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Energy and environmental characterization of operational modes of plug-in vehicles

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Abstract

This paper presents an energy and environmental characterization of the two most relevant Plug-in Hybrid Electric Vehicles available in the market (Opel Ampera and Toyota Prius Plug-in), in order to provide an estimate of fuel and electricity consumption, tailpipe emissions and charge depleting mode mileage for any drive cycle studied, based on vehicle specific power methodology. These vehicles were monitored under real-world operation with a portable laboratory that collects data from vehicle sensors (via on-board diagnosis port), exhaust gas composition and GPS in a second-by-second basis.

An indirect method to measure battery energy fluxes and consequently estimating electric range was developed, providing maximum errors for the Charge Depleting driving range of 4.2% for the Toyota Prius Plug-in and -0.2% for the Opel, when comparing with measured data. Regarding fuel consumption, the maximum error verified was of -4.1%.

Using two driving profiles measured in Portugal and the USA, the performance of the two vehicles under charge depleting (CD) and charge sustaining (CS) conditions was compared. Major findings indicate that Opel Ampera is more efficient in CD mode, while the Prius Plug-In is more efficient under CS conditions, but highly dependent on driving behavior when in CD mode.

Keywords: Plug-in Hybrid Electric Vehicles, driver behavior, on-road monitoring, energy efficiency, tailpipe emissions

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1 Introduction

According to Society of Automotive Engineers, an hybrid vehicle is “a vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently” [1].The increasing prices of fuel and the local benefits in terms of pollution have increased the interest of manufacturers to develop Hybrid Electric (HEV), Plug-in Hybrid (PHEV) and Battery Electric vehicles (BEV) to complement conventional gasoline and diesel powered engines.

Plug-in electric vehicles can be defined as hybrid electric vehicles (HEV), with the capacity to recharge the batteries using an off-board source [2]. The PHEV drivetrain can adopt configurations similar to HEV, namely series, parallel and parallel/series and are designed to fully or partially use the electric energy stored to replace the chemical energy source used on an internal combustion engine (ICE), for instance.

Therefore, in a PHEV vehicle there are two driving modes, which are Charge-Depleting (CD) and Charge-Sustaining (CS) [3]. Charge-Depleting is an operating mode in which the battery state of charge (SOC) may fluctuate but, on average, decreases while driving. Charge-Sustaining consists on an operation mode in which the battery SOC may fluctuate but, on average, is maintained constant by action of the ICE at a defined level while driving.

This way, PHEV present some advantages over ICE and HEV, as they can use only electricity stored on the batteries, without local emissions, and benefit by having less battery weight when compared with a BEV. Considering these premises, according with the national power mix CO_2 intensity, the advantages of a series PHEV in CD can be around 3 to 6 g/km CO_2 lower than BEV in medium-intensity power mix grids (such as in U.S.) and the best option in their entire driving range for high intensity power mixes (such as China), when compared with BEV and conventional ICE vehicles [4].

The advantages in terms of fuel use and pollutant emissions of PHEV comparing with conventional vehicles are still unbalanced by the total ownership costs, with payback periods around 8 years, accounting for vehicle initial cost, fuel and electricity consumption (considering a PHEV with 30 miles of all electric range) and consequent energy costs [5]. According with a study developed by Neubauer et al. [6], considering battery use, charging management and replacement, the driving pattern plays a significant role on the PHEV-to-conventional vehicle cost ratio by up to a factor of 1.64, which has a much larger impact than the variation of technical design parameters.

Despite the studies presented, PHEV technology is still very recent and needs to be better characterized regarding real-world use, although different configurations and strategies can be evaluated using numerical tools, the offer from major vehicle manufacturers is still reduced. In 2013 there are two PHEV solutions available for sale in Portugal: the Toyota Prius Plug-in and Opel Ampera (comparable to the Chevrolet Volt). Regarding the case of Toyota Prius, HEV and PHEV versions are conceptually similar, though the last has higher battery capacity – 1.3 kWh on HEV [7] and 4.5 kWh on PHEV [8].Due to its full hybrid configuration, both electric motor and ICE are connected directly to the drive wheels. The Opel Ampera concept is significantly different, being also defined as an electric vehicle with a range extender. Hence, the ICE does not have a physical connection with the drive wheels and is used as a generator to charge the batteries on-board.

Due to CD and CS modes, the analysis of a PHEV energy use is complex and, regarding certification, there is not an established worldwide standard procedure, although there are recommendations from Society of Automotive Engineers for calculation of fuel consumption and pollutant emissions in U.S. [9], there are studies proposing methods to harmonize certification practices [10].

The characterization of PHEV and their impact on real-world driving is still not clear in literature. A study developed by Frey et al. [11] on a 2nd generation Toyota Prius converted to Plug-in by A123 Hymotion presented a methodology to perform real-world evaluation of a PHEV, regarding electricity use, fuel use and emissions. A portable emission measurement systems (PEMS) was used to quantify fuel and emissions under on-road conditions. Voltage and current to and from the batteries were reported from an electronic control unit data-logger. All data collected was converted and synchronized into a 1 Hz basis. Using Vehicle Specific Power methodology (VSP) [12], on-road data can be grouped in modes with similar power demand (according with vehicle speed, acceleration and road grade) where each mode has associated fuel consumption, electricity use and pollutant mass emission rates. This analysis was done for CD and CS driving conditions.

The Vehicle Specific Power methodology is a road-load model, which simplifies the forces acting on the longitudinal axis of the vehicle, based only on vehicle speed, acceleration and road grade, and is useful to compare different vehicle technologies. It is also used in US EPA MOVES model [13] to provide an estimate of fuel consumption and pollutant emissions for a given drive cycle.

Therefore, the objective of this work is to perform an energy and environmental characterization of the two most sold Plug-in vehicles (Toyota Prius Plug-in and Opel Ampera) in CD and CS modes and their impact on energy use and pollutant emissions, providing an estimate of energy requirements and mass of pollutant emissions for any desired drive cycle according with initial battery SOC conditions.

2 Methodology

The Toyota Prius Plug-in and Opel Ampera were measured under on-road conditions using a portable emission measurement system (PEMS) collecting data at 1Hz, comprehending more than 5 hours of valid driving data for each vehicle (around 38400 s for both vehicles).

The routes chosen included urban, rural and highway roads around the Lisbon metropolitan area, for more than 500 km considering both vehicles tested.

2.1 PEMS description

A PEMS was installed in the vehicles and used to collect data at a second by second basis, regarding engine parameters, vehicle dynamics, tailpipe emissions, road topography and battery state of charge [14, 15].

The PEMS includes an OBD reader that collects vehicle speed, engine speed and load, engine mass air flow, intake air temperature, manifold absolute pressure, throttle position and coolant temperature. In addition to these standard OBD parameters, an additional parameter was used to collect battery state of charge from OBD: Hybrid/EV Battery Pack Remaining Charge. All the data collected from OBD is provided by the vehicle sensors.

Exhaust gas concentration is determined using a Vetronix PXA 1100 portable 5-gas analyzer, which measures simultaneously CO_2, CO, HC, NO and O_2 tailpipe concentrations

A Garmin GPSMap 76CSx GPS receiver with built-in barometric altimeter was used to collect road topography with an adequate resolution.

All the equipments are connected to software developed purposely in LabView to integrate and synchronize the data. With this information it is possible to estimate fuel consumption and pollutant mass emission rates in a second by second basis, in CD and CS operation.

2.2 Vehicle Specific Power methodology

In order to characterize the power demand for vehicle motion, a useful definition is the Vehicle Specific Power (VSP) methodology which is a simplification of all the forces present on the vehicle. This methodology is a road-load model which allows estimating instantaneous tractive power per unit vehicle mass, making useful to use VSP as a basis to perform energy and environmental characterization of vehicles [12, 14]. Equation 1 allows estimating the power demand for light duty vehicles at every second of driving of a given trip [12].

$$\mathrm{VSP} = \mathrm{v} \cdot (1.1 \cdot \mathrm{a} + 9.81 \cdot \mathrm{grade} + 0.132) + 3.02 \cdot 10^{-4} \cdot \mathrm{v}^3 \quad (1)$$

A modal analysis is used to group points of similar power demand per mass unit (W/kg). Thus, the points collected during on-road measurements are grouped in modes, where each mode has an associated fuel consumption estimate based on ICE and exhaust emissions data [16]. The same approach is used for tailpipe emissions, where statistical information of pollutant emissions mass flow is provided for each VSP mode. A value of electric energy rate is also assigned to each VSP mode, as defined by Frey et al. [11], therefore a method to estimate electric consumption was developed from battery SOC data.

3 Results

3.1 Electricity consumption estimate

3.1.1 Method

To perform a full characterization of a PHEV it is necessary to characterize the electricity use, namely under CD mode, as this can be the only energy source to move the vehicle. Considering the risks and the technical knowledge required to perform direct measurements of battery voltage and currents under on-road conditions, a method to indirectly measure these values was developed.

Collecting the data corresponding to battery SOC from OBD using a specific parameter identification code was possible to assess SOC variation (ΔSOC) under constant VSP situations. This requires driving at constant speeds at a flat area during the necessary time to achieve battery SOC changes.

Figure 1 shows the variation of battery SOC according to the VSP value for the Toyota Prius Plug-in and Figure 2 present a similar analysis for the Opel Ampera.

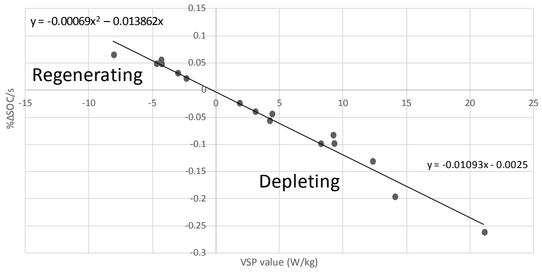

Figure1: Variation of SOC with VSP value for Toyota Prius Plug-in

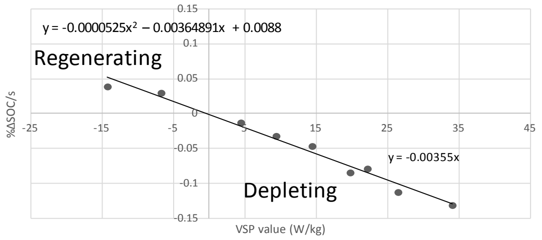

Figure2: Variation of SOC with VSP value for Opel Ampera

As a remark, using the OBD data for the Toyota Prius Plug-in, 73% SOC corresponds to a fully charged vehicle in the user perspective and 30% SOC on OBD correspond to 0% SOC for the user. For the Opel Ampera, the 0-100% in the vehicle display corresponds to 24% to 84%, respectively, from OBD data. This means that a smaller range of the battery energy storage is used, possibly allowing enhancing their duration and operation properties during charge and discharge.

3.1.2 Validation

The validation of the methodology to indirectly estimate the energy flows includes two analysis: compare the evolution of measured SOC in real trips with the estimates provided by the methodology developed; and compare the results provided by the method with battery energy flow measurements performed on a Toyota Prius HEV.

Figures 3 and 4 presents the evolution of SOC over time measured from OBD on a real trip and the estimate provided by the model for Toyota Prius Plug-in and Opel Ampera, respectively. It is only necessary information about the initial SOC value and the instantaneous VSP value along the trip to determine the correspondent SOC variation at each second of driving.

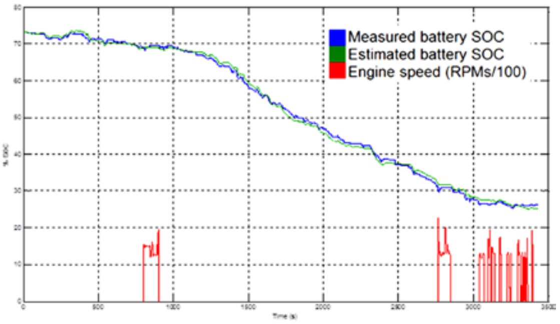

Figure3: Comparison between measured and predicted battery SOC for Toyota Prius Plug-in

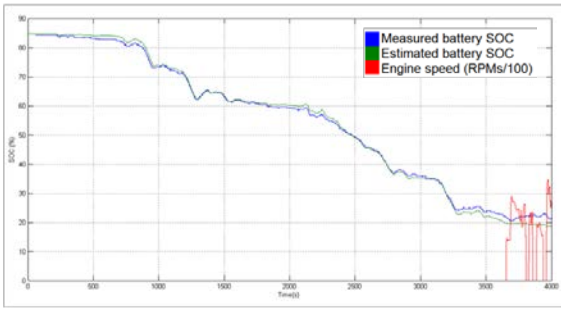

Figure4: Comparison between measured and predicted battery SOC for Opel Ampera

From Figures 3 and 4 can be seen that the method developed follows the measured data regarding the battery SOC evolution using only initial SOC value and instantaneous VSP values.

Using the raw data from a previous work [17] where currents were measured directly on the battery of a Toyota Prius HEV and the SOC collected from OBD, the prediction of ΔSOC (%) according with VSP was divided in two main areas: a linear regression for positive VSP and a quadratic for negative VSP adapted for the vehicle studied.

Table1: Comparison between predicted and measured values for electricity consumption

	Predicted		Measured	
Mean VSP (W/kg)	ΔSOC/s	W	W	Error (%)
-6.90	0.275	12881	9658	33.4
-3.88	0.248	11584	11504	0.7
-3.53	0.237	11102	11010	0.8
2.08	-0.156	-7290	-7355	-0.9
2.27	-0.164	-7681	-8014	-4.2
3.99	-0.243	-11365	-10516	8.1

Considering the HEV battery capacity, to each ΔSOC/s, was possible to assign the respective Wh/s (or Watts) regenerated or depleted.

From Table 1 it can be seen that there is a high error for VSP equal to approximately -7 W/kg, however all the other values are predicted with accuracy better than 9%. This is a good result considering that these are approximate values, because this vehicle is a HEV and was not tested following the procedures of this methodology. Therefore, these two constraints created some problems on the data acquisition for this validation, since the small battery capacity of the conventional Toyota Prius reduces the possibility of operating the EM on a full electric mode, which makes more difficult to obtain on-road data points where only the EM is operated with a constant VSP.

3.2 Energy and environmental characterization of on-road measurements

On-road monitoring with the PEMS included driving conditions under charge depleting and charge sustained modes, which were analyzed separately.

3.2.1 Toyota Prius Plug-in

When performing vehicle on-road monitoring it is desirable to cover the widest possible range of driving conditions, therefore a more aggressive behavior of the driver is necessary to cover a broad range of power demand conditions. The Toyota Prius Plug-in was found to have a strong dependence on the driver´s behavior as it influences the amount of time the ICE is maintained OFF under CD operation. This occurs because this vehicle has both the ICE and EM connected to the wheels and on high power demands, the ICE is used to provide most of the power needed to move the vehicle.

The time distribution with ICE OFF per VSP mode is presented in Figure 5, for the tests performed in CD.

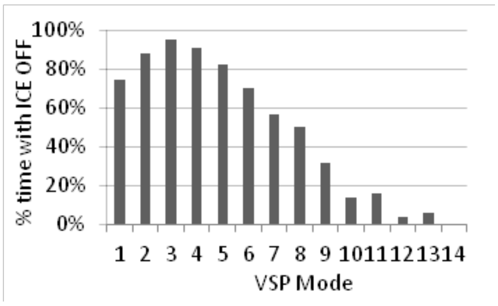

Figure5: Percentage of time with ICE OFF in CD for an aggressive driving (Toyota Prius Plug-in)

It can be seen that with the increase of VSP mode, the time in which the ICE is OFF decreases significantly.

When a soft driving behavior is considered, the driver benefits from sole electrical propulsion and the ICE will be maintained OFF most of the time, as shown in Figure 6

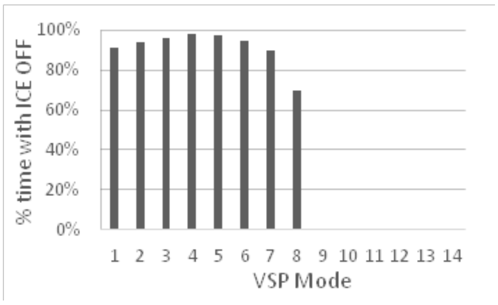

Figure6: Percentage of time with ICE OFF in CD for a soft driving behavior (Toyota Prius Plug-in)

The soft driver will be able to maintain the ICE OFF for longer periods of time and will not reach high VSP modes (in general). This behavior will have influence on the fuel consumption under CD mode for this vehicle due to its configuration.

In Figure 7 fuel consumption is present both for CS and CD mode. Under CD mode the values obtained reflect the ICE OFF distribution presented in Figure 6.

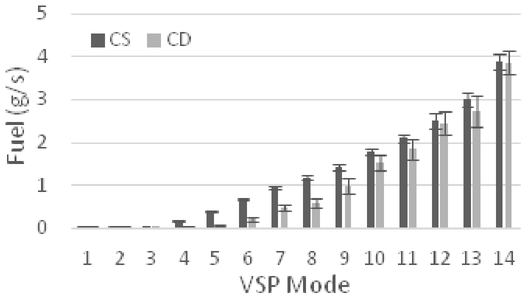

Figure7: Fuel consumption for each VSP mode in CS and CD (Toyota Prius Plug-in)

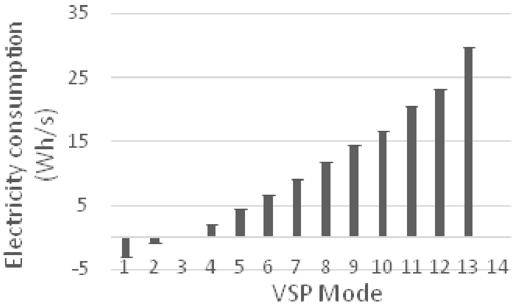

Figure8: Electric energy rate for each VSP mode in CD (Toyota Prius Plug-in)

As shown in Figures 7 and 8, the energy use rate increases with VSP mode, as expected. The electricity consumption is obtained by the direct application of the developed methodology. It is positive when batteries are providing power to the wheels and negative when regeneration occurs.

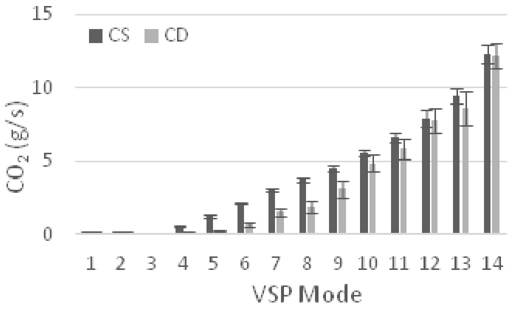

Figure9: CO_2 mass emission rate for each VSP mode in CS and CD (Toyota Prius Plug-in)

Figure 9 presents the CO_2 mass emission rates for CD and CS, which follow the trend of fuel consumption.

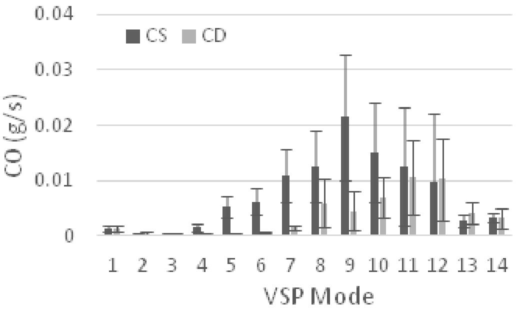

Figure10: CO mass emission rate for each VSP mode in CS and CD (Toyota Prius Plug-in)

Figure 10 presents the CO mass emission rates for CD and CS. Under CD operation, low VSP modes, where sole electric propulsion is dominant, present very low emission rates. The VSP modes correspondent to the triggering of ICE in CD (11, 12, 13 and 14) present similar emission rates to CS operation. Due to sparse use of ICE under CD, low catalytic converter temperatures can also increase pollutant emissions.

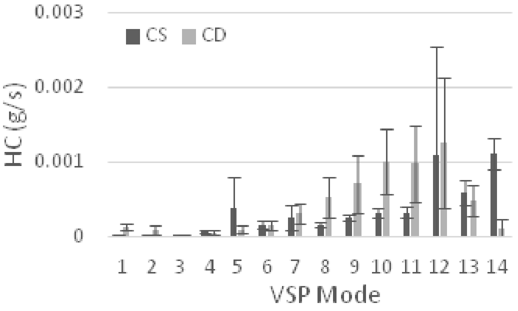

Figure11: HC mass emission rate for each VSP mode in CS and CD (Toyota Prius Plug-in)

Figure 11 presents the HC mass emission rates for CD and CS. Under CD, ICE ON/OFF operation at higher VSP modes provides higher emission values than under CS conditions, probably due to low catalytic converter temperatures.

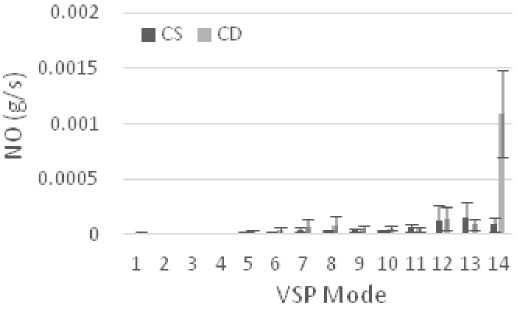

Figure12: NO mass emission rate for each VSP mode in CS and CD (Toyota Prius Plug-in)

Figure 12 presents the NO mass emission rates for CD and CS. As expected on a spark-ignition engine, NO is very low. Once again, due to ICE ON/OFF operation, NO emission is higher at the highest VSP mode in CD than in CS.

3.2.2 Opel Ampera

The Opel Ampera presents a series hybrid configuration and does not have a direct connection between the ICE and vehicle wheels. Therefore, under CD mode propulsion is made only from the battery, while under CS the ICE provides most of power.

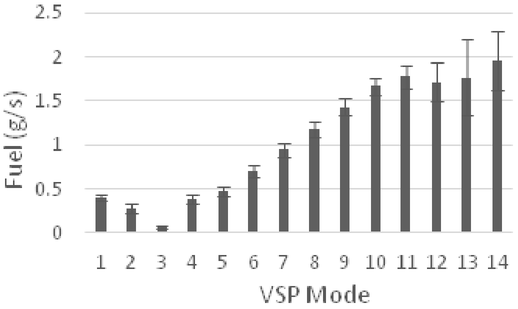

Figure13: Fuel consumption for each VSP mode in CS (Opel Ampera)

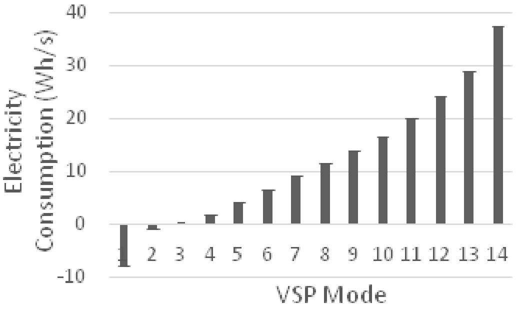

Figure14: Electric energy rate for each VSP mode in CD (Opel Ampera)

Figures 13 and 14 present the energy consumption rates in CS mode (liquid fuel) and on CD mode (electricity), respectively. As referred for the Toyota Prius, the energy rate required to power the vehicle is higher for higher VSP modes. In CS operation, due to the limited ICE power of the Opel Ampera, on high VSP modes some power is provided by the batteries.

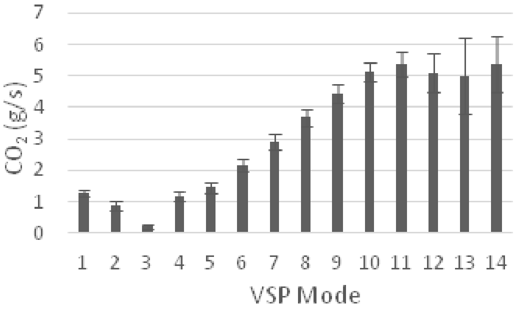

Figure15: CO_2 mass emission rate for each VSP mode in CS (Opel Ampera)

Figure 15 presents the CO_2 mass emission rate for each VSP mode, which follows the same trend of fuel consumption.

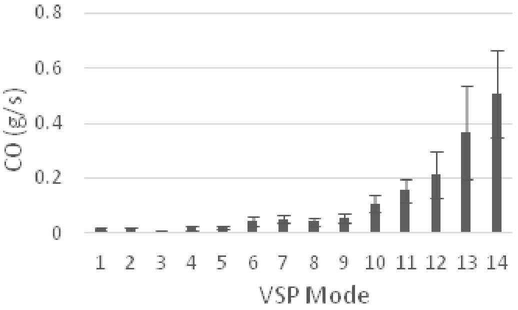

Figure16: CO mass emission rate for each VSP mode in CS (Opel Ampera)

Figure 16 presents the CO mass emission rate for each VSP mode, which increases consistently with the power demand. Part of the points collected in higher VSP modes resulted from changing from CD to CS and the results might be biased due to a high preponderance of points with the ICE operating under cold conditions.

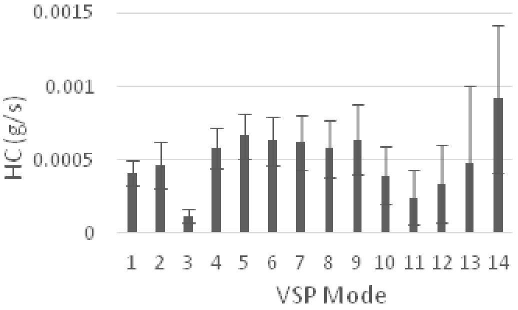

Figure17: HC mass emission rate for each VSP mode in CS (Opel Ampera)

Figure 17 presents HC mass emission rates, which are very low for the 14 VSP modes.

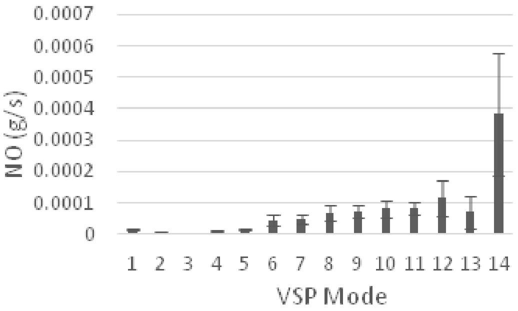

Figure18: NO mass emission rate for each VSP mode in CS (Opel Ampera)

The ICE used in the Opel Ampera is a spark-ignition engine and as was verified for the Toyota Prius Plug-in, the NO mass emission rates are low, except for the highest VSP mode, as shown in Figure 18.

4 Case Studies

4.1 Validation with real trips

Simulations of real trips measured on-board were carried to validate the developed methodology to assess electricity consumption according to the VSP mode.

One trip was simulated for the Opel Ampera and two trips were simulated for the Toyota Prius Plug-in with different driver behaviors. These trips comprehend the full length of CD driving.

Table2: Validation of CD autonomy using real trips performed with Opel Ampera and Toyota Prius Plug-in

Vehicle		Opel Ampera	Toyota Prius Plug-in[a]	Toyota Prius Plug-in[b]
Initial State of Charge (%)		100	100	100
CD (km)	Measured	55.5	18.2	35.1
	Estimate	55.4	18.9	34.6
Electricity consumption (kWh/km)		0.244	0.172	0.098
Fuel consumption (l/100km)		---	0.7	3.7

[a] ICE ON/OFF operation according with Figure 6
[b] ICE ON/OFF operation according with Figure 5

Table 2 presents a validation of the CD autonomy for the vehicles tested using real trips. For the Opel Ampera, a real trip with 55.5 km of length was simulated, resulting in a deviation of -0.2% for the CD distance.

For the Toyota Prius Plug-in two trips were tested, with different ICE ON/OFF behavior as it influences the amount of time the ICE is switched ON. For that reason two separate validations were carried in order to simulate an aggressive and a soft driver. The results obtained with the developed methodology present an error below 4.3% in absolute value both for CD driving autonomy as well as for average fuel consumption.

4.2 Application

The modal data presented can be used to perform an estimate of the total energy use and pollutant emission for a given driving profile. Driving profiles must be characterized according to their time distribution for each VSP mode and average speed. As long as this information is available, any driving profile can be simulated in terms of CD driving autonomy, fuel consumption, electricity consumption and pollutant emission.

Two different typical drivers were analyzed: a typical Lisbon metropolitan area (LMA) driving profile and a North Carolina State University driving sample (NCSU). Both driving profiles are different in terms of aggressiveness and power demands. The LMA driver is characterized by a more aggressive driving with high VSP modes and high speeds. The NCSU driver is characterized by a softer driving behavior with less preponderance on high VSP modes and consequently more time spent on low power demands.

4.2.1 Lisbon metropolitan area driver

The information about these drivers resulted from monitoring 49 drivers during one week each. It represents almost 500 hours of driving with an average speed of 52,7km/h, which represented a total of 26209 km driven [18]. This data allowed simulating the use of both vehicles in this geographical area according to a typical driving pattern.

Table3: Energy use and pollutant emission in CD and CS in Lisbon metropolitan area (Opel Ampera)

	Charge Depleting					Charge Sustaining
Initial State of charge (%)	100	75	50	20	10	0
CD driving (km)	44.2	33.1	22.1	8.8	4.4	---
Electricity consumption (kWh/km)	0.306					---
Fuel Consumption (l/100km)	---					5.8
TTW CO_2 emissions (g/km)	0					154
TTW CO emissions (g/km)	0					3.100
TTW HC emissions (g/km)	0					0.030
TTW NO_x emissions (g/km)	0					0.004

Table4: Energy use and pollutant emission in CD and CS in Lisbon metropolitan area (Toyota Prius Plug-in)

	Charge Depleting					Charge Sustaining
Initial State of charge (%)	100	75	50	20	10	0
CD driving (km)	27.0	20.2	13.5	5.4	2.7	---
Electricity consumption (kWh/km)	0.125					---
Fuel consumption (l/100km)	3.8					5.4
TTW CO_2 emissions (g/km)	100					136
TTW CO emissions (g/km)	0.130					0.300
TTW HC emissions (g/km)	0.016					0.010
TTW NO_x emissions (g/km)	0.004					0.002

The energy use and pollutant emissions for the Opel Ampera and the Toyota Prius Plug-in, regarding the typical Lisbon driver are presented in Tables 3 and 4. Charge depleting range is higher for the Opel Ampera than the Toyota Prius Plug-in and the first only uses electric energy during this period. The Toyota Prius Plug-in presents liquid fuel consumption both in CD and CS operation. Due to the presence of high power conditions, the Toyota Prius Plug-in presents a fuel consumption of 3.8 l/100 km, which also enhances the CD range.

4.2.2 North Carolina State University driver

Information about this typical driver was obtained from previous works of Professor Christopher Frey from the Department of Civil, Construction and Environmental Engineering, North Carolina State University.

Table5: Energy use and pollutant emission in CD and CS in North Carolina State University (Opel Ampera)

	Charge Depleting					Charge Sustaining
Initial State of charge (%)	100	75	50	20	10	0
CD driving (km)	82.9	62.2	41.4	16.6	8.3	---
Electricity consumption (kWh/km)	0.163					---
Fuel Consumption (l/100km)	---					5.2
TTW CO_2 emissions (g/km)	0					139
TTW CO emissions (g/km)	0					2.2
TTW HC emissions (g/km)	0					0.030
TTW NO_x emissions (g/km)	0					0.003

Table6: Energy use and pollutant emission in CD and CS in North Carolina State University (Toyota Prius Plug-in)

	Charge Depleting					Charge Sustaining
Initial State of charge (%)	100	75	50	20	10	0
CD driving (km)	27.9	20.9	13.9	5.6	2.7	---
Electricity consumption (kWh/km)	0.121					---
Fuel consumption (l/100km)	2.0					4.0
TTW CO_2 emissions (g/km)	50					100
TTW CO emissions (g/km)	0.10					0.300
TTW HC emissions (g/km)	0.012					0.008
TTW NO_x emissions (g/km)	0.003					0.001

The energy use and pollutant emissions for the Opel Ampera and the Toyota Prius Plug-in, for the NCSU sample, are presented in Tables 5 and 6. Like was verified for Lisbon, CD is higher for the Opel Ampera than the Toyota Prius Plug-in. While the Opel Ampera almost doubles the CD range in NCSU comparing with LMA (which can be explained by an overestimation on the regenerative part due to the small number of VSP modes to cover regeneration conditions), the Toyota Prius Plug-in does not present significant differences however, the fuel consumption is almost half for NCSU. This result is mostly related with the amount of time spent on low VSP modes (reducing the use of ICE) and the time spent on regeneration conditions.

5 Conclusions

This research work presented the energy and environmental analysis of the two most sold Plug-in hybrid electric vehicles, based on on-road vehicle monitoring with a PEMS.

Both charge depleting and charge sustaining operation modes were characterized in terms of electricity and fuel consumption and pollutant emissions, based on Vehicle Specific Power methodology.

A novel method to indirectly estimate electricity consumption and regeneration was developed based on battery state of charge status collected from the OBD port in a second-by-second basis.

Using the modal energy use and pollutant mass emission rates it is possible to estimate the impact of PHEV use for any driving profile.

The validation of the methodology shows errors below 5% regarding CD range and fuel consumption comparing estimates and real trips.

Regarding the application to typical Lisbon and NCSU driving profiles, in CD operation, the latter, due to the dominant use of low power demands presents a driving range that is the double of Lisbon in Opel Ampera and a fuel consumption that is half for the Toyota Prius Plug-in.

Regarding CS operation, the Lisbon driving profile presents the highest fuel consumption for both vehicles; however, the Toyota Prius Plug-in is more efficient than Opel Ampera under this operation condition.

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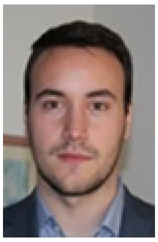

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