Energy assessment of operation management strategies in plug-in electric hybrid vehicles

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Abstract

In a context where alternative vehicle technologies are widely being adopted, the aim of this work was to assess control strategies of the electric motor (EM) and internal combustion engine (ICE) in the operation of a plug-in hybrid vehicle (PHEV). For that purpose, two plug-in hybrid electric vehicles (PHEV), "A" and "B", were monitored during two trips and their dynamic data, energy consumption and emissions were recorded. Models were created to predict the operation of both ICE and EM. A matrix of operating zones was created gathering data of each second of the trip according to the powertrain used at each moment. The Vehicle Specific Power (VSP) methodology was also taken into consideration. The developed analysis made it possible to verify energy consumption and emissions in charge depleting (CD) and charge sustaining (CS) modes. A is more dependent on the ICE, using it in 27% of the route in CD and 84% on CS, compared to only 4% in CD and 67% in CS used by B. Consequently, energy consumption was higher for A (2.7 l/100km on CD and 7.2 l/100km on CS) when compared to B (0.2 l/100km on CD and 4.4 l/100km). Carbon dioxide emissions followed the similar, being CS emissions greater than the European target for 2021 of 95 g/km (A: 171 g/km, B: 103 g/km). Emissions of hydrocarbons and nitrogen oxides were higher in DC as there were more cold starts from the ICE. A was the least economical option accounting for fuel and electricity, ranging from 0.078 to 0.110 € / km, compared to 0.037 to 0.068 €/km for B, for the distances and charging options studied.

1. Introduction

The growing global motorization delivers pressure on ecosystems, which are increasingly threatened by the impacts resulting from the growing number of vehicles in circulation. Regarding the totality of greenhouse gases (GHG), the automotive sector is already the second most emitting source in the European Union, overtaking the industry sector in 2009 [1]. The implementation of more efficient electric motors (EM) than conventional internal combustion engines (ICE) in vehicles has been one of the most popular measures regarding the paradigm shift in the automotive sector. The electrification of motor vehicles led to its recent development, increasing their production, having led to a decline in their price, making vehicles with electric motors more competitive [2].

This work focus on a type of hybrid electric vehicles (HEV), the plug-in hybrid electric vehicles (PHEV). Conventional HEV have small batteries which can't be recharged on the grid. PHEV offer an alternative to that and can be charged as a normal battery electric vehicle (BEV) and have a fuel tank as an internal combustion engine vehicle (ICEV). Since PHEV has two main power sources (battery and fuel tank) their assessment is more complex when compared to other types of vehicles. Their advantage among other technologies may depend on the conditions in which they're operating, such as charging frequency, distance traveled and dynamic characterization of the trips [3].

A PHEV has two main operating modes: charge depletion (CD), where the battery state of charge (SOC) decreases continuously, depending on the vehicle's energy management strategy, and charge sustaining (CS), in which the SOC reaches a level where it tends to stabilize (typically around 25%), with the charge variation being approximately zero [4]. Once CS SOC level is reached the ICE becomes the most used source of power and the electric consumption becomes nearly zero [5].

SOC management is not uniform across all PHEVs. Manufacturers are responsible for creating the necessary mechanisms to achieve more sustainable energy consumption. Drivers and driving conditions also play an active role in the energy management of PHEV, since for different driving styles and routes with the same distance, but with different characteristics, fuel consumption can vary widely for the same car [6]. The other factor that can change the energy efficiency of a PHEV is the frequency of charging [7].

PHEVs are an expensive technology when compared to ICEVs with similar characteristics. It is necessary to consider several factors when choosing a PHEV. The budget, the daily mileage or even the energy and environmental concerns of the user are important data to be considered when purchasing this type of vehicles [8].

There is not yet a significant number of empirical analyzes of energy consumption and environmental impacts of PHEV that confirm in real context the advantages. The aim of this work was to assess control strategies of the EM and ICE in the operation of a PHEV, quantifying consumption and emission impacts and considering distance traveled and charging frequency.

2. Methodology

In this work, two PHEVs (**vehicle A** and **vehicle B**) were assessed during two trips with the same characteristics but done by different drivers. The trips had an urban section, a highway section and a rural section. The data had been previously collected at 1Hz and consisted in dynamic variables (speed, acceleration, road grade), emission variables (CO_2, CO, HC, NO_x), gasoline consumption, ICE rotations per minute (RPM) and battery SOC.

The Vehicle Specific Speed (VSP) methodology was used in this work. It is a simplified road load model based on the forces exerted on the vehicle and divides the power spectrum in 14 modes [9]. This methodology allows to group points of similar power demand per unit mass (W/kg) and gives the opportunity to identify information that is not possible to identify with an overall analysis.

The methodology done in this work included the following processes:

I. **Development of an ICE activation model that correlates the instant dynamic conditions to the activation of ICE during CD.**

For the development of this model, instant VSP was considered to verify correlations between the driving conditions at each instant or time interval and the activation of the ICE.

II. **Development of an electric consumption indirect measurement model.**

Because of high electric currents the risk of direct measurement is high, a model for indirect measurement was developed considering the dynamic conditions and SOC evolution**.** The characterization of battery consumption was made by analyzing the SOC variation and associating it to the average VSP value. Dividing the SOC variation by the time interval in which it occurs, it is possible to obtain a real battery consumption per second (% ΔSOC / s) for an average VSP. Knowing SOC variation and usable battery for each vehicle, it was possible to estimate the energy consumption.

III. **Development of a working zones matrix, that gathers all instant data according to the motors working during CD, considering the instant VSP, gasoline consumption and RPM.**

It is a 5-index matrix (A, B, C, D, E). A and D is are the all-electric points being A for regeneration points and D for supplying points. B and E are the blended points where EM and ICE are working together. B is for regeneration points with ICE on, E is for supplying points with ICE and EM on. C is for points where the only power supply is the ICE. The matrix is represented in **Table 1**. 0 Is for moments where the motor isn't activated, 1 is for moments where motors are providing energy, -1 is for the moments where EM is regenerating energy.

Table 1 – Working zones matrix: Zone definition

		ICE	
		0	1
EM	-1	**A**	**B**
	0	-	**C**
	1	**D**	**E**

3. Results and discussion

3.1. ICE activation model

The developed model has an accuracy of 73% for **vehicle A** and 83% of **vehicle B**. The ICE activation model estimated that **vehicle A** ICE activated if the average VSP was above 20.8 W/kg for 15s. For **vehicle B** this trigger value was 24.0 W/kg. ICE deactivation occurred for **vehicle A** when the average VSP for 5s was below -9.0 W/kg and for **vehicle B** when it was below -15.0 W/kg.

3.2. Battery consumption model

SOC variation rate (ΔSOC/s) as a function of VSP value for **vehicle A** and **vehicle B** are estimated by the expressions in Eq 1 and 2.

$$\frac{\Delta SOC}{s} = -1.445 * 10^{-4} * VSP^2 - 7.300 * 10^{-3} * VSP \quad \text{Eq 1} \qquad \frac{\Delta SOC}{s} = -5.940 * 10^{-4} * VSP^2 - 5.017 * 10^{-3} * VSP \quad \text{Eq 2}$$

Vehicle A's average relative error (between real SOC and estimated SOC) was 7% and for **vehicle B** the same error was 4%.

3.3. Working zones assessment

Using the working zones matrix in **Table 1**, it was possible to do a more complex analysis for the two vehicles in CD. **Figure 1** shows the distance traveled in each zone for both vehicles studied.

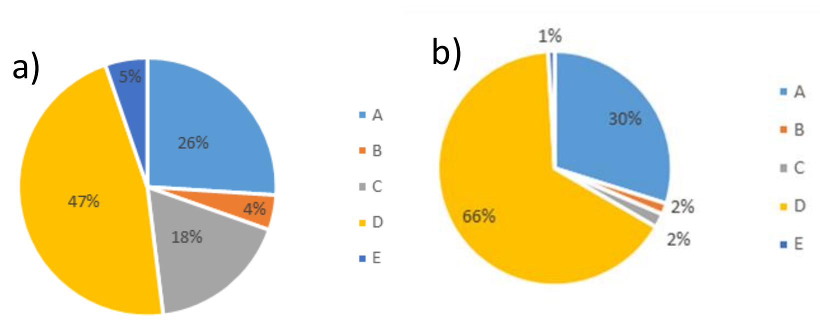

Figure 1 - Distance traveled per working zones: a) vehicle A; b) vehicle B

As **Figure 1** shows, vehicle A depends more on its ICE than vehicle B. ICE was on 27% of the distance traveled due to the 4% in vehicle B. 18% of vehicle's A trips were done exclusively depending on ICE in comparison to only 2% for vehicle B's.

The gasoline consumption was also assessed for the two vehicles. **Figure 2** shows the gasoline consumption in l/100km and gives picture of the impact of each zone in terms of fuel economy.

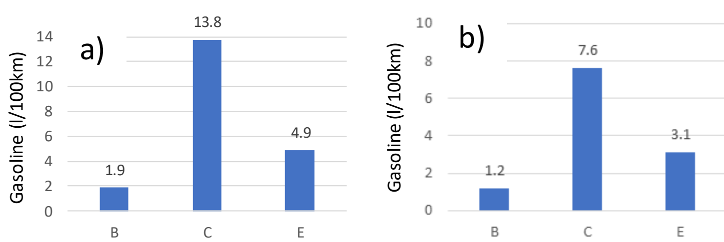

Figure 2 - Gasoline consumption per working zone: a) vehicle A; b) vehicle B

Vehicle B's ICE consumed less fuel than Vehicle A's overall. For both vehicles, Zone C (ICE working only) consumption was more than double when compared with zone E (EM and ICE working) consumption and the consumption in zone B was significantly lower which is in line with expected since zone B is a deceleration zone.

The emissions were also assessed, and the data is shown in **Table 2**. CO_2 values follow a linear correlation with fuel consumption with **vehicle A** having more emissions compared to **vehicle B**. Regarding the other pollutants emitted the differences between the two vehicles are smaller having **vehicle B** a slightly bigger emission rate for HC and NO_x whenever ICE was on. The bigger emissions of **vehicle B** in terms of HC and NO_x may be related to the less frequent activation of the ICE in this car which lead to a larger emission average since these pollutants are more emitted when the engine is cold[10]. For the instants where EM was operating CO_2 emissions were smaller than today's EU CO_2 emission average (120 g/km [11]), meaning that the values were only higher when the vehicles were operating in zone C (ICE on only).

Table 2 – On- emissions per working zone (g/km)

		B	C	E
Vehicle A	CO_2	46	320	116
	CO	0.14	5.5	0.81
	HC	6.5E-03	0.10	0.02
	NO_x	0.01	0.09	0.09
Vehicle B	CO_2	28	181	70
	CO	0.02	1.4	1.3
	HC	8.2E-03	0.13	0.03
	NO_x	0.02	0.13	0.39

3.4. VSP modes assessment

Another analysis was done grouping the data by VSP mode. The assessment of both vehicles was made dividing the periods CD and CS. In CD vehicles spent most of the time in lower VSP modes when compared to CS. From modes 1 to 6 the percentage of time per VSP mode was higher in CD compared to CS for both vehicles. PHEVs rely more on the ICE during CS to preserve the battery SOC in the same level. This makes the fuel consumption during CD lower overall. **Figure 3** gather the data about fuel consumption in CD and CS for both vehicles studied.

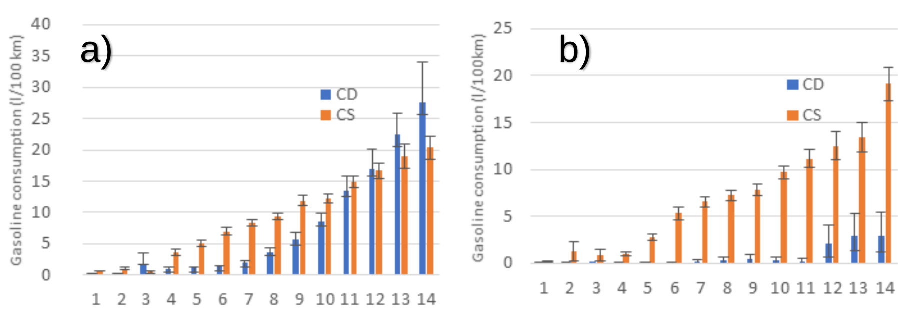

Figure 3 - Consumption per VSP mode in CD and CS: a) Vehicle A; b) Vehicle B

It is possible to see several differences in the operation of these cars. **Vehicle A** in CD demonstrates a lower gasoline consumption in VSP modes from 1 to 11 (except mode 3) but a higher consumption in modes 12 to 14. This shows that vehicle A's powertrain dependence on ICE increases with power. The frequent activation/deactivation of the ICE in CD mode leads to a lower engine temperature and consequently to a higher fuel consumption when compared to CS in high VSP modes. On the other hand, Vehicle B showed almost no dependence on ICE, working almost as an EV in CD. However, there's a substantial increase in gasoline consumption from mode 11 to 12 in CD, showing that at very high loads occurs the activation of the ICE. However, ICE impacts in all VSP modes are bigger in vehicle A than in vehicle B.

Figure 3 also shows that in CS Vehicle A consumes more than Vehicle B in all VSP modes. This is the result of the bigger ICE displacement of vehicle A comparing to vehicle B and the more frequent utilization of the ICE in CS by vehicle B. Vehicle A utilizes ICE 59% of the time in CS while vehicle B only utilizes it in 50% of the time.

The EM consumption in CD estimated with the model described in II was used to quantify electrical consumption per VSP mode in both vehicles. **Vehicle A** consumed at an average rate of 4.3 kW of electricity and **vehicle B** 5.9 kW. This difference is comprehensive due to small utilization of the ICE by **vehicle B**.

On-board emissions were also considered in this assessment. Carbon dioxide (CO_2) emissions are highly correlated with fuel consumption, so emissions per VSP mode followed the same pattern seen in **Figure 3**. Carbon Monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) depend not only on fuel consumption but also ICE's temperature [12]. In CD when ICE is more often deactivated its temperature tends to be lower, so the number of cold starts is higher. This creates more emission peaks in CD which make in some VSP modes the emissions be greater than CS where the ICE worked more time.

3.5. Impacts per distance traveled

The trips made during this offer are a wide variety of driving conditions, due to the different stages of the routes taken. Thus, the conditions of the test trips establish an embracing trip profile that allows a global analysis of impacts by distance traveled. With the data presented in **3.4** and **3,** it was possible to trace the average profile of impacts and consumption for both vehicles in CD and CS. For each vehicle, and assuming the start of the trip with the battery fully charged, it is possible to perform an analysis of impacts by average travel distance, addressing energy consumption (gasoline and electric) and pollutant emissions. For trips made by vehicle A and vehicle B, the average consumptions are shown in **Table 3**.

With the information in Table 3 it is possible to calculate consumptions between two charges. Through the analysis previously made in 3 and 3.4, an average depleted mileage of 39.4 km was verified for **vehicle A** and 43.8 km for **vehicle B**. The results are shown in **Figure 4**.

Figure 4 quantifies the impacts of the extension of trips made by a user of the vehicles studied. It shows that consumption is greatly increased for trips that exceed the vehicle's electrical range. **For vehicle A,** consumption is 2.6 times higher in CS compared to CD, and for **vehicle B** consumption is 14.3 times higher in CD. For a more economical use of these vehicles, the distance traveled daily must be less than 40 km, guaranteeing a purely CD use.

Table 3 – Gasoline consumption and on-board emissions for trips made by vehicle A and vehicle B

		gasoline	CO_2	CO	HC	NO_x
		l/100 km	g/km			
V. A	**CD**	2.8	64.6	1.0	2.0E-02	1.8E-02
V. B		0.3	4.5	3.8E-02	2.9E-03	6.2E-03
V. A	**CS**	7.3	171	0.63	1.8E-03	2.0E-02
V. B		4.3	103	4.5E-02	3.0E-03	1.9E-02

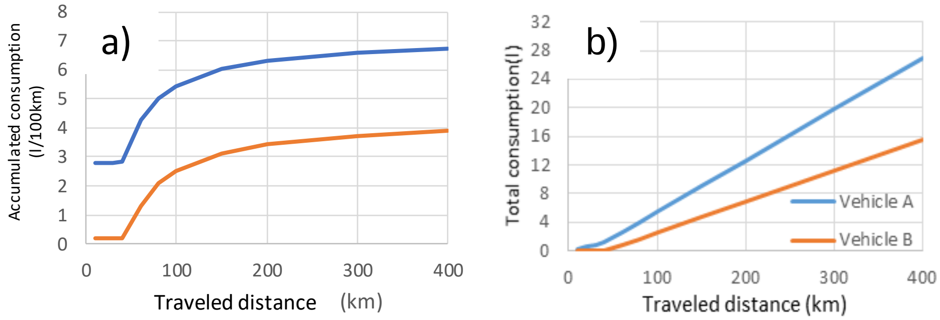

Figure 4 – Fuel consumption per distance traveled: a) accumulated consumption; b) total consumption

The same type of analysis was made for on-board emissions. CO_2 emissions follow a similar pattern to gasoline consumption. Vehicle A emits more CO during the CD phase, so there is a gradual decrease in the average consumption after 40 km, and in vehicle B the CO emissions are practically constant during the entire length of the trip, with a very slight increase in emissions after 40 km. In relation to HC emissions, vehicle A also produces a higher rate of this pollutant on CD, so there is a decrease in the average HC emission with the increase in kilometers traveled. Vehicle B has a slightly higher HC emission in CS. Finally, in vehicle A, in relation to NO_x, there is a short increase in emission with increasing mileage, due to the lower emission during the CD phase. For vehicle B, there is a greater difference in the rates issued on CD and CS, thus leading to a greater increase in the average NO_x emitted as a function of mileage.

Currently, the average CO_2 emitted is around 120 g / km for the European car fleet and the target for 2021 is set at 95 g / km [11]. **Vehicle A** emits 64.6 g / km of CO_2 on average during the CD phase, whereas in CS these values rise to 171 g / km. Thus, if the route taken by **vehicle A** between two recharges is up to 80 km, CO_2 emissions will be lower than the global average for the European car fleet. **Vehicle B**, on the other hand, has CD and CS values lower than the European average, which is why it is always a more favorable option considering CO_2 emissions regardless of the route traveled between two charges. In relation to the other pollutants (CO, HC and NO_x), there are European Union (EU) standards that define emission limit values for gasoline passenger vehicles (Euro 6).

3.6. Impacts of charging frequency

According to the National Statistics Institute of Portugal (INE), in the Metropolitan Area of Lisbon the average distance covered for trips made by inhabitants is 10.3 km and an average of 2.6 trips/day are done

(2017 numbers [13]). Impacts of the charging frequency for vehicle A and vehicle B were studied, based on the energy consumption and emissions presented in **Table 3** and the current average prices of gasoline in Portugal (95 Simple gasoline: 1.55 €/l [15]), as well as the cost of charging electric vehicles that can be consulted in [14] and [15].

In order to evaluate the performance of vehicle A and vehicle B, the estimated values of emissions of on-board pollutants and gasoline consumption were compared with the values of the best-selling ICEV of 2019 in Portugal[16].

<u>Gasoline and electricity – consumption and cost</u>

Gasoline and electricity prices were considered in this analysis. There are several options for electric charging available to the user of an electric vehicle. Each option has different costs that can vary a lot. To calculate the cost of electric charging, two options were taken as an example: Fast Charging, based on the tabulated values of a charging station at a gas station in the Lisbon area; Slow Charging, accounting for the average electricity price per kWh in Portugal. Note that these values are merely illustrative and may vary depending on the user's accessibility to different types of charging.

Adding the prices of gasoline and electricity for both vehicles and the price of gasoline for the ICEV, the distance traveled between two charging opportunities and the frequency of charging it was possible to calculate the cost per km traveled. The results of this calculation are presented in **Figure 5**.

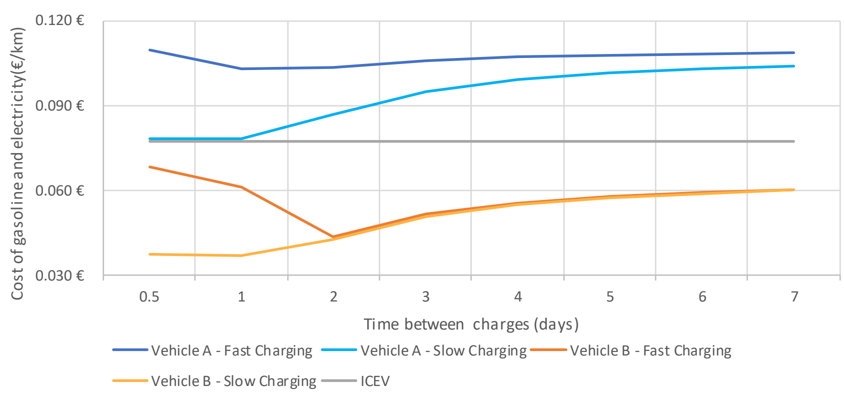

Figure 5 - Energy costs per time between charges

As can be seen in **Figure 5** the best option studied is home charging. However, with the increase of charging intervals, this advantage fades, being even practically null from charging every 3 days in **vehicle B**. For a period between loads between 0.5 to 2 days the option for fast charging is the less economically indicated for both **vehicle A** and **vehicle B**. In a scenario of slow daily or bi-daily charging the advantages are similar, so bi-daily charging only pays off in situations where the user has a reduced charging time or need to travel exceptionally. The least economically indicated vehicle is **vehicle A**, which for any type of charging is the most expensive option. **Vehicle B** is the cheapest option and has a competitive advantage even considering the two types of charging. The ICEV has an average of 0.078 € / km, so it is the intermediate option when it comes to energy cost saving

Global and local pollutants emissions

A comparison was also made of the emissions of pollutants from the 3 vehicles under consideration. Two examples of this analysis for CO_2 and CO emissions are compiled in **Figure 6**. **Vehicle B** on-road emissions were lower for all pollutants in comparison with **vehicle A** and the ICEV. CO_2 and NO_x emission rates increased with the time interval between charging and for CO and HC they remain practically constant. **Vehicle B** NO_x and HC emissions were lower than the ICEV considered. However, **vehicle A**'s are greater, being even higher when the time between charges is small. **Vehicle A** emits less CO_2 than the ICEV if the user has the chance to charge the battery with a frequency that does not exceed 2 days between charges. **Vehicle A**'s HC and NO_x emissions are lower regardless of the charging frequencies considered.

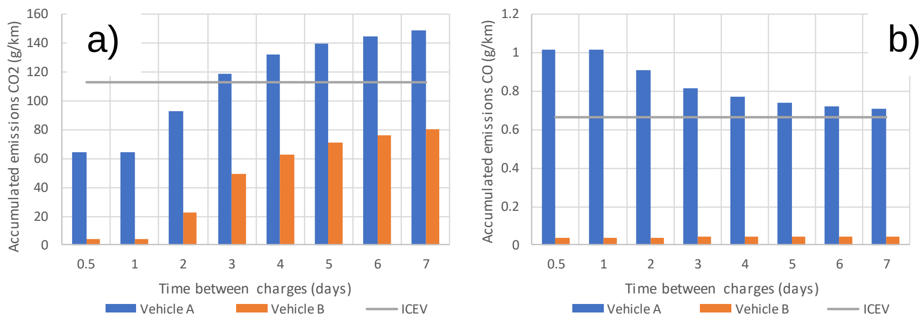

Figure 6 - Accumulated average on-board emissions: a) CO2; b) CO

4. Conclusions and future work

Data of two trips and the models developed were used to assess control strategies of PHEVs.

ICE activation mode predicted that for a 15s average VSP of 20.8 W/kg **vehicle A**'s ICE turns on and for **vehicle B** the average VSP required is 24.0 W/kg. This evidences a bigger fuel dependence for **vehicle A**.

With the working zones assessment was verified that **vehicle A** used the ICE during 27% of the trip in CD and **vehicle B** only relied on its ICE in 4% which originated more emissions per km traveled for **vehicle A** (ex - CO: 1.0 g/km for **A** and 0.038 g/km for **B**). Considering only the moments were ICE was activated the fuel consumption was 10.1 and 4.4 l/100km for **vehicle A** and **B** respectively. VSP assessment showed that **vehicle A** and **B** worked almost full-electrically in lower modes (VSP 3 to 7) and relied more on ICE for higher loads (VSP 10 to 14). 35% of **vehicle A**'s energy in CD was generated from the battery and for **B** the battery assured 87% of total energy consumption. In CS ICE was not activated during 42% of the time for **vehicle A** and 50% for **B**.

The evaluation of distance traveled showed **vehicle A** and **B** met emission standards for CO (≤1.0 g/km), HC (≤0.1 g/km) and NO_x (≤0.06 g/km). It takes 55km for **vehicle A** and 200km for **vehicle B** to surpass 2021's CO_2 emission goal (≤95 g/km). In terms of energy consumption and costs, **vehicle A** was in general the less favorable option, with the prices ranging from 0.078€/km to 0.109€/km according to charging options and frequency. **Vehicle B** showed the best energy costs ranging between 0.037€/km and 0.060€/km.

This work offered a more detailed view of the PHEV operation, analyzing real trip data. It was possible to obtain not only a global picture of the vehicles' performances but also an instant impact analysis of demanded power on emissions and consumptions. For the purposes of future work in this area, it would be important to obtain a larger data set (do more trips) which would allow a better characterization of the global impacts of the PHEV under study. It will also be important for this type of study to cover a wider range of PHEV, which will allow an increase in the still limited knowledge of the operational and energy management of these cars. This type of studies can not only help manufacturers to detect problems with their vehicles, but also users to use their car more efficiently and choose the best option in an eventual purchase.

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