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OBD-II sensor diagnostics for monitoring vehicle operation and consumption

Dimitrios Rimpas[a], Andreas Papadakis[b,*], Maria Samarakou[a]

[a] Department of Informatics and Computer Engineering, University of West Attica, Agiou Spyridonos, Egaleo, 12243, Greece
[b] Department of Electrical and Electronics Engineering Educators, School of Pedagogical and Technological Education, Athens, 14122, Greece

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Abstract

Road vehicles operations are continuously monitored through physical parameters (temperature, air flow, rotation rate); such measurements are retrieved by electronic sensors and communicated, over the internal vehicle communications protocol, towards the Main Control Unit for further processing. In this paper we present our selection of parameters for monitoring key vehicle operations and briefly describe the sensors employed for the retrieval of these parameter values. The values are retrieved through the OBD-II diagnostics protocol and they are related with the vehicle operation and with the fuel consumption. As proof of concept, focused experimentation has taken place, through a 5 km trip with low and heavy traffic. Values retrieved from the OBD-II scanner are presented and discussed. In terms of evaluation, the raw values as well as the calculated measurements related to fuel consumption are compared with manufacturer standards and the user driving behaviour has been identified as the key factor influencing the fuel consumption for a given model.

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Keywords: Vehicle; Sensors; OBD-II; CANBus; Control; Values; Fuel consumption

1. Introduction

Road vehicles are going through constant evolution, since the first automobile was put to mass-production in 1913 by Ford, radically changing their operational philosophy and principles. These include the improvements in combustion efficiency, the aerodynamics and the multiplication of electronics systems collaborating with each other and the central unit.

Road Vehicle, as a complex ecosystem, consists of multiple sub-processes, responsible for the smooth operations of the vehicle. Each module is monitored and controlled with the usage of one or more sensors which inform and collaborate with the Main Control Unit (MCU). The micro-controllers (supporting the sensors) communicate with the MCU and with each other using typical bus-based communications standards such as CANBus (Controller Area Network). CANBus is a message-based protocol, allowing priorities in transmission, designed for multiplex

* Corresponding author.
E-mail address: apapadakis@aspete.gr (A. Papadakis).

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electrical wiring [1]. The system offers information to the end user (the driver) after processing the values retrieved by the sensors, visualized by the vehicle monitoring modules either offering directly the values (temperature, speed, rotation) or providing a consolidated engine status (smooth operation, malfunctioning). The driver can retrieve the processed values without further information on the way they are retrieved, how they are processed and without the possibility of connecting with metrics such as the consumption of the engine during driving. In this view the overall system is typically considered a black box with limited hooks of monitoring possibilities.

1.1. Our objectives

In our work we have attempted to directly retrieve values from vehicle microcontroller in vivo (i.e. during vehicle operation), using the OBD-II (on Board Diagnostics version 2) protocol. As discussed, vehicle electronic units communicate with each other through a network (CANBus or similar) for monitoring and data transfer (errors, value adjustments). OBD is a diagnostic and reporting capability of a vehicle allowing the vehicle operator or technician to access the status of the engine subsystems. Vehicles typically provide an external port which allows the mechanic to retrieve values and read errors and identify the source of the error code. The access to the monitored values is achieved through OBD scanners.

In this context, we have selected a set of key parameters, briefly discuss the operation of the sensors that are responsible for monitoring them and, using the OBD-II protocol, we have retrieved them in real time. In addition, they have been used to estimate the instantaneous fuel consumption. During pilot experimentation, we have verified the values (comparing them with the manufacturer ones for a specific vehicle) and identified the relation between the driving style (conservative–aggressive) and the consumption.

1.2. Structure of the paper

The rest of the document consists of two main sections: the methodology and the experimentation along with the results. The methodology section includes background information as per the related work as well as the types of parameters to be monitored are selected for monitoring and the related sensors. The Experimentation section describes the retrieval of measurements that have been performed and their transformation from raw values to meaningful information providing a set of diagrams. In this Section we process the results in order to estimate the consumption of the vehicle under different driving conditions. This section includes the discussion on the results. The paper closes with the conclusions.

2. Methodology

2.1. Related work

Monitoring the operations taking place in the vehicle engine has long attracted researchers who have been interested in effectively monitoring, understanding and even improving their usage. Gilman presented a driving assistant system called Driving Coach which monitors certain parameters to help increase fuel efficiency depending on the driving style [2]. Szalay et al. modelled two different scanning methods (CANBus and FMS CANBus) which allowed third party access and found that the measurements were almost identical [3].

Kushiro et al. logged OBD-monitored data and transmitted them to a telematics centre via mobile network. This data is used for a prognostics model (in python), as built on correlations among fault codes (cautions/warnings from sensors in the vehicle), to prevent potential components breakdown [4]. Sik compared OBD and CAN sampling on the go with the Sensor HUB Framework and using GPS made a prediction model helping drivers with recommendations for their route (avoid traffic jams, find empty parking space) [5]. D'Agostino used OBD data to create a model for the upgrade of a conventional vehicle to hybrid. Thus, through operation in pure electric mode or hybrid mode (depending on which gear is engaged), the kit can help achieve 18%–22% save in fuel and CO_2 emissions [6]. While the interest in remote monitoring and control is being increased, we expect that will be gradually used to support innovative services sharing the values in real time in cloud facilities for more effective monitoring, logging and pattern extraction [7].

In our work we have employed the established methods and protocols and 3rd party (off-the-shelf) tools to extract the values of sensor parameters through the CAN (Controlled Area Network) using the OBD-II diagnostics protocol.

In parallel we have proceeded further with the verification of the values and their processing for the calculation of more complex parameters. In the past our research team has investigated in the part innovative methods for harvesting energy to potentially support auxiliary vehicle modules [8].

2.2. Selection of monitored parameters

A key decision of our research work has been the selection of the parameters to be monitored. A rich portfolio of parameters can be monitored during the operation of the vehicle engine. Our selection has been based on the importance of these parameters as related to their association with key composite parameters (including consumption), the consequences of their possible malfunctioning and the feasibility of their retrieving through the CANBus and subsequent translation into the OBD-II protocol. In the following, the parameters selected for retrieval are presented along with justifications for their selection.

The *proportion of oxygen in the exhaust gases* as measured by the Lambda Sensor. Lambda (λ) sensor retrieves the stoichiometric Air–fuel ratio (14.7:1 for gasoline engines with the ideal value for the combustion being 1). The signal is sent to the ECU (Electronic Control Unit). The air–fuel ratio is affecting performance and horsepower, the emissions (Nitrogen Oxides, Carbon Monoxide) and the consumption. The application of correct ratio prevents engine pinging and knocking, while it supports the lifetime of the catalytic converter.

The *adjustment of the fuel quantity* as measured by the Short-Term Fuel Trim (STFT) sensor. As the driver presses the accelerator pedal, the airflow intake in the engine is changed. The fuel injection is then controlled by the ECU. Sensors are used to measure airflow and then send the correct pulse to the central unit, to match the airflow by adjusting (add or reduce) the fuel quantity and keep the stoichiometric ratio. This adjustment is called Fuel Trim. Short Term Fuel Trim (STFT) is related to the immediate changes in fuel flow occurring several times per second, while Long Term Fuel Trim (LTFT) includes the average changes over time.

The *air flow* as measured by the Mass Air Flow Sensor (MAF). MAF measures the air flow rate in the engine and it is installed between the air filter and the intake manifold. There are two types of MAF sensors: the hot wire sensor, where the wire is electrically heated. When the intake air runs through, it gets colder and a small current is needed to keep it hot. This current is proportional to the air flow and it is sent as a pulse to the ECU. Cold wire sensor, which has the same principle as the hot wire but with the addition of a cold wire measuring ambient air as a reference point. Then the temperatures of the two wires can be compared. A malfunctioning MAF sensor can cause issues at the engine unit such as: Running rich at idle, low fuel efficiency, stalling and uneven idle.

The *vehicle speed* as measured by the Vehicle Speed Sensor (VSS). The VSS is responsible for speed calculation and it is usually mounted at gearbox's output shaft. The speed is typically measured using a Hall effect sensor, which uses a reference voltage from the PCM (Powertrain Control Module) to produce a DC voltage to the ECU. The vehicle speed is a key parameter as perceived by the driver and it will be attempted to be associated with the consumption.

The *temperature of the engine coolant* as measured by the Engine Coolant Temperature Sensor (ECT). The PCM recognizes this signal and activates other components (such as the engine's cooling fan to maintain proper operating temperature). The PCM uses different strategies programmed into its lookup tables for hot and cold operating conditions. This signal affects EGR (Exhaust Gas Recirculation) valve flow, enriches fuel mixtures, and delays torque converter or A/C compressor engagement. Excessive resistance in the connector or anywhere in this circuit can alter the signal to the PCM, increasing injector pulse width and advancing the engine's ignition timing. When the engine reaches operating temperature the coolant sensor gives way to the lambda sensor. The coolant temperature affects the engine overheating, influencing its lifetime, as well as the fuel consumption.

2.3. Access to parameter values

The sensors are operating in an independent manner and regularly collect values, at discrete intervals depending on their nature. These values are transferred within the vehicle electronics system using the CANBus protocol. CAN (International Standardization Organization, ISO 11898-1 standard) is a communications serial bus typically used for the automobile industry in order to replace the complex wiring strap with a simple two-wire system standard. It is highly immune to electrical interference and it allows for priorities among the communicating entities.

In order to retrieve the exchanged values, the On-Board Diagnostics (OBD) system is used (version II). Road vehicles (starting from 1996) are required to be equipped with the OBD-II system, which is accessed through the Data Link Connector (DLC). DLC is the 16-pin connector that allows access to the underlying protocol that each vehicle uses for module communications.

In principle the OBD-II system uses 2 types of codes:

1. Diagnostic Trouble Code (DTC): Each code is used to describe an issue, for example Pxxxx is a powertrain code error and Cxxxx a chassis error. Each code can be unique or manufacturer specific.
2. Parameter ID (PID): Codes used to require data from the ECU, like RPM in idle speed.

The selected parameters along with their OBD-II IDs are depicted in Table 1.

Table 1. Parameters selected for measurement and OBD-II IDs.

A/A	OBD-II ID	Parameter
1	0 × 05	Engine coolant temperature
2	0 × 06	Short term fuel trim
3	0 × 0C	Engine RPM
4	0 × 0D	Vehicle speed
5	0 × 10	Air flow rate
6	0 × 34	O2 lambda equivalent

The values are retrieved through the OBD-II port (16 pin connector) using the OBD-II scanner which allows access to the continuous flow of information.

3. Experimentation and results

In our experimentation, we have decided to retrieve values in vivo, during vehicle movement. The Elm 327 Mini Bluetooth scanner and ScanMaster software by ELM Electronics have been selected.[1] The scanner is connected to the vehicle OBD-II platform, it retrieves the values of the parameters and communicates through Bluetooth with a laptop. Values have been retrieved while driving a route of 5 km residential road with 2.5 km of a double-lane high road (with overtaking allowed) and 2.5 km of one-lane road with traffic lights and medium traffic. Ambient temperature was 17 °C at 4 pm and the whole project lasted 11 min or 660 s.

During the experimentation, we retrieved speed and RPM measurements and they were compared with those presented to the driver in the speedometer and tachometer (since both dashboard and the OBD-II monitor the same values) as a first validation of the system.

The average speed of the car was 20 km/h. The engine load varied from 14.5% (idle) to 88.8% which is referred to the moment the car is at medium to high RPM at uphill and maximum torque is required. S.T.F.T reached values from −9% to 7%, so fuel injection from the ECU was stable overall. The average Lambda value was 1.030 and the oxygen sensor is working properly. Fuel flow with 0 km/h speed (idle or accelerating) has an average amount of 0.44 l/h while for other conditions, consumption is in average 1.36 l/h. Fuel flow mass rate range: 0.094 g/s for idle to 1.32 g/s at max load (inclined road). More fuel was consumed at lower speeds. In the following a set of results is presented and discussed, related to the values that have been retrieved.

3.1. Short fuel trims — lambda value

As depicted in Fig. 1, short fuel trim is constantly changing; this can follow a change in the value of air flow (as represented by the lambda sensor). When the driver accelerates thus air flow increases, ECU reads the lambda sensor value and adjusts fuel injection. When STFT = 0%, the car is cruising with no acceleration.

[1] https://www.elmelectronics.com/products/ics/obd/.

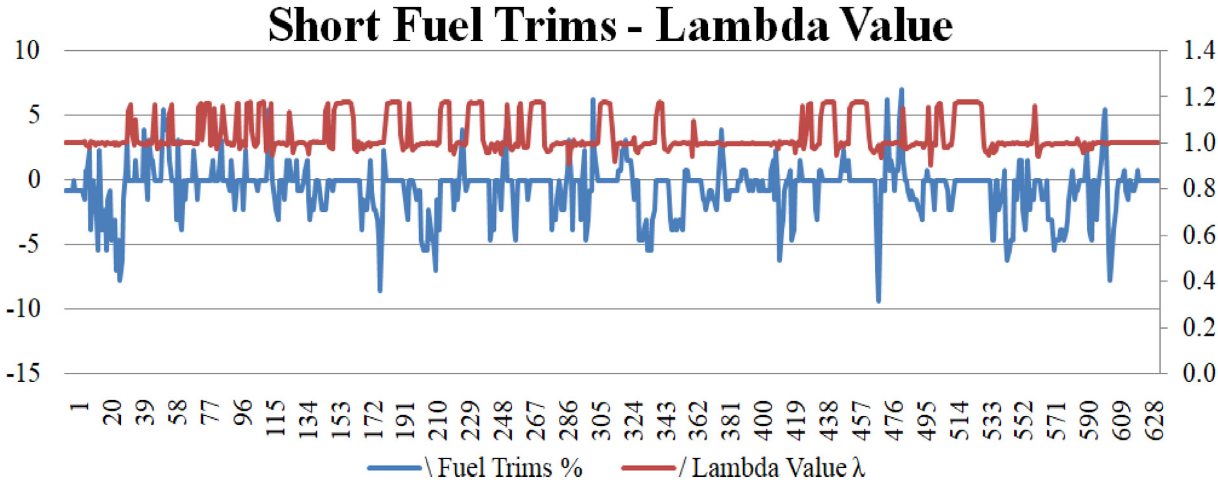

Fig. 1. Short load fuel trim versus lambda values. The Left Axis represents the fuel trim percentage (Blue one) while the right one is the lambda value (Red) at each measurement. The ECU responds adjusting fuel depending on lambda output. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Fuel mass flow rate — load

Load is an important factor for the vehicle operation. When the car is not accelerating, engine loading comes from forces are acting against the motion of the engine. Internal friction (pistons, crankshaft, transmission), external friction (tyres on road surface), drag, gravity (when going uphill). "Load" means how much power is required from the engine for the car to have some speed and acceleration. When a vehicle is cruising on the highway, it only needs a small percentage of its total available power output to maintain speed. We calculate the load based upon the following formula:

$$Engine\_Load = \frac{Current\_Airflow}{Max\_Airflow\,(Rpm)\,x\,\frac{Baro}{29.92}x\sqrt{\frac{298}{T_{amb}+273}}} \tag{1}$$

In the load calculation formula, Current_AirFlow is the MAF output in g/s, Max_Airflow in Rpm, Baro is the barometric Pressure found by the MAP sensor and its changes are considered unsignificant. *Tamb* is the ambient Temperature which is stable. At cruising both MAF and MAP sensors outputs were zero. As depicted in Fig. 2, fuel mass flow peak is at no. 505 while engine load peak is reached 3 times (num. 55, 91, 480). That leads to the observation that load is the main factor that determines fuel flow – thus consumption – but driving style (aggressive or balanced) is also important.

While the car is cruising (that means going over 2200–2500 RPM with gear on but not accelerating, e.g. at measurements 153–172), the wheels have been *driving the engine* and almost no fuel was used so efficiency is maximized.

3.3. Vehicle speed — fuel consumption

As depicted in Fig. 3, the vehicle speed (per se) is associated with the fuel consumption; in fact fuel consumption changes when the vehicle speed increases (during acceleration), meaning that it is mainly affected by ineffective driving and traffic. For example, random starts and stops, present massive fuel consumption whereas normal driving without aggressive acceleration–deceleration provides solid gas consumption. Low consumption has appeared also at top speeds. Again, at idle status fuel consumption is cut-off.

3.4. Fuel efficiency — lambda value

Fig. 4 depicts the role of lambda value on engine-fuel efficiencies. High to maximum fuel efficiencies (up to 56 km/l or 1.78 l/100 km) are achieved at lean fuel mixture — high lambda values. On the opposite when lambda

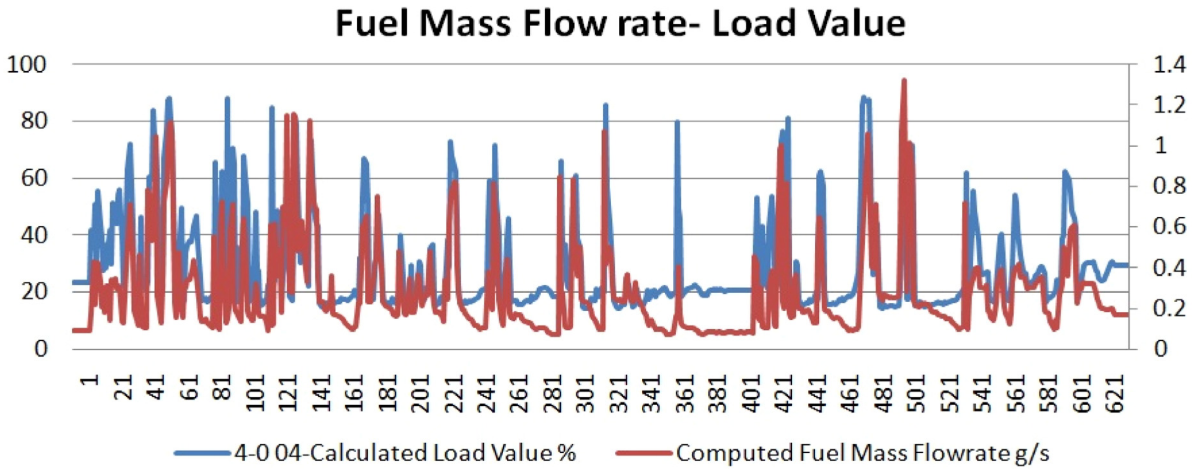

Fig. 2. Fuel mass flow rate versus load. Left axis describes load value while the right one stands for Fuel Mass Flow rate.

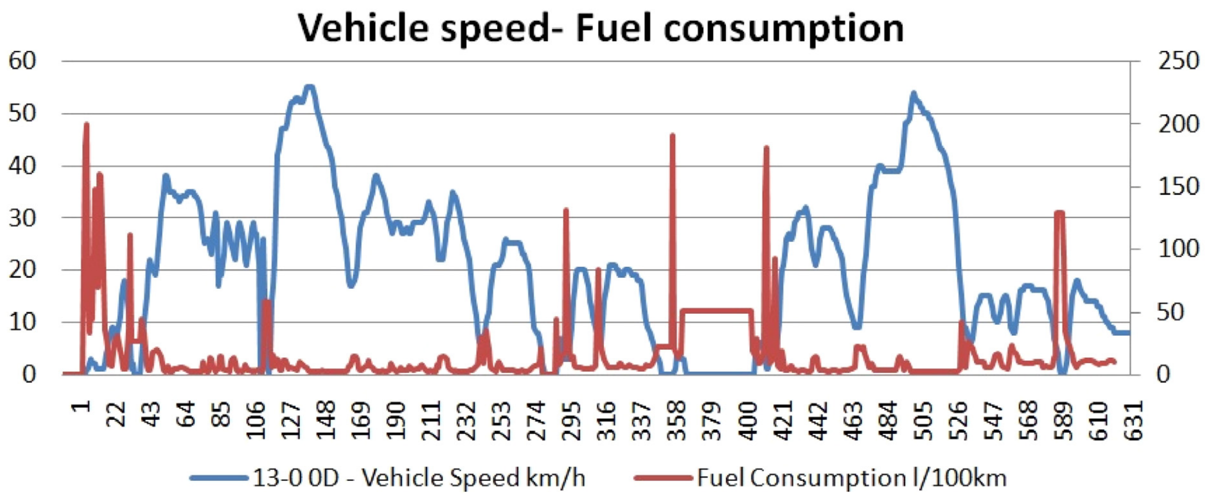

Fig. 3. Vehicle speed versus fuel consumption. Left axis presents vehicle speed and right one is the fuel consumption in litres per 100 km. The high values at consumption typically precede the increase in speed.

reaches very low values, thus the fuel mix is enriched, fuel efficiency drops down to 0.99 km/l - that is almost 100 l/100 km. At lambda close to one ($\lambda \approx 1$) efficiency goes to factory standard values (4.4 l/100 km mixed cycle). Idle status is cut off.

As presented in measurements (e.g. at num. 153–172), while car is cruising going over 2200–2500 RPM with gear on but not accelerating, the wheels were *driving the engine*, almost no fuel was used and efficiency's been maximized.

3.5. Calculation of consumption

In order to estimate the consumption of the vehicle, we have considered the approach presented at [9,10]. The objective is to have a consumption estimation in litres per 100 km of distance. The fuel consumption is calculated dividing the Air Mass (grams per second as retrieved by the MAF sensor) with the value of the lambda sensor (λ lambda value as retrieved from the system) and the AFR stoichiometric ratio (14.7) [11]. Then the fuel grams

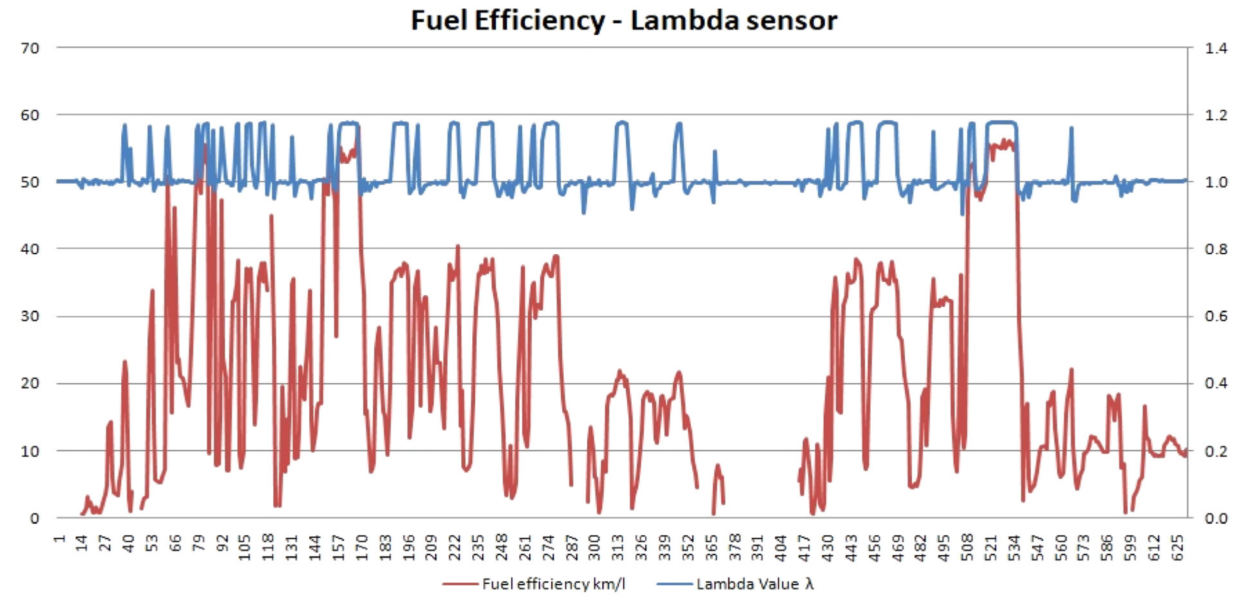

Fig. 4. Fuel efficiency versus lambda. Left axis presents fuel efficiency and right one is the lambda equivalent.

are calculated and converted to litres. We consider that Mass equals Density multiplied by Volume (m = ρ * V), so volume = mass/density and the energy density is 770 g/l. In order to calculate the consumption (in volume) per distance, we convert the consumption to 100 km, dividing the distance by the litres used to get the km/l and converting the km/l to L/100 km i.e. dividing 100 by km per litre. The vehicle's fuel consumption was calculated to be 4.67 l/100 km. The specifications report for the manufacturer supported fuel consumption is depicted in Fig. 5 [12].

By engaging data from the excel sheet this formula concludes (see Table 2).

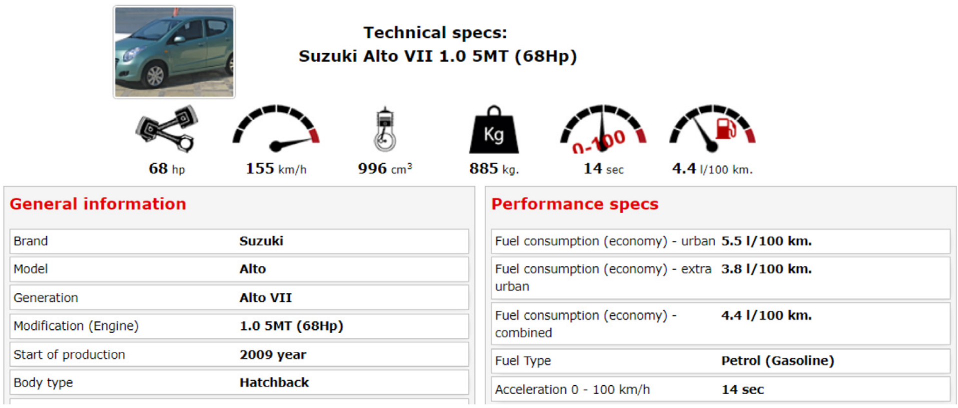

Fig. 5. Manufacturer specifications.

Table 2. Fuel consumption comparison using stoichiometric and real lambda at specific distance covered.

	Total grams	Energy density	Total litres	Distance	km/l	l/100 km
Ideal lambda	182.15 g	770 g/l	0.2366	5 km	21.13	4.73
Real lambda	179.82 g	770 g/l	0.2335	5 km	21.41	4.67

3.6. Consumption calculations

The following equations were used to calculate certain parameters:

$$Fuel_{(grams)} = \frac{Air\ Mass_{(grams)}}{\lambda \times AFR_{(stoich)}} \tag{2}$$

where:

∋ λ is the lambda value computed by the Obd Scanner
∋ $AFR_{(stoich)}$ is the stoichiometric ratio (14.7)
∋ Air Mass in g/s by MAF Sensor

According to Meseguer et al. [11], to calculate the fuel flow, the following equation is used:

$$Fuel\ Flow = \frac{Fuel\left(\frac{\mathrm{g}}{\mathrm{s}}\right) \times 360\ \mathrm{s}}{\rho} \tag{3}$$

Where ρ is the gasoline's density and according to AA motoring, 770 g/l was chosen as an approach.

To calculate fuel consumption at l/100 km:

$$Fuel\,consumption_{\left(\frac{\mathrm{l}}{100\ \mathrm{km}}\right)} = \frac{Fuel\ Flow}{Vehicle\ Speed} \times 100 \tag{4}$$

4. Discussion

4.1. Verification of results

At this experiment using the specific engine and car model, the average consumption with the ideal lambda was 4.73 [l/100 km] while with the measured lambda it was 4.67 [l/100 km]. So on average, the records are accurate even without the measured lambda value. These estimations can be further altered, dependent on how the vehicle is treated in respect to maintenance. Also preservative and efficient driving behaviour is critical to the task of maximizing the driving experience and protecting the environment. In our experimentation, the vehicle was driven both at highway and traffic streets with the mixed cycle value of 4.4 l/100 km.

5. Conclusions

In this work we selected and retrieved values for key parameters related to road vehicle operation. In terms of the equipment and tools used, the work has proceeded seamlessly verifying collaboration of the underlying vehicle platform with the OBD-II reader and software. This was further confirmed during parameter (speed and load) retrieving in vivo and verifying with the vehicle instruments, as available for the driver.

During our experimentation, we have retrieved the specified parameters and analysed them. The results have been consistent and the diagnostic protocol as well as the hardware and software equipment worked as expected. Composite parameters have been calculated, including the load and the fuel consumption.

Fuel consumption calculations have been aligned with the expected manufacturer values. It has been verified that driving behaviour affects the consumption, as random starts and stops present massive fuel consumption whereas normal driving without aggressive acceleration–deceleration provides solid gas consumption. Aggressive driving style causing inconsistent changes at engine load is the main factor leading to consumption increase. Low consumption appeared at top speeds where normally high fuel usage is expected. It has also been experimentally identified that vehicles get better fuel economy when cruising at highway speeds.

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