Proposal of a dynamic performance index to analyze driving pattern effect on car emissions

Jesús CASANOVA*, Natalia FONSECA* & Felipe ESPINOSA**

* Department of Energy and Fluid Mechanic Engineering. Universidad Politécnica de Madrid. C/José Gutiérrez Abascal, 2. 28006 Madrid. Email: jesus.casanova@upm.es

** Department of Electronics. Universidad de Alcalá. Campus Universitario. Ctra. Madrid-Barcelona, km. 33,600 | Alcalá de Henares (Madrid). Email: felipe.espinosa@uah.es

Abstract
The contributions of driver behaviour as well as surrounding infrastructure are decisive on pollutant emissions from vehicles in real traffic situations. This article deals with the preliminary study of the interaction between the dynamic variables recorded in a vehicle (driving pattern) and pollutant emissions produced over a given urban route. It has been established a “dynamic performance index”-DPI, which is calculated from some driving pattern parameters, which in turn depends on traffic congestion level and route characteristics, in order to determine whether the driving has been aggressive, normal or calm.

Two passenger cars instrumented with a portable activity measurement system -to record dynamic variables- and on-board emission measurement equipment have been used. This study has shown that smooth driving patterns can reduce up to 80% NO\textsubscript{X} emissions and up to 20% of fuel in the same route.

Keys-words: real emissions, driving pattern, emission factors, on-board emission measurement, dynamic performance index.

Introduction
It is well known that the actual driving pattern can highly affect real emission levels and energy efficiency in urban traffic. The average speed in urban areas is mainly a function of the number of stops and starts by kilometre. It has been demonstrated that an increase in average speed in urban areas can improve fuel efficiency by 25 – 50 %, De Vlieger (2000), due to less stops.

Pollutant emissions and fuel consumption of a motor vehicle in a real driving circuit are affected by street configuration, traffic flow, vehicle type and driving style, Casanova and Margenat (2005). The dynamic behaviour of the vehicle in terms of speed, acceleration, engine speed, thermal engine conditions and exhaust after-treatment temperature, most influence the emission and fuel consumption factors. Emission factors are widely used to estimate total emission and fuel consumption inventories in urban and regional environments, which have been developed by simulation of driving cycles on chassis dynamometers derived from vehicle activity data obtained from instrumented cars. CO and HC emission factor are usually a decreasing function of average speed (including stops) in the range of 0 to 60 km/h, but NO\textsubscript{X} emission factors could be an increasing function of average speed, Ntziachristos and Samaras (2000).

Pelkmans (2006), showed that emissions quantities from European Driving Cycles are quite different to real life values. The real world emissions and fuel consumption of a single vehicle in different driving situations can vary by a factor of 1 to 6. The use of “eco-driving” has shown its capability to 15 – 20 % fuel consumption reduction in real urban situations, Johansson et al (2003) and Takada (2007), but more realistic and specific situations measurements are needed in order to better understanding the influence of which driving pattern most influence results and in what sense. Also, previous author’s research showed that street and urban configuration affect emissions and consumption of the total vehicle fleet travelling by an urban zone very much depending on slope.

In order to take real life data from vehicles of different technologies and for different driving patterns, on board emission measurement systems (PEMS) have been widely used, some details could be found in Miyazaki et al (2002), Casanova et al (2004) and Gao and Checkel (2007). Direct fuel consumption measurement is difficult to be
done in a vehicle without dismantling some parts of the fuel system, and also it could affect the results. Then, fuel consumption is generally calculated from instantaneous emissions concentrations and exhaust flow. The problem of uncertainty can be solved by a good route characterization and by enough number of tests. When dealing with the relation between driver and emissions, not only emissions should be measured but also other parameters associated with driver behaviour as engine revolutions, speed, gear shifting and gas pedal actuation.

This paper presents the results of a research intended to advance in the knowledge of the relation between car driver behaviour and the surrounding, characterized by the street configuration. This preliminary study seeks to establish a “dynamic performance index”-DPI, which can be calculated based on some driving pattern parameters, which in turn depends on traffic congestion level and route characteristics, in order to determine whether the driving has been aggressive, normal or calm. For this study two different passenger cars -with different engine type- instrumented with a portable activity measurement system specifically designed and developed by the Engines Laboratory (Universidad Politécnica de Madrid) for these tests, have been used. The measures were undertaken on different streets of Madrid City and specifically on selected routes according to a preliminary study.

1 – Methodology

EXPERIMENTAL vehicles AND MEASUREMENTS SYSTEMS DETAILS

The first instrumented vehicle has been a petrol passenger car, Peugeot 205, 1400 cm³, 900 kg. The operating parameters registered in this vehicle have been: vehicle speed, engine speed, fuel consumption, angle position of throttle valve, cooling water and oil temperatures. The emissions measured have been: carbon dioxide CO₂, carbon monoxide CO, hydrocarbons HC, nitrogen oxides NOₓ and oxygen O₂, as specified in Casanova and Ariztegui (2004). A scheme of on-board instrumentation is shown in Figure 1.

The second vehicle used is a diesel passenger car, Peugeot 406 BK STDT 2.1, with a direct injection turbo engine, 2088 cm³ and 1485 kg. It has been instrumented with a non-intrusive universal on-board emission measurement system (MIVECO-PEMS) and a portable global activity measurement system (PGAMS), both developed as part of research project for real life emission measurement. The block diagram of the MIVECO PGAMS/PEMS and the scheme of MIVECO PEMS are shown in Figure 2.

The electronic prototype PGAMS (Portable Global Activity Measurement System) aims to record, simultaneously and synchronously, the activity of the main agents involved on car pollutant emissions: driver, vehicle and route. Its hardware architecture is based on three subsystems: sensorial, conditioning and acquisition, processing and monitoring (local and remote). The PGAMS is a system that can be boarded on any type of vehicle.

The MIVECO on-board emission measurement system (MIVECO-PEMS) for Diesel/petrol HD and LD vehicles, depicted in Figure 3, is based on fast response commercial analysers and a self designed exhaust flow meter. The MIVECO-PEMS are conformed by a NDIR analyzer for CO₂ and CO, a non-sampling Zirconia type NOₓ -O₂ analyzer, a FID for unburned hydrocarbons (HC), and a Lambda Meter. The signals generated by each analyzer are collected by an acquisition system that uses Labview® software at 10 Hz data recording frequency. The flow meter consists of a Pitot tube for gases with high moisture content, which prevents that condensation may block pressure ducts and a differential pressure gauge of high sensitivity and response rate, capable of detecting pressure changes at a frequency up to 1kHz. This makes it possible to detect the pulses of flow that occur in the engine at idle.

Figure 1: Scheme of on-board instrumentation in the petrol car.
Urban circuit

The measures were carried out in a specific urban circuit in Madrid City, called “Madrid-UPM Circuit”, which include most of the types of streets there are downtown, like local, secondary, principal and arterial. To know the influence of the type of street, the whole route was divided into 10 sectors, as shown in Figure 4 and whose characteristics are presented. 50 journeys were realized by this route, 40 of them with the petrol passenger car and the others with the diesel passenger car. A portion of the petrol car journeys were made in days off, in order to obtain experimental data about average speed without traffic, which were used as a baseline. Remaining trips were made in normal traffic conditions.

**Figure 2:** On-board instrumentation in the diesel car a) Block diagram of the MIVECO PGAM/PEMS. b) Scheme of the MIVECO PEMS (portable emission measurement system).

**Figure 3:** MIVECO-PEM System arrangement in the diesel car.

**Urban circuit**

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**Figure 4:** Madrid-UPM Circuit and table of characteristics per sector.

<table>
<thead>
<tr>
<th>SECTOR</th>
<th>DISTANCE (M)</th>
<th>CROSSROADS PER KM</th>
<th>AVERAGE SLOPE</th>
<th>AVERAGE SPEED WITHOUT TRAFFIC</th>
<th>LANES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>517</td>
<td>5,60</td>
<td>-1,58</td>
<td>35,36</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>271</td>
<td>7,38</td>
<td>-2,81</td>
<td>30,63</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1681</td>
<td>5,32</td>
<td>2,40</td>
<td>34,57</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>230</td>
<td>4,35</td>
<td>1,75</td>
<td>30,68</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>303</td>
<td>13,20</td>
<td>-2,78</td>
<td>18,06</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>385</td>
<td>10,39</td>
<td>2,53</td>
<td>22,95</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>796</td>
<td>12,56</td>
<td>-2,53</td>
<td>23,24</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>761</td>
<td>6,57</td>
<td>-2,06</td>
<td>41,10</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>289</td>
<td>3,46</td>
<td>-3,05</td>
<td>44,28</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>257</td>
<td>3,69</td>
<td>1,02</td>
<td>25,14</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5690</td>
<td>7,21</td>
<td>0,00</td>
<td>32,31</td>
<td>-----</td>
</tr>
</tbody>
</table>
Real-time dynamic variable profiles that characterize the driving patterns like vehicle speed, engine speed, current gear and engine load (gas pedal position) were registered in all trips. In addition, the following dynamic variables were calculated –for each sector and for the entire route-, based on the results of several researches carried out by Ericsson (2000, 2001 and 2006): average speed (km/h), average running speed (km/h) – average speed excluding idle time, average acceleration (m/s²), average deceleration (m/s²), percentage of time spent in different operating modes (gear) or idle, like percentage of time on high gears (3rd, 4th and 5th), percentage of time over 2000 min⁻¹, average value of the product of Instantaneous speed and acceleration, called “demand of acceleration” as defined by Ericsson (2001), stop time per crossroad.

Driving STYLE, Street and Traffic variables

Because of driving style have a great influence over driving patterns, three kinds of driving styles have been compared as defined by De Vlieger (1997-2000), Ericsson (2000-2001) and Takada (2007): calm driving -where the driver anticipates movements avoiding sudden accelerations-, normal driving -where accelerations and decelerations are moderated- and aggressive driving, -where violent or sudden acceleration and heavy braking are present-. The calm driving corresponds with the concept of “Eco-driving style”, described above.

In addition to the fact that the driving style strongly affects the specific driving pattern, many research works - Brundell-Freij and Ericsson (2005), Ericsson (2001), Ericsson (2000), Rosqvist (2003), De Vlieger (2000) and Ericsson (2006)- have showed that road infrastructure and traffic density have great influence too. So, in this study a Street-Index and a Traffic-Index have been defined in order to measure the degree of constriction that those aspects impose on the way to any driver to make a particular trip.

The variables included in the Street-Index are: type of road, slope and density of crossroads. The type of road is an index defined from 0 to 1 that indicates the traffic constriction as follow: 0 for very high constriction and 1 for very low constriction. In this order, 0.15 for local street, 0.30 for secondary, 0.45 for main, 0.6 for arterial, 0.75 for bypass street and 0.9 for highway. The Street-Index was based on a statistical study conducted with the experimental data obtained with the petrol car during day off journeys, following that average speed without traffic can be expressed in terms of those static variables as follows:

\[
\text{Average speed without traffic} = 34.25 - 0.90 \times \text{slope} + 32.28 \times \text{Type of street} - 2.15 \times \text{crossroads/km}
\]

(R-squared: 83.4%, indicated that this model explains 83.4% of the variability in Average speed without traffic. And, since P-value in the ANOVA table is less than 0.01, there is a statistically significant relationship between the variables at the 99% confidence level)

To obtain a normal Street-Index –from 0 for low constriction and 1 for high constriction-, was necessary to apply the following equation:

\[
\text{Street-Index} = S_i = 1.25 - 0.025 \times \text{Average speed without traffic}
\]

In order to determinate the Traffic-index, two associated variables that are naturally related with traffic flow were studied: stop time per crossroad and average speed per average speed without traffic. The Figure 5 shows the relationship between these variables.

Since there has been statistically demonstrated that neither average speed nor these two variables have any correlation with the specific driving style (maximum R_Squared=5%, indicating that the driving style explains maximum 5% of the variability in Average speed and in these traffic variables), and Average speed without traffic depends only on road infrastructure, the Traffic-Index has been defined proportionally to the Average speed per average speed without traffic, with a numerical value from 0 to 1 indicating very low and very high traffic density respectively, as shown bellow:

\[
\text{Traffic_index} = T_i = 1 - 0.67 \times \text{Average speed per average speed without traffic}
\]

This makes it possible to obtain an equation to predict the average speed for a given route based on the street-index and traffic-index, as shown in the next equation and in the Figure 6 obtained for different street types:

\[
\text{Average speed} = 60.31 - 46.78 \times \text{traffic index} - 30.06 \times \text{street index} \quad (\text{R-squared} = 95\%, \text{P-value}=0.00)
\]
2 – Results

The only linearly independent variables related to driving style are average acceleration and percentage of time over 2000 min\(^{-1}\). This has enabled to define the Dynamic_Performance_Index that allows assessing the driving style, as shown below:

\[
\text{Dynamic\_Performance\_Index} = DPI = -0.17 + 0.55 \times \text{Average\_acceleration} + 0.006 \times \%\text{time}>2000rpm \quad (R^2 = 70\%, \ P-value=0.00)
\]

The definition of the Dynamic_Performance_index lets to predict the value of the most important dynamic variables based only on the characteristics of the road infrastructure (Street_index - Si), traffic density (traffic_index - Ti) and driving style (Dynamic_Performance_index-DPi) as shown in the following equations:

\[
\text{Average\_acceleration} = 0.05 + 0.29 \times Si + 0.34 \times Ti + 1.13 \times DPI \quad (R^2 = 83\%, \ P-value=0.00)
\]

\[
\%\text{time}>2000 \, \text{rpm} = 23.33 - 26.34 \times Si - 31.27 \times Ti + 61.39 \times DPI \quad (R^2 = 75\%, \ P-value=0.00)
\]

\[
\%\text{time on large gear} = 123.99 - 61.46 \times Si - 95.94 \times Ti - 29.45 \times DPI \quad (R^2 = 55\%, \ P-value=0.00)
\]

\[
\text{Demand of acceleration} = 25.54 - 11.75 \times Si - 22.43 \times Ti + 25.48 \times DPI \quad (R^2 = 82\%, \ P-value=0.00).
\]

The accuracy of the fitted models for these variables is shown graphically in Figure 7. Additionally, the prediction of the average acceleration, for different types of streets, is shown in Figure 8.

Due to the differences between both cars -petrol and diesel- the study of the influence of the different variables (dynamics, traffic and road infrastructure), on the emission factors has been performed separately.
Petrol Passenger car Emission factors

To investigate the linear relationship between emission factors and each of the variables considered, analysis of variance was carried out using Pearson coefficient. The Table 1 presents a summary of the main variables (for better visualization only are shown correlation coefficient greater than 0.2, although correlation is considered significant when the coefficient is greater than 0.3).

Table 1: Pearson Correlation coefficients for emission factors

<table>
<thead>
<tr>
<th>Driving behaviour</th>
<th>FE HC</th>
<th>FE CO</th>
<th>FE CO2</th>
<th>FE NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving index</td>
<td>0.24</td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic performance</td>
<td>0.23</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic</td>
<td>0.40</td>
<td>0.41</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Dynamic variables</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average acceleration</td>
<td>0.25</td>
<td>0.28</td>
<td>0.52</td>
<td>0.47</td>
</tr>
<tr>
<td>Average deceleration</td>
<td>-0.30</td>
<td>-0.31</td>
<td>-0.34</td>
<td>-0.32</td>
</tr>
<tr>
<td>% time on large gear</td>
<td>-0.25</td>
<td>-0.29</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>% time&gt;2000 rpm</td>
<td>-0.37</td>
<td>-0.39</td>
<td>-0.38</td>
<td></td>
</tr>
<tr>
<td>Demand of acceleration</td>
<td>-0.37</td>
<td>-0.40</td>
<td>-0.41</td>
<td></td>
</tr>
<tr>
<td>Average speed (km/hr)</td>
<td>-0.37</td>
<td>-0.39</td>
<td>-0.38</td>
<td></td>
</tr>
<tr>
<td>Stop time / crossroad</td>
<td>0.31</td>
<td>0.29</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>Average speed / Average speed without traffic</td>
<td>-0.37</td>
<td>-0.40</td>
<td>-0.41</td>
<td></td>
</tr>
<tr>
<td>Type of street</td>
<td>-0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crossroads/km</td>
<td>0.89</td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMISSION FACTORS (g/km)</td>
<td>FE HC</td>
<td>FE CO</td>
<td>FE CO2</td>
<td>FE NOx</td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>0.40</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>0.40</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

The table of Pearson correlation coefficients –Table2–, confirms that the petrol car fuel consumption (CO2 emission) increases with average acceleration, stop time per crossroad and decreases with average speed and the use of high gears. Additionally, it is noted that the NOx emission is primarily associated to the acceleration and hence to the driving style. This is an expected result due to the fact that stronger accelerations are related to higher cylinder gas temperatures, which favours NOX formation. Furthermore, the emissions of HC and CO, closely related to each other, are affected by traffic density, although the correlation is weaker.

To quantify the influence of traffic, street infrastructure and driving style over emissions and fuel consumption, multiple linear regression analysis was performed. It has been found that only CO2 emissions are directly related to the three factors (traffic, street infrastructure and driving style), the others emission factors are related only to one of them, according to the following equations and as illustrated in the Figure 9:
Influence study of driving behaviour in real traffic in Madrid city

**INSTANTANEOUS FUEL CONSUMPTION**

\[ EF_{CO2} = -31.57 + 131.89 \times Si + 127.94 \times DPI + 220.26 \times Ti \]  
(R-squared = 48%, P-value=0.00)

\[ EF_{CO} = 0.76 + 3.90 \times Ti \]  
(R-squared = 17%, P-value=0.00)

\[ EF_{HC} = 0.04 + 0.18 \times Ti \]  
(R-squared = 16%, P-value=0.00)

\[ EF_{NOx} = -0.02 + 0.14 \times DPI \]  
(R-squared = 21%, P-value=0.00)

The model generated for CO2 emission factor (fuel consumption) explains nearly 50% of its variability, while only explained 16%, 17% and 21% of the variability of the factors CO, HC and NOx respectively. However to illustrate the trends found, the Figure 10 shows the prediction of the CO2 emission factor (fuel consumption) with respect to driver style, for different types of streets and traffic conditions.

**Figure 9: Accuracy of the fitted models for emission factors.**

**Figure 10: CO2 Emission Factor & Dynamic performance index.**

*Predictions are based on streets with 0% slope and 5 crossroads/km in Madrid-city*

Petrol Passenger car Emission factors

The Figure 11 illustrates the comparative curve for instantaneous consumption and average emission factors for two different driving styles. It is noted that in addition to the peaks of consumption are higher in aggressive driving, emission factors are also.

**Figure 11: Instantaneous fuel consumption and total emission factor for diesel car in different driving style.**
3 – Discussion and conclusion

Average speed in day off trips with “normal” driving, depends only on the street configuration, and is useful to independently evaluate the effect of the street characteristics over the driving style. It is the best parameter to define the Street Index.

In spite of the fact that the Traffic Index has been defined only as a function of the average speed to day off average speed ratio, for future research the spot time per crossroad should be included, because it has a significant influence on fuel consumption.

Traffic density has almost double weight that aggressiveness and street constrictions on CO2 emissions, it confirms that congestion and traffic flow is a relevant factor to be controlled to reduce these emissions in a big town as Madrid Town.

In the case of the petrol car, CO and HC emissions are correlated, as shown in table 1. It is due to the fact that both pollutants are coming from combustion problems with rich mixtures. The fact that no correlations could be found between these pollutants and vehicle dynamic variables, are probably due to the fact that there are some moments in which the injection system cannot control the air fuel ratio dealing to transitory rich mixtures when the gas pedal is released. But probably with a more advanced injection system, this situation will not appear.

Although correlation between NOx emissions and DPI obtained in this work is lean, it is actually a correlation that should be previously expected because of higher engine loads when aggressiveness is higher. Then more tests in different types of car are needed to understand better the relationship between NOx emissions and real traffic situations.

The graphics of instantaneous emissions in the diesel car tests show a significant influence of driving style on pollutant emissions and fuel consumption, as should be expected. More tests are needed obtain more statistically consistent results.

Acknowledgments

The authors would like to acknowledge the financial backing for this project provided by the Ministry of Environment and Rural and Marine Affairs of Spain. The authors also wish to acknowledge the contributions of Emilio Cano by the preliminary treatment of the experimental data and to David Nieto, Diego Perez and Alfredo Gonzalez for mounting equipment in vehicles and carrying out of tests.

References


