Consumption calculation of vehicles using OBD data

Adriano Alessandrini*, Francesco Filippi*, Fernando Ortenzi *

*CTL, Centre For Transport and Logistics, University of Rome “La Sapienza”

Abstract

The European type approval procedure, based on a fixed driving cycle for all vehicles, is not representative of their real on-road usage: the driving style and its influence on consumption and emissions cannot be neglected and their real-world environmental impact is not simple to measure.

The objective of this work is to develop a methodology to calculate in real-time the energy and environmental impact of spark ignition and diesel vehicles.

An on-board instrumentation capable to communicate with the electronic system of the vehicle (OBD/CAN) have been developed to collect all the sensor data available (rpm, vehicle speed, engine load, lambda sensor voltage, catalyst temperature, intake airflow, pressure and temperature etc.) and use them as input for power and consumption models.

The models have been applied on several vehicles and validated on a dynamometer chassis running NEDC and ARTEMIS cycles. Consumption has been measured with the CVS and with a portable emission analyzer (HORIBA OBS-1300).

A calibration procedure has been also developed in which 3 tests on a dynamometer chassis are needed: the maximum power curve, the curve at idle and a curve at fixed rpm varying the engine load. For spark ignition engines, an additional test should be needed to calibrate a coefficient that takes into account of the enrichment during accelerator pedal gradients, but this coefficient is not much variable for different vehicles (~10).

All the vehicles show a difference between measurements and models never greater than 4% so this can be an accurate methodology to calculate the power and consumption of vehicles during their real use.

Keywords: Instantaneous Vehicle Consumption, Engine Power, OBD, On-Board Data Collection.

1. Introduction

Although the recent technological improvements in engine, fuel and after-treatment devices, road transport is still responsible for air pollution in urban area due to increasing number of circulating vehicles and their relative travelled distances. The actual European type approval procedure for passenger cars and light-duty vehicles fixes standard limits for exhaust pollutants to be respected during the execution of a normalized driving cycle.

This kind of procedure is not representative of the real on-road use of vehicles, characterized by a more dynamic speed profile: a fixed driving cycle, equal for all the vehicles penalizes low power-weight ratio vehicles that see the driving cycle more hard to execute than vehicles with higher ratios and does not take account for the driving style; the influence of driving style to the emissions in driving the same vehicle is not negligible [1,2].

In the last years, a lot of on-board pollutant measurements at the exhaust of vehicles was carried out in order to assess the real emission and consumption behavior: the high costs of portable emissions analyzers (PEMS), their continuous maintenance and calibrations, the fragility of the components and the weight and the encumbrance do not allows big acquisition campaigns.

Another method is to calculate the on-road emissions using then on-board vehicle speed collected as input data [3,4] and calculate emissions using database could be an approach but speed (instantaneous or averaged) does not take into account of the real engine conditions.

In previous works [5,6] a tool to collect in real time the engine and vehicle parameters from OBD connector while has been developed and, in conjunction with an exhaust analyzer (Horiba OBS 1300, named OBS in this paper), a set of power, consumption and emission models have been developed for vehicles equipped with spark ignition engines. Such tool, has the advantages to be compact (the volume and weight of an automotive pc), cheap (the order of 1.000 €) and does not requires maintenance as the emission analyzers; it can be installed on a vehicle and it can communicate with a data server to upload all the data collected and no maintenance is needed.

In the present work a generalized method, using the data collected from OBD, to calculate the consumption and power for both spark ignition and diesel vehicles is reported.

The paper is organized as follows:

- a first part in which the onboard instrumentation is reported together with the improvements respect to that described in [3];
- a second part describes the models to calculate consumption and power for the vehicles tested;
- a calibration procedure then is reported to calculate the coefficients required by the models;
- in the section 6 a comparison between models and experimental data has been reported. The measurements have been made on a dynamometer chassis with CVS (Constant Volume Sampler) running NEDC and ARTEMIS driving cycles or with OBS system.

In the last part of the paper are reported the conclusions.

2. Onboard acquisition tool

All the European vehicles equipped with a lambda sensor, so all the vehicles from 1993 have an electronic system to control the fuel injection and then a diagnostic system to read sensor data and to store trouble codes.

In Europe, starting from 2001 (in USA from 1996) with the Euro III standard, all the vehicles have also to supply in a standardized way, from a standardized connector, a common set of engine parameters so it could be possible to connect to all the vehicles with a unique OBD interface and with a unique communication protocol (OBD).

In the present work, a tool to connect to the OBD connector has been developed and all the engine parameters have been collected. The tool is based on an automotive pc with a OBD/CAN interface, a GPS receiver, a Wi-Fi interface and a UMTS modem to transfer the data to a database located on a server.

The parameters, collected, with high frequencies (2-5 Hz) are: vehicle speed, air/fuel ratio, the intake airflow, rpm, engine load, accelerator pedal position, lambda sensor voltage, catalyst temperature, Close/Open Loop information, absolute load (volumetric efficiency), intake air pressure, EGR and ignition advance. There are also some other parameters, with slow temporal variation, collected every 30 seconds: the intake air temperature, the coolant temperature, the ambient temperature and pressure, the tank fuel level and the battery voltage.

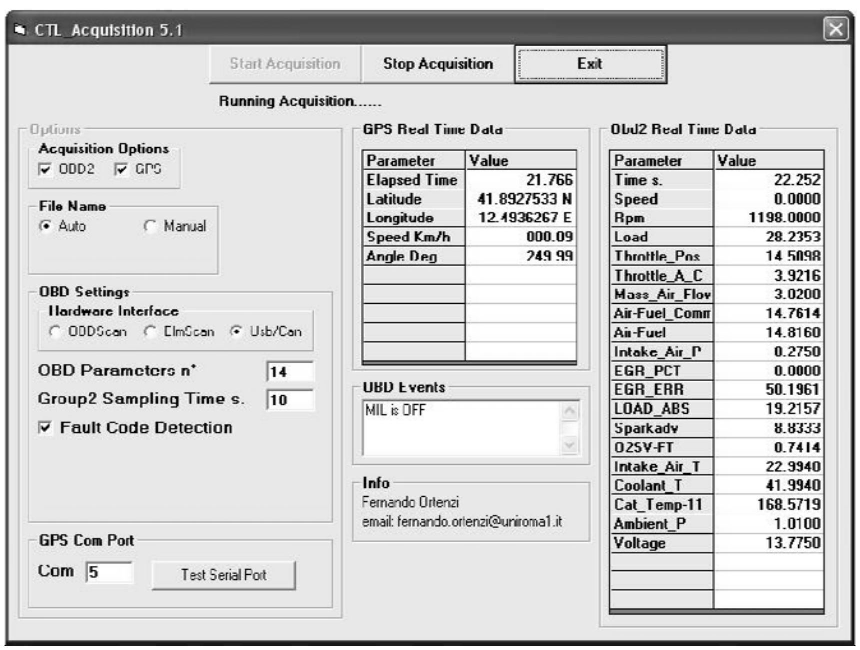

Fig. 1 Screenshot of the acquisition software to collect the engine parameters from the OBD connector of the vehicle.

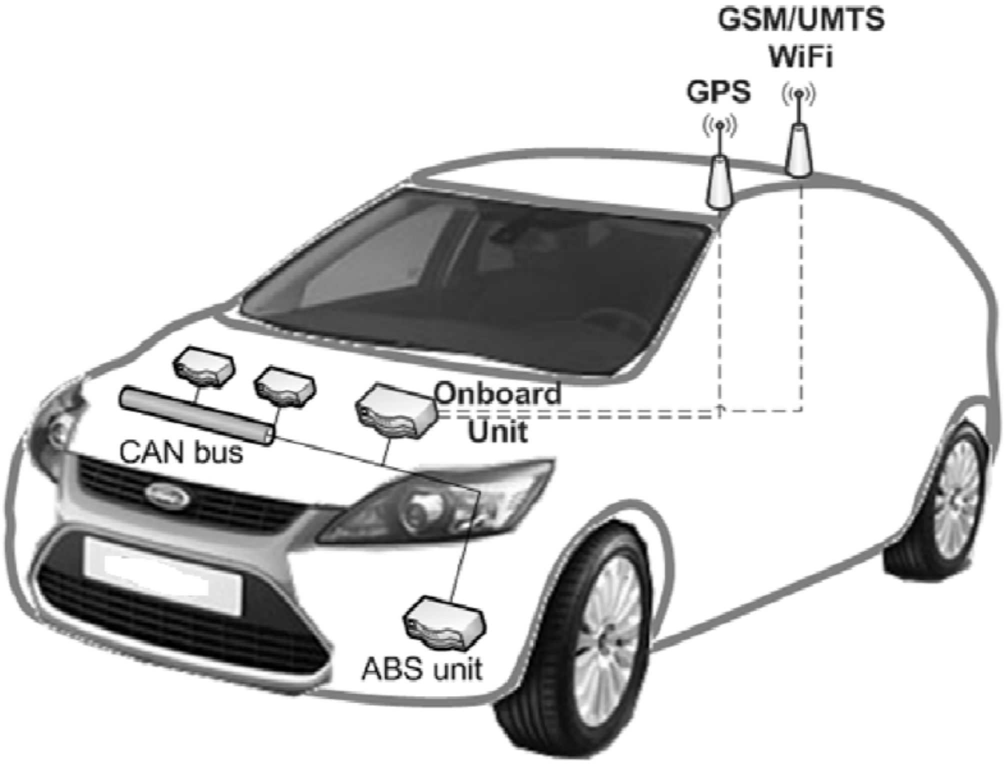

Fig. 2 The On Board instrumentation

A parameter from OBD that requires a more detailed description is the Calculated Load Value %. During the years this parameter changed definition: from SAE J1979 [2] (2010 revision) there are two definitions:

$$Engine\_Load = \frac{Current\_AirFlow}{Max\_Airflow(Rpm)\cdot\frac{Baro}{29.92}\cdot\sqrt{\frac{298}{T_{amb}+273}}}$$

Equation 1.

A newer definition is made:

$$Engine\_Load = \frac{Current\_Torque}{Max\_Torque(Rpm)\cdot\frac{Baro}{29.92}\cdot\sqrt{\frac{298}{T_{amb}+273}}}$$

Equation 2

The properties of engine load are [7]:

- Reaches 1 at full open throttle for any altitude, temperature and pressure or rpm for both naturally aspirated and boosted engines;
- Indicated percent of peak available torque;
- Linearly correlated with engine vacuum;
- Often used to schedule power enrichment.

- Compression ignition engines (Diesels) shall support this parameter using fuel flow in place of airflow.

There is not a unique common definition of this parameter that all car manufacturer adopt, but its characteristics are much important for the present work and each vehicle has been tested on a dynamometer chassis to check if the linearity between engine load and airflow or power are valid.

The characteristics of this parameter have been used to calculate the instantaneous engine consumption and power: if there is linearity between load% and torque then it's possible to know the instantaneous power supplied by the engine simply by knowing two values for each rpm. If there is linearity between engine Load and airflow the same method used for power can be used.

3. Consumption calculation

Consumption can be evaluated from OBD data directly from a parameter (PID) of SAEJ1979 standard [7] (or using a non-standard car manufacturer parameter) or if not available, from intake airflow sensor and air/fuel ratio sensor.

Vehicles that from OBD port supply directly the instantaneous consumption are not frequent, but also those that supply both intake airflow AFR are rare.

In the present section the methods to calculate the intake airflow and the AFR are reported and discussed.

3.1. Airflow

To calculate the fuel consumption of vehicles, the intake airflow value is needed: the intake airflow sensors are usually found in diesel vehicles and in some spark ignition vehicles.

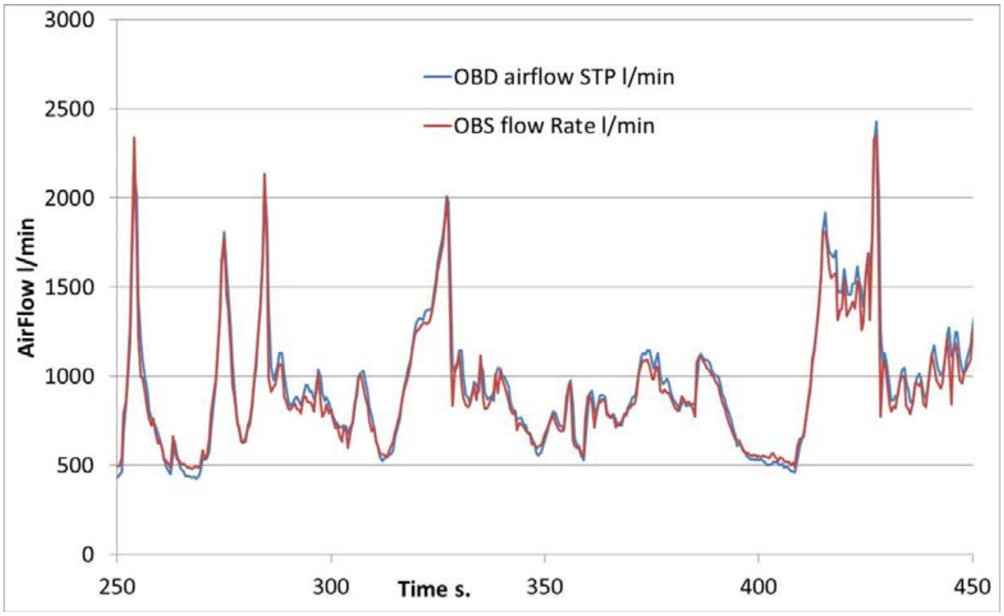

Figure 1 Intake airflow sensor of a Citroen C3 1.4 HDi (Diesel engine) compared with Horiba OBS 1300 exhaust flow sensor.

The values from those sensors have been compared with those measured by Horiba OBS 1300 as in Figure 1 for a Citroen C3 1.4 HDi.

The graph shows good accordance between OBD collected data and OBS measured for all the ranges.

If the airflow sensor is not installed onboard, it can be calculated creating a 3D map with input data rpm and engine load. This map need to test the engine in all the ranges of use: for all the rpm and all the loads.

To avoid that amount of experimental tests a further hypothesis is done: the linear correlation, for each rpm, between airflow and engine load. In this way, for each rpm only two points are needed and all the other values can be calculated using interpolation. The points used in the present work are those at WOT (Wide Open throttle) and at idle so for all the other values of engine load, the airflow have been calculated with interpolation.

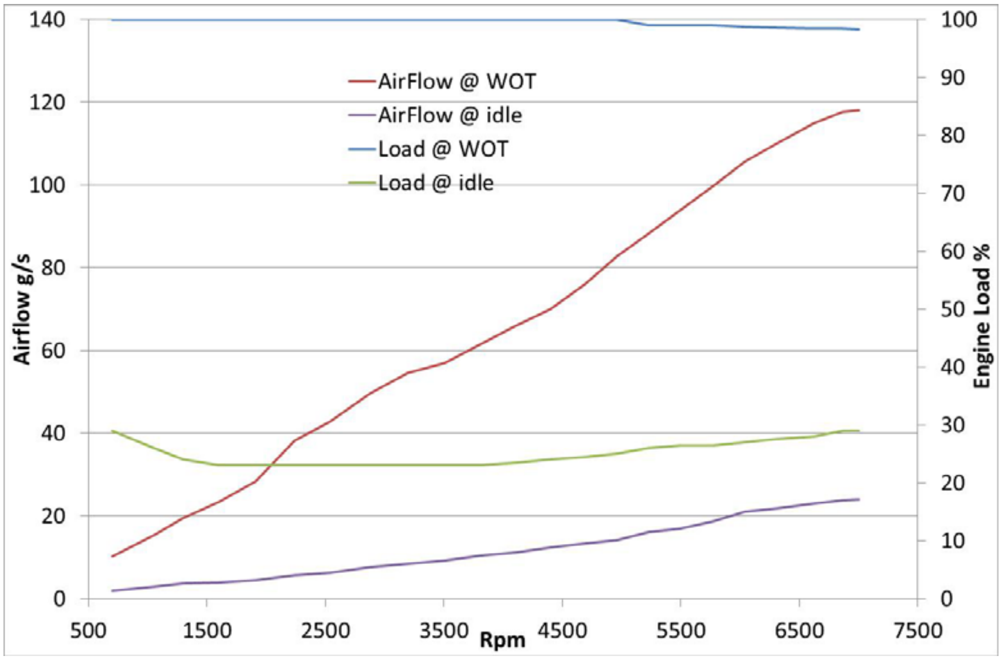

Figure 2 Airflow curves at idle and WOT (Wide Open Throttle) for a Honda Civic 2.0 (Spark ignition engine)

To calculate the airflow using only these curves the following method is used:

first of all, for a given Rpm and engine load value, the WOT and the idle values at that rpm are calculated (for example with linear interpolation between the nearest rpm values), then with linear interpolation the airflow is calculated as follow:

$$AirFlow_{actual} = AirFlow_{idle} + \frac{AirFlow_{WOT} - AirFlow_{idle}}{Load_{WOT} - Load_{idle}} \cdot \left(Load_{actual} - Load_{idle}\right) \qquad \text{Equation 3.}$$

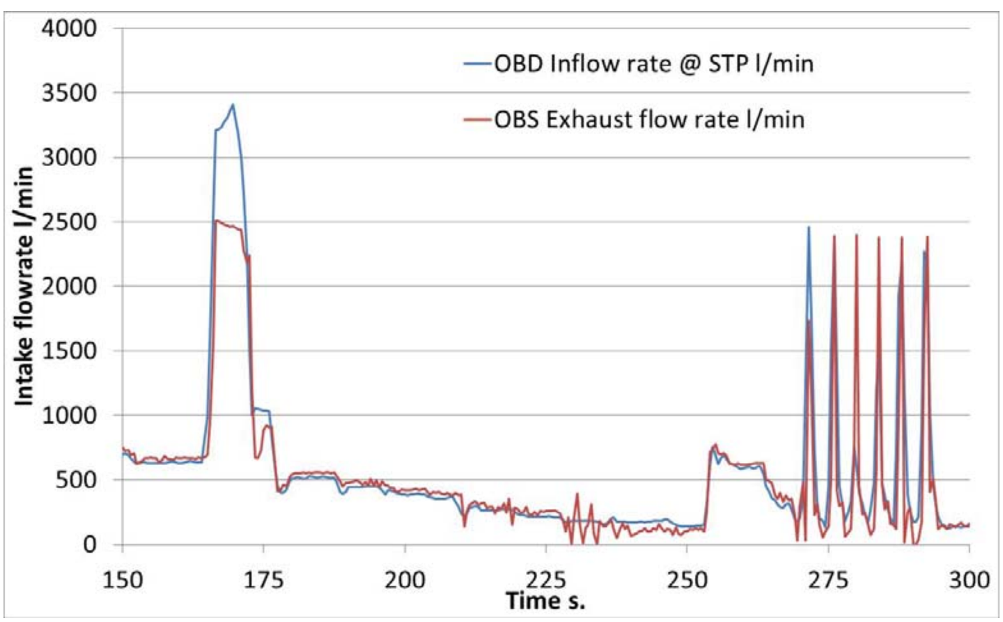

Figure 3 Calculated intake flow rate and measured by OBS on a Honda Civic 2.0

The results of such model, compared with the exhaust sensor of the Horiba OBS 1300 are reported in Figure 3: there is a good accordance between the two set of data, with the exception of the seconds 160-175 where the is a WOT condition and the flow rate exceed the end scale value of the OBS sensor (3000 l/min @ STP) so the difference is due to the inaccuracy of the OBS instrumentation. The other difference is that with lower flow rates the OBS shows some oscillations due to its inaccuracy.

3.2. Lambda for Spark ignition vehicles

If there is a Wide-Band O2 Sensor installed on-board, the λ value is available directly from the OBD acquisition tool: in Figure 4 are reported the values of λ commanded from ECU, λ measured from the on-board O_2 Sensor (read from the OBD instrumentation) and the measured value form HORIBA OBS 1300. The graph shows that the λ commanded (imposed by ECU) and that measured by exhaust Lambda sensor have, in partial loads (seconds 200 to 250) oscillations around the stoichiometric values, while between 250-250 seconds there is a full load condition. In seconds between 270 and 280 a cut off phase is recognized (λ more than 2, that is the end scale value from OBD instrumentation). These values are according to those measured by Horiba OBS, also reported in the graph: the oscillation around the stoichiometric values are smoothed because the OBS sensor has been installed at the end of the exhaust manifold and the gas transport process tends to smooth the signal. Also the cut off phase, for the same reason shows a difference between the λ values available from OBD instrumentation: however in cut off condition the airflow is null so the differences in mass are negligible.

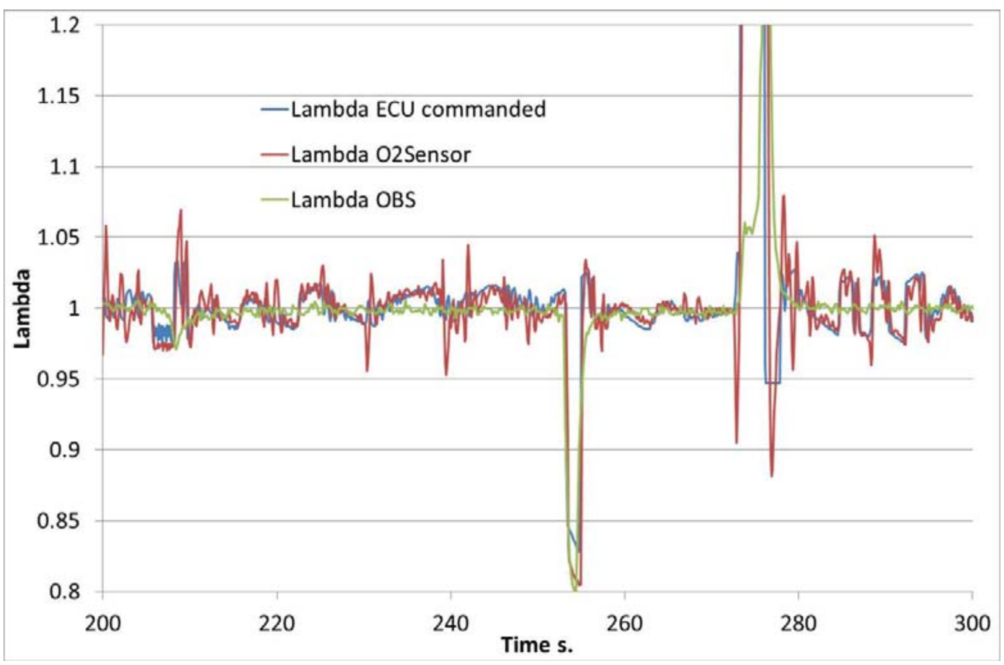

Figure 4 Lambda Commanded , measured from 02Sensor and measured from OBS on a Honda Civic hybrid running Artemis Motorway driving cycle.

If the λ value is missing, it can be calculated dividing the engine behavior in three phases and calculate it for each phase: full load, partial loads and cut off.

When the engine run in full load condition, to reach the maximum power, the mixture is rich and the engine ECU does not take into account for the exhaust lambda sensor information (Open Loop condition).

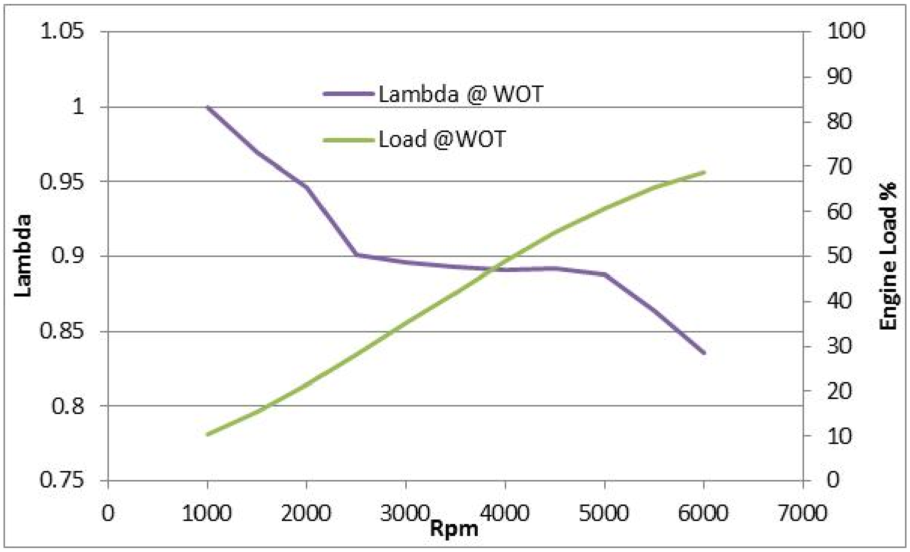

Figure 5 Curve for λ and engine load % at WOT for a Fiat 500 1.2.

The fuel to inject in these conditions is mapped into the engine ECU maps and can be calculated for the present work as function of Rpm (Figure 5).

Table 1 Summary of equation used to calculate λ for spark Ignition vehicles

Engine condition	λ Value
Full Load	$\lambda = \lambda(Rpm)$
Partial Loads	$\lambda = 1 - \min\left(0.1, \max\left(0, \frac{\Delta Pedal}{\Delta t} \cdot Cost\right)\right)$
Cut off	$\lambda = \lambda_{\max}$

At partial loads, the engine run in Close Loop condition so the air/fuel ratio is stoichiometric. The only exception is during the accelerator pedal gradients in which there is a fuel enrichment. The third case is the cut off in which there is not injection of fuel. The summary of the equations used to calculate λ are reported inTable 1.

3.3. Lambda for Diesel vehicles

The calculation of the λ value for Diesel vehicles is quite different than above explained for Spark Ignition engines: the fuel is injected within the combustion chamber and the its amount is the main parameter to control the power of the engine.

Two methods have been analyzed: the first is to correlate the air/fuel ratio (measured with Horiba OBS 1300) with the engine load as reported in Figure 6: the vehicle is a Citroen C31.4 HDi and in the test executed is a number of steady tests made on a dynamometer chassis. All these points are made at different rpm and different engine loads and a good correlation is found with only last parameter.

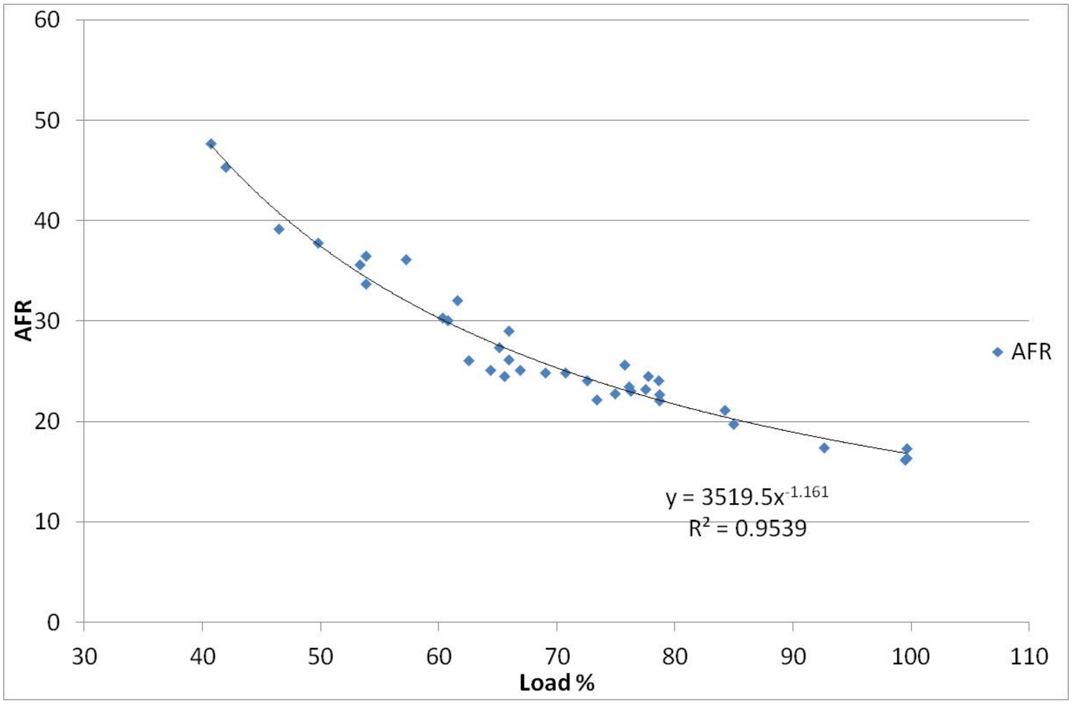

Figure 6 Correlation between Air/fuel ratio and engine load % for a Citroen C3 1.4 HDi

The second method is to correlate the fuel injection with another parameter: the product between airflow and engine load.

The Figure 7 reports the result of the same test executed for the Citroen C3: steady test at fifixed rpm and engine Load. for tree different vehicles: a Fiat Punto 1.3 Multijet, a Fiat Bravo 1.6 Multijet and a Ford Focus..

A linear correlation with higher correlation index than the previous method can be observed and the second method will be used for the consumption calculation.

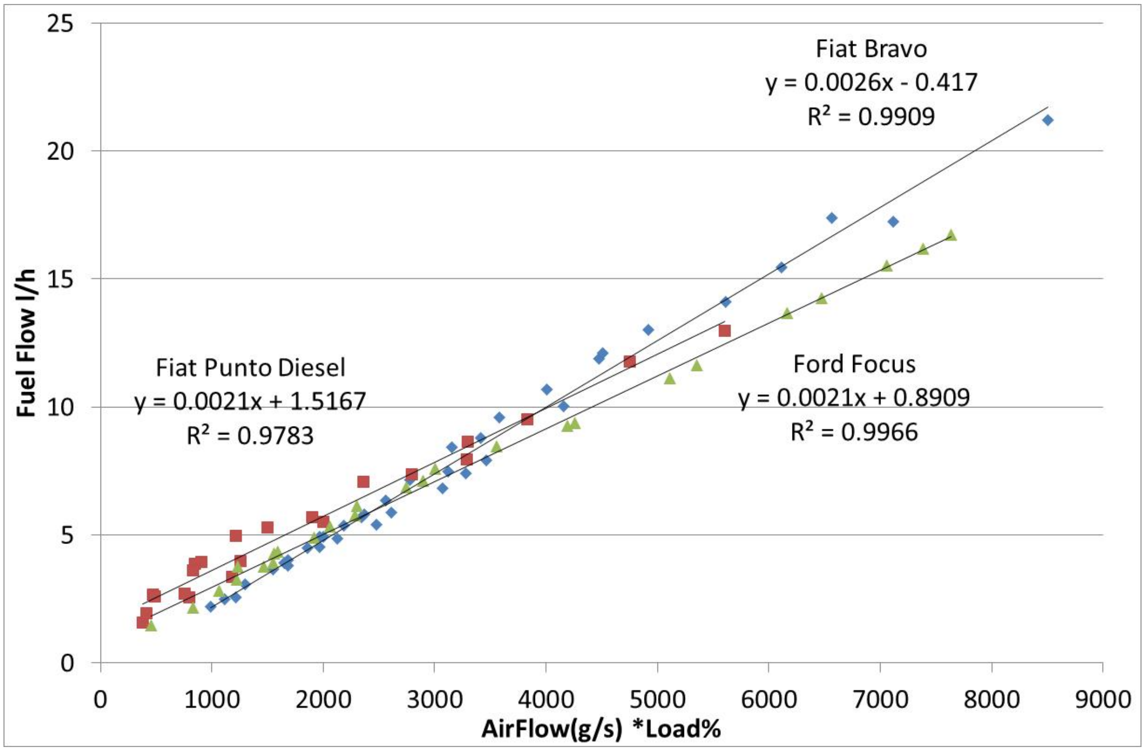

Figure 7 Correlation between fuel flow and the product between airflow and engine load for the Fiat Punto Diesel, Fiat Bravo diesel and Ford Focus.

The equation to be used is in the following form:

$$FuelFlow\left(\frac{l}{h}\right) = a \cdot \left(Airflow \cdot Load\right) + b$$

Equation 4

Where

a,b: calibration coefficient directly found on the Figure 7

taking also account for the cut-off condition (FuelFlow=0) which can be identified when the accelerator pedal=0 and Rpm >1200.

Other vehicles have been tested for other car manufacturers and all show the same correlations.

4. Power

The instantaneous power supplied by the engine is an important parameter to characterize the energy impact of the vehicles during their real on-road usage. The calculation of such parameter for spark ignition vehicles using the available data from OBD technology have been discussed in [2] and in the present work an analogue work have been done for diesel vehicles.

The method used is to correlate the engine power with rpm and Engine Load and, to avoid the complete drawing of the power map, to find a correlation between engine load and power with fixed rpm. Only two curves of power are then required: one at WOT and the other at idle.

As reported in [7] the linearity between load and power is one of the properties of the Calculated engine Load and this linearity have been discussed and validated.

The tests have been made on a dynamometer chassis and the power have been recorded in order to use it for the calculations.

The first vehicle analysed is the Citroen C3 reported in Figure 7: a correlation index between Engine Load and Power of about 0.999 for 3 different rpm have been observed. With the knowledge of the maximum and minimum value of power for each rpm, it is possible to calculate the instantaneous power for each condition using the engine load value.

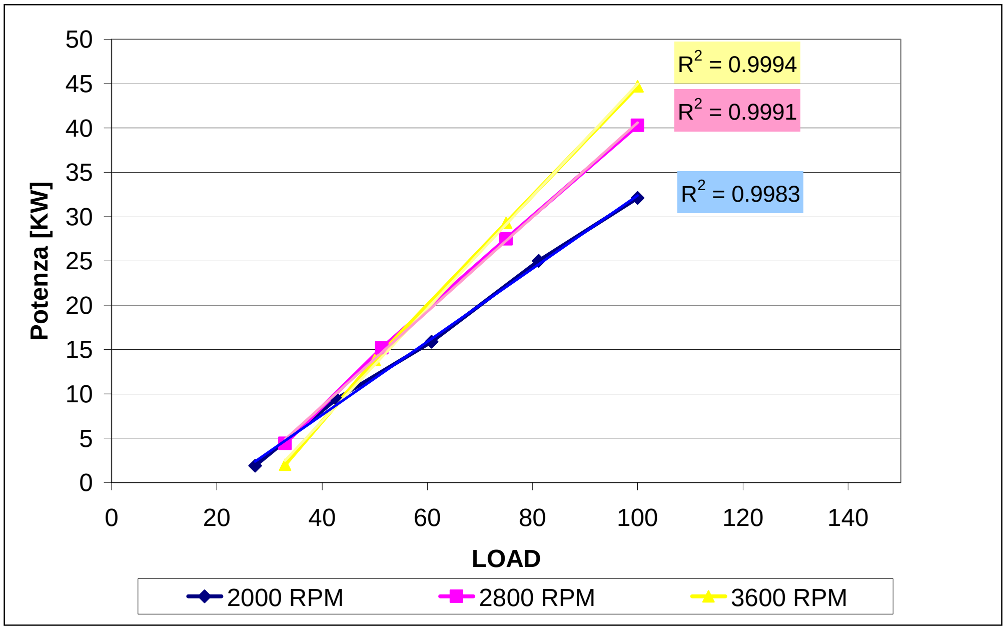

Figure 8 Correlation between Load and Power measured for 3 different rpm on a Citroen C3 1.4 HDi

Every car manufacturer, adopting each engine electronic and control strategy, have different sensors on-board and different meaning of the engine load value; another method to calculate the power, for some vehicle such Fiat Bravo and Ford Focus, show good correlation between power and the product between intake airflow and engine load instead of engine load only.

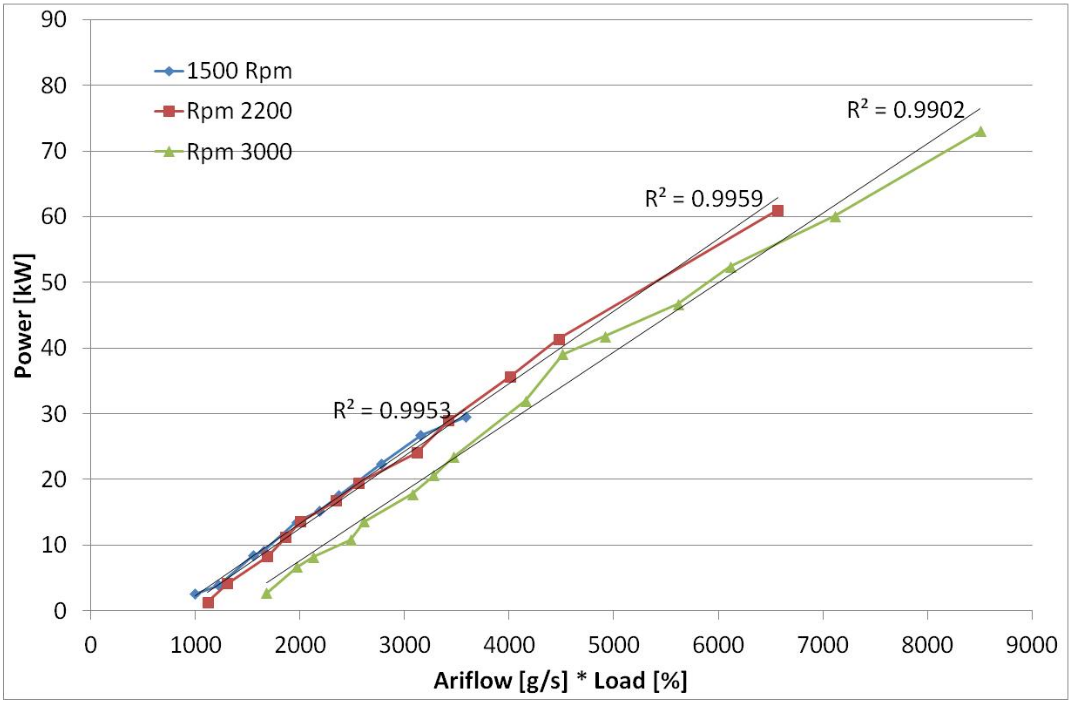

Figure 9 Correlation between power and product of intake airflow and engine load for a fiat Bravo 1.6 Diesel Multijet

In Figure 9 the results of a Fiat Bravo are showed and the correlation indexes are always greater than 0.99: for these kind of vehicles this method has been used.

5. Calibration procedure

For those vehicles that have directly the power and fuel consumption from the OBD data, the calibration procedure is not required; these vehicles are a minimum part of the present market (hybrids for example) so for the all other cars this procedure is fundamental.

In order to calibrate the models to calculate the power and the consumption of vehicles, a set of tests are needed. The instrumentation required to make the tests are a dynamometer chassis and an instrumentation to measure the consumption: in the present work the first was a braked dynamometer and the HORIBA OBS 1300 analyzer to measure the consumption.

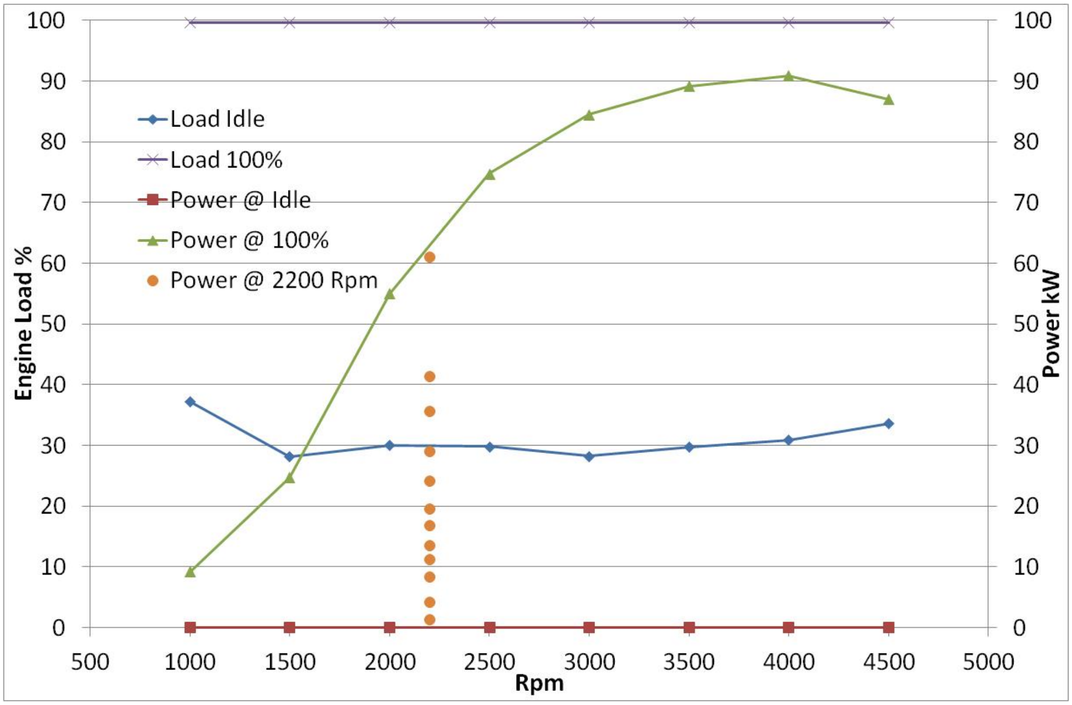

Figure 10 Calibration test made on a Fiat Bravo 1.6 diesel Multijet

In Figure 10 is reported a summary of the minimum set needed to calibrate all the models on a Fiat Bravo 1.6 Diesel: to calculate the power the maximum and minimum power curve are needed and its associated engine load curve. When the engine is running at its maximum power, the engine load value could be not 100% and this fact is dependent on which meaning of engine load is stored in the Engine Control Module, so it is important to store also this parameter. The second curve required is a test at idle: the engine, with the gear in neutral position is set in steady condition from the minimum idle to the maximum rpm.

The third test, is at fixed rpm. In Figure 10 the engine rpm is fixed at 2200 and the engine load goes from the minimum value to the maximum: also this test is executed in steady condition and the power, airflow, air/fuel ratio and engine load are recorded.

With these data, depending the engine type (spark ignition or diesel) the fuel-flow or air/fuel ratio curve can be built.

For spark ignition vehicles an additional test is required in order to calibrate a coefficient at partial loads (“Cost” in Table 1) that improves the accuracy during accelerator pedal transients.

However this values is about 10 and does not influences much the consumption accuracy: it is more important when the emissions have to be calculated. The CO is produced when the mixture is rich and this condition can be found during pedal transients.

6. Results

Once the models have been calibrated, a set of experimental tests have been done to compare the results with those measured on a dynamometer chassis.

Several vehicles have been tested on different driving cycles on a dynamometer chassis: NEDC and Artemis cycles have been run and the consumption has been measured with the CVS on standard driving cycles (NEDC or ARTEMIS driving cycles) or with the HORIBA OBS 1300.

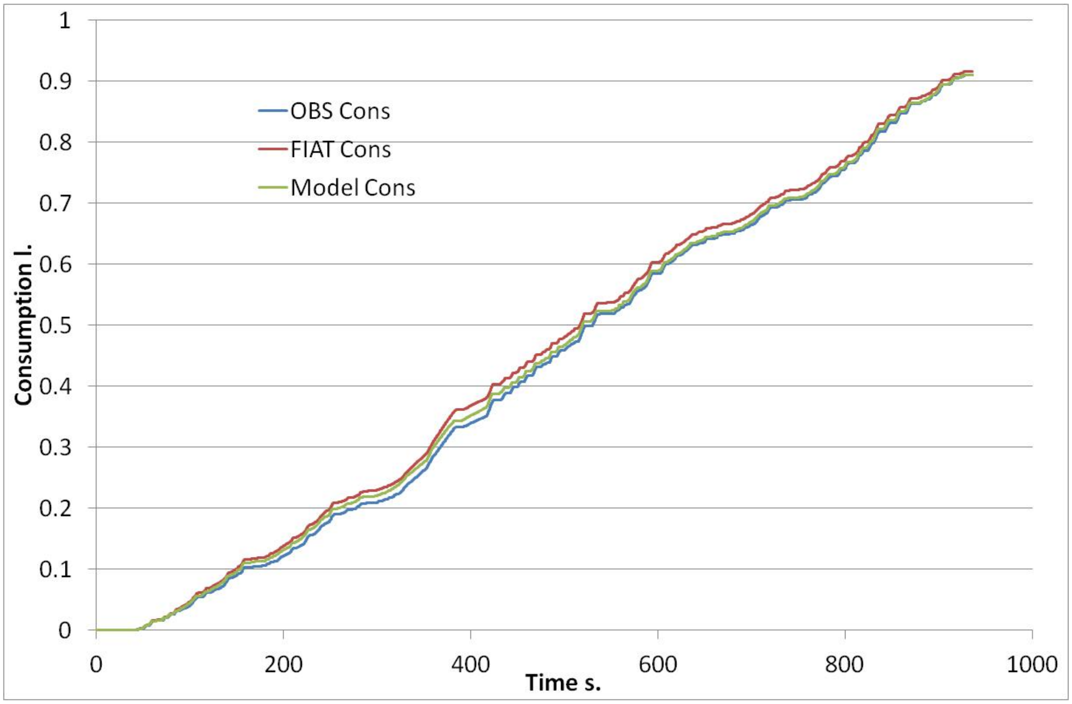

Figure 11 Fiat Punto Diesel: Consumption measured by HORIBA OBS 1300 compared with that collected with Fiat parameter and calculate by model

In Figure 11 is reported the consumption of the Fiat Punto diesel measured with the HORIBA OBS 1300 and compared with the consumption value from Fiat protocol and with the model developed and calibrated. The driving cycle had a duration about 940 second and the consumption of about 0.9 liters, have been calculated very well from the model and also the value collected from Fiat Protocol is accurate. The value from Fiat protocol does not need calibration so it is preferable when available, but it is a nonstandard parameter and it is not available however newer vehicles compatible with the SAE J1979 standard rev. 2010[7] shall have it.

In the Table 2 there are the results of 4 diesel vehicles tested: the sensors used to calculate consumption, the measurement system and the error % between model and measurement are reported.

Table 2 Diesel vehicles tested and results obtained compared with measured values

Vehicle	Sensors used	Meas. System	Error %
Fiat Punto Diesel Multijet 1.3 (Diesel)	Fiat Prot.	OBS	0.71
Fiat Punto Diesel Multijet 1.3)	AirFlow	OBS	0.06
Fiat 500 Diesel Multijet 1.3 (Diesel)	Fiat Prot	CVS	3.184
		AMA	3.07
Ford Focus 1.6	Airflow	OBS	3.25
Fiat Bravo	Airflow	OBS	2.93

The Fiat Punto Diesel consumption have been calculated using 2 methods: one collecting the value from Fiat protocol and the other using airflow sensor and a model to calculate the air/fuel ratio. The errors with the measurements are very low and less than 1%.

A second vehicle, a Fiat 500 diesel 1.3 Multijet have been tested on dynamometer equipped with CVS system (from Istituto Motori, Naples – Italy) and the results compared with the CVS (constant volume sampler) and also the instantaneous values from the analyzed installed on the Tunnel. The driving cycles run were a combination of 5 NEDC cycles and the 3 Artemis driving cycles. Both the measurements show an error of about 3%.

The last two vehicles, the ford focus and the fiat Bravo have been tested on a dynamometer chassis with the HORIBA OBS 1300 installed and the difference between the models and the measurement are also about the 3%.

The results for spark ignition vehicles are reported in Table 3: 3 vehicles have been tested, an Alfa Romeo 147 1.6, a Honda Civic Hybrid and a Fiat 500 1.2. The first two vehicles have been tested with a CVS system (from Istituto Motori, Naples – Italy) and the last on a dynamometer using the HORIBA OBS 1300 analyzer. Each vehicle had a different number of sensor on-board and the models used has been different. The Alfa Romeo 147 vehicle, had the intake airflow sensor so the air/fuel ratio has been calculated by model. That vehicle run 3 NEDC cycles and the 3 Artemis cycles: the average error with the CVS is about 3.8%.

Table 3 Spark ignition vehicles tested and results obtained compared with measured values

	Sensors used	Measurement System	Error %
Alfa Romeo 147 1.6	Airflow	CVS	3.8
Honda Civic Hybrid	Airflow AFR	CVS	4.00
Fiat 500 1.2	Fiat Prot	OBS	2.37

The Honda Hybrid, more technologically advanced, had many more sensors on-board and between them the airflow sensor and also the Air/fuel ratio sensors were available. No models had to be calibrated and consumption was directly available. the vehicle has been tested using the CVS on 5 NEDC cycles and 3 Artemis Cycles and the error between CVS and values collected by the OBD was about 4%. The last vehicle, the fiat 500, has been tested with the OBS and the difference between measured values and the collected from Fiat protocol are about 2.37%.

7. Conclusions

The instantaneous power supplied by the engine and the consumption can be calculated using the sensors that vehicles themselves have installed onboard.

In the present work, an instrumentation able to communicate with the electronic system of vehicles (OBD/CAN) [5,6,7] has been used to collect sensors data from spark ignition and diesel vehicles, and models to calculate power and consumption have been developed. To calculate the consumption if there is not the specific parameter from OBD that supplies directly that value, intake airflow and air/fuel ratio are needed. If both values are not available models have been developed to calculate them.

Intake Airflow is a function of rpm and engine load so a three-dimensional map is needed to evaluate it, but using the linearity property between load and airflow at fixed rpm, only two point for each rpm are needed. Two curves in function of rpm can be built and all the values can be calculated with linear interpolation.

The intake air/fuel ratio for spark ignition vehicle is stoichiometric at partial loads and is a function of rpm at WOT (wide open throttle) with an enrichment during accelerator pedal transients. Diesel vehicles show that fuel consumption is a function of the product of intake airflow with engine load.

The engine power is calculated using the same procedure for airflow.

A calibration procedure has been also developed in which 3 tests on a dynamometer chassis are needed: the maximum power curve, the curve at idle, and a curve at fixed rpm varying the engine load. For spark ignition engines an additional test should be needed to calibrate a coefficients that takes into account of the enrichment during accelerator pedal gradients, but this coefficient is not much variable for different vehicles(~10).

All the vehicles show a difference between measurements and models never greater than 4% so this methodology can be an accurate methodology to calculate the power and consumption of vehicles during their real use.

As future developments, the emissions models can be developed both for spark ignition and diesel vehicles together with a calibration procedure for different kind of vehicles and different electronics on-board.

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