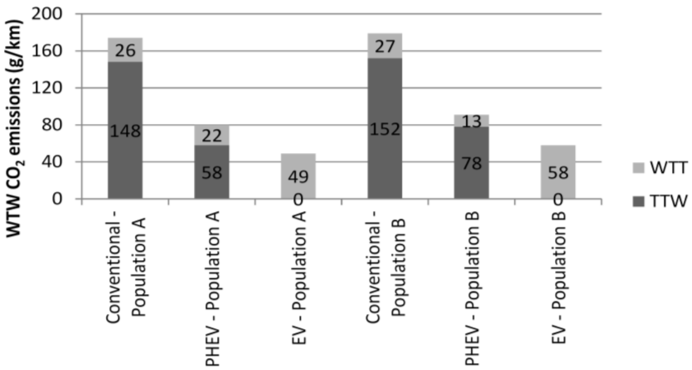

Figure 7 – CO2 emissions by vehicle in the WTW methodology.

4. Conclusions

The on-road monitoring of two distinct populations allowed the characterization of their mobility patterns, in order to compare the potential application of fully or partially electric propulsion vehicles in the two different contexts presented: the Lisbon region, coincident with a city pattern; and the São Miguel Island, corresponding to a rural pattern. The adequacy of PHEV and EV was tested, to evaluate de availability to charge in daily situation and what would be the expected impacts if these vehicles were used in real world use. These impacts were quantified in a fuel life cycle approach.

In terms of mobility patterns, São Miguel drivers (Population B) are those which have a more suitable pattern for using alternative vehicles comparably to the region of Lisbon, since they travel about 47% less than the Lisbon population (33 km daily compared to 62 km per day) and, thus, presenting a higher charging time availability (+30%). The population B has also greater dominance in lower VSP modes, with an average speed 25% lower than population A.

When considering the impacts of using the two alternative technologies in the two case studies, population B has greater efficiency since they benefit from a 25% reduction in electricity consumption per kilometer compared to the Lisbon population (0.551 MJ/km compared to 0.799 MJ/km for the PHEV and 0.425 MJ/km compared to 0.547 MJ/km in the case of the EV, providing a higher electric range of about 30 km). Contrary, population B also presents an average fuel consumption per 100 km (for the PHEV) 15% higher than the Lisbon region. However, due to the low number of kilometers driven per day it has 60% and 94% lower energy consumption in absolute value, comparably to population A.

Finally, the application of the WTW methodology allowed concluding that the conventional vehicle has a 37% and 59% higher energy consumption and 41% and 68% more CO_2 than the PHEV and the EV, respectively. Comparing the two regions, population B shows a decrease from 10% to 20% in energy consumption per kilometer and 60% in absolute value. Regarding CO_2 emissions, although São Miguel drivers are 6% more pollutant per kilometer than population A, they present a CO_2 reduction in absolute value of 30% and 25 % for the PHEV and EV, respectively.

In summary, this work allowed the application of methodologies for characterizing driving patterns and the development of an innovative methodology for evaluating the possible impact of fully or partly electric technologies in two different contexts in Portugal, allowing to better understand to what type of drivers alternative vehicle technologies may be better suited. Future work will be done on the socio-economic characterization of users and correlation with driver behavior and EV applicability.

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