RESEARCH ON LOW-EMISSION VEHICLE POWERED BY LPG USING INNOVATIVE HARDWARE AND SOFTWARE

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Abstract

LPG is a cheap and ecological fuel for spark ignition engines. The sequential gas injection system can be installed at the factory and is then the Original Equipment of the Manufacturer. A vehicle with a spark ignition engine can also be converted to gas in an authorized workshop. In both cases, the vehicle must meet the same exhaust emission standards when running on alternative fuel as it does with the original fuel. Conversion of vehicles to LPG and CNG is regulated by law at the European Union level. The article describes the conversion of a low-emission gasoline vehicle that meets the Euro 6 emission standard to LPG. The configuration and calibration of the LPG system is described in detail. The compatibility of the gas system with the vehicle's on-board diagnostic system was then checked. Finally, road tests of the vehicle were carried out to compare the performance with the original fuel and the alternative fuel.

Keywords: hardware; software; on-board diagnostics; alternative fuels; LPG; on-road testing

1. Introduction

The availability of adequate amount of conventional fossil fuel for internal combustion engines and the associated effects of global warming and other environmental problems arising from the burning of fossil fuels are the two most serious problems of our civilization today [3]. The most realistic scenario to reduce air pollution from outdated vehicles is the use of fuels that do not require any changes to the engine systems [39]. The use of alternative fuels is one of the main solutions allowing the reduction of pollutant emissions nowadays [7]. The growing awareness of fossil fuel depletion leads to an intensive search for renewable fuels [11, 27, 51]. According to [10] and [58] the main areas of fuel development are the following areas: improvement of oil refining technology, search for new additives and use of alternative fuels. A very important group are fuels of biological origin, so-called biofuels [3, 14, 54]. Another aspect of improving the ecological properties of vehicles is the replacement of vehicles with internal combustion engines with electric vehicles. More information on electro mobility can be found in the

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following publications [15, 26, 45]. However, the replacement process is very complex and multi-faceted.

In connection with the VW gate scandal, the European Commission and independent governments of member states have paid particular attention to the nuisance of diesel vehicles. The emission of regulated and unregulated toxic exhaust components from these engines is high especially during city driving [12]. In various countries, processes have begun to restrict the entry of diesel vehicles into city centers, as well as bold plans to completely withdraw from the production of diesel-powered passenger cars. In connection with the above steps, both car concerns and scientific units have returned to more intensive development of spark ignition propulsion units [9, 33, 34]. These are gasoline engines as well as engines powered by other alternative fuels burned in an internal combustion engine operating on the basis of the Otto cycle. The newest spark ignition units are very often equipped with direct petrol injection and turbo charging [57]. It turns out that spark ignition engines still have great development potential [42]. Scientists and engineers in automotive concerns focus on reducing CO_2 emissions in the engines being developed [32]. The reduction of CO_2 emissions is possible by reducing fuel consumption. Another regulated component of vehicle exhaust is NOx [24, 31]. Their emission depends on the proper combustion of the fuel in the engine and the efficiency of the catalytic converter.

Another important attribute is the ease of their supply at the factory level or subsequent conversion to alternative fuel supply [49]. European and Polish law allow both of these possibilities [38]. The ecology and economy of a vehicle powered by a spark ignition engine depends on many factors, to which we can, among others include:

- chassis and vehicle body structure affecting the curb weight and aerodynamic drag that affect fuel consumption,
- efficiency of an internal combustion engine, depending on the design solutions and control of main engine processes and systems,
- the type of fuel used, taking into account its price and ecological properties, i.e. emissions of individual exhaust components regulated in Euro standards and CO2 emissions,
- the design of the propulsion system taking into account hybrid solutions that can show better performance and lower exhaust emissions than individual propulsion sources.

For many years, LPG has been extremely popular in Poland, Europe and selected countries around the world. Initially, the liquefied mixture of propane and butane was treated as a side effect of the refining process of crude oil and there were not many applications for it except for supplying domestic gas cookers. Later, however, attention was paid to the obvious qualities of LPG as a fuel. And it was no longer just about its price compared to gasoline [6], but above all about high calorific value and lower CO2 emissions compared to gasoline [37]. This is due to the chemical structure of propane and butane compared to the heavier gasoline-forming hydrocarbons [48].

Numerous scientific papers [4, 5, 46] were devoted to research on fuel consumption, transport costs or choosing the optimal route [29] and transport safety [59]. Dobrowolski et al. [4] presents a statistical analysis of daily kilometrages of vehicles operated by a selected transport company in the period of three consecutive years. Statistical analyses of daily vehicle kilometrages showed statistically significant differences in daily kilometrage across different vehicle categories and in various months throughout the year [4]. Transport costs depend on many factors- purchase price of the vehicle, labor costs of the drivers, costs of maintenance and repairs, fuel costs etc. [5]. The aerodynamic design of the vehicle also makes a significant contribution to reducing fuel consumption [43]. For these reasons uses route optimization methods using graph theory to reduce costs and transport time [2, 5]. Application of the operational research method to determine the optimum transport collection cycle of municipal waste in a predesignated urban area was shown in [46]. Similar studies with the use of heuristically optimizing transport were presented by Misztal [29].

Gaseous fuels can power various types of engines on their own. They are very often additional fuel for diesel engines [28]. In this way, a significant reduction in the exhaust gas components regulated by the Euro standards is achieved [18]. Most often, LPG, CNG and hydrogen are used as additional fuel for diesel [19]. In order to obtain lower fuel consumption and lower exhaust emissions, new fuel mixtures [13] and new methods of combustion are created [16].

Economical and ecological hybrid vehicles can be even more economical and ecological [37]. This can be achieved by feeding the internal combustion engine of the hybrid vehicle with a gaseous fuel, for example LPG. Scientists are considering a range extender for electric vehicles to also run on LPG [25].

In connection with the above problems in the operation of vehicles, the article describes innovative hardware and software for testing low-emission vehicles fueled with LPG. The process of calibration of the LPG system and the use in road tests of applications for mobile devices communicating with the vehicle's OBD are presented in a practical way.

2. Development of LPG vehicle power supply systems in Poland and worldwide

LPG vehicle supply systems began to be popular in Western Europe in the early 1990s. These were especially the first and second generation systems in Italy and the Netherlands. At the end of the 1990s, they appeared in Poland along with the infrastructure quickly refueling them. By then, Western companies had already developed and implemented sequential gas injection systems - so-called fourth generation. They provided very good vehicle performance, but in Poland they were very expensive. The high price of Italian and Dutch sequential gas injection installations has become an impulse for their research and development in Poland [17, 55]. In 2005, the first Polish 4th generation systems appeared and by 2010 they consolidated their position on European and global markets. Their safe operation and low emission values to the atmosphere were confirmed by obtained approvals in accordance with UN/ECE Regulation R115 [38]. The development of gas supply systems must keep pace with the development of internal combustion engines and meet the current Euro emission standards. Research has confirmed that modern low-emission gasoline engines are also able to meet Euro 5 and Euro 6 emissions standards also powered by LPG.

3. Methodology

The research used a low-emission Renault Megane vehicle with a 1.6 SCe engine with a nominal power of 84 kW, having an indirect fuel injection system for the engine intake manifold. The vehicle was manufactured in 2016 and meets Euro 6 exhaust gas standards on gasoline. The vehicle was then converted into LPG in accordance with the requirements of UN/ECE Regulation 115. Pursuant to the said regulations, it was equipped with an additional sequential LPG injection system for the engine intake manifold. Components produced by Polish LPG system manufacturers were used.

In the first year, the vehicle ran 25,000 km on petrol and was converted to LPG. In the next two years it traveled 36,000 km. The data read from the LPG ECU memory shows that during this time 88% of the time the vehicle ran on LPG and 12% on petrol. Based on such data, it is easy to calculate the lower costs of using LPG instead of petrol. The aim of the research was to determine the correct operation of the vehicle engine both with gasoline and LPG.

The appearance of the vehicle itself and the components of the LPG system built into the vehicle are shown in Figures 1 and 2.

Fig. 1. The vehicle on which the road tests were performed

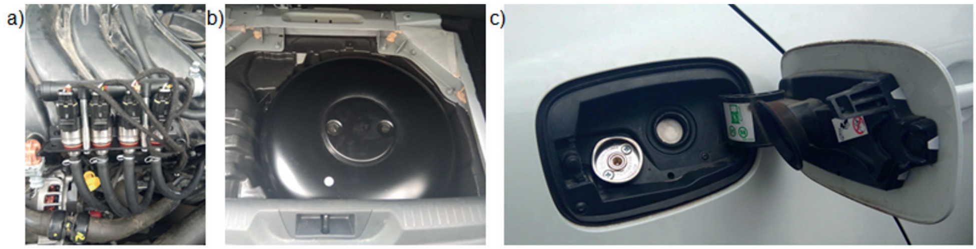

Fig. 2. The LPG system components, a) LPG injectors, b) LPG tank, c) LPG refuelling valve

The conversion was carried out under the supervision of authors with extensive experience in this field. The installed sequential LPG injection system is one of the market leaders in Poland. It is chosen and respected by both assembly workshops and users for the reliability of operation resulting from the high quality of components as well as the sophisticated firmware cooperating with the vehicle's ECU and controlling LPG injection.

4. Hardware and software of the gas supply system

The hardware of the LPG injection control unit is the Electronic Control Unit. It is a multi-layer electronic board made in SMD technology with a number of control inputs and outputs together with a microcontroller. The signals measured by the inputs are used to control the gas injection time in all rotational speed and load conditions of the internal combustion engine. For a specific value of petrol injection time, the gas injection time must be calculated taking into account its temperature and pressure. To this end, complicated control algorithms are used to ensure the safe operation of the gas system. In addition, they must ensure a high culture of engine operation during alternative fuel supply and engine performance (power, acceleration) comparable to gasoline [17]. Another customer requirement is the economics of operation resulting from low fuel consumption [1].

An important element of every installation is the software enabling communication of authorized persons with the gas system ECU. After the physical conversion of a gasoline vehicle to LPG, it requires proper configuration and calibration [50]. It is necessary to download the relevant software from the manufacturer's website and install it on a portable computer or mobile device. Due to easier configuration and calibration, a laptop computer and a wired laptop connection with the diagnostic socket of the LPG system were selected on the large screen.

To carry out a careful analysis of the correctness of operation of the engine on the fuel supply original and alternative fuel it is necessary to observe a number of operating parameters of the individual engine systems. Such a task was associated with the need to view engine operating parameters available via the OBD on-board diagnostics connector as well as retrofitting the engine with additional testing sensors.

Communication with the gas injection system controller was carried out using the manufacturer's software, which allows the appropriate calibration of the vehicle and preview of system parameters such as:

- gasoline injection time on individual cylinders,
- engine speed,
- gas injection time on individual cylinders,
- vacuum in the engine intake manifold,
- injected gas pressure,
- gas injection temperature,
- LPG ECU temperature,
- battery voltage etc.

After the vehicle conversion into LPG, the gas system must be configured. Then follows the initial calibration of the system idling. After it it's possible to calibrate and properly calibrate the gas system in all engine operating conditions. Calibration of the gas system should also be performed during each technical inspection. Such inspection includes the replacement of LPG filters and checking the tightness of the gas system. manufacturers recommend that such inspections should be made every 10,000 km. All inspections required during the warranty period and after its completion were carried out on the tested vehicle. The calibrator can use the advanced features offered by the software. To determine the correct operation of the gas system, 2D (Figure 3 and 4) and 3D (Figure 5) maps are used.

In order to obtain the graphs of the characteristics shown in Figure 3, road tests were performed, first with gasoline and then with LPG. While driving on the selected fuel, the LPG ECU collects data on the dependence of the fuel injection time expressed in [ms] as a function of the engine load expressed in [%]. These values should be collected for all engine operating conditions. Should include the engine idling, light duty, medium duty and running at maximum power. The progress of the calibration process is shown by the bars presented at the bottom of the graph in Figure 3. The blue bars represent the progress of driving on petrol and the blue bars on gas. We continue the calibration drive until all the bars are completed, both on petrol and on LPG. A regression model in the form of a polynomial is built from the measurement data collected during the calibration drive. This is called Petrol Injection Characteristic (red) and LPG Injection Characteristic (blue). If the gas system is properly calibrated, both curves should match. The shift in the LPG injection characteristics in relation to the gasoline injection characteristics indicates incorrect adjustment of the gas system. The characteristics of petrol injection and gas injection as a function of engine load shown in Figure 3 are identical. This proves that the system is properly calibrated. We can only notice a discrepancy at high engine load corresponding to injection times of 9 ms. Petrol data collection bar is incomplete. The petrol test drive should still be continued to obtain more reliable results.

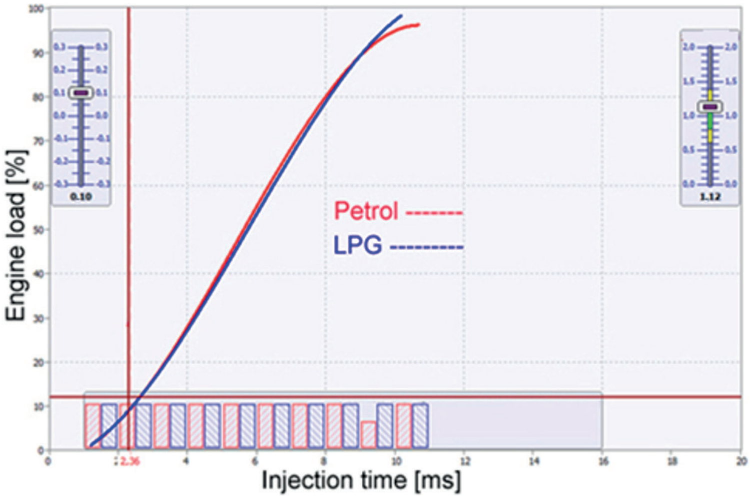

Fig. 3. Window Map-> Map 2D software

The measurement points collected during the road tests can be seen in the diagram presented in Figure 4. Their close proximity to the diagonal of the diagram proves that the gas system has been correctly calibrated.

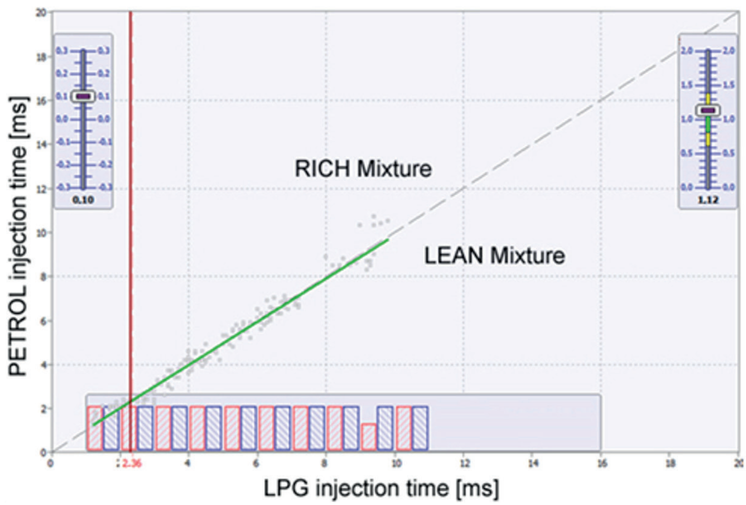

Fig. 4. Window Map-> Map 2D software

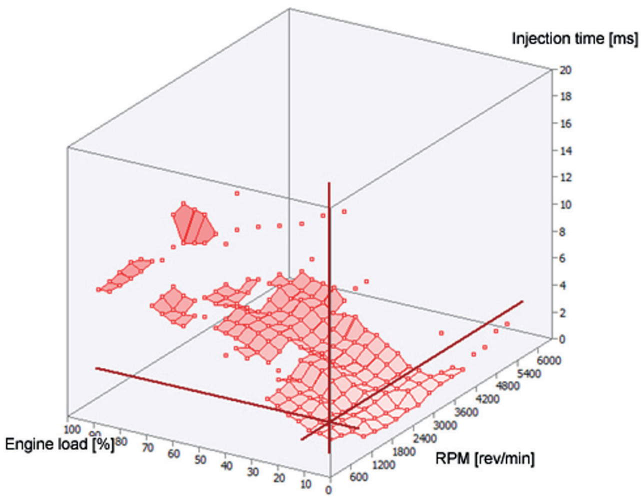

Fig. 5. Window Map-> Map 3D software

The system also performs many statistical calculations to determine the deviations of the mixture composition from stoichiometric values. To obtain low exhaust emissions during LPG supply, the calibration must be very precise and the gas system components should maintain consistent performance over a long period of operation.

5. Determining the compatibility of the LPG system with the vehicle's OBD system

One of the basic requirements for converting a vehicle into LPG is its compatible cooperation with the vehicle's on-board diagnostic (OBD) system [37]. This is only possible if the LPG fueling system is always able to reproduce the control strategy implemented by the gasoline system. He is then called the so-called dependent system. The vehicle's ECU implements all engine operation and control strategies stored in the ECU firmware in the form of algorithms. They are the result of the research and development centers of individual concerns in the field of control strategies to achieve high performance and low emissions. Alternatively, the vehicle manufacturer may purchase a control unit with software from companies developing such systems for many manufacturers. These include AVL, Bosch and several other European manufacturers. To develop advanced gasoline vehicle power systems in accordance with customer expectations and exhaust emissions requirements, they must have very well equipped research laboratories including engines, engine brakes and exhaust gas analyzers. In addition to scientists able to create new engine control strategies and algorithms implementing them (constituting firmware), electronics are also needed to design appropriate hardware. Software is also needed to communicate with the ECU firmware. It can be concluded that a very well-equipped laboratory and a team of top-class scientists and engineers from many scientific disciplines are needed to develop innovative alternative fuel supply systems.

The compatibility of the LPG supply system with the vehicle's OBD system can be determined with the use of generally available hardware and free or cost-effective software for a mobile device [16]. There is a wide range of devices running on an integrated circuit known as ELM 327 communicating by wire with desktop computers (Figure 6a) or handheld or wireless with mobile devices such as tablet or smartphone (Figure 6b). Examples of such devices are shown in the figures below.

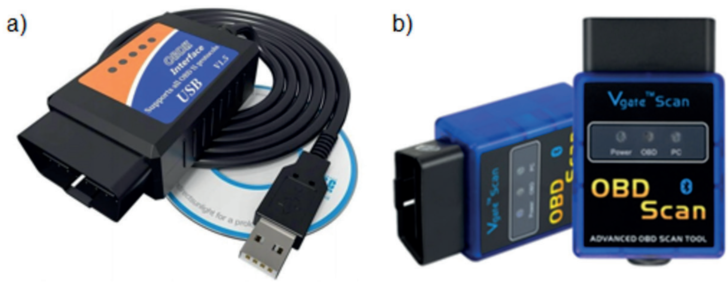

Fig. 6. a) OBD interface with USB plug, b) OBD interface communicating via Bluetooth

Torque, which is a free (Light version) or paid (Pro version) diagnostic program necessary for vehicle diagnostics, is often used and very helpful both in workshop diagnostics and in scientific research [60].

The Torque Pro program allows you to:
- reading standard and specific error codes (DTCs),
- clearing codes and "check engine" (MIL).

In addition, it is possible to display in real time and save information from sensors to a file, such as:
- Engine speed (RPM),
- Calculated Load Value,
- Coolant Temperature,
- Fuel System Status,
- Vehicle speed,
- Short-term correction of the injection time (Short Term Fuel Trim),
- Long-term correction of injection time (Long Term Fuel Trim),
- Vacuum in the intake manifold (Intake Manifold Pressure),
- Timing Advance,
- Intake Air Temperature,
- Mass air flow - indication of the flow meter (Air Flow Rate),

- TPS (Absolute Throttle Position) throttle position,
- Indications of the oxygen sensor (Oxygen sensor voltages),
- Fuel Pressure and other.

Compatibility tests of the LPG system with the vehicle's OBD system showed the absence of error codes in the ECU's memory and the correct operation of all diagnostic procedures and monitors in the field of monitoring exhaust emissions systems and systems in the vehicle (Figure 7) [56]. In a similar way, compatibility is checked by accredited test bodies. An additional test is the simulation of a fault important due to the component emission and checking the reaction time of the OBD system by displaying the "Check engine" indicator on the vehicle instrument panel.

A very important function of the innovative software is the ability to present the course of selected engine or vehicle operating parameters using various functions. The simplest of them is the display of parameters using analog or digital indicators. More advanced controls for building software can provide information about the minimum and maximum value of a given parameter (Figure 8). This is especially helpful when observing and measuring fast-changing signals that the human eye is unable to pick up.

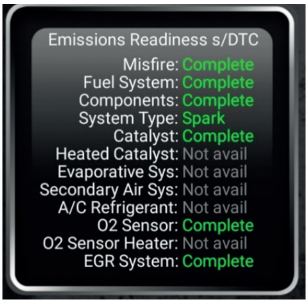

Fig. 7. Emissions Readiness window

Fig. 8. Real-time parameter observation window

6. Road tests

Almost every mobile device has a built-in GPS satellite positioning system. Parameters from the OBD system, GPS and other applications available on the device can be combined and used effectively.

Fig. 9. Map of the route during road tests

During the tests, the car traveled over 18 km. The route began in the Lublin Science and Technology Park at 3 Dobrzańskiego Street in Lublin. After leaving the park, the car traveled several kilometers in a typically urban cycle. Then it took the S17 expressway towards Lublin-Zamość. As shown in Figure 10, the speeds on this part of the route were much higher, but also much more stable. All the research was completed in the same place where they started.

An interesting solution is the overlay of the route on Google maps and the use of a color scale to indicate the speed of travel, as shown in Figure 9. Green and yellow colors mean low and medium speeds, while orange and red are high. The presented map clearly shows in what moments and on which sections the tested vehicle was moving at low speeds, and in which at high speeds. Thanks to the map depicted in this way, it can be noticed that during the study, the distance covered was both in the urban and non-urban cycle - the so-called mixed cycle.

The collected data from road tests can be easily transferred to a spreadsheet and presented in the form of a text in the form of a table. Thanks to this, it is possible to analyze only a selected part of the journey and analyze only the data that interest us. Based on the data from the text file, graphs were made, examples of which are shown in Figure 10. Each graph shows the time course of a different parameter. In this case, 5 main information from the sensors were taken into account:

- Vehicle speed in km/h.
- Engine speed in rpm.
- Engine load in %.
- Long and short fuel trims in %.
- O_2 Sensor Equivalence Ratio.

Road tests with on-line and off-line data analysis showed the correct course of all diagnostic signals. The gas control unit carries out the strategies of the gasoline injection control unit. This can be inferred from the short and long term fuel injection correction and O2 Sensor Equivalence Ratio. The vehicle speed and engine speed charts show a smooth course. On this basis, it can be concluded that the vehicle is fully operational and in very good technical condition.

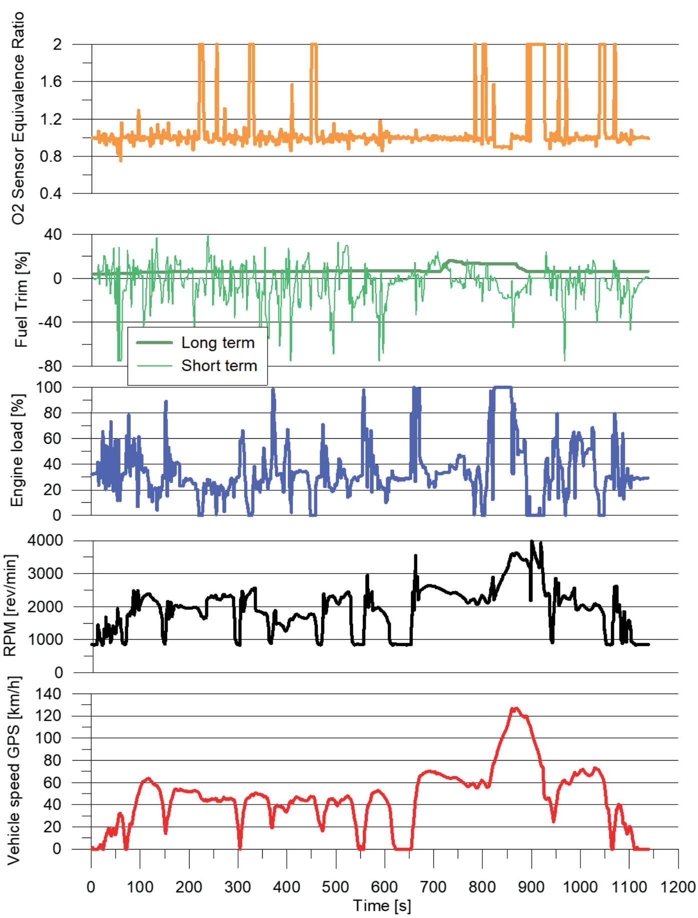

Fig. 10. Test drive data shown in the graph

The innovative software, in addition to data from the OBD system, can save a lot of data from the GPS system. These include the height above sea level, which affects the engine load and fuel consumption. In Figure 11, we can observe that the changes in altitude above sea level were very large, reaching 100 m.

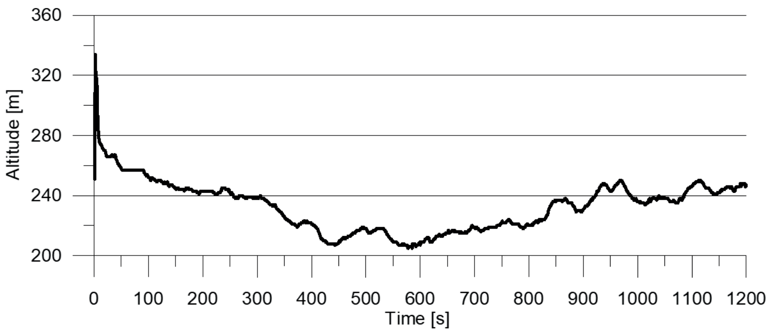

Fig. 11. Altitude change during road test

Road tests have shown that there are very useful diagnostic devices that are able to acquire and process data from the vehicle's OBD connector. Anyone with a smartphone or tablet can download a free or low-cost application with which they can contact their vehicle. This hardware and software allows error codes to be read and erased. Until recently, such a service could only be performed at an authorized service center.

More detailed tests of a low-emission vehicle can be performed on a chassis dynamometer with the use of multi-component exhaust gas analyzers [44]. Then the NEDC or WLTP driving test is carried out, during which the emissions of components regulated in Euro standards are measured [53]. Such research may be of a cognitive and scientific nature when carried out in well-equipped scientific units or for approval when officially carried out in accredited research laboratories [8, 36]. In Poland, this role is played by the Motor Transport Institute and The Automotive Industry Institute in Warsaw and Automotive Research and Development Institute BOSMAL in Bielsko-Biała. In addition to research with high-class measuring equipment, scientists are developing low-cost methods of measuring fuel consumption and exhaust emissions [40, 41].

From September 1, 2018, the official research test is the WLTP [21]. Despite the greater rigor of research, the WLTP cycle remains a purely laboratory test [12]. In general terms the WLTP appears to be a significant improvement compared to the NEDC [35]. Researchers then began to compare the results obtained in the new WLTP test with those obtained when driving normally under real conditions [47, 52]. This is possible thanks to mobile exhaust gas analyzers that have become cheaper and more accessible to various research institutes [30]. The authors noticed a large research trend consisting in increasing road tests in relation to laboratory tests [20]. This makes sense both in the study of vehicles with internal combustion engines and electric vehicles.

In order to ensure even more representative results, a second test procedure is introduced, which is called the RDE (Real Driving Emissions Test) [23]. It requires that cars be tested on the road under conditions that more closely reflect real-world scenarios on the road in order to measure real fuel consumption and real exhaust emissions [41]. The RDE test covers uphill and downhill gradients, low-speed city driving, medium-speed country road driving and high-speed motorway driving [22]. In addition, it takes into account the height above sea level of the car, its load and driving in different ambient temperatures. All new passenger cars and light commercial vehicles must undergo RDE testing from September 2019. The road tests performed and presented in the article meet all the requirements with regard to the RDE tests. The innovative hardware and software used in this article can also be used to carry out RDE tests, but it must be supplemented with a portable exhaust gas analyzer.

7. Conclusions

The mixture of liquid propane with butane, under the trade name LPG, is very popular in Poland and other European countries and around the world for driving vehicles. This is due to the lower price of this alternative fuel compared to gasoline, but also due to its features that result in lower exhaust emissions to the atmosphere. According to the tests carried out, vehicles with indirect gasoline injection into the engine intake manifold, meeting the Euro 6 emission standard on gasoline, can be converted to LPG. Such installation must be in accordance with the requirements of UN/ECE Regulation 115, which guarantees the safe operation of such a vehicle.

On the basis of the analyzes and research presented in the article, it can be concluded that:

1. The firmware of the LPG electronic control unit consists of complex control algorithms that are designed to ensure the safe operation of the gas system. In addition, they must ensure high engine work culture when fueled with alternative fuel and engine performance (power, acceleration) comparable to gasoline.
2. For configuration and calibration of the LPG system, innovative software has been developed with advanced functions for displaying selected engine operating parameters. The methods of displaying computational data from calibration runs, which are currently in the form of three-dimensional 3D surface plots, are also innovative.
3. The on-board diagnostic (OBD) system has been developed to monitor the correct operation of the vehicle's on-board systems responsible for exhaust gas emissions. The OBD system has been available in petrol vehicles since 2000 and in diesel vehicles since 2003. At present, the OBDII / EOBD system is in force in the world.
4. There are very useful diagnostic devices available on the market that are able to acquire and process data from the vehicle's OBD connector. Anyone with a smartphone or tablet can download a free or low-cost application through which they can contact their vehicle. This hardware and software allows error codes to be read and erased. Until recently, such a service could only be performed at an authorized service center.

5. The software installed on the mobile device communicates with the OBD socket, usually via Bluetooth wireless transmission and wi-fi. Cable transmission via RS-232 interface is also possible. The latter is used with the use of an OBD connection with a laptop.
6. Using hardware and software for communication with the vehicle's OBD system, you can check the correct calibration of the LPG system and its compatibility with the vehicle's OBD system itself.
7. The conducted tests showed that there are no errors stored in the memory of the OBD system of the Euro 6 vehicle converted to LPG after driving 36,000 km. Moreover, road driving in the real mixed cycle with on-line and off-line data analysis showed the correct course of all the observed diagnostic signals. On this basis, it can be concluded that the vehicle is fully operational and in very good technical condition.
8. The performed road tests meet all the submissions with regard to the RDE tests. The innovative hardware and software used can also be used to carry out RDE tests, but must be supplemented with a mobile exhaust gas analyzer.

8. Nomenclature

CNG – Compressed Natural Gas
ECU – Electronic Control Unit
LPG – Liquefied Petroleum Gas
NEDC – New European Driving Cycle
OBD – On-Board Diagnostics
RDE – Real Driving Emissions
UN/ECE – Economic Commission for Europe of the United Nations
WLTP – Worldwide Harmonised Light Vehicles Test Procedure

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