Comparative performance analysis of an OTTO engine equipped for petrol or liquefied petroleum gas propulsion

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Abstract

Today, in the development of engines for the propulsion of motor vehicles, the greatest importance is given to the environmental aspect in terms of finding the ideal fuel. In solving this problem, it can be said with certainty that liquefied petroleum gas (LPG) has emerged as an ideal alternative fuel because it is more environmentally friendly and currently available in sufficient quantities. After showing the basic physical and chemical characteristics of LPG, the elements that must be installed in a vehicle that uses this type of fuel are listed. The paper analyzes the performance of OTTO engines with a subsequently installed LPG system in one group of vehicles that consisted of vehicles of the same manufacturer and type of engine. Using a chassis dynamometer in the laboratory power measurements were performed. The basic technical characteristics of the measuring equipment used in the laboratory are also stated. Based on the obtained measurements, the results of the operation of the engine on both fuels, as well as their mutual comparison are given. Considering that quite good results of testing the power of LPG aggregates were obtained in the following research, the parameter of the ratio of consumption of this fuel in relation to gasoline should be investigated for economic reasons.

Keywords: *OTTO aggregate, Chassis dynamometer, LPG, Engine power.*

1 Introduction

There are strong tendencies in the world to develop motor vehicles that use environmentally friendly and sufficiently available fuels. One of the ways to solve the current tasks of the automotive industry is the use of alternative fuels, or alternative energy potentials. The paper is based on liquefied petroleum gas (LPG) as an alternative fuel of known basic physical and chemical characteristics, which will be briefly described in this paper. Previous research has been mainly based on the analysis of the basic indicators of the powertrain (power, economy and environmental characteristics) in the use of LPG, which confirmed that this fuel is more economical and environmentally friendly than gasoline and diesel fuel, while much less research was based on measuring the engine power when working on these fuels.

Traction characteristic is one of the most important parameters of a motor vehicle and previous tests have given very little data on the operational dynamic characteristics of OTTO aggregates when using LPG. Certain changes to the powertrain, such as the installation of a system to supply the powertrain with liquefied petroleum gas, may lead to a change in the traction characteristics of the motor vehicle (power and torque). Tests of traction characteristics can be performed on the test site or on dynamometers intended for testing the traction characteristics of motor vehicles (chassis dynamometers).

Using the *AVL Roadsim Chassis Dyno 48" 4WD MiM´´* chassis dynamometer, laboratory testing of the dynamic characteristics (power and torque) of the OTTO aggregate powered by two different types of fuel (petrol or LPG) will be performed. This paper will present all the results of research and analysis of the results obtained from the standpoint of changes in the engine power.

Power research will be conducted on a number of passenger motor vehicles that have a factory-installed system for supplying the engine with gasoline fuel, and on which a system for supplying the engine with LPG was subsequently installed. The tests were performed when the vehicle was powered only by gasoline and then only by LPG. The paper will present the components and the principle of operation of the built-in LPG system.

2 Methodological settings of the work

The subject of the research is a comparative analysis of the performance of OTTO aggregate equipped with gasoline or liquefied petroleum gas. The paper will investigate the performance of the OTTO aggregate when it is powered by gasoline or liquefied petroleum gas.

The paper will also present the applied system for propulsion on liquefied petroleum gas. The vehicles tested have a retrofitted LPG engine supply system.

For the purposes of the research, tests will be performed on several Volkswagen motor vehicles. These are Golf IV vehicles, the age range of the vehicle is from 1999 to 2003 with petrol engines, in which the LPG engine supply system is subsequently installed.

The power test of the vehicle and the propulsion aggregate powered by gasoline and liquefied petroleum gas will be performed in the laboratory using the *AVL Roadsim Chassis Dyno 48" 4WD MiM´´* chassis dynamometer.

The aim of the research, within the paper, will be focused on:

- laboratory testing of dynamic characteristics (power and torque) of OTTO aggregate powered by two different types of fuel,
- Interpretation of laboratory test results and comparative analysis of the advantages of using fuels from the point of view of dynamic characteristics.

The motive for the choice of work refers to the research of generally accepted attitudes about the advantages of using liquefied petroleum gas as a fuel.

3 Liquefied petroleum gas (LPG)

During the distillation of oil, individual hydrocarbons (C_nH_m) of different structure and different ratio of carbon and hydrogen are released, starting from the lightest fractions (with one to two carbon atoms C in the hydrocarbon molecule - such as methane CH_4 and ethane C_2H_6), through medium (such as heptane C_7H_{16} and octane C_8H_{18}) and heavy fractions (such as cetane $C_{16}H_{32}$), to the heaviest (such as hydrocarbons that make up fuel oil). Hydrocarbons between light and medium fractions (such as propane C_3H_8 and butane C_4H_{10}), at atmospheric pressure and normal temperature of about 20 [°C], are in the gaseous state, but at slightly lower temperature or at slightly higher pressure in the tank remain in the liquid state. Mixtures of these fractions form the so-called. liquefied petroleum gases.

Liquefied Petroleum Gas (LPG), or auto gas, is a mixture of saturated hydrocarbons (so-called paraffin) and impurities of other hydrocarbons, primarily unsaturated hydrocarbons (so-called olefins) and isomers of these hydrocarbons. Therefore, liquefied petroleum gas is a mixture of hydrocarbons with 3 and 4 carbon atoms (propane - C_3H_8, butane - C_4H_{10}, ethane, pentane, propene, butene, isobutane...). Propane and butane are colorless and odorless gases, but they are added the compound ethanethiol (CH_3CH_2SH), ethyl mercaptan, dimethyl sulfide, which contains sulfur to facilitate the detection of possible leaks.

Table 1. Properties of propane and butane

Properties	Propane	Butane
Chemical sign	C_3H_8	C_4H_{10}
Molar mass (M)	44,1 [g mol^{-1}]	58,12 [g mol^{-1}]
Density 0 [°C] and at 101,3 [kPa]	2,0098 [kg/m^3]	2,480 [kg/m^3]
Boiling temperature at 1 [bar]	-42 [°C]	-0,5 [°C]
Critical temperature	95,7 [°C]	152,8 [°C]
Critical pressure	43,6 [bar]	32,8 [bar]
Specific gravity in the liquid state	0,510 [kg/dm^3]	0,575 [kg/dm^3]
Lower caloric value	11070 [Kcal/kg]	10921 [Kcal/kg]
Spontaneous ignition temperature	540 [°C]	500 [°C]
Flammability limits in the air	2,1 – 9,5 %	1,9 – 8,5 %
Maximum combustion temperature	1925 [°C]	1897 [°C]

One of the most important characteristics of liquefied petroleum gas is high resistance to self-ignition, which means that LPG has a high octane number. This makes it particularly suitable for use in OTTO aggregates. A vehicle that uses liquefied petroleum gas for propulsion less pollutes the environment, has better operating economy with a relatively small reduction in the traction characteristics of the vehicle. Research shows (Rakić, 2008) that the increase in fuel consumption in engines that have a built-in sequence system (direct gas acceleration system) is a maximum of 15%.

4 Application of LPG on OTTO aggregates

Application on OTTO aggregates is also known as bi-fuel conversion of gasoline engines, where the engine is powered by either gasoline or LPG.

In order to use LPG on an OTTO aggregate (ie those that normally use gasoline), it is necessary to install an additional LPG system. The LPG system must be adapted to the engine operation technology and the design features of the engine. Since LPG can be used on petrol engines with virtually no intervention on the engine itself, LPG systems in principle only provide storage and evaporation of LPG.

There are several different LPG systems that basically followed the technological development of engines and vehicles (they differ in the way the mixture of fuel and air is prepared), so that today there are mainly the following LPG systems:

- carburetor system,
- system for indirect injection without catalytic converter,
- system for indirect injection with catalytic converter,
- direct LPG injection system.

4.1 Direct LPG injection system

The system with direct injection of LPG is also called sequential system or system with multipoint injection.

The sequence system is intended for use in vehicles that use direct injection to prepare a mixture of fuel and air. It works by using injectors for the injection of LPG, on the same principle as with gasoline, which at any time, depending on the mode of operation of the aggregate, dose the optimal amount of LPG directly into the intake manifold of the aggregate. A very efficient system with an excellent history of reliability, is the best solution for installation in all vehicles on which it is technically possible to install.

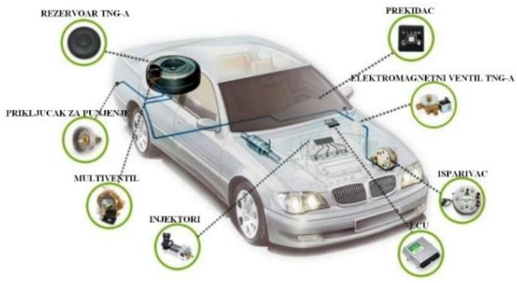

Fig. 1. Direct injection LPG system

The advantage of a system with direct injection of LPG is that it essentially has an ECU (Electronic Control Unit), atomizers, a large number of sensors and finally gas injectors. The system uses signals from the unit on which it is installed (speed, temperature, exhaust condition, injection time and injection torque for each cylinder separately) and its own parameters (temperature, pressure and amount of LPG in the tank). All input parameters are calculated by the ECU in real time and determines the amount of gas that will be injected into each cylinder of the unit. In this way, the best possible use of the engine power in relation to gas consumption is achieved.

The research examined vehicles that had new LPG equipment installed, and whose installation was performed in the same service workshop. Also, when choosing the vehicle, it was taken into account that the built-in LPG system has executive elements from the same manufacturer. The vehicles were equipped with STAG equipment, which was prescribed by the manufacturer for the given power and working volume of the propulsion aggregate.

Fig. 2. Embedded elements of sequential LPG system

4.2 Tested vehicles

As part of the research, tests were performed on five Volkswagen motor vehicles that have OTTO aggregate with a factory-installed system for supplying the propulsion aggregate with gasoline fuel, and which were subsequently fitted with a system for supplying the propulsion aggregate with LPG.

The test covered vehicles with 2.0 aggregate. The test vehicles had a different unit code. Two test vehicles had the code number of aggregate the AZJ, while three vehicles had the code number AQY, whose technical data for aggregates are shown in Table 3. Technical data for the tested vehicles are given in Table 2.

Table 2. Data of test vehicles with 2.0 aggregate of 85 [kW]

Tested vehicle	Chassis number	Aggregate number	The year of production	Mileage	Tested date
Vehicle 1	WVWZZZ1JZ3W640883	AZJ070012	2003	264591 [km]	02.05.2020.
Vehicle 2	WVWZZZ1JZ3W639445	AZJ070177	2003	236769 [km]	08.10.2020.
Vehicle 3	WVWZZZ1JZYW648070	AQY047085	2000	229391 [km]	27.09.2020.
Vehicle 4	WVWZZZ1JZ1W670184	AQY201396	2001	207512 [km]	21.08.2020.
Vehicle 5	WVWZZZ1JZYW227642	AQY037748	1999	219537 [km]	09.06.2021.

Table 3. Data of AZJ and AQY aggregates

Description	Value	Value
Aggregate code	AZJ	AQY
Number of cylinders	4	4
Number of valves	8, OHC	8, OHC
Aggregate volume	1984 [cm^3]	1984 [cm^3]
Stroke/piston diameter ratio	82,5/92,8	82,5/92,8
Compression ratio	10,5:1	10,5:1
Maximum power	85 [kW] at 5400 [rpm]	85 [kW] at 5200 [rpm]
Maximum torque	175 [Nm] at 2400 [rpm]	170 [Nm] at 2400 [rpm]
Compression pressure	10 – 13 [bar]	10 – 13 [bar]
Oil pressure	Minimum 2,0 [bar] at 2000 [rpm] and temp. 80 [^{0}C]	Minimum 2,0 [bar] at 2000 [rpm] and temp. 80 [^{0}C]
Type of unit control	Bosch Motronic ME 7.5	Bosch Motronic M 5.9.2.
Spark plug type	NGK PZF R5 D-11	NGK BKUR 6ET-10
Permissible clearence between spark plug electrodes	1,0 - 1,1 [mm]	0,9 - 1,1 [mm]
Ignition schedule	1-3-4-2	1-3-4-2
Fuel supply pressure	2,5 – 3,0 [bar]	2,5 – 3,0 [bar]
Minimum vacuum pressure on the intake manifold	590 [mbar]	590 [mbar]

5 Experimental testing of the power of OTTO aggregates

The shape of the towing characteristics of the car is influenced by the external characteristics of the installed aggregate, but also the applied transmission, as well as the dimensions of the drive tires. The external characteristic of the aggregate includes all its most important parameters, ie. it represents a form of obtained mechanical energy that has reached the flywheel of the aggregate and which represents the display of available energy at the entrance to the transmission [1].

In transmission, the unacceptable form of energy received from the powertrain (too many revolutions and insufficient torque) is transformed into the shape needed on the car's drive wheels. During this transformation, part of the available energy will be converted into an unwanted form (heating of the transmission, noise ...), resulting in a smaller or larger loss of energy obtained from the aggregate. Part of the total energy produced that reaches the drive wheels in an acceptable form will be used to perform the basic function of the motor vehicle, its movement.

Some of the parameters that determine the obtained available energy for driving a motor vehicle on its wheels can be calculated, ie. to predict, but some of them are not always simply predictable. That is why it is very important, in certain situations, to perform tests on a specific vehicle, in order to determine its actual performance, which gives the motor vehicle user a clear picture of what he really has at his disposal [1].

Tests of traction characteristics of the vehicle, ie its performance can be performed on the road (polygon) or can be tested in stationary conditions. Since stationary test conditions provide much greater benefits, as well as greater comfort, solutions have been found that enable this, primarily through devices for testing traction characteristics in stationary conditions, or devices called dynamometers.

A chassis dynamometer is most often used for such tests, because it is very suitable for testing the performance of vehicles for different road load conditions, control operating modes, as well as checking the legally prescribed technical characteristics of vehicles.

The research presented in this paper was performed at the Technical Laboratory Center of the Faculty of Traffic and Transport Engineering Doboj, using a chassis dynamometer *AVL Roadsim Chassis Dyno 48 "4WD MiM´´* manufactured by AVL Austria, which belongs to the class of very precise meters for measuring vehicle traction and belongs to the group of active dynamometers . This chassis dynamometer is equipped with roller sets on which vehicles with front, rear and all four wheel drive can be tested. The device is primarily designed and intended for testing motor vehicles in various road load conditions at different speeds (from 0 to 200 [km/h]). It enables very precise measurement of: vehicle speed and acceleration, traction force on the roller surface, power on the drive wheels, power of the aggregate, torque of the aggregate, rolling resistance of the vehicle. With the use of additional equipment, it can be used to measure vehicle exhaust emissions, fuel consumption, noise, etc.

Figure 3 shows one tested vehicle on the chassis dynamometer *AVL Roadsim Chassis Dyno 48 "4WD MiM´´* in the laboratory for testing motor vehicles of the Faculty of Traffic and Transport Engineering Doboj.

Fig. 3. Tested vehicle on chassis dynamometer

6 Test results

The measured engine power was performed by laboratory testing when the propulsion aggregate, ie the vehicle, was powered by gasoline or liquefied petroleum gas. Six measurements were performed for all vehicles, three measurements when the propulsion aggregate was supplied with liquefied petroleum gas and three tests when the propulsion aggregate was supplied with gasoline. The test was repeated in order to check the repeatability of the measurement results and obtain the most accurate results.

Table 4 shows the measured engine power for each tested vehicle with propulsion of the gasoline and LPG.

Tabela 4. Power of tested vehicles

Tested vehicle	Chassis number	Power on gasoline	Power on LPG
Vehicle 1	WVWZZZ1JZ3W640883	83,475 [kW]	80,345 [kW]
Vehicle 2	WVWZZZ1JZ3W639445	84,138 [kW]	81,849 [kW]
Vehicle 3	WVWZZZ1JZYW648070	82,576 [kW]	79,603 [kW]
Vehicle 4	WVWZZZ1JZ1W670184	81,972 [kW]	79,013 [kW]
Vehicle 5	WVWZZZ1JZYW227642	84,358 [kW]	81,136 [kW]

Here it is very important to note that in all measurements, the correction of the net power of the aggregate was performed depending on the atmospheric conditions. The power factor includes a correction factor that takes into account air temperature, humidity and air pressure, so that accurate test data are obtained that are considered physically relevant regardless of weather conditions. After testing the power of aggregate on the chassis dynamometer, the measured net power of the aggregate is corrected depending on the type of tested aggregate. Correction of net power of aggregates depending on atmospheric conditions is performed in accordance with the directive EC 80/1269/ISO 1585.

Then, the analysis of the obtained laboratory measurements was performed using the comparative method. Table 5 shows the percentage of power drop for each of the tested vehicles running on LPG in relation to running on gasoline. Based on the presented results, it can be seen that in all tested vehicles, the power of the aggregate decreased when running on liquefied petroleum gas. The largest decrease in power was obtained in the test vehicle number five and it is 3.82%, and the smallest decrease in power is in the test vehicle number two and it is 2.72%.

Table 5. Percentage of aggregate power drop during LPG operation

Data	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5
Vehicle power on LPG [kW]	80,345	81,849	79,603	79,013	81,136
Vehicle power on gasoline [kW]	83,475	84,138	82,576	81,972	84,358
The decrease in the power of the aggregate on LPG in relation to gasoline (%)	**3,75**	**2,72**	**3,60**	**3,61**	**3,82**

Figure 4 shows the results of measuring the power and torque of one of the tested vehicles during its operation on gasoline.

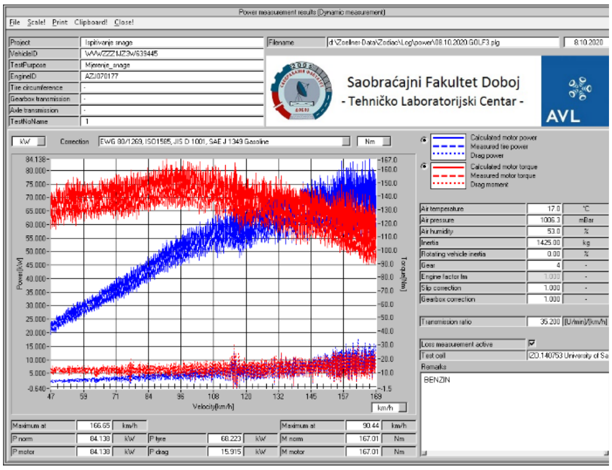

Fig. 4. Measurement results of one of the tested petrol-powered vehicles

The diagram in Figure 4 shows the different measurement results obtained, and within this research the most important are:

- the maximum power of the vehicle's aggregate is 84,138 [kW],
- the maximum torque of the aggregate is 167.01 [Nm].

Also, Figure 5 shows the results of measuring the power and torque of one of the tested vehicles during its operation on liquefied petroleum gas. This is the same vehicle for which the measurement results are shown in Figure 4.

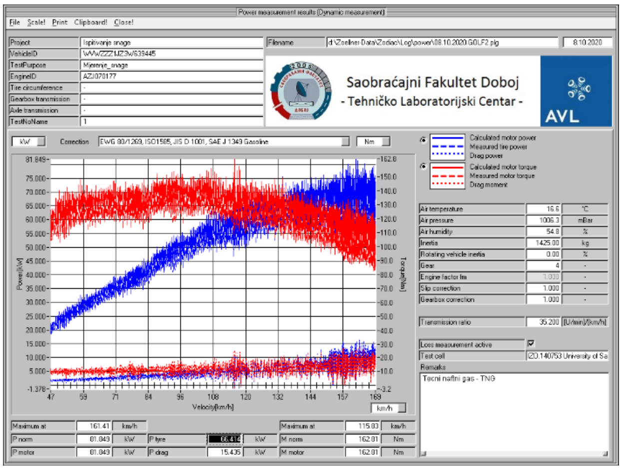

Fig. 5. Measurement results of one of the tested vehicles with LPG system

The diagram in Figure 5 shows the different measurement results obtained, and within this research the most important are:

- the maximum power of the vehicle's aggregate is 81,849 [kW],

- the maximum torque of the aggregate is 162.81 [Nm].

For a given aggregate whose measurement results are given in Figures 4 and 5, a decrease in the power of the aggregate when working on liquefied petroleum gas by 2.72% compared to its work on gasoline. Figure 5 shows that the torque diagram of the propulsion aggregate has slightly lower values compared to the torque diagram of the same propulsion aggregate in Figure 4. The reason for the lower torque is operation on liquefied petroleum gas, which resulted in lower traction. drive wheels. The end result was lower power of the propulsion aggregate when working on liquefied petroleum gas. As with this aggregate, this was the case with all other tested aggregates.

When the power ratio of gasoline and liquefied petroleum gas was determined, the search for average values was performed for all tested vehicles, and the obtained result of the average power drop when working on LPG is 3.50%.

The lack of research is that when measuring the power of propulsion aggregate, the analysis of the quality of propellant fuels used to supply the aggregate was not performed. In order to eliminate this shortcoming, the certificates of quality control of fuels used during the research were obtained from the authorized distributor, ie from the gas station where the fuel was poured. Based on these certificates, it was stated that the quality of fuel meets the prescribed standards for used fuels.

7 Conclusion

Power measurements were performed on an *AVL Roadsim Chassis Dyno 48" 4WD MiM´´* chassis dynamometer. These measurements gave the results of the power of the aggregate for five Volkswagen vehicles running on gasoline and LPG. It is characteristic that all tested vehicles had lower power of the aggregate when working on LPG in relation to the power when working on gasoline. The smallest percentage drop in power of the aggregate when working on LPG was measured at 2.72%, and the largest percentage drop in power was 3.82%. The mean value of the percentage power drop for all tested vehicles is 3.50%.

Most of the research has been based on tests of exhaust emissions from the operation of LPG motor vehicles in relation to petrol and /or diesel fuel operation. These studies have proven that LPG is a much more environmentally friendly fuel compared to the aforementioned fossil fuels.

As part of this work, research has shown that the performance (power and torque) of the aggregate during its operation on LPG compared to gasoline is slightly worse. From the point of view of the average driver, this drop in power in real operating conditions is extremely difficult to notice.

In some future research, should be tested more vehicles of different types and manufacturers in order to make the results more relevant. Also, in addition to examining the already mentioned performance and environmental characteristics of the research, it should also focus on the consumption of LPG in order to obtain economic indicators of the justification of driving on this fuel.

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