Influence of Driving Style on Fuel Consumption and Emissions in Diesel-Powered Passenger Car

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Abstract

This paper presents the main results of a study on the influence of driving style on fuel consumption and pollutant emissions of diesel passenger car in urban traffic. Driving styles (eco, normal or aggressive) patterns were based on the “eco-driving” criteria. The methodology is based on on-board emission measurements in real urban traffic in the city of Madrid. Five diesel passenger cars, have been tested. Through a statistical analysis, a Dynamic Performance Index was defined for diesel passenger cars. Likewise, the CO, NO_X and HC emissions were compared for each driving style for the tested vehicles.

Eco-driving reduces by 14% fuel consumption and CO_2 emissions, but aggressive driving increase consumption by 40%. Aggressive driving increases NO_X emission by more than 40%. CO and HC, show different trends, but being increased in eco-driving style.

Introduction

The Driving style of the driver refers to aspects of the actual driving action, where the driver can exercise their free will, although he is conditioned by external agents such as the configuration of the streets and roads (slope, crossroads per kilometre, etc.) and traffic congestion. Thus, the dynamic behaviour of the driver is reflected in how he acts on the vehicle controls such as: throttle, clutch, brake, gear shift and steering wheel. In order to asses the benefits of one driving style versus another, some real data were needed. Nevertheless, this study is not based on actual measurements of driver direct actuation on the vehicle controls, but on dynamic variables, recorded in real time, that are directly affected by the way the vehicle engine is operated, such as vehicle acceleration, engine speed and current gear shift.

Three different driving styles have been studied: eco-driving –in which shifting is made as soon as possible at a maximum of 2000 rpm for diesel engine to as high a gear as possible as defined by TNO (Vermeulen, 2006; Van Mierlo et al., 2004), normal driving and aggressive driving. Aggressive driving is defined as the driving style contrary to eco-driving, characterized by hard accelerations, increased use of first and second gear and driving at high engine speed (Casanova et al., 2005).

In order to have real figures of some relationships between real driving style and fuel consumption and emissions, data collected in real traffic conditions and using different diesel powered vehicles of different technology level were needed. Then, five different diesel passenger cars have been tested in real traffic use along two circuits in the city of Madrid. The testing methodology and the main results are presented.

Methodology

This study is based on about 1000 km driven in real traffic, equivalent to approximately 100 hours of emission measures, consumption and dynamic variables with five light duty diesel vehicles whose characteristics are presented in the table 1. Also, five different drivers have driven the cars, to somehow reduce the bias that could cause their own way of driving. Three different circuits have been used in the city of Madrid, the Madrid-UPM circuit (Casanova et al., 2009), Tetuan circuit and extraurban circuit, whose characterizations are shown in Figure 1 and Table 2 and 3. These circuits were chosen because they include the different types of streets normally found in a city like Madrid (local streets, secondary, main, arterial and highway), allowing to analyse the influence of road infrastructure. All trials were made with the engine at normal operating temperature to avoid the inherent variability of the cold start.

Table 1: Overview of the tested passenger cars

Make and model	Year of manufacture	Engine: make / model	Engine displacement (cm^3)	Max. power (kW)	Weight (kg)	Emission legislation EURO
PEUGEOT 406 BK STDT 2,1	1998	PEUGEOT / D-P8C	2088	80	1485	Euro 2
RENAULT LAGUNA	2005	RENAULT / D/F 9Q D6	1870	88	1350	Euro 3
CITROEN C4 HDI92 LX	2007	CITROEN / D-9HX	1560	66,2	1332	Euro 4
RENAULT LAGUNA	2008	RENAULT / D/K 9K 37	1461	81	1386	Euro 5
SEAT LEON	2008	VOLKSWAGEN /(D) BKD	1968	103	1315	Euro 4

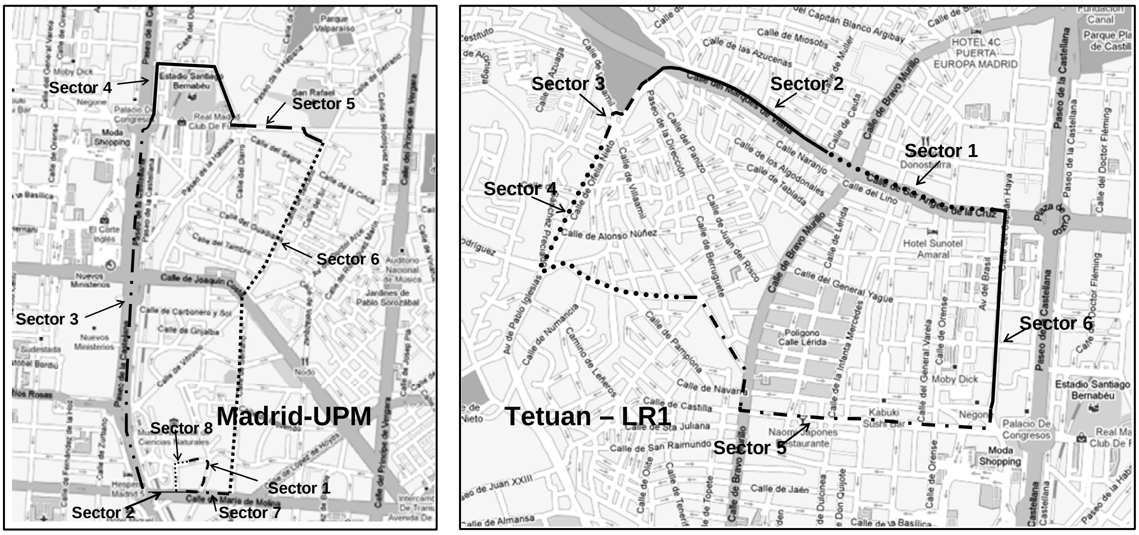


Figure 1: Madrid-UPM and "Tetuán" LR1 circuits.

Table 2. "Tetuan" – LR1 circuit. Table of characteristics per sector.

Sector	Distance (m)	Crossroads per km	Average Slope (%)	Average speed without traffic km/hr)	Lanes
1	610	8.2	0.86	31.6	3
2	680	7.6	-2.84	35.5	2
3	340	2.9	-0.63	42.5	2
4	1080	8.3	2.33	30.9	1
5	1400	6.4	-1.69	17.2	4
6	890	4.5	1.76	28.0	4
TOTAL	5000	6.6	0.02	25.6	---

Table 3. Madrid-UPM circuit. Table of characteristics per sector.

Sector	Distance (m)	Crossroads per km	Average Slope (%)	Average speed without traffic km/hr)	Lanes
1	517	5.80	-1.58	35.36	1
2	271	7.38	-2.81	30.63	3
3	1881	5.32	2.40	34.57	8
4	230	4.35	1.75	38.66	2
5	303	13.20	-2.78	18.06	3
6	385	10.39	2.53	22.95	3
7	796	12.56	-2.53	23.24	3
8	761	6.57	-2.06	41.10	4
9	289	3.46	-3.05	44.28	3
10	257	3.89	1.02	25.14	1
TOTAL	5690	7.21	0.00	32.31	----

The five cars tested, were instrumented with a self-developed non-intrusive universal on-board emission measurement system (MIVECO-PEMS) and a portable global activity measurement system (PGAMS), described by Casanova et al. (2009). So, The most important variables that ware recorded in real time at 10 Hz have been: exhaust gas flow, exhaust gas temperature, and exhaust gas pressure; concentration of CO (ppm), CO_2 (%), HC (ppm), NO_X (ppm) and air/fuel ratio (lambda); engine speed (rev/min), vehicle speed (km/h), oil and cooling water temperatures and weather conditions such as atmospheric pressure, humidity, temperature and headwind speed. As part of signal post-processing work (synchronization of real time recorded signal and thermodynamic and fluid mechanics calculations), the instantaneous mass emissions, total emissions and emission factors were calculated, both for each trial and for each of the sectors studied into each circuit.

Results and discussion

In a preliminary study presented in ETTAP09 (Casanova et al, 2009) a dynamic performance index "DPI" for a light duty gasoline vehicle was experimentally determined to evaluate the specific driving style used in a specific trial. In this work, a new dynamic performance index has been defined for light duty diesel vehicles. It is based on emission and dynamic measurements done in real traffic conditions for 5 light duty diesel vehicles (see Table 1). Various dynamic variables have been analysed over each entire circuit and over each sector in which it was divided. These are: average speed, positive average acceleration, percentage of time above a certain engine speed, percentage of time in each gears (first, second, third, etc.) and power demand (speed x acceleration) as defined by Ericsson (2001). The percentage of time does not include the time when car is stopped. So the Dynamic Performance Diesel index "*DPDi*" can be expressed as:

$$\textbf{\textit{DPDi}} = 1.58\text{e-}3\textbf{\textit{*\%\_time\_1gear}} + 2.05\text{e-}3\textbf{\textit{*\%\_time\_2gear}} + 1.48\text{e-}3\textbf{\textit{*\%\_time\_>1850rpm}} + 5.82\text{e-}2\text{*}\textbf{\textit{Average\_acceleration}}$$

Where it appears that the most influential parameters to quantify the driving style are the percentage of time that the driver runs in the first gear *(%_time_1gear)*, in second gear *(%_time_2gear)*, the percentage of time that leads to more than 1850 rpm *(%_time_>1850rpm)* and the positive mean acceleration (*Average_acceleration*) - that does not include periods of deceleration. The DPDi thus defined let to distinguish typical ranges of average accelerations that can occur in the three driving styles for the range of average speeds that can be had downtown in a city like Madrid, as shown in Figure 2.

The DPDi takes values in a range between 0 and 1.2 approximately, as shown in Figure 3, where in addition, the probability distribution of the DPDi according to the intention of the driver for eco and aggressive driving is shown.

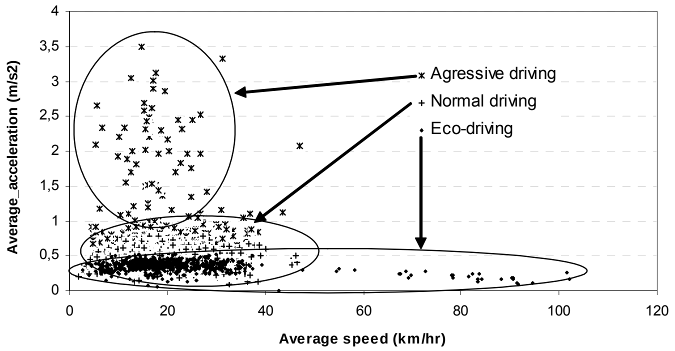


Figure 2: Average acceleration in real urban traffic for different driving styles.

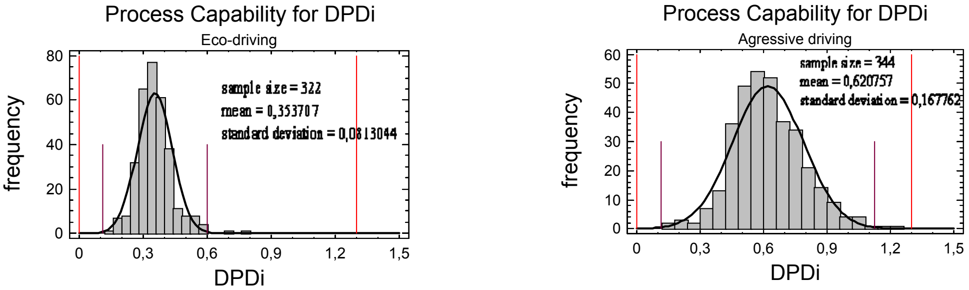


Figure 3: Probability distribution of the DPDi according to the intention of the driver for eco and aggressive driving.

The driver cannot always drive with his desired style due to the randomness characteristic of real traffic, as can be shown in figue 3. Thus the DPDi allows to reclassify each driving pattern according to driving style as follow: eco-driving DPDi ≤ 0.4, normal driving 0.4 < DPDi <0.6 and aggressive driving DPDi ≥ 0.6. As an example, figure 4 shows the effect of the driving style on fuel consumption for one of the tested cars.

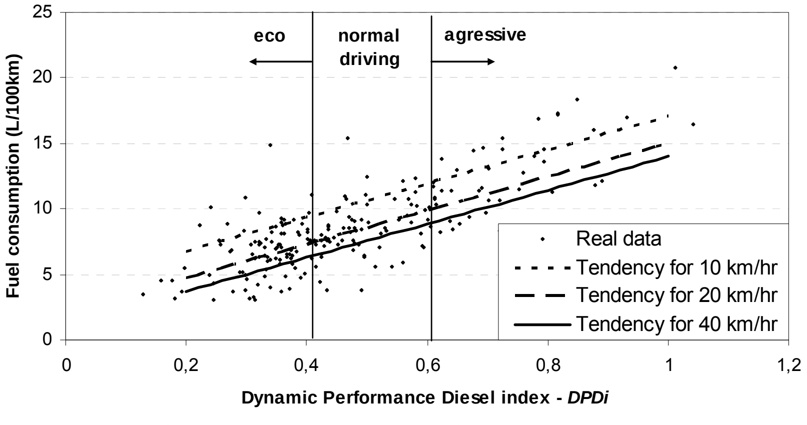


Figure 4: Influence of the dynamic behavior of the driver on fuel consumption in real traffic. Measurements made on Renault Laguna 2005 in Madrid City, 30 trials and 200 km of travel. Trends calculated for 0% slope.

One of the features of the DPDi is that it let us to compare the different vehicles in real traffic, because guarantees the equality of the driving style used in each route. Moreover, as discussed in the previous paper (Casanova et al., 2009), driving in real traffic is determined by three factors: driving style, road and traffic congestion. The congestion is reflected in the relationship between real traffic average speed and average speed without traffic, where real traffic average speed is independent of the driving style and average speed without traffic depends on the type of street. Based on these ideas, there was made a statistical study for each of the cars, of which the follow empirical equation was obtained:

$$\text{Consumption (L/100 km)} = k0 + k1 * (1/\text{average\_speed}) + k2 * \%\text{slope} + k3 * \text{DPDi}$$

Where k0, k1, k2 and k3 are the constants calculated by multiple regression analysis. The constants for each of the vehicles tested are shown in Table 4.

Table 4. Fuel consumption of cars tested. Coefficients of empirical equation of multiple regression.

Test vehicle	k0	k1	k2	k3	Model P-Value	R-squared (%)	Confi-dence level
Peugeot 406	-0.3474	48.2355	0.5899	12.8849	0.0000	90.1	99%
R_Laguna 2005	0.1196	41.1305	0.6620	12.8349	0.0000	84.6	99%
Citröen C4	0.4077	39.0072	0.6390	8.8021	0.0000	87.1	99%
R_Laguna 2008	-0.9273	41.9819	0.7481	14.9574	0.0000	87.3	99%
Seat León	-1.6971	34.6786	0.8766	17.6009	0.0000	90.8	99%

The figure 5 shows graphically the previous fuel consumption tendencies, for streets with slope of 0% and for the three driving styles: eco-driving (DPDi = 0.33), normal driving (DPDi = 0.49) and aggressive driving (DCI = 0.74).

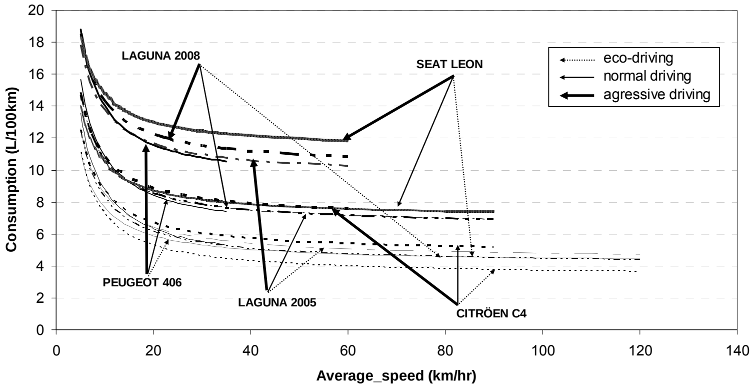
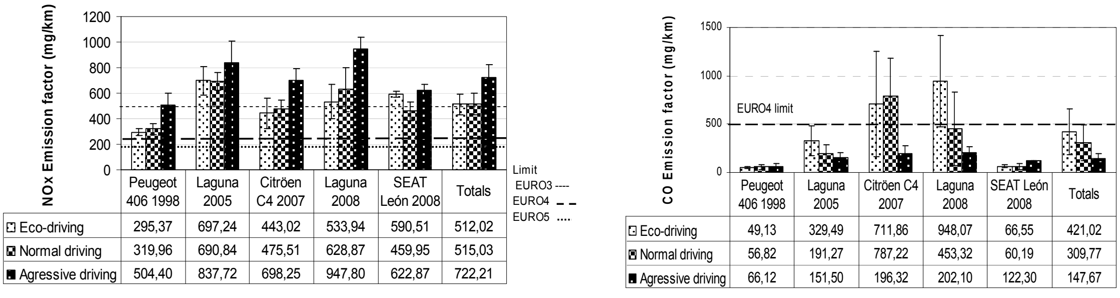


Figure 5: Fuel consumption tendencies for tested vehicles, based on urban and extra-urban routes in Madrid City.

It confirms that the driving style has a very high influence on fuel consumption and hence over carbon dioxide emissions. This graph shows that in normal driving conditions, fuel consumption are very similar for all tested vehicles, except for the Citroën C4 that is a car with energy classification A (lowest consumption in its range).



	Peugeot 406 1998	Laguna 2005	Citröen C4 2007	Laguna 2008	SEAT León 2008	Totals
▨ Eco-driving	295,37	697,24	443,02	533,94	590,51	512,02
▩ Normal driving	319,96	690,84	475,51	628,87	459,95	515,03
■ Agressive driving	504,40	837,72	698,25	947,80	622,87	722,21

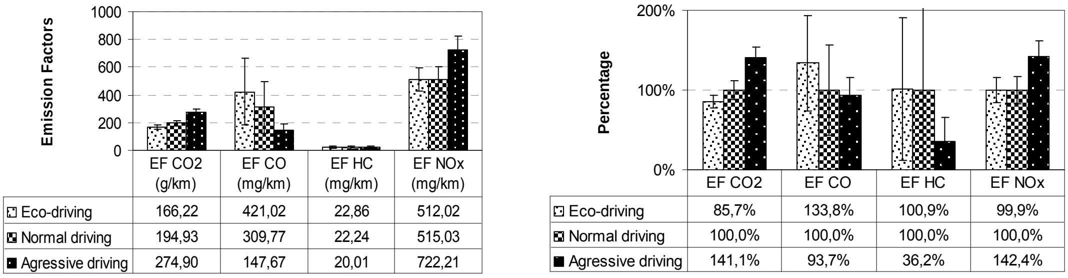
	Peugeot 406 1998	Laguna 2005	Citröen C4 2007	Laguna 2008	SEAT León 2008	Totals
▨ Eco-driving	49,13	329,49	711,86	948,07	66,55	421,02
▩ Normal driving	56,82	191,27	787,22	453,32	60,19	309,77
■ Agressive driving	66,12	151,50	196,32	202,10	122,30	147,67

Figure 6: Influence of driving style on NO_X and CO emission factors for urban traffic.

Additionally, based on the total results of each of the circuits, comparative studies were made between vehicles tested, as seen in Figure 6, for CO and NO_X emissions, with average speed of 19.3 km/h. The effect of driving style is not the same in all cars for those emissions, which agrees with the TNO results (Vermeulen, 2006). The reason could be the different calibration of each engine electronic control. In eco-driving pattern when low engine speed and medium to high gas pedal positions are used, CO and NO_X emissions can increase, probably because of mixture enrichment, due to low oxidation catalyst efficiency at high combustion temperature at high fuel/air equivalence ratio.

Conclusion

Figure 7 shows a summary of the influence of driving style on emissions, which shows that for all the cars tested, the advantage of eco-driving is clear in terms of reducing consumption and CO_2 emissions by 14%, and the disadvantage of aggressive driving that increases consumption and CO_2 by about 40% (Figure 7), which agrees with De Vlieger (2000) and Van Mierlo et al. (2004). But CO, HC and NO_X emissions depend on the engine design and calibration. Anyway, on average for NO_X emissions, eco-driving do not have advantages, but aggressive driving increases this emission by more than 40%. Another important aspect observed is that NO_X emissions in real traffic generally exceed the statutory emission limits.



	EF CO2 (g/km)	EF CO (mg/km)	EF HC (mg/km)	EF NOx (mg/km)
☐ Eco-driving	166,22	421,02	22,86	512,02
▦ Normal driving	194,93	309,77	22,24	515,03
■ Agressive driving	274,90	147,67	20,01	722,21

	EF CO2	EF CO	EF HC	EF NOx
☐ Eco-driving	85,7%	133,8%	100,9%	99,9%
▦ Normal driving	100,0%	100,0%	100,0%	100,0%
■ Agressive driving	141,1%	93,7%	36,2%	142,4%

Figure 7: Summary of influence of driving style on emission factors for urban traffic.

Dynamic Performance Diesel index "*DPDi*" determined experimentally, is a tool that could be used to develop an eco-driving assist system, similar to that developed by Mukai et al. (2009).

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