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Energy Assessment of a Plug-in Hybrid Vehicle Propulsion Management System

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Abstract

Plug-In hybrid vehicles have a complex propulsion system management, trying to manage the conventional and electric motorization in the most energy efficient way according to the driving dynamics, topography and battery charge state. In this sense, the aim of this work is to analyze the energy performance of plug-in hybrid vehicles, based on road tests, under real conditions of use, focusing on the management system of the two energy sources present, varying the level of battery charge at the start of the test to visualize the impact of this change. To complement the analysis and in order to better understand the operation of the management system, a methodology for applying the VSP parameter is used, which allows the load state to be approximated according to the vehicle's operating mode, alternating between the three modes according to the conditions at the time in question, prioritizing the electric motor when the state of charge of the battery is maximum. These results confirm the fact that plug-in hybrid vehicles allow better electricity management due to the diversity of external or internal charging sources, which makes this type of vehicle more efficient and versatile than conventional hybrids, allowing a reduction in fossil fuel consumption and consequently a reduction in the emission of pollutant gases, making this type of vehicle a very competitive alternative in the transport sector in view of the current challenges due to the goals present in the current European regulations.

Keywords: Plug-in hybrid vehicles, Energy assessment, Climatization systems, Load support, State of charge

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1. Introduction

The continuous deterioration of environmental conditions requires society to seek more environmentally friendly solutions in order to preserve the quality paradigm of human life. Over the last decade, international organizations have introduced new legislation which have created new challenges for the automotive industry in order to produce vehicles with lower fossil fuel consumption and consequently lower pollutant

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emissions. It is noted that in 2000, the emissions of Carbon dioxide (CO_2) for newly sold vehicles were on average 170,2 gCO_2/km, in 2018 were 120,4 gCO_2/km and it is intended to achieve in Europe the goal of 95 gCO_2/km by 2020 [1]. These measures come in the context of reducing the greenhouse gases responsible for climate change currently being experienced. To meet these challenges, as the conventional transport sector represents on average 10% of the total CO_2 emit globally [2], the automotive industry has been forced to design more efficient thermal engines, more sophisticated emission control systems and hybrid or fully electric vehicles. A hybrid vehicle is an interesting solution for optimizing the propulsion system and reducing emissions due to the complement of the electric motor with an internal combustion engine allowing to keep the thermal motor running at low revs, or to inhibit its operation in situations of stable and low throttle driving. This allows a reduction in fuel consumption, a reduction in the emission of pollutants and is not exclusively dependent on electricity. With the development of the technology, different types of hybrid vehicles were introduced, differing in the management between the use of the electric motor and the internal combustion engine. Parallel hybrids use the electric motor and the internal combustion engine generate traction to move the wheels of the vehicle; in series hybrids the electric motor generates traction and the internal combustion engine is used as a backup to recharge the battery and; full hybrids, being the most common type of vehicle, characterized by the use of the electric motor and the internal combustion engine depending on an instantaneous assessment of the vehicle's condition and route or the user's preference.

Battery charging of a hybrid vehicle is also a feature that makes possible to differentiate between conventional hybrid vehicles and plug-in hybrid vehicles. Conventional hybrid vehicles only have the ability to recharge the battery from internal sources, namely thermal engine and regenerative braking, while plug-in hybrid vehicles have the ability to recharge the battery from internal sources such as conventional hybrid vehicles but also from external sources by connecting the car battery to a charging station, similarly to an electric vehicle.

As a result of the introduction of new standards for vehicle certification in Europe [3], using real-time monitoring under real driving conditions (Real Driving Emission), the quantification of energy flows (fuel and electricity both from sources outside the vehicle) in a plug-in vehicle is crucial in order to attribute the actual energy impacts and emissions associated with its use. However, although monitoring fuel consumption and emission over a road test is currently well defined in methodological terms and the equipment to be used [4], monitoring of electrical consumption implies specific care (magnitude of voltage and current involved) and the installation of specific equipment and technical care to ensure safety.

Consequently, this work explores the development of indirect techniques to estimate at each second of driving, under real-world conditions, the electricity consumption using information available on the OBD interface, which indicates at 1 Hz the state of charge of the battery (SOC).

2. Materials and Methodology

2.1. Vehicle

In this study a Plug-In hybrid vehicle was tested under real driving conditions, and its main characteristics are shown in Table 1. It is a light passenger vehicle whose typology fits into the vehicle SUV category.

TABLE 1: Characteristics of the vehicle under study [5];

Vehicle	**Vehicle A**
Displacement	1499 cc
Power	221 hp
Transmission / Gearbox	Automatic- 6
Vehicle Mass [kg]	1635
Fuel	Otto
Battery [kWh]	7.6

2.2. Test Cycle

A fixed test cycle, as shown in Figure 1, was performed during the test in order to meet the necessary conditions for interpreting and evaluating the management of the integrated propulsion system according to the state of charge of the battery.

The tests were carried out in the Lisbon metropolitan area over a two-hour period (around 7200 s of data collection per trip), in which the car was initially exposed to an urban environment, then to a highway environment and finally, again exposed to an urban environment. The tests were performed during the morning and late afternoon, in order to avoid the influence of external factors on the collected data, such as temperature peaks and excess traffic. Figure 2 is an example of a test cycle where the different conditions to which the vehicle is exposed are evident, which shows the use of different driving modes by the vehicle propulsion management system.

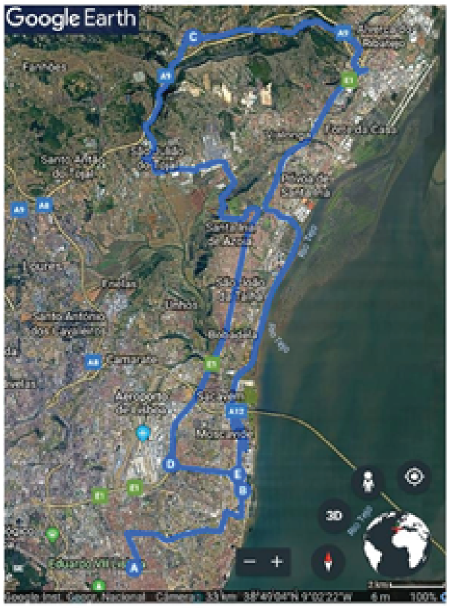


Figure 1: Path performed during the tests performed [6];

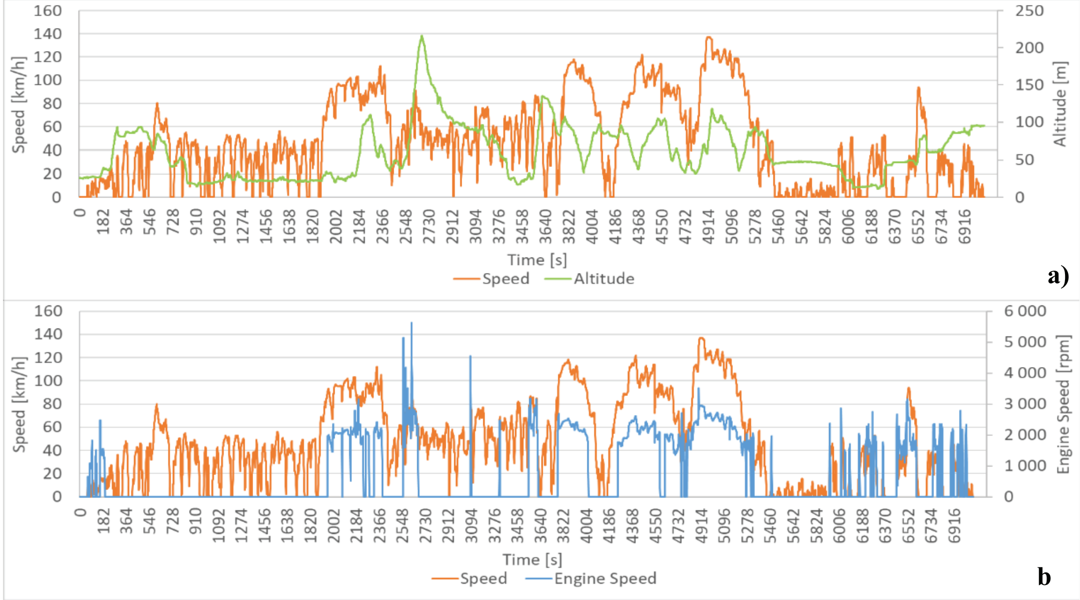


Figure 2: Example of a test cycle performed, divided into three phases (urban, highway, urban). (a) speed and altitude as a function of time; (b) engine speed and speed as a function of time;

2.3. Portable Emission Measurement System

The measurement equipment used to obtain the desired data was a portable emission measurement system (PEMS). This system provides detailed instantaneous vehicle information throughout the test and consists of an On-Board Diagnostic (OBD) reading port, a Global Positioning System (GPS) with barometric altimeter and an exhaust gas analyzer, as shown in Figure 3. The OBD interface reader allows monitoring of parameters associated with the internal combustion engine, but also the state of charge of the battery (SOC) throughout the test trip. All devices are connected to a laptop, collecting at 1Hz and synchronizing the data through LabView software in a program designed for this purpose. This way it is possible to acquire the engine data, vehicle dynamics, road topography and all the involved vehicle parameters.

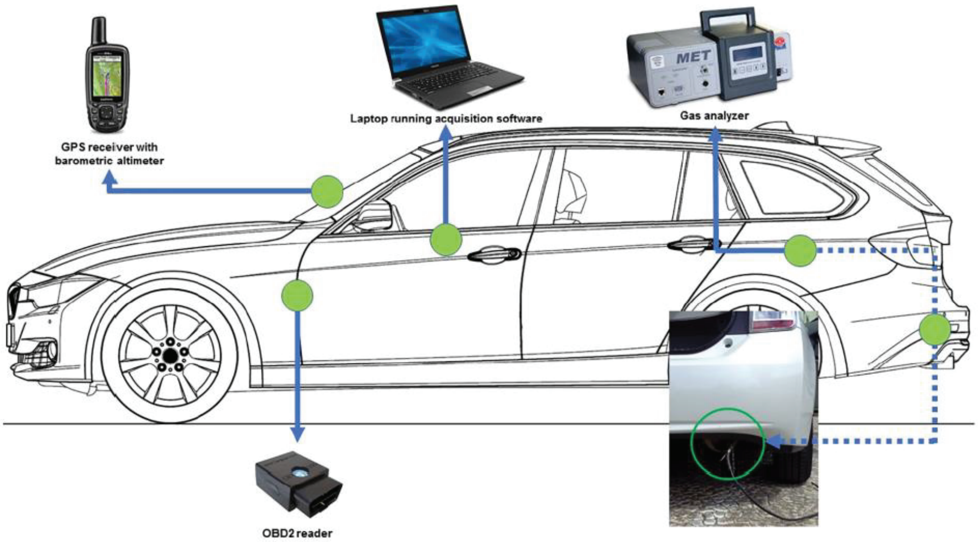


Figure 3: Major PEMS components installed in vehicles, [7].

2.4. On road data processing

The data processing used to achieve the previously determined objectives uses the Vehicle Specific Power (VSP) methodology, calculated at each second of each test trip. This parameter is defined as a road load model and provides an estimate of the instantaneous power on the wheel necessary to overcome vehicle to ground friction, aerodynamic resistance and increase vehicle kinetic energy and potential [8]. Although VSP is a widely used parameter for determining vehicle emissions [9, 10], supported by other parameters it will be used in this case to estimate the battery state of charge. Therefore, this parameter can be calculated according to Equation 1.

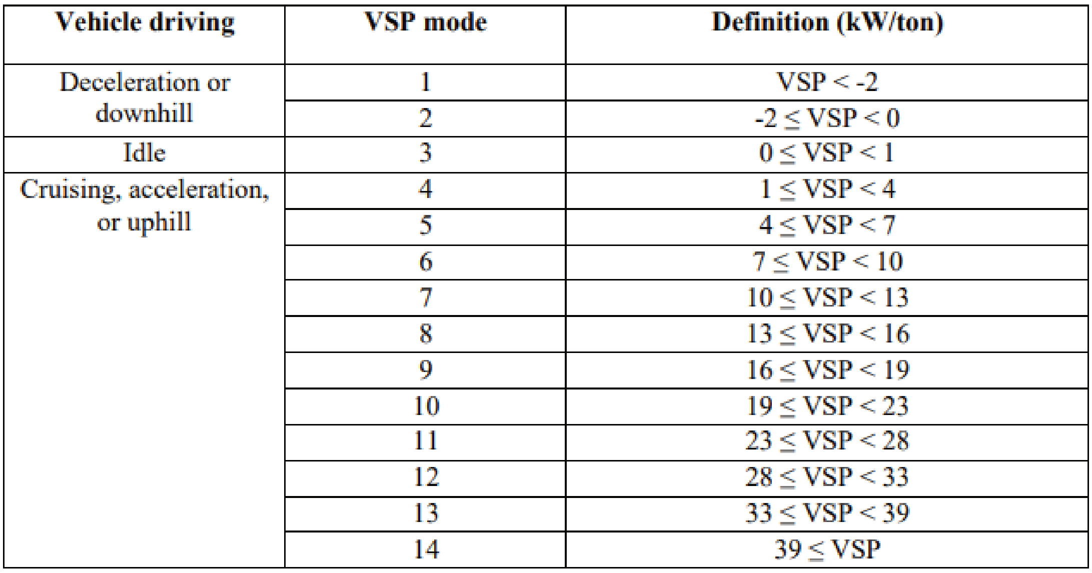
$$\begin{aligned} &\textit{Vehicle Specific Power} \\ &= \frac{\frac{d}{dt}(KE+PE)+F_{rolling}\times v+F_{aerodynamics}\times v}{m} = \\ &= \frac{\frac{d}{dt}(\frac{1}{2}\times m\times(1+\varepsilon_i)\times v^2+m\times g\times h)+C_R\times m\times g\times v+\frac{1}{2}\times\rho_a\times C_D\times A\times(v+v_w)^2\times v}{m} = \\ &= v\times(a\times 1+\varepsilon_i)+g\times grade\times g\times C_R)+\frac{1}{2}\times\rho_a\times\frac{C_D\times A}{m}\times(v+v_w)^2\times v \end{aligned} \tag{1}$$

Where *v*, corresponds to vehicle speed, *a* corresponds to vehicle acceleration, ε_i corresponds to the mass factor, *g* is the gravitational constant (9,81 m/s^2), *grade* corresponds to the relationship between altitude and distance traveled, C_R corresponds to the coefficient of friction between vehicle and ground, C_D corresponds to the drag coefficient, ρ_a corresponds to the outside air density, *A* corresponds to the frontal area of the vehicle, *m* corresponds to the mass of the vehicle and v_w corresponds to the wind speed striking the vehicle. Equation 1 can be further simplified by taking into account typical vehicle coefficients and VSP is calculated according to Equation 2.

$$VSP = v\times(1.1\times a+9.81\times grade+0.132)+0.000302\times(v+v_w)^2\times v \tag{2}$$

The calculation of the VSP value is performed every second of the trip and is typically divided into fourteen modes, or more for easier understanding, into three categories as shown in Table 2.

Table 2: Vehicle Specific Power Modes [11]



Vehicle driving	VSP mode	Definition (kW/ton)
Deceleration or downhill	1	VSP < -2
	2	-2 ≤ VSP < 0
Idle	3	0 ≤ VSP < 1
Cruising, acceleration, or uphill	4	1 ≤ VSP < 4
	5	4 ≤ VSP < 7
	6	7 ≤ VSP < 10
	7	10 ≤ VSP < 13
	8	13 ≤ VSP < 16
	9	16 ≤ VSP < 19
	10	19 ≤ VSP < 23
	11	23 ≤ VSP < 28
	12	28 ≤ VSP < 33
	13	33 ≤ VSP < 39
	14	39 ≤ VSP

Using VSP modes makes possible to stratify vehicle analysis and verify vehicle behavior in different VSP modes, taking into account only parameters from vehicle dynamics. For example, the average fuel consumption in each VSP mode, with low or zero fuel consumption expected in the first three VSP modes and increasing fuel consumption in the other modes, as shown in Table 3 in section 3.1.

After the VSP data is properly analyzed and processed, it is possible to apply the methodology of approximation of the energy consumption based on the VSP. This is a methodology for approximating the battery state of charge of the vehicle, taking into account its operating mode, electric, electric-thermal and only internal combustion engine based only on VSP modes, fuel consumption, vehicle speed, engine speed and trend curves created from actual energy consumption.

The approach taken to analyze the battery SOC estimate requires obtaining a relation between the change in SOC over a specific time period in relation to the mean value of VSP in this interval. Therefore, Plug-in operation modes must be first identified. Charge depleting was set to be above 10% SOC level, since below this value the vehicle energy management system maintains this charge sustaining state, using mostly the internal combustion engine.

Consideration was also given to analyzing small load state intervals, in which there were slight variations in VSP, this way it is analyze the SOC relating to the engine speed in tests performed when the vehicle SOC was maximum, consisting of load state analysis when the internal combustion engine is off (rpm = 0) and load state analysis when the internal combustion engine is operating (rpm $\neq$ 0). From this analysis, several points were obtained regarding the variation of the SOC level in relation to the average VSP, allowing the creation of two trend lines, according to the analysis in question.

It is also taken into account its electrical, electric-thermal and only thermal mode of operation based solely on VSP modes, fuel consumption and engine speed through a second-by-second comparative analysis of fuel consumption at the time under study compared to the average consumption of VSP mode of that second, trying to differentiate between electric-thermal and only thermal operation.

3. Results and Discussion

3.1. Indirect method of assessing electrical consumption

Figure 4 presents the behavior of the battery SOC level along the road tests, indicating the energy consumed or regenerated as a function of time, as well as the use of the internal combustion engine during the trip. Thus, in the tests in Figure 4 shown on the left, the vehicle started the full load test, distinguishing the initial phase of the charge depleting test. In Figure 4 b) and d), it is possible to observe a high use of the internal combustion engine, resulting from a low charge sustaining battery level.

In Figure 4 b) there was a dependence of the internal combustion engine of 63.5% and in Figure 4 d) the use of the internal combustion engine was of 58.8%. This small difference may be justified by the fact that Figure 4 d) is a shorter trial than Figure 4 b).

Comparatively, Figure 4 a) results in a thermal engine use of only 32.8%, and in the case of Figure 4 c) a thermal engine utilization of 45.3%. The difference between the tests is justified by the increase in traffic intensity and the use of higher power at the end of the test, leading to greater use of the internal combustion engine.

On the other hand, the fact that starting the trip with the battery fully charged, is a remarkable reduction of approximately 30% of the internal combustion engine utilization when compared to Figures 4 b) and d), resulting in a lower fuel consumption and lower pollutant emissions.

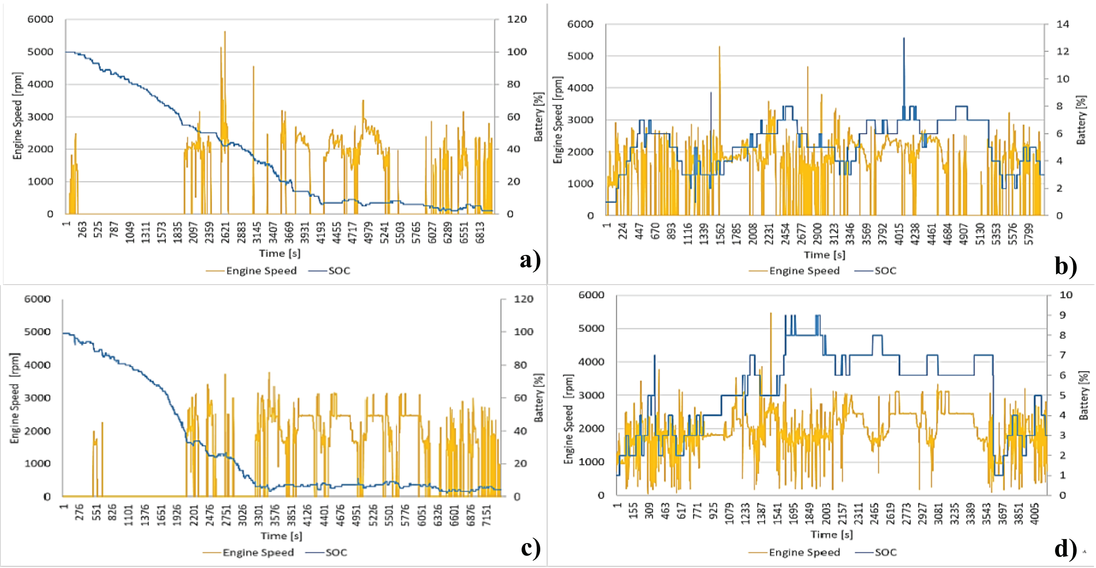


Figure 4: Graphical representation of the variables Frequency and Capacity of the Battery as a function of the time of the tests carried out in Vehicle B. a) High Battery; b) Low Battery; c) High Battery; d) Low Battery;

The SOC estimates based on the VSP require a relation between the variation of SOC over a time period and the VSP in the same period. This was analyzed in the two trips that took place when the initial capacity of the vehicle battery was maximum, consisting of the analysis of the state of charge when the engine speed was zero and the state analysis load when the motor speed was nonzero.

Based on the described methodology, it was possible to obtain the relation between the variation of SOC per unit of time and the value of VSP, according to Figure 5, composed by a trend line of the various points selected from the two trials based on the assumptions considered previously.

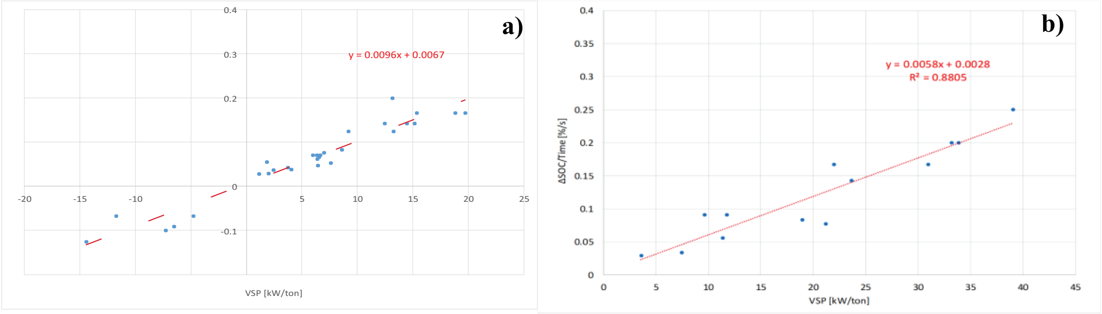


Figure 5: Trend line between the variation of the load state over time and the mean value of the VSP in this interval. a) RPM = 0; b) RPM ≠ 0);

According to Figure 5, the methodology used may introduce some error, since the results are entirely dependent on the amount of points obtained through the collection, as it happens in the non-zero RPM situation, where it is perceived that linearity follows a trend but for lack of points is not fully confirmed.

Table 3: Average consumption by VSP mode and the respective standard deviation.

Mode	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
St. Deviation	0.248	0.192	0.108	0.397	0.538	0.691	0.871	0.974	1.178	1.133	1.277	1.340	1.268	1.496
Average	0.052	0.053	0.019	0.166	0.300	0.480	0.770	1.162	1.591	1.836	2.471	2.935	3.262	3.910

Based on the relations obtained in Figure 5 and again taking into account the methodology described and the three possible hypotheses presented (electric, electric-thermal and thermal), considering also the average fuel consumption according to each VSP mode as shown in Table 3, it became possible to approach the charge state as shown in Figure 6.

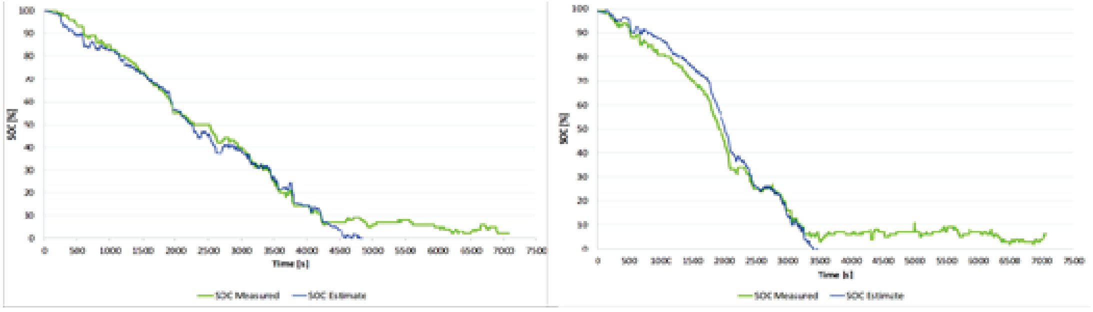


Figure 6: Approximation of charge state in tests performed with maximum battery capacity;

In order to compare the real SOC level with the estimated SOC, a graphical representation of was made, presenting a linear relation, close to the equation of line y = x as expected and indicating the accuracy of the approach made, visible in Figure 7.

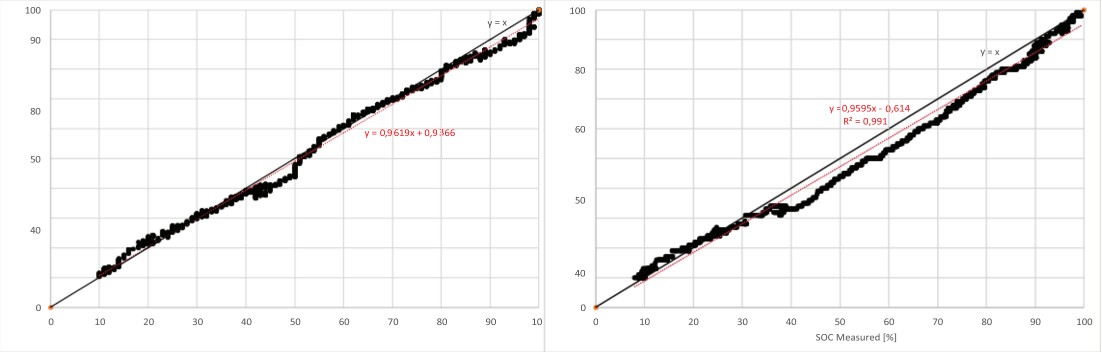


Figure 7: Comparison between actual charge state and approximate charge state;

Therefore, in both trips tested, the SOC estimate provide values of R^2 around 0.99, which means that by determining the VSP, it is possible to accurately recreate the evolution of the battery SOC level over a test by knowing the initial state of charge. This information indicates that the method tested distinguishes points of use of the electric motor, the combination of the electric and internal combustion engine, and only thermal, providing a good estimate of regeneration. Consequently, this method allows to accurately estimate the electric consumption of the car from the total capacity of the battery.

3.2. Qualitative assessment between direct measurement of electrical consumption and estimation

Preliminary results of a road test of a vehicle of the same typology as the vehicle under study, equipped with a monitoring system equivalent to that of Figure 2, plus additional equipment for direct measurement of motor current and voltage can be seen in Figure 8. The results obtained are visible in Figure 8, indicating the existence of two variables, one being the engine speed and the power consumed or regenerated over test trip time. Thus, as an example, the test shown in Figure 8 is characterized by an initial full charged battery and the vehicle auxiliaries on, thus resulting in a 41.8% thermal engine utilization.

Comparison both approaches to obtain electric energy use, it is apparent that in both cases there are advantages and disadvantages associated with each. In the case of a direct measurement of the electrical consumption, which collects the power used and regenerated directly in the battery, it was found that an initial verification of the direct current polarity is necessary due to the way the connections are made to the battery poles. This leads to possible signal inversions which at 1Hz imply an extensive data analysis effort if no initial verification is performed. This issue is even more important

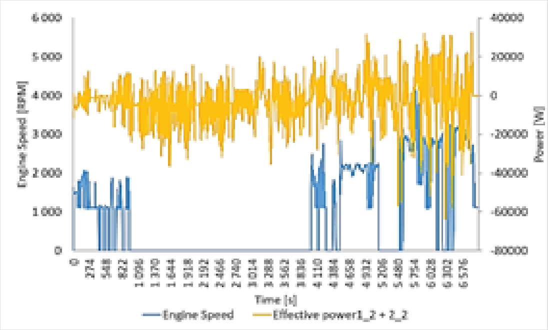


Figure 8: Graphical representation of the variables Frequency and Power versus Time in one of the tests per- formed on a vehicle of the same typology;

considering that there is consumption and regeneration and there may be more than one electric motor. It has yet another disadvantage inherent to the risk that occurs when making the connections, since the current and voltage magnitudes are quite high. Finally, due to the need to perform several readings, it is necessary to use dedicated equipment, which results in the existence of several files with collected data requiring alignment after the test.

Using an indirect approach based on data collected through the OBD interface, synchronized with the other dynamic data, it is also possible to obtain a good estimate of the evolution of the battery charge state and therefore, the use of electricity. However, because 100% scale of the battery is divided only in 256 bits, the accuracy is relatively low, which means that under low power conditions a long period of driving time is required before the SOC reduces by 1%. However, the method presented here allows to add some intermediate level of precision as it allows estimation at 1Hz. However, it still has the disadvantage of being an indirect analysis, which presents some difficulty in case of insufficient data, preventing the approximation of the SOC level with good accuracy. It is also interesting how the VSP was developed to predict emissions of polluting gases and in this case allows to predict the state of charge of an electric car, being a simple parameter but containing a lot of information together with other parameters.

4. Conclusions

The aim of this work was to analyze the propulsion management system of a plug-in hybrid vehicle, which had four real tests to verify the impact on the management system decision, by correctly identifying the energy use, both from internal combustion engine (Table 3) and battery SOC level (Figures 6 and 7).

Plug-in vehicles are quite versatile due to the possibility of external charging, not depending entirely on the internal combustion engine or braking regeneration to charge the battery, thus introducing an additional level of difficulty in their energy and environmental characterization under real conditions of use in accordance with vehicle certification standards in Europe. Calculated VSP and SOC information collected from the OBD interface allows for easier and safer collection, providing 1Hz estimates of SOC with proven accuracy of R^2 values around 0.99 in both tests when compared with actual charge state. Validating the SOC level over two real- world trips allow to conclude that the methods used are suitable to predict the vehicle energy management.

Moreover, the methodology used facilitates the analysis of the test data, being a more logical and less complex approach, when compared with direct methods of electrical energy measurement that endanger the testers, as well as mislead the testers responsible for data analysis.

Finally, this analysis will be expanded to other tested vehicles in order to better understand and identify driving regimes, whereby the management system chooses and compares between the different tested vehicles, seeking a broader validation of the method.

In future work it is intended to define in real time the type of propulsion system selected by the management, verify the possibility of system optimization given the external conditions, but also the influence of the auxiliaries in the decision making of the propulsion management system according to the initial SOC level of the vehicle. Moreover, it is intended to explore the possibility of optimizing the emission of pollutants, aiming to make these vehicles as “green” as possible in order to reverse the years of large-scale pollutant emission that cause climate change.

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