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A METHODOLOGY FOR MEASURING AN INTERNAL COMBUSTION ENGINE PERFORMANCE MAP USING ON-BOARD ACQUISITION

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Abstract. *This work aims the experimental data collection of the fuel map of engines powered by internal combustion engines. Through the acquisition of parameters available on OBD-II port (on-board diagnosis), such as speed, engine speed, fuel flow and others, it is possible to determine the typical fuel consumption for a specific engine in a given condition. This data collection is useful in the determination of the best operating conditions, to evaluate the quality of a drive (how efficient it was) and to simulate fuel consumption for a given route and others. Currently, the fuel map is obtained through engine dynamometer testing, which is expensive and requires the engine to be removed from the vehicle. As consequence, the number of tests is limited and it is often difficult to compare two different vehicles, for example. This work introduces a different approach so the fuel map can be obtained through chassis dynamometer and on-road acquisitions, making this data more accessible. Another contribution of this work is the development of a method to evaluate the drive conditions and compare against other conditions (for example, on-road to laboratory fuel consumption tests), once this comparison will be one of the methods used to validate the methodology*.

Keywords: *Fuel economy, performance map, OBD-II, Drive cycle*

1. INTRODUCTION

Transportation sector is, together with industry sector, the highest responsible for carbon dioxide (CO_2) emissions. Although internal combustion engines have improved significantly their efficiency, they are limited to the operating temperatures, which determine the maximum efficiency that they can deliver. Many countries and regions worldwide have established CO_2 emission and fuel consumption targets to reduce the transportation sector contribution on CO_2 emissions. Customers are demanding more efficient vehicles due to constant highs on fuel prices, and also due to growing concerns about environment and sustainability. The International Council on Clean Transportation (ICCT) compared CO_2 regulations worldwide (ICCT, 2014). It is presented that the highest reduction rate in CO_2 emissions is observed in USA regulation (150 g/km in 25 years), and the lowest reduction rate is observed in Japan (70g /km in 20 years). That difference in the reduction rate is caused by the difference in the average fleet CO_2 emissions in the year 2000, with USA having the highest average fleet CO_2 emissions, requiring a more aggressive reduction.

Although automakers complied with the regulations, reducing their fleet CO_2, a study realized with 28,000 vehicles in real world usage presented that the ratio between the fuel economy observed by the drivers and the official fuel economy is consistently growing (ICCT, 2013), which means that the customers are driving in different conditions than the conditions used to homologate the fuel economy. This divergence is presented in Fig. 1.

The engine performance map relates fuel consumption in a specific operating condition (engine speed and brake torque). Current measurement procedures of the performance map require the engine to be removed from the vehicle. In many situations, it is not practical to remove the engine to perform this test, limiting the analysis to the whole vehicle fuel economy testing, which gives little information about engine operating conditions. The main purpose of this work is to present a methodology to measure the performance map of an internal combustion engine using on-board acquisition, through signals available on OBD-II protocol. The performance map obtained through this methodology was used to simulate the fuel consumption for a specific route. The difference between the measured fuel consumed and the simulated fuel consumed is within 10% range.

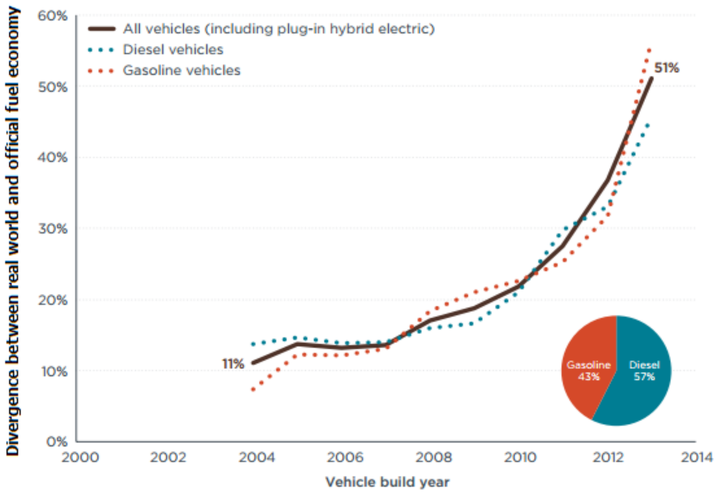

Figure 1. Divergence between real world and official fuel economy (ICCT, 2013)

2. METHODOLOGY

2.1 Logitudinal dynamics model

The engine provides the power required for a specific condition of speed and acceleration. This power is given by:

$$P_e = T_e \cdot \omega_e \tag{1}$$

where P_e is the engine power, T_e is the engine torque and ω_e is the engine speed. Engine torque and engine speed characterizes the engine operating conditions. Specific fuel consumption is dependent of the operating conditions, thus, same engine power delivered by different operating conditions can have different fuel consumption.

The relationship between the tractive force and engine torque, according to Gillespie (1992), is given by:

$$F_x = \frac{T_e \cdot N_{tf}}{r} - \frac{\left((I_e + I_t) \cdot N_{tf}^2 + I_d \cdot N_f^2 + I_w\right) \cdot a_x}{r^2} \tag{2}$$

where F_x is the tractive force, N_{tf} is the transmission reduction ratio times the differential reduction ratio, N_f is the differential reduction ratio, a_x is the longitudinal acceleration (in the same direction of the vehicle movement and the force F_x), r is the dynamic radius of the tires, and I_e, I_t, I_d and I_w are the rotational inertias of the engine, the transmission, the differential and the wheels, respectively.

The first term on the right hand side of Eq. (2) is the force provided by the engine, while the second is the force used to spin the rotating components. Therefore, Eq. (2) can be reduced to:

$$M \cdot a_x + \frac{\left((I_e + I_t) \cdot N_{tf}^2 + I_d \cdot N_f^2 + I_w\right) \cdot a_x}{r^2} = \frac{T_e \cdot N_{tf}}{r} \tag{3}$$

The second term on the left of the Eq. (3) that multiplies the acceleration can be interpreted as an apparent inertia, leading to:

$$(M + M_r) \cdot a_x = \frac{T_e \cdot N_{tf}}{r} \tag{4}$$

Adding the rolling resistance force, the aerodynamic force and the force to overcome track grade into Eq. (4) leads to:

$$(M + M_r) \cdot a_x = \frac{T_e \cdot N_{tf} \eta_{tf}}{r} - R_x - D_A - W \cdot \sin\theta \tag{5}$$

The term R_x is the force to overcome tires losses, D_A is the force to overcome aerodynamic drag, and $W \cdot \sin\theta$ is the force to overcome track grade. The last term can be positive (uphill) or negative (downhill). Also, it was included the transmission and differential efficiency (η_{tf}). This efficiency factor must be less than one, since it is the relationship between the power output of the differential and the power input of the transmission. Gillespie (1992) suggests that this factor is within the range of 0.92 to 0.97.

The testing to determine the resistive forces is known as the coastdown test (ABNT, 2014). It consists in accelerating the vehicle up to 105 km/h, disengage the gear and let the vehicle decelerate until 30 km/h. The time difference between each speed interval of 5 km/h is used to calculate the average acceleration for each of these intervals. Hence the resistive force as a function of the speed is obtained. The resistive force is modeled by a second order polynomial as a function of the speed, with only the second order term and the constant term, according to:

$$(M + M_r) \cdot a_x = -R_x - D_A = f_0 + f_2 \cdot V^2 \tag{6}$$

The power is obtained by multiplying the force [Eq. (5)] by the speed:

$$(M + M_r) \cdot a_x \cdot V = \frac{T_e \cdot N_{tf}\eta_{tf}}{r} \cdot V - R_x \cdot V - D_A \cdot V - W \cdot \sin\theta \cdot V \tag{7}$$

Then the power provided by the engine will be:

$$P_e = T_e \cdot \omega_e = T_e \frac{V \cdot N_{tf}}{r} \tag{8}$$

The kinetic power (the power effectively used to move the vehicle) is the term on the left of Eq. (7), described mathematically by:

$$P_{kin} = (M + M_r) \cdot a_x \cdot V \tag{9}$$

The resistive power is given by the product of resistive force [Eq. (6)] and the speed, leading to:

$$P_{res} = f_0 \cdot V + f_2 \cdot V^3 \tag{10}$$

Following the same procedure, the grade power can be obtained by:

$$P_{gr} = W \cdot \sin\theta \cdot V \tag{11}$$

Combining Eq. (8) to Eq. (11), it can be concluded that:

$$P_e = \frac{P_{kin} + P_{res} + P_{gr}}{\eta_{tf}} \tag{12}$$

Equation (12) relates the power that must be provided by the engine for a given condition of speed, acceleration and track grade. One can conclude that the power provided by the engine is a function of the vehicle (f_0, f_2 and η_{tf}), the track ($\sin\theta$) and the speed (V and a_x). Combining Eqs. (8) and (12), the engine torque is obtained by:

$$T_e = \frac{P_{kin} + P_{res} + P_{gr}}{\omega_e \cdot \eta_{tf}} = \frac{r}{V \cdot N_{tf}\eta_{tf}} (P_{kin} + P_{res} + P_{gr}) \tag{13}$$

According to this last equation, the engine torque can be obtained by knowing the resistive coefficients of the vehicle (f_0 and f_2), the overall transmission efficiency (η_{tf}), the overall transmission ratio (N_{tf}), track grade ($\sin\theta$) and the speed as function of the time (V). The transmission ratio is not necessary when the engine speed is known.

2.2 Engine performance map

A common way to present the engine operating conditions is to plot brake specific fuel consumption (BSFC) over engine's full load and speed range (Heywood, 1988). The upper envelope of the map is the full load map (or wide-open-throttle map), and the points below this curve define the partial load operating conditions. This map is called the engine performance map. This map can be presented either in brake specific fuel consumption versus break mean effective pressure (BMEP) and engine speed; or in absolute fuel consumption versus torque and engine speed. An example is presented on Fig. 2.

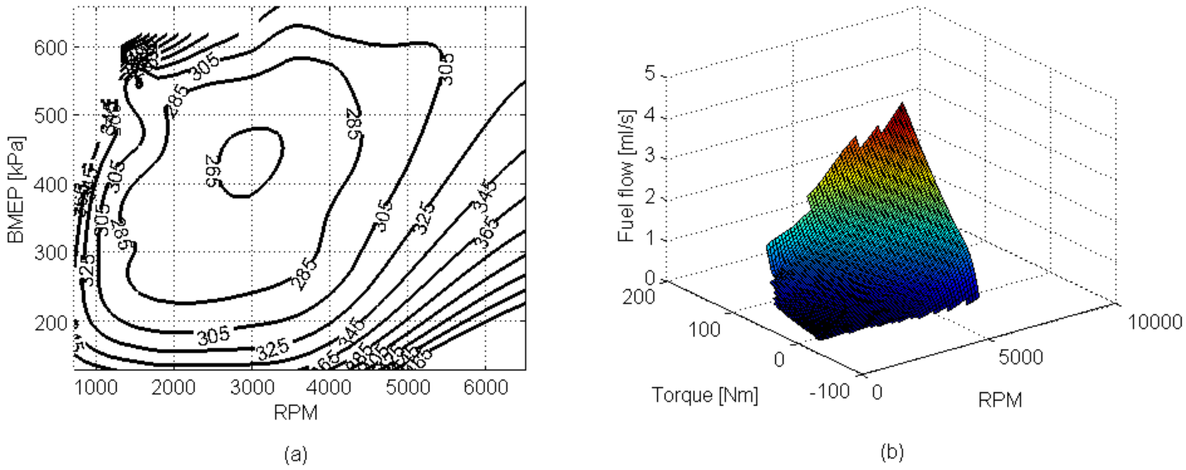

Figure 2. Engine performance map: (a) BSFC versus BMEP and engine speed and (b) absolute fuel consumption versus torque and engine speed

The engine performance map for absolute fuel consumption [presented in Fig. 2 (b)] is approximated by a polynomial equation as a function of engine torque and engine speed, as presented in Eq. (14):

$$f_c = a_{00} + a_{01} \cdot \omega_e + a_{10} \cdot T_e + a_{11} \cdot \omega_e \cdot T_e + a_{02} \cdot \omega_e^2 + a_{20} \cdot T_e^2 \tag{14}$$

The determination of the coefficients $a_{00}, a_{01}, a_{10}, a_{11}, a_{02}$ and a_{20} establish the mathematic relationship between the fuel consumption and the operating conditions that will be used in this work.

2.3 Data acquisition

In order to obtain the polynomial coefficients of Eq. (14), it is required many samples of engine torque, engine speed and fuel consumption data. The engine torque is obtained by using Eq. (13). The vehicle used for data collection has a known f_0 and f_2 coefficients, as well as the overall transmission efficiency η_{tf}. A GPS is used to obtain the speed and track grade. The engine speed information and the fuel consumption are obtained through CAN Network.

The CAN network is a module responsible to manage the information flow through vehicle modules (Papaioannou, 2005). This information flow can be intercepted through the OBD-II connection. The main information that can be obtained through OBD-II connection is: trouble codes, engine speed, vehicle speed, accelerator pedal position, intake mass air flow and fuel flow (Guimarães, 2003).

2.4 Test route

To validate the methodology, the tests will be done in two routes. The first route (reference route) is the fuel economy cycle defined by ABNT (2012). Figure 3 presents the speed as a function of time for this route. This test is performed on chassis dynamometer, and it will be used to determine the polynomial coefficients in Eq. (14).

The second route (validation route) was obtained during a real world testing. The driver was instructed to drive according to the traffic, with no additional recommendation. It was not the intent that the real world route should be similar to the fuel economy cycle, since it was subject to external influences, such as traffic, weather, etc. Figure 4 presents the speed as a function of time for the validation route.

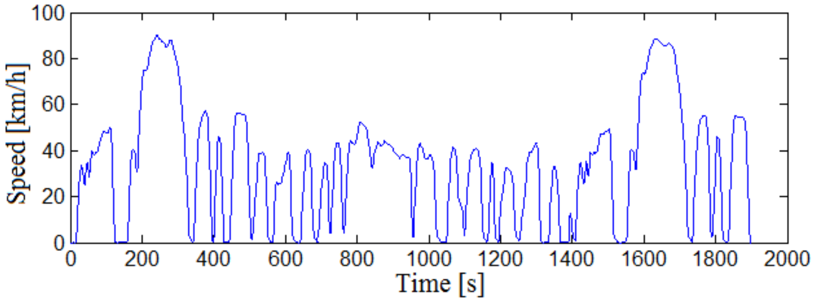

Figure 3. Reference route speed as function of time

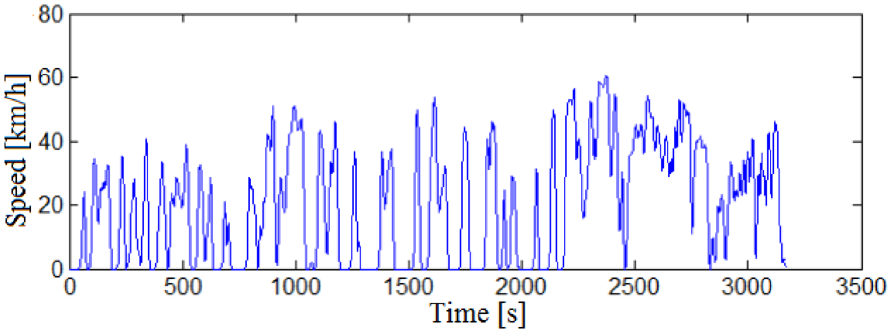

Figure 4. Validation route speed as function of time

It is convenient to determine the conditions which the vehicle is operating during a cycle. A classification of the operating modes is provided by the U. S. Environment Protection Agency - EPA (1993). According to this classification, there are basic 4 modes of operation: idle, acceleration, cruise and deceleration. Table 1 presents the condition that characterizes each of these modes.

Table 1. Characterization of each operating mode

Operating mode	Condition
Acceleration	$\bar{a}_t > 0.086\ \mathrm{m/s^2}\ v_t > 0.6\ \mathrm{km/h}$
Cruise	$\lvert\bar{a}_t\rvert, \lvert\bar{a}_{t-1}\rvert, \lvert\bar{a}_{t+1}\rvert < 0.086\ \mathrm{m/s^2};\ v_t > 0.6\ \mathrm{km/h}$
Deceleration	$\bar{a}t < -0.086\ \mathrm{m/s2}\ vt > 0.6\ \mathrm{km/h}$
Idle	Any other condition.

The data collected on the reference and the validation routes are used to calculate, through Eq. (13), the engine torque and the engine speed for each instant of the acquisition. Specifically, for each instant t, the engine operating conditions [$T_e(t)$ and $\omega_e(t)$], as well as the engine power [$P_e(t)$], are determined.

2.5 Validation

The procedure proposed for the validation is presented in Fig. 5. As aforementioned, the reference test is used to determine the coefficients for Eq. (14). The validation test is used to obtain the engine operating conditions and fuel consumption in a different situation than the conditions visited in reference test. The operating conditions for the validation test are used in Eq. (14), and the estimated fuel consumption is compared with the measured fuel consumption.

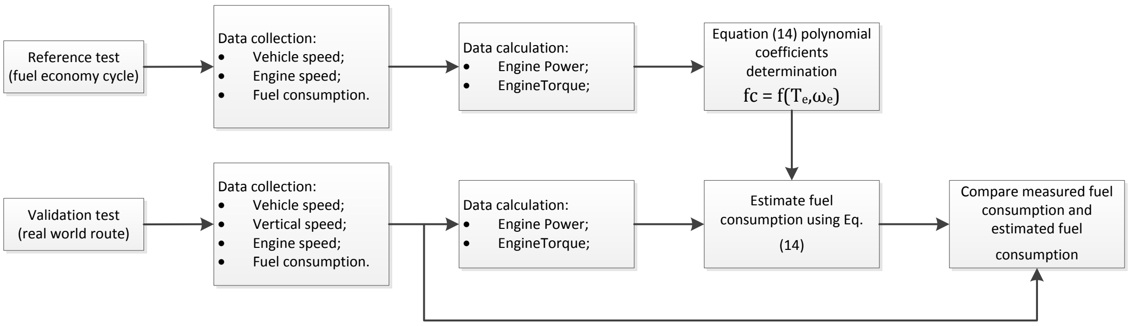

Figure 5. Flowchart of the validation methodology

3. RESULTS AND DISCUSSION

The operating conditions obtained in both reference test and validation test are presented in Fig. 6. It can be observed that the validation test has a large amount of data points in the region between 800 RPM and 1750 RPM, which is not observed during the reference tests. Also, the overall power is higher on reference test than the validation test.

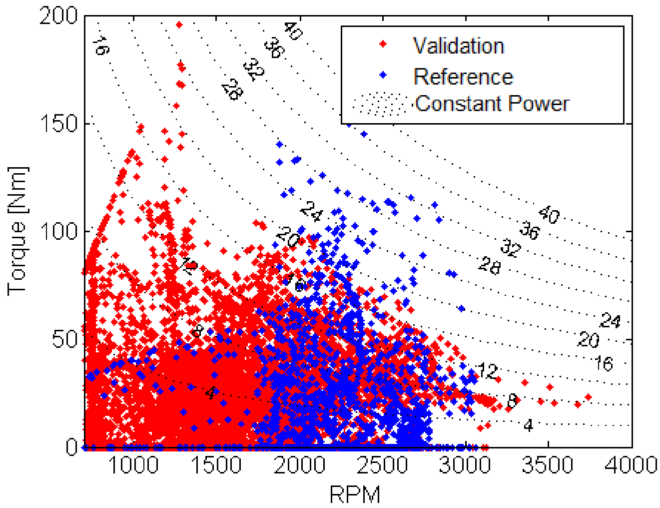

Figure 6. Engine operating conditions during reference and validation tests

This difference helps the validation of the methodology, proving that it can be efficient even on conditions that were not visited on the test used to determine the polynomial coefficients. The engine performance map obtained using the reference test data is presented in Fig. 7.

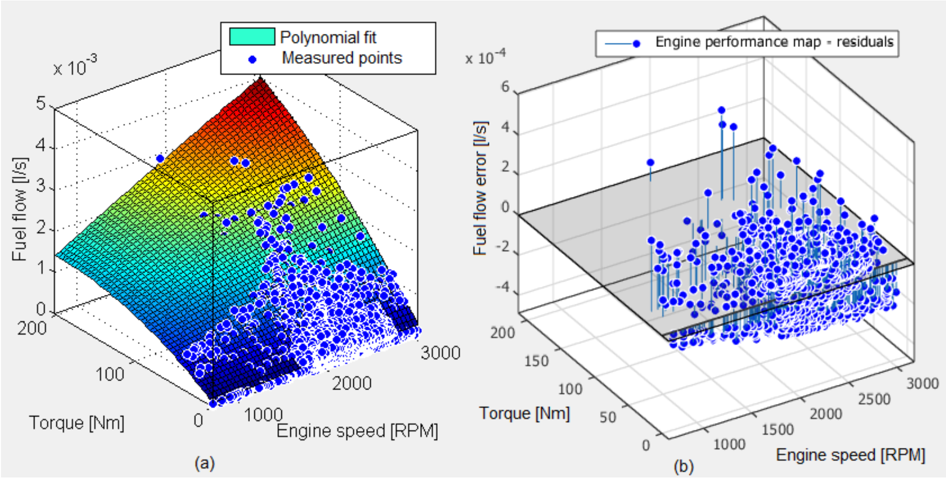

Figure 7. Engine performance map obtained from reference test (a) and the fuel flow error between polynomial surface and measured points (b).

The error, presented in Fig. 7 (b), have order of magnitude 10 times smaller than the order of the fuel flow. According to test results, the correlation coefficient (R^2) is 0.96, confirming that the second order polynomial surface represents the absolute majority of the measured points.

The performance map obtained in reference test is used to estimate the fuel consumption on the validation test. The engine operating conditions measured during the validation test are applied on Eq. (14), which relates fuel consumption and the engine operating conditions. The result is presented on Fig. 8.

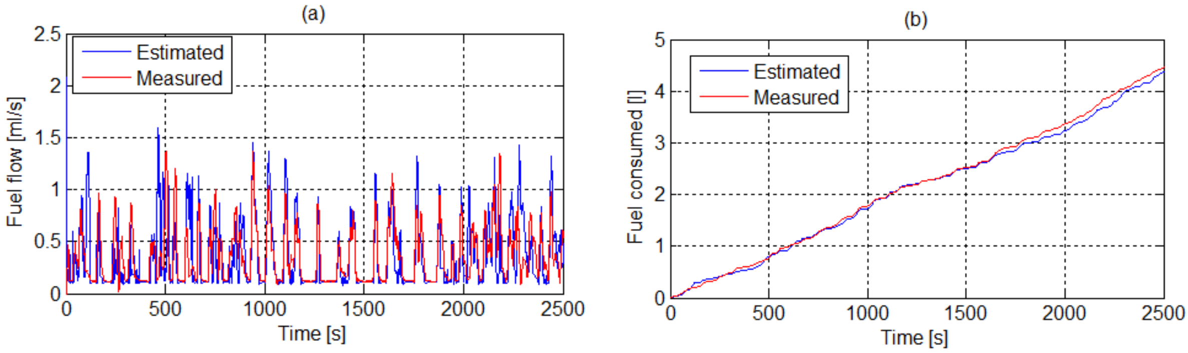

Figure 8. Comparison for the validation test between estimated and measured data for: fuel flow (a) and fuel consumed (b)

Comparing the estimated and the measured fuel flow [Fig. 8 (a)], punctual differences can be seen. These differences are expected, since the model is not accounting for engine calibration strategy, such as fuel enrichment, torque fluctuations, However, these punctual effects tends to have little influence on cumulative fuel consumption [Fig. 8 (b)], suggesting that the effect of the total power required to move the vehicle superimposes other effects. The relative difference between estimated fuel consumed and measured fuel consumed is presented on Fig. (9).

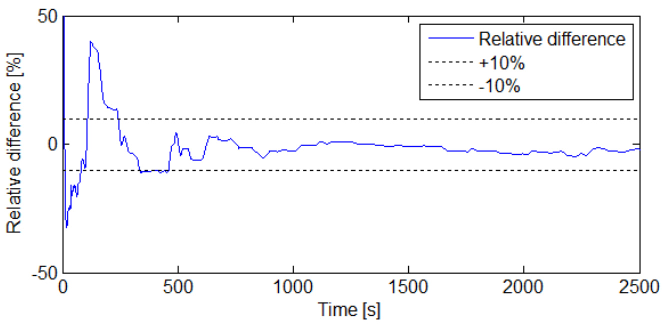

Figure 9. Relative difference between estimated fuel consumed and measured fuel consumed

The relative difference observed between measured and estimated fuel consumed is close to 0%, much better than 10% range considered acceptable, proving the methodology efficient on measuring the engine performance map. It is important to notice that this work is based only on GPS and OBD-II signals. The results can be further improved if more precise measurement techniques are employed to acquire longitudinal acceleration, engine torque and oxygen sensor (in order to determine if air-to-fuel ratio is stoichiometric).

4. CONCLUSION

This work presents a methodology to measure the fuel consumption performance map of an internal combustion engine using on-board acquisition, through the estimation of required engine torque based on vehicle characteristics and instantaneous speed and acceleration levels. The fuel consumption is modeled as a second order polynomial, with engine speed and engine torque as independent variables. The coefficient of correlation (R^2) between the polynomial regression and the measured points is 0.96, and the fuel consumption estimated using this methodology differs from the measured fuel consumption in less than 10%. This methodology is particularly useful in the following situations: when there is little information available about the studied vehicle; when it is not possible to remove the engine of the vehicle; and to identify most efficient engine operating conditions.

Further works could refine the results obtained through the presented methodology by: adding more input data, such as transmission efficiency as a function of engine speed and engine torque; employing more precise measurement techniques for engine torque, acceleration and oxygen sensor; and the application of a more sophisticated resistive force model.

5. ACKNOWLEDGEMENTS

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