Abstract

Petrol and diesel vehicles were monitored by means of an OBD data logger (i2D) recording data at 1 Hz, in order to acquire the necessary information for the calculation of the instantaneous fuel consumption of the vehicles. Using the "Vehicle Specific Power" (VSP) methodology, the collected data allowed producing generic distributions of fuel consumption and CO2 emissions depending on the specific power of the motor at a given time, as well as defining and characterizing different driving profiles.

In VSP, points with different operation conditions and characteristics are grouped in homogeneous classes of similar power demand and hence, the methodology presents some limitations. Thus, the robustness of the methodology was challenged and therefore the influence of the parameters on which VSP depends directly (acceleration, speed and road grade), and of the rotational speed of the engine were studied. In order to obtain a more robust and reliable methodology, able to distinguish the different driving situations and produce estimates closer to reality, some changes to the original VSP were then introduced. The new tool has been named "Improved Vehicle Specific Power", I-VSP.

After the new methodology was tested and validated, it was used to combine different vehicles and drivers, allowing to assess the impact of each one of the combinations in terms of energy consumption. On average, the error between the real fuel consumptions and the values estimated with I-VSP was only 3.97% for the a conventional gasoline vehicle and 4.05% for a conventional diesel vehicle.

Keywords:
Driving Profile; Vehicles Characterization; Combine vehicles and drivers; Energy efficiency
1. Introduction

Modern society is deeply dependent on the transportation sector, especially road transport. However, the raising motorization rate [1], while providing easier mobility and higher comfort has also brought concerns related to its negative environmental impacts: the uncertainty of future availability of fossil energy resources (mainly oil) at affordable prices due to its depletion, the greenhouse gases emissions and the local pollution [2] [3] [4]. So, the biggest transport sector challenge in the near future is to provide feasible alternatives to fuel vehicles more efficiently, providing the same levels of comfort and mobility. This has led car manufacturers to make huge investments in the development of new vehicles technologies, trying to achieve a commitment between its affordability, environmental impacts and energy consumption. Thus, over the last few years, some new vehicle technologies have appeared in the market, as for example, hybrid (HEV), plug-in hybrid (PHEV), electric (EV) and more recently hydrogen (HV), in addition to the conventional diesel (DI) and gasoline (SI) vehicles. For the customer, this has been making more and more difficult to select which is the vehicle that best fits their purposes, taking into account different usages and driving patterns. The traditional analysis based on kilometers driven per year and the published values for fuel consumption and emissions does not take into account two factors: the published values for fuel consumptions and emissions do not correspond to real use (because they are obtained under a test driving cycle) and the driving behavior of each driver. Therefore, the main objectives of this thesis are to assess how different variables affect energy and environmental performance of cars and to develop, test and validate, with subsequent application to case studies, a methodology able to estimate fuel consumption and CO\textsubscript{2} emissions based on different driving profiles for different vehicle technologies (in the present work only conventional gasoline and diesel vehicles were addressed), using real-world driving data collected experimentally. The major challenge is then to obtain a robust methodology, able of produce realistic results for a large variety of operation conditions.

2. Background

Presently, published vehicle fuel consumptions and pollutant emissions are calculated based on pre-defined test cycles performed on “chassis dynamometers”. The objective of these type-approval test cycles is to make it possible to compare all vehicles under similar conditions. Each county or community has its own official test cycle and emissions legislations, prevailing currently in Europe NEDC (New European Driving Cycle) [5] and EURO VI [6] respectively. However, it is consensual amongst researchers and engineers that the results obtained performing type-approval test cycles are not an accurate reproduction of the real-world driving conditions. The NEDC cycle is inclusively described as being “too smooth to be realistic” [7], being characterized by its low accelerations, low maximum speed, high idling time, constant speeds and favorable shifting points [8], resulting in underestimations of the real fuel consumptions and pollutant emissions. Another factor that renders the homologation values less representative of real conditions is the fact that the car’s usage pattern
and the driving behavior of each driver are not taken into account. Amongst others, acceleration, vehicle velocity and engine rotational speed are independent driving pattern factors associated to different driving behaviors that affect significantly energy consumption and emissions [9]. So, this work is mainly focused on assessing the real impacts that different real-world driving profiles (driving patterns) and different light duty vehicle technologies (diesel and gasoline) have in vehicle’s fuel consumptions and consequently CO₂ emissions.

3. VSP – Vehicle Specific Power

VSP is an accredited methodology demonstrated to characterize vehicles and driving profiles using real-world on-road measured data [10] [11] [12]. VSP is usually expressed in kilowatt per tonne [KW/ton] and can be obtained by the following expression:

\[ VSP = v \cdot (1,1 \cdot a + g \cdot \sin(\varphi) + 0,132) + 0,000302 \cdot v^3 \] (1)

Where:

- \( v \) is the instantaneous speed of the vehicle (m/s)
- \( a \) is acceleration of the vehicle (m/s²)
- \( \varphi \) is the inclination of the road (rad)
- 0,132 is the rolling resistance term coefficient (m/s²)
- 0,000302 is the aerodynamic drag term coefficient (m⁻¹)

The calculation of VSP, on a second to second basis, allows obtaining the vehicle's power distribution throughout a trip. In order to ease the visualization and the analysis, it is then possible to group VSP points in 14 classes of required power, as shown in Table 1. This division in power ranges allows mapping the vehicle fuel consumption and emissions according to the VSP category.

<table>
<thead>
<tr>
<th>Modo VSP</th>
<th>Gama VSP [W/kg]</th>
<th>Modo VSP</th>
<th>Gama VSP [W/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VSP &lt; -2</td>
<td>8</td>
<td>13 ≤ VSP &lt; 16</td>
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<tr>
<td>2</td>
<td>-2 ≤ VSP &lt; 0</td>
<td>9</td>
<td>16 ≤ VSP &lt; 19</td>
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<tr>
<td>3</td>
<td>0 ≤ VSP &lt; 1</td>
<td>10</td>
<td>19 ≤ VSP &lt; 23</td>
</tr>
<tr>
<td>4</td>
<td>1 ≤ VSP &lt; 4</td>
<td>11</td>
<td>23 ≤ VSP &lt; 28</td>
</tr>
<tr>
<td>5</td>
<td>4 ≤ VSP &lt; 7</td>
<td>12</td>
<td>28 ≤ VSP &lt; 33</td>
</tr>
<tr>
<td>6</td>
<td>7 ≤ VSP &lt; 10</td>
<td>13</td>
<td>33 ≤ VSP &lt; 39</td>
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<tr>
<td>7</td>
<td>10 ≤ VSP &lt; 13</td>
<td>14</td>
<td>39 ≤ VSP</td>
</tr>
</tbody>
</table>

Table 1 - VSP mode values [10]

In this study, on-board measurements were performed in several cars, a PEMS was used in a preliminary phase and then an OBD data logger (i2D) was utilized for the final tests and measurements. PEMS is a “Portable Emissions Measuring System” used to evaluate vehicle emissions. In the measurements performed the PEMS used was VE-LAB [10], developed by the Transportation, Energy and Environment Team of Instituto Superior Técnico. OBD, “On-board diagnostic” is a communication interface present in most of the vehicles and it is has a standard connection (OBD port) from which information to ease the repair of the car can be obtained. By using
a data logger, through this OBD port, it is also possible to obtain a given set of variables collected in real time while driving.

Having said that, VSP is particularly suitable for the intended type of analysis, because it was designed from scratch to use experimentally collected data (either by PEMS or by non-intrusive tools such as data loggers) and it is scalable to combine data from different vehicles with drivers regardless of the sample size. However, this methodology presents some limitations and, to illustrate them, an example trip in a petrol car “Mixed C. SI” will be used. Firstly, VSP groups all different driving situations in classes of similar power demand and, being a function of the acceleration, speed and road grade, it is possible to obtain similar specific power values for a wide variety of combinations, resulting in distinct fuel consumptions. Thus, to evaluate the importance of each parameter and then prove VSP’s inability to distinguish between different driving situations, its formula was expanded in three independent terms, each one of them corresponding to one of its variables, VSPv (velocity), VSPa (acceleration) and VSPg (road grade), as is shown in the expression bellow:

\[ VSP_v = 0,000302v^3 + 0,132v + 1.1. va + vgsin(\varphi) \]  

This new development of VSP expression allowed calculating the relative contribution of each one of the three variables, having been possible to conclude that speed and acceleration are the most important. As it is shown in Figure 1, between modes 4 and 11, where typically the biggest part of the fuel consumption occurs, speed and acceleration together represent always more than 70% of the total specific power of the vehicle.

![Figure 1 – VSP Components relative weight – “Mixes C. SI”](imageURL)

Then, to distinguish events of similar power demand dominated by speed, by acceleration or on the other hand situations where there is a balanced compromise between the two of them, a ratio between VSPv and VSPa was developed and its influence in the fuel consumption was studied.

\[ \frac{VSP_v}{VSP_a} = \frac{[0,000302v^3 + 0,132v]}{1.1. va} \]
According to Figure 2 it is then possible to evidence that for $VSP_v/VSP_a \leq 0.1$, i.e. when acceleration is predominant in VSP, the fuel consumption is higher than for the other situations. Also, when a balanced contribution for the vehicle power from speed and acceleration is achieved, the minimum fuel consumption is observed. It is then possible to identify the first of VSP’s limitations.

Secondly, because VSP was developed in the USA, where most of the vehicles have automatic transmissions, the engine rotational speed is not a variable controlled by the driver, and then its effect in both fuel consumption and emissions is not accounted for in this methodology. Figure 3 shows, again for the trip “Mixed C. SI”, that higher engine rotational speeds (in this specific case, events with rpm>3000) are associated with higher fuel consumptions. It is also possible to extract from the figure that the actual instantaneous fuel consumption given by VSP methodology is always in between the values obtained for high and low engine speeds. Thus VSP considers fuel consumption independent of the engine speed, when in fact, for the same power, events with different rpm result is different fuel consumptions.
4. I-VSP – Improved Vehicle Specific Power

To minimize VSP’s limitations, some modifications were introduced in the original methodology, giving then origin to the “Improved Vehicle Specific Power”, I-VSP. This new version of the methodology seeks to differentiate the various driving situations recorded for similar power requirements, in particular situations with different engine rotational speeds and events where the vehicle’s acceleration or speed are clearly dominant. For that, the aforementioned distinctions between high and low rpm as well as the categorization in VSP/VSPa classes were taken into account in I-VSP. Thus, for the trip “Mixed C. SI”, the fuel consumption mapping present in Figure 4 results from I-VSP.

![Figure 4 – Instantaneous Fuel Consumption – I-VSP – “Mixed C. SI”](image)

4.1. Validation

The validation of the I-VSP methodology was made for two different cars, a 1.0L gasoline vehicle and a 1.6L diesel vehicle, being based in three different aspects: the study of the optimal vehicle characterization; the study of the recommended parameters for the methodology application and; the testing of the methodology’s robustness for vehicle characterizations that are not optimal.

Thus, for the gasoline vehicle (Toyota Yaris 1.0L), several combinations of vehicle characterizations and test trips were tested, aiming to find the most suitable way of characterizing the car fuel consumption. In that direction, with the objective of replicate the widest possible set of driving conditions, urban, extra-urban and mixed characterizations and trips were used. Table 2 and Table 3 summarize the details of the used characterizations and tips, respectively.

<table>
<thead>
<tr>
<th>Characterizations SI</th>
<th>Time [s]</th>
<th>Distance [km]</th>
<th>Average Speed [km/h]</th>
<th>Mean rpm</th>
<th>Fuel Consumption [l/100km]</th>
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<tbody>
<tr>
<td>Extra-Urban C. SI</td>
<td>16954</td>
<td>280.13</td>
<td>59.48</td>
<td>2498</td>
<td>7.13</td>
</tr>
<tr>
<td>Urban C. SI</td>
<td>8474</td>
<td>83.64</td>
<td>35.53</td>
<td>1857</td>
<td>7.30</td>
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<tr>
<td>Mixed C. SI</td>
<td>10484</td>
<td>138.02</td>
<td>47.39</td>
<td>2198</td>
<td>6.94</td>
</tr>
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Table 2 – Gasoline vehicle characterizations details
<table>
<thead>
<tr>
<th>Trips Sl</th>
<th>Time [s]</th>
<th>Distance [km]</th>
<th>Average Speed [km/h]</th>
<th>Mean rpm</th>
<th>Fuel Consumption [l/100km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban T. SI</td>
<td>3517</td>
<td>32.49</td>
<td>33.00</td>
<td>1820</td>
<td>7.04</td>
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<tr>
<td>Mixed T. SI</td>
<td>2450</td>
<td>34.28</td>
<td>50.36</td>
<td>2212</td>
<td>7.12</td>
</tr>
<tr>
<td>Extra-Urban T. SI 1</td>
<td>6055</td>
<td>127.21</td>
<td>75.63</td>
<td>2925</td>
<td>7.47</td>
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<tr>
<td>Extra-Urban T. SI 2</td>
<td>3099</td>
<td>53.23</td>
<td>61.84</td>
<td>2506</td>
<td>6.44</td>
</tr>
</tbody>
</table>

**Table 3 – Gasoline vehicle validation trips details**

According to both the engine rotational speed and the VSP/VSPa ranges limiting values, the error convergence was studied for each of the “characterization-trip” combinations and it was observed that for the particular case of this gasoline Toyota Yaris 1.0L, the recommended parameters would be a cutoff engine rotational speed of 3000 rpm and VSP/VSPa delimiting values of 0.1 – 0.6.

<table>
<thead>
<tr>
<th>Recommended Parameters</th>
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<tr>
<td>Cutoff Engine Speed</td>
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<tr>
<td>VSP/VSPa</td>
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**Table 4 – Gasoline vehicle recommended parameters**

By applying I-VSP methodology, using the recommended parameters and different vehicle characterizations, to each one of the test trips, it was possible to obtain the error relative to the respective on-board measured fuel consumptions and to compare it with the resulting error from the conventional VSP analysis application. Finally, as it is shown in Table 5, it was concluded that a mixed characterization (“Mixed C. SI”), reproducing a broad variety of driving situations, is the best option and results in an average 5.81% relative error reduction compared to the original VSP methodology. For the four test trips, with an “hybrid” characterization, I-VSP methodology estimated the fuel consumption with an average error of 3.97% compared to the measured consumptions. Regarding the robustness of the methodology, it is equally important to note that I-VSP, regardless of the characterization performed to the vehicle, always allows more realistic fuel consumption estimates than VSP, for example, for the characterizations “Extra-Urban C. SI” and “Urban C. SI” the I-VSP error was still 3.92% and 4.26% lower than the error obtained with VSP.

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<td>I-VSP</td>
<td>VSP</td>
<td>I-VSP</td>
<td>VSP</td>
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<tr>
<td>Extra-Urban C. SI</td>
<td>10.27%</td>
<td>24.45%</td>
<td>5.93%</td>
<td>5.94%</td>
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<tr>
<td>Urban C. SI</td>
<td>10.21%</td>
<td>13.15%</td>
<td>0.53%</td>
<td>3.76%</td>
</tr>
<tr>
<td>Mixed C. SI</td>
<td>2.57%</td>
<td>11.43%</td>
<td>1.27%</td>
<td>4.74%</td>
</tr>
</tbody>
</table>

**Table 5 – Relative error comparison between I-VSP & VSP**

Since it has already been concluded above that the characterization of the vehicle must be based on trips that recreate as varied driving conditions as possible, only “Mixed C. DI” was used for the methodology validation in the diesel vehicle. Therefore the following tables show the details of the characterization used for the diesel vehicle as well as the details of the three test trips.
Proceeding in a similar fashion to what was done for the gasoline vehicle, the ideal parameters were established, so it is recommended for the particular case of the 1.6L diesel vehicle studied a cutoff engine rotational speed of 1800 rpm and the same 0.1 – 0.6 values used for the gasoline car to the VSP$_v$/VSP$_a$ ratio.

The application of the recommended parameters to the "Improved - Vehicle Specific Power", in particular through the use of the "Mixed C. DI" and its combination with each of the defined routes, allowed to estimate the average fuel consumption with a relative error of only 4.05% compared to the actual values recorded.

5. Case Studies

In order to exemplify the utility of the developed tool, a possible practical application is presented here. By using the I-VSP methodology and the mixed characterization of each one of the two vehicles for which the methodology was validated, it was possible to estimate the fuel consumption resulting from two different people driving each of the two cars. The drivers’ characteristics and corresponding trips details are shown in Table 9.

The fuel consumptions and CO$_2$ emissions resulting from the application of I-VSP and the respective comparison with VSP are present in Table 10 for the petrol car and in Table 11 for the diesel car.
Fuel Consumption | CO₂ Emissions | Fuel Consumption | CO₂ Emissions
---|---|---|---
**Driver A** | 6,13 l/100km | 140,95 g/km | 6,46 l/100km | 148,67 g/km
**Driver B** | 7,03 l/100km | 161,63 g/km | 6,78 l/100km | 155,96 g/km

Table 10 – Fuel consumption and CO2 estimates for the gasoline diesel – I-VSP vs VSP

Fuel Consumption | CO₂ Emissions | Fuel Consumption | CO₂ Emissions
---|---|---|---
**Driver C** | 6,64 l/100km | 179,23 g/km | 6,48 l/100km | 175,08 g/km
**Driver D** | 5,94 l/100km | 160,31 g/km | 5,90 l/100km | 159,30 g/km

Table 11 – Fuel consumption and CO2 estimates for the gasoline diesel – I-VSP vs VSP

6. Conclusions and Future Work

In order to produce the most reliable and realistic fuel consumption estimates, the characterization of the vehicles used in I-VSP must comprise a set of points and driving situations as varied as possible, allowing then to cover and characterize the full range of different driving conditions. In the particular cases studied, "Mixed C. SI" and "C. Mixed DI" should be respectively used for the petrol and diesel vehicle. However, even if the characterization performed for the vehicles is not the most suitable, I-VSP proved to be still better than conventional VSP, allowing obtaining better results.

Equally important to obtain accurate and representative results of the reality are the values chosen for the parameters that are considered in I-VSP, cutoff engine rotational speed and the VSP_v/VSP_a ratio. Therefore, in addition to a correct characterization of the vehicle in use, and according to its technology, the following parameters are recommended:

- Gasoline Vehicle: Cutoff Engine Speed = 3000 rpm; VSP_v/VSP_a = 0,1 – 0,6
- Diesel Vehicle: Cutoff Engine Speed = 1800 rpm; VSP_v/VSP_a = 0,1 – 0,6

Finally, the developed methodology, Improved Vehicle Specific Power, represented an increase in the resolution of different driving situations relatively to conventional VSP, the latter being translated into a significant improvement in the fuel consumption estimates accuracy. The registered errors relating to the real fuel consumptions were always less than 10% and, by using the recommended parameters and procedures for the vehicles characterization the application of I-VSP produced an average error among all tested trips of 3,97% for the Toyota Yaris (gasoline car) and of 4,05% for the diesel vehicle. In the particular case of the Toyota Yaris, the average error reduction compared to original VSP was of 5,81%, i.e. from 9,78% to 3,97%.
7. Bibliography


