Influence of the stop/start system on CO_2 emissions of a diesel vehicle in urban traffic

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A R T I C L E   I N F O

A B S T R A C T

This paper presents measurements of CO_2 emission and efficiency of stop/start technology on a diesel vehicle in urban traffic. Two four-wheel-drive diesel vehicles with on-board exhaust emission and vehicle activity measurement systems were tested in two urban driving circuits representative of downtown Madrid. The vehicles had similar turbocharged and intercooled diesel engines fulfilling the same Euro 4 emissions regulation; but one had an improved engine incorporating stop/start technology. CO_2 emission reduction of more than 20% for the car equipped with the stop/start system was obtained. Regardless of the variability in driving style, the grade and type of streets, traffic congestion, and the engine operating temperature, the car equipped with the stop/start system has intrinsically a lower CO_2 emission factor.

1. Introduction

Reduction of carbon dioxide emission from light-duty vehicles is one of the priorities in most environmental policies. An agreement to reduce CO_2 emissions from light-duty vehicles (European Parliament, 2009) has been signed in Europe Union, limiting CO_2 emissions to 130 g/km, with progressive implementation from 2012 to 2015.

To fulfil such requirements, vehicle manufacturers have been forced to incorporate technological improvements such as weight lightening, engine size reduction, low-rolling-resistance tires, improved aerodynamics and hybridisation and electrification of vehicles. The "stop/start" (S/S) technology is an easy and low-cost solution, in which the internal combustion engine is automatically powered off when the car is stopped and restarted upon driver's demand or when needed. Thus, it eliminates fuel consumption during idling, as in the case of stops at traffic lights or jams, which can account for up to 10% of total consumption (Rueger, 2008).

The influence of the S/S system on fuel economy and emissions has been studied mainly because of the current interest in hybrid vehicles. Henein et al. (2000) studied the effect of start transients on fuel consumption and hydrocarbon (HC) and NO_x emissions using direct-injection diesel engines. They proved that stopping the engine reduces fuel consumption, even if some energy is consumed stopping and starting the engine. Moreover, they showed that the shutdown time had a considerable influence on NO_x emissions. Bishop et al. (2007) performed chassis dynamometer tests to determine the fuel economy improvement of an S/S system, noting a 5.3% reduction in fuel consumption in the city FTP75 test cycle. Yu et al. (2008) conducted experiments on a gasoline engine coupled to an eddy-current dynamometer and showed that HC transient emissions are higher when the engine is quickly started in the original engine calibration mode.

In order to asses the benefits of the S/S system in real life, tests should be conducted in real traffic with on-board emissions and activity measurement systems. Portable emission measurement systems (PEMS) are nowadays state of the art

technology. They are based on instantaneous measurement of the different pollutant concentrations and exhaust gas flow. By a subsequent signal processing, instantaneous mass emissions of each pollutant and fuel consumption could be determined.

When dealing with on-board measurements in urban traffic, the grade of the road plays a significant role in instantaneous emissions and fuel consumption, as well as in averaged values. Fuel consumption increase in upgraded streets could not be compensated by downgraded streets, thus it is an important parameter to be also registered. Also, average speed is a variable that affects significantly to fuel consumption.

To explain the fuel economy and pollutant emissions results, the instantaneous power at wheels (based on the tractive force in each moment) need to be measured. It could be calculated from vehicle specification data, vehicle speed and acceleration, front wind speed and road grade. In this work, the vehicle specific power (VSP) has been computed from the car characteristics and real traffic collected data.

2. Methodology

Forty-one driving are evaluated over 300 km driven in real traffic conditions; equivalent to about 20 h of instantaneous emission, atmospheric condition and dynamic variable measurements. Two four-wheel-drive vehicles equipped with an on-board emission and vehicle activity measurement system are used and all tests were conducted with the air conditioning system turned off.

Two urban circuits were chosen to be representative of the congestion found in the city of Madrid, the "Tetuan" and the "Chamberí" circuits; both include streets with high average daily traffic. Each circuit has different types of streets, traffic light sequences and road grades. Figs. 1–4 show the characteristics of the circuits, including the locations of traffic lights and the orographic profile of the streets. Table 1 shows the characterisation of the circuits, including the speed without traffic recorded on a holiday morning.

The tests used two diesel Land Rover Freelander2 vehicles, one, a conventional 2009 year model (9MY) and the other one a 2010 model equipped with a stop/start system (10MY) that can be turned on and off (the latter designated as 10MY-eco off). The S/S system has some refinements over the original diesel engine as controlled smooth throttle closing and ramping down of fuel, an alternator that can be turned off during the shutdown procedure, modified engine calibration, a heavy-duty starter motor, a strengthened dual-mass flywheel and a special absorption glass mat battery.

A non-intrusive, universal on-board portable emission measurement system, MIVECO-PEMS and a portable global activity measurement system, PGAMS, were installed in the cars. The systems are designed and developed, based on commercial analysers and self designed components to be installed on-board. At the frequency of 10 Hz they measure CO, HC, NO_x, λ and exhaust gas flow, as well as other activities such as vehicle speed, engine speed, engine temperatures and atmospheric
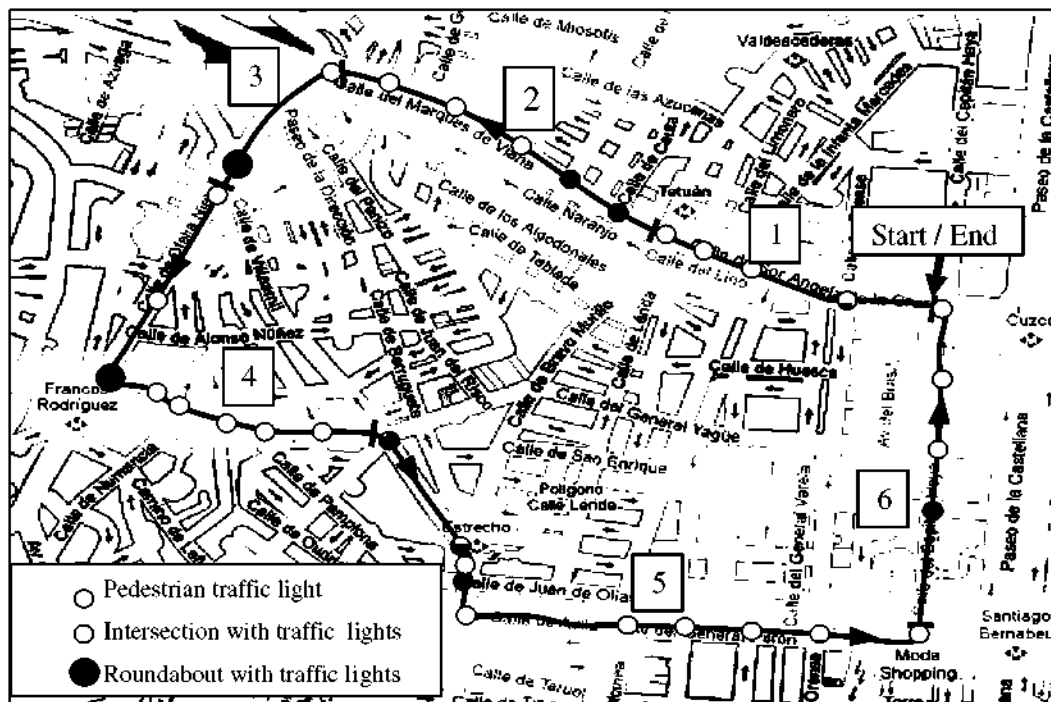

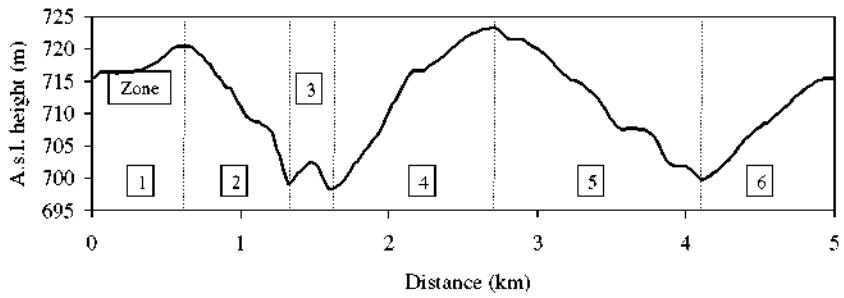Fig. 1. Map of the Tetuan circuit (LR1).

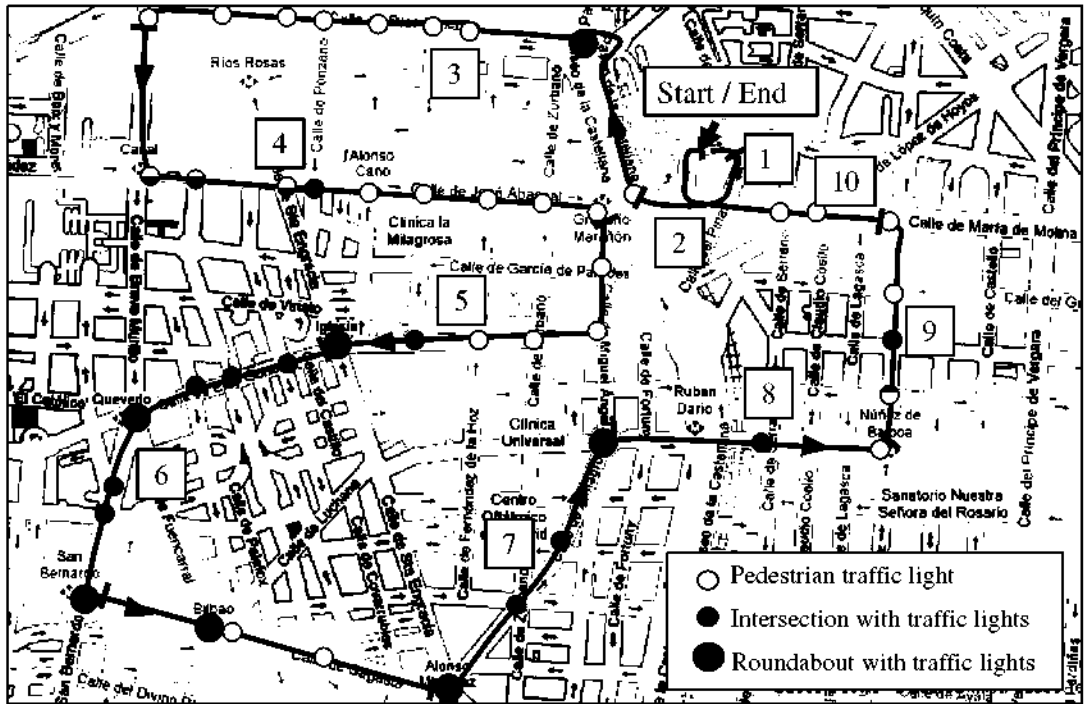**Fig. 2.** Orographic profile of the Tetuan circuit (LR1).

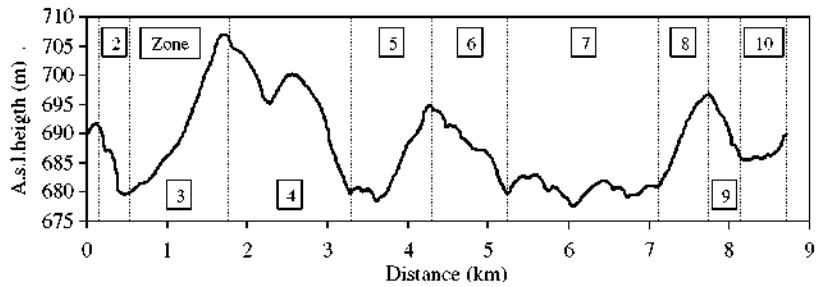**Fig. 3.** Map of the Chamberi circuit (LR2).

Fig. 4. Orographic profile of the Chamberi circuit (LR2).

parameters including temperature, pressure, humidity and headwind speed. Fuel consumption is calculated from the emission data along with exhausts (Fonseca and Casanova, 2009).

Circuit name		Distance (km)	Number of intersect.	Intersect. per km	Speed without traffic (km/h)	Average daily occupation (vehicles/ day)	% Local streets	% Secondary streets	% Main streets	% Arterial streets
Tetuán	LR1	5.1	33	6.5	25.6	12,402	–	69	31	–
Chamberí	LR2	8.7	47	5.4	27.6	25,632	11	38	29	23
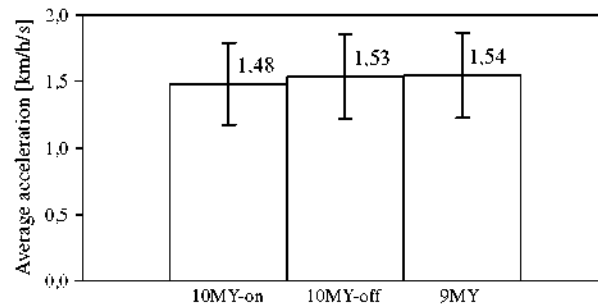
Fig. 5. Positive mean acceleration for version 2009 (9MY) versus version 2010 (10MY) with the S/S system on and off.

As part of the signal post-processing (synchronisation of real-time recorded signals and thermodynamic and fluid mechanics calculations), the instantaneous mass emissions, total emissions and emission factors are calculated for each tests and for the sectors in the two circuits. The on-board instrumentation set, including the energy supply system, had a weight of 110 kg, corresponding to a vehicle loaded of 110 kg plus a driver and passenger.

A professional driver instructed to use the same pattern and driving style in all tests drove both vehicles. A "normal" driving style was used, in which acceleration and deceleration are varied according to the classification of Casanova et al. (2009). Fig. 5 shows average and standard deviation of the positive mean acceleration of all tests for each car.

3. Results

The tests were performed on weekdays for different levels of traffic congestion, therefore, travel times, average speeds, and stop/start times varied between tests. The results are presented as plots of trends as a function of speed, the most representative variable in traffic conditions. For example, Fig. 6 shows the trend of CO_2 emissions versus average speed based on total emissions for each test and shows the strong influence of this variable. The average speeds for all tests were between 9 and 20 km/h, whereas the average speeds without congestion were 25.6 km/h on the Tetuan and 27.6 km/h on the Chamberí circuit.

Fig. 7 shows the average and standard deviation values of CO_2 emission factors for each vehicle for all tests of both urban circuits. Compared with the conventional car (9MY), the figure shows that, in congested urban traffic (average speed of
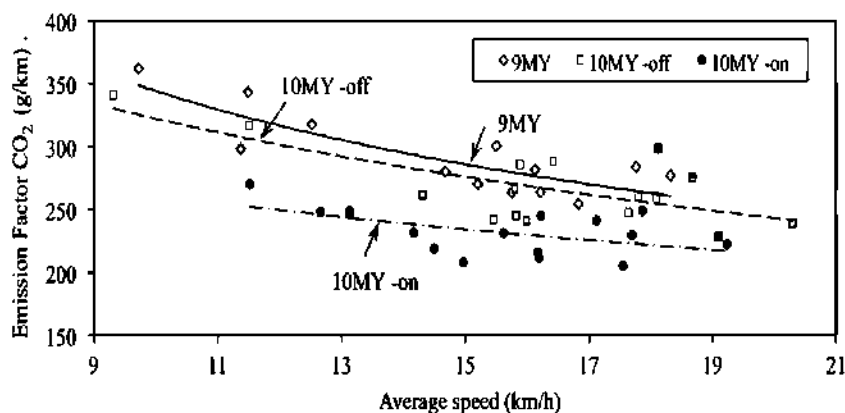
Fig. 6. Trends and measured data of the CO_2 emission factor versus average speed. Version 2009 (9MY) and version 2010 (10MY) with the S/S system on and off.
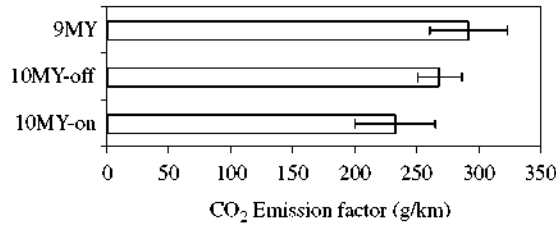
Fig. 7. Average and standard deviation values of CO_2 emission factor. Version 2009 (9MY) and version 2010 (10MY) with the Start/Stop system on and off. Madrid urban traffic, average speed 15.5 km/h.

15.5 km/h), the CO_2 emission is reduced by more than 20% when using the car equipped with the S/S system (10MY-on). From these results, it can be estimated that a 12.2% fuel consumption reduction (10MY-off versus 10MY-on) can be attributed to idle consumption and 8% (9MY versus 10MY-off) to engine calibration and optimisation of the version 10MY with the S/S system.

To better understand the reasons for such fuel economy improvements, a multivariable modal analysis has been performed to analyse the influence of the new engine calibration of the stop/start version on CO_2 emission factor in real urban traffic. It is known that in real urban traffic, fuel consumption and pollutant emissions depend mainly on specific engine characteristics, but the variability observed is due to the influence of factors related to traffic congestion (average speed: S_{Va} in km/h) (De Vlieger et al., 2000), driving style, street configuration and engine operating conditions. Each circuit was divided into different zones (six zones in the Tetuan circuit and 10 zones in the Chamberí circuit), as shown in Figs. 2 and 4.

For the multivariable analysis, average acceleration (A_V in km/h/s) was included in order to represent the driving style. Although the average acceleration is quite similar in all tests, small differences caused by the randomness of traffic strongly influence the CO_2 emission factor (e_{vCO2} in g/km).

The variables related to the configuration of the streets are road grade (G in %) and type of street (t_S). t_S is an index that evaluates the flow of traffic for which the street was designed, being 0 for streets with very low traffic flow and 1 for those with very high traffic flow. The values used are as follows: 0.15 for local streets, 0.30 for secondary streets, 0.45 for main streets, 0.6 for arterials, 0.75 for bypass streets and 0.9 for highways. The most important variable related to the engine operating conditions is the average engine oil temperature (T_E in °C), because CO_2 emissions increase when the engine is cold due to reduced mechanical efficiency. The general mathematical expression for each vehicle is

$$e_{vCO2} = c_0 + \frac{c_1}{S_{Va}} + c_2 \cdot A_V + c_3 \cdot G + \frac{c_4}{t_S} + c_5 \cdot T_E \qquad (1)$$

Coefficients for the tested vehicles are shown in Table 2 and the fitting values in Fig. 8.

The regressions indicate that regardless of the variability imposed by external factors such as traffic congestion, driving style, configuration of the streets and engine operation conditions, the vehicle equipped with S/S system has the lower intrinsic CO_2 emission factor (c_0[10MY-on] = 165.7 g/km), showing a significant improvement over the conventional model

Table 2
Coefficients of the empirical models.

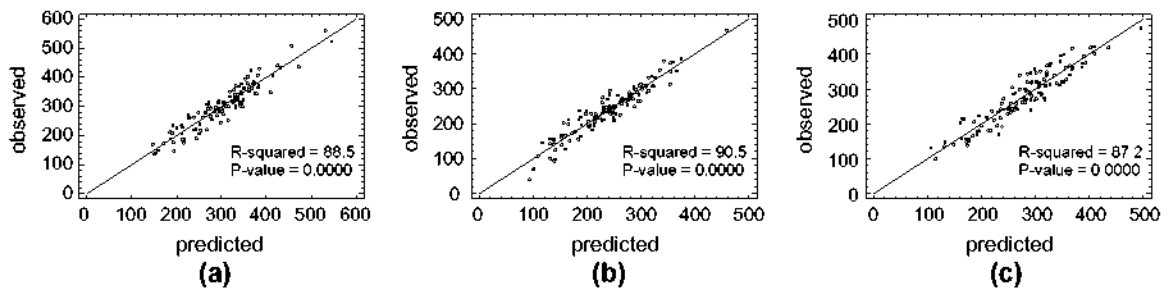| Tested car	c_0	c_1	c_2	c_3	c_4	c_5
9MY	221.4	1382.4	46.9	31.7	18.1	−2.1
10MY-on	165.7	912.5	50.8	29.8	14.0	−1.4
10MY-off	176.0	1760.7	61.1	32.4	14.3	−2.0

Fig. 8. Fitted values for the CO_2 emission factor models: (a) version 2009 (9MY), (b) version 2010 (10MY) with the start/stop system on and (c) off. *Note*: Calculated for normal driving style, normal operating condition of the vehicle, and average speed of 20 km/h.

($c_0[9MY] = 221.4$ g/km). The coefficients show the strong influence of average speed on CO_2 emissions and, ipso facto, on fuel consumption in the three cases; nevertheless its influence is less critical for a car equipped with the S/S. For example, for the same driving style, engine temperature, type of street and a grade of 0%, a reduction in the average speed from 25 km/h to 15 km/h implies an increment of 37 g/km of CO_2 in a normal diesel vehicle, whereas for the vehicle equipped with S/S system the increment is only 24 g/km.

Fig. 9 shows that the slope and the type of street affect in a similar way to the two vehicles tested. An increase in the street gradient of only 1% can cause an increase in CO_2 emissions of approximately 30 g/km when maintaining the same speed profile in the three cases. Also CO_2 emissions may increase by 20% in local streets over secondary streets because of the higher frequency of stops. In contrast, Fig. 10 shows that the engine temperature and driving style do not affect in the same way to both tested vehicles. The vehicle with the S/S system (10MY-on) is less affected by low engine temperatures; therefore, CO_2 emissions during a cold start are much lower than in the conventional version (LR-9MY). Furthermore, aggressive driving (about 3 km/h/s) can result in an increase of more than 76 g/km of CO_2 emissions in the vehicle with S/S system turned on and almost 92 g/km in the vehicle equipped with S/S system turned off.

To calculate the energy CO_2 emission factor (e_{ECO2} [g/kW h]) for each vehicle, instantaneous tractive power (P_t [kW]) is calculated based on the dynamic variables recorded in real-time, including road grade and wind speed. Thus, e_{ECO2} is calculated as the ratio between mass emission of CO_2 (calculated by summation of the instantaneous mass emission values $\dot{m}_{CO2}$ averaged for each Δt period) and positive tractive work (PW_t) for each zone and for each overall test, as shown in Eq. (2). PW_t was calculated as the integral of the positive areas of the curve of instantaneous tractive power.

$$e_{ECO2} = \frac{\sum_1^n \dot{m}_{CO2} \ [\text{g/h}] \cdot \Delta t}{PW_t [\text{kW h}]} \tag{2}$$
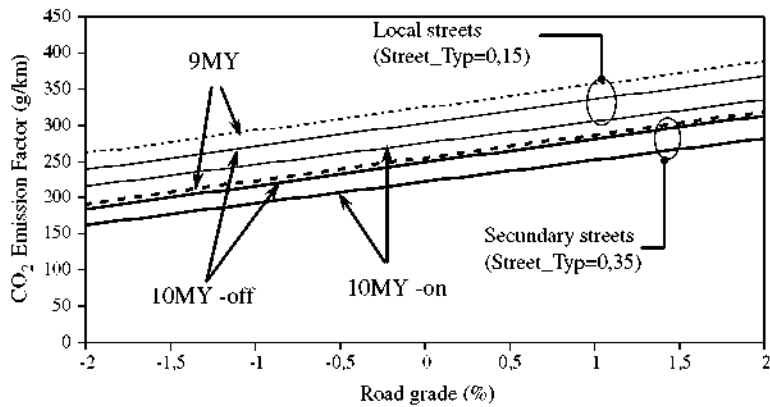

Fig. 9. Trends of CO_2 emission factor versus road grade (%) for local and secondary streets. Version 2009 (9MY) and version 2010 (10MY) with the start/stop system on and off.
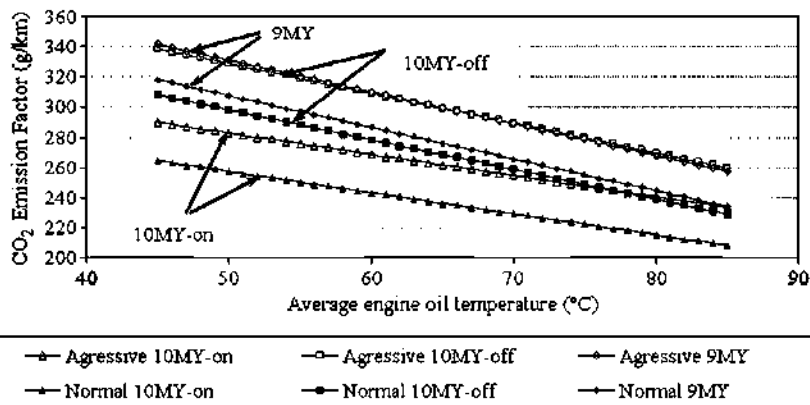

Fig. 10. Trends of CO_2 emission factor versus average engine temperature for normal and aggressive driving styles, for the 2009 model and the 2010 model with the start/stop system on and off.
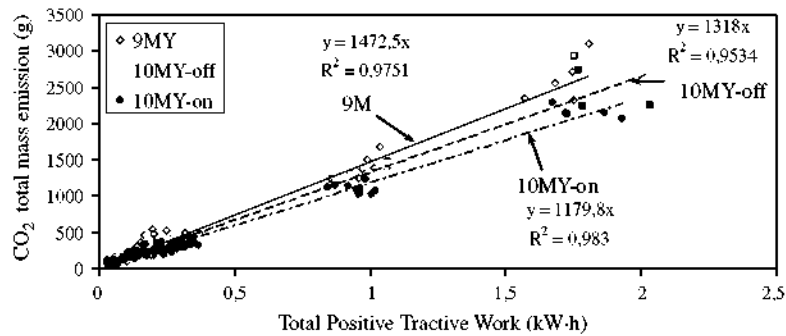
Fig. 11. Mass emission of CO_2 versus total positive tractive work (kW h) for version 2009 and version 2010 with the start/stop system on and off.

Fig. 11 shows the energy CO_2 emission factor as the linear relationship existing between mass emission of CO_2 and PW_t for each car. The factor is a measure of the overall efficiency of the vehicle because total positive tractive work represents the engine energy demand for kinetic energy, road grade, rolling resistance, and aerodynamic drag and mass emission of CO_2 represents the fuel consumption of the vehicle. It can thus be used to compare the vehicle's "global efficiency" and to predict the emission of CO_2 in urban traffic for a given circuit, based only on a characterisation of the road and the driving pattern.

Therefore, following Fig. 11, there is an increase in overall efficiency due to integration of the S/S system in the vehicle (LR_10MY), even when driving with S/S disabled (LR_10MY-off). These results confirm the trend shown in Fig. 6 and the improvement in engine efficiency when it is operating in low-load conditions.

4. Conclusions

The three methods have been used to study the influence of the S/S on a four-wheel-drive diesel vehicle: measurement of average CO_2 emissions, modal statistical analysis and energy emission factor, show a significant reduction in CO_2 emissions in actual urban traffic; up to 20% at an average speed of 15.5 km/h. The reduction could be partly attributed to changes in the engine and partly to zero idling emissions. Additionally, modal statistical analysis explains the variability observed in the CO_2 emissions found in actual traffic flows. Finally, the energy emission factor analysis confirms that CO_2 emission reduction is due to better global energy efficiency of the vehicle with S/S system.

Acknowledgements

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