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USE OF LIQUIFIED PETROLEUM GAS AS FUEL IN MOTOR VEHICLES

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Miomir Raos[1], Zoran Marjanović[2], Ljiljana Živković[1], Milan Protić[1], Nenad Živković[1], Jasmina Radosavljević[1], Milena Jovanović[1]

[1]Faculty of Occupational Safety of Niš, University of Niš, Serbia
[2]City of Kragujevac, City Administration for Inspection Affairs, Serbia

Abstract. *Rapid development of motorization, increasingly strict environmental requirements, as well as the fact that fossil fuel reserves are limited, inevitably led to the question what kind of fuel for motor vehicle, can meet increasingly strict environmental and safety requirements, in addition to well-known petrol and diesel, and thus allow acceptable further development of road traffic. In a broad sense, alternative fuels are the fuels that are able to replace existing traditional fuels for motor vehicles, such as engine petrol and diesel fuel. New types of fuels for internal combustion engines have been explored for many years. We are looking for fuel which can be found in sufficient quantities, at an affordable price and which will have favorable environmental properties. Attention is paid to various alternatives, one of which is a mixture of propane-butane, publicly known as liquefied petroleum gas. The economic crisis, especially in transition countries, and the need for environmental protection are the reasons why liquefied petroleum gas has been increasingly used as a fuel in motor vehicles. This paper analyzes liquefied petroleum gas as an alternative fuel for motor vehicles. It also analyses basic engine indicators (power and environmental characteristics) when liquefied petroleum gas is used as a fuel, which confirm that this kind of fuel is environmentally cleaner than petrol and diesel fuel.*

Key words: *liquefied petroleum gas, exhaust gases, environmental protection*

1. INTRODUCTION

Due to its environmental, economic and safety advantages, liquefied petroleum gas (LPG), also known as autogas, is one of the leading alternative fuels today. By the end of the ‘80s of the twentieth century, liquefied petroleum gas was used primarily as a cheaper

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Corresponding author: Miomir Raos
University of Niš, Faculty of Occupational Safety, 10a Čarnojevića St, 18000 Niš, Serbia
E-mail: miomir.raos@znrfak.ni.ac.rs

fuel for motor vehicles. At the beginning of the ‘90s of the twentieth century, environmental advantages of this fuel were increasingly recognized, and liquefied petroleum gas has been used to a great extent as an environmentally friendly energy source, the use of which significantly reduces harmful emissions.

Liquefied petroleum gas has become one of the most important alternative fuels in global automotive scene and one of the most important factors for the modification of the internal combustion engine. With growing demands for preservation of nature and rigorous regulations for harmful gases in the air, liquefied petroleum gas should become one of the primary fuels in the automotive industry; for this reason, it is an ecological recommendation to include liquefied petroleum gas among priority alternative fuels. Therefore, many European countries already provide legal benefits to owners of cars powered by liquefied petroleum gas.

2. LIQUEFIED PETROLEUM GAS

Liquefied petroleum gas (in Serbia known as TNG) is a mixture of hydrocarbons, mainly of propane (C_3H_8, up to 94%) and butane (C_4H_{10}, up to 5%) and small amounts of other hydrocarbons (C_nH_{2n+2}, up to 1%). The mixture of propane and butane is defined by standard SRB.B.H2.134 in Serbia.

The use of LPG in internal combustion engines has a very long tradition, but only in the early 20th century did liquid petroleum products take over the primate as fuel for engines, and the reason for this were difficulties in manufacturing, storage and handling of gas.

Today, a fleet of approximately nine million vehicles using LPG as fuel is moving across the world. This number is on the rise and according to the information of THE GLOBAL AUTOGAS INDUSTRY NETWORK it is 12 ÷ 15% per annum. In Europe, the largest consumers of LPG are Italy, with approximately 1.4 million vehicles, followed by Poland with 600,000, Norway 400,000 the Netherlands 360,000, United Kingdom 250,000 etc. [1].

In everyday speech, LPG is referred to as propane-butane. When intended for domestic use, it is simply called gas, and when used as fuel for cars, the name autogas is used. Due to its favorable characteristics, LPG is widely used as fuel for households, industry, agriculture, and as fuel for internal combustion engines.

LPG is obtained in two ways. One way to obtain it is from natural gas, during procedures of fractionation of crude natural gas, when ethane, propane, butane, and other gases are separated. These procedures are carried out in special facilities for "degasification" near the sources of natural gas. Another way to obtain LPG is during primary and secondary processing of oil.

In normal atmospheric conditions, LPG is in gaseous state. The name liquefied petroleum gas indicates that LPG is easily condensed, because at normal temperature, even at pressures of 2 ÷ 8 bar (depending on the composition of the mixture), it changes to liquid state. LPG is heavier than air, so when there is any leakage from the tank, it settles near the ground. In liquid state, LPG has half the weight of water. LPG is colorless, both as a gas and a liquid, without odor, so for safety reasons, a strong aromatic substance (ethyl mercaptan and dimethyl sulfide) that is of sharp and unpleasant smell is added, warning of a gas leak from the tank. The intensive smell of added substance is felt when even 0.4% of LPG is in the air.

LPG is not toxic, but in higher concentrations in the air it acts as an anesthetic, and may even cause suffocation due to lack of oxygen. It is highly inflammable, but there needs to be a proper mixture of gas and air for its ignition. Limits of its flammability rating, given the volume ratio of gas and air, are from 1:50 to 1:10, which means that it can easily be ignited even when there is a small leak. Therefore, there must not be open flames in the vicinity of the installation or places where gas is handled. Ignition temperature of LPG is 500°C. LPG is chemically very aggressive, so it causes degradation of rubber and plastic. Having this in mind, when LPG installations are built, materials that are used must be carefully selected. [1]

Depending on the ratio of individual components in a mixture of LPG, lower heating value of common commercial mixture of propane and butane is approximately 25.4 MJ/l. Compared to lower heating value of petrol of 32.3 MJ/l, the equivalence coefficient petrol/LPG is approximately 1.27. This leads to conclusion that 1 liter of liquid petroleum gas has heating value as 0.78 liters of petrol, that is, the engine using LPG as fuel would consume 22% more gas than petrol. One of the most important characteristics of liquid petroleum gas is high resistance to spontaneous combustion, because LPG has a high octane number, which makes it particularly suitable for use in spark ignition engines.

The power of engine using LPG as fuel is by approximately 10÷15% lower when compared to the power of engine using petrol, which is explained by:

- lower filling coefficient of the cylinder, as a result of the low density of the mixture,
- mixture of gas and air, which is warmer than the mixture of air and petrol.

This was confirmed by examining the power of vehicle Yugo 1.3 CW (chassis no. 01,078,501, engine no. 0086447) using petrol and LPG (system ZAVOLI, mixer MDS 22/23.4 mm). Testing was done on dynamometer rolls SCHENK LNC-0052 in Zastava automobili - Car development department, Kragujevac in March 2010 (Figure 1).

Fig. 1 Vehicle Yugo 1.3 CW on dynamometer roll SCHENK LNC–0052

Measuring the force on the vehicle wheels (F_1, F_2, F_3, F_4) is done in the second gear and the measurement results are given in Table 1. On the day of the measurement, the atmospheric pressure was p = 994.6 mbar.

Table 1 Measurement results

n r.p.m	Petrol					LPG				
	v_1 km/h	F_1 V	t_{v1} °C	F_2 V	t_{v2} °C	v_2 km/h	F_3 V	t_{v3} °C	F_4 V	t_{v4} °C
1500	16,85	3,13	22,59	3,14	22,59	16,55	2,88	20,86	2,95	22,02
2000	22,6	3,01	23,75	3,04	23,17	22,15	3,11	20,86	3,22	22,59
2500	27,3	3,63	23,75	3,57	22,59	26,9	3,47	22,59	3,46	23,75
3000	32,75	3,62	27,82	3,69	24,33	32,5	3,59	24,33	3,58	25,49
3500	38,85	3,65	28,98	3,64	25,49	38,1	3,61	25,49	3,63	27,82
4000	43,8	3,64	27,82	3,62	26,65	44	3,45	26,65	3,51	30,16
4500	49,75	3,5	27,82	3,52	28,40	49,6	3,29	27,24	3,29	28,98
5000	55,05	3,46	28,40	3,4	29,57	55,15	3,24	28,40	3,22	29,57
5500	61,2	3,23	31,33	3,2	30,74	60,8	3,05	29,57	3,04	32,50

Based on the measured values from Table 1, and using equation 1, we get the value of power on the wheels of the vehicle using petrol as fuel (P_{PET}) and the one using LPG (P_{LPG}), as shown in Table 2 (values of power were brought to temperature of 20°C and pressure of 1013 mbar using coefficient K):

$$P = K \cdot \frac{735 \cdot 75}{3600} \cdot v \cdot F \tag{1}$$

where: coefficient $K = \frac{1013}{p}\sqrt{\frac{273 + t_v}{293}}$, p – atmospheric pressure on the day when measurement is done (mbar), t_v – air temperature at the engine intake (ºC), v – vehicle speed (km/h), F – force on the wheels (V).

Table 2 Value of power on vehicle wheels

n r.p.m	Petrol					LPG				
	K_1	P_{1PET} kW	K_2	P_{2PET} kW	P_{PET} kW	K_3	P_{1LPG} kW	K_4	P_{2LPG} kW	P_{LPG} kW
1500	1,02	11,03	1,02	11,06	11,04	1,02	9,94	1,02	10,20	10,07
2000	1,02	14,25	1,02	14,38	14,31	1,02	14,36	1,02	14,91	14,64
2500	1,02	20,76	1,02	20,38	20,57	1,02	19,52	1,02	19,50	19,51
3000	1,03	25,01	1,03	25,34	25,17	1,03	24,46	1,03	24,44	24,46
3500	1,03	29,97	1,03	29,71	29,84	1,03	28,90	1,03	29,17	29,03
4000	1,03	33,63	1,03	33,38	33,50	1,03	31,95	1,04	32,70	32,33
4500	1,03	36,73	1,03	36,97	36,85	1,03	34,38	1,03	34,48	34,43
5000	1,03	40,21	1,03	39,59	39,90	1,03	37,72	1,04	37,56	37,64
5500	1,04	41,93	1,04	41,51	41,72	1,04	39,23	1,04	39,29	39,26

Based on the values shown in Table 2 (power on the wheels and the number of revolutions per minute of the engine using petrol and LPG), a dependency diagram of these two values was made (Figure 2).

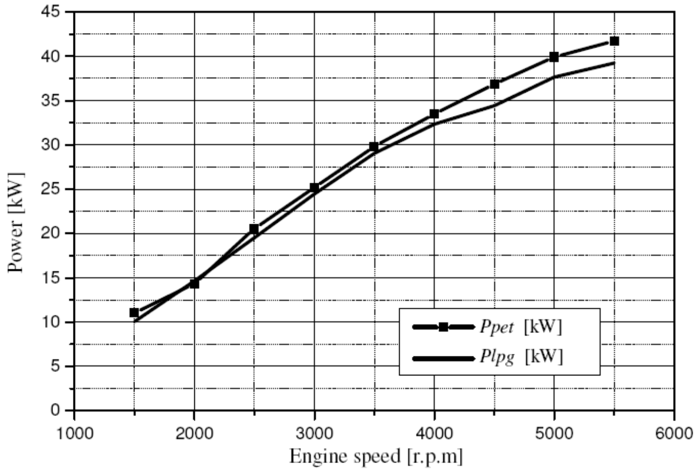

Fig. 2 Dependency of the power on the wheels on the number of revolutions of the engine

Figure 2 clearly shows that the power on the wheels of the vehicle using petrol is by approximately 8% higher than the power on the wheels of the vehicle using LPG.

In order to change to gas propulsion of road vehicles, it is necessary to convert petrol engines. A lot of factories produce equipment for conversion of petrol engines to LPG, especially in Italy, and there are thousands of workshops in which this conversion is done very quickly.

Basic parts of the supply installation of LPG engines are: tank or so called gas bottle, filling port, safety valve, evaporator, gas mixer, switch, regulator, inlet pipes, and in complex systems, control electronics (Figure 3).

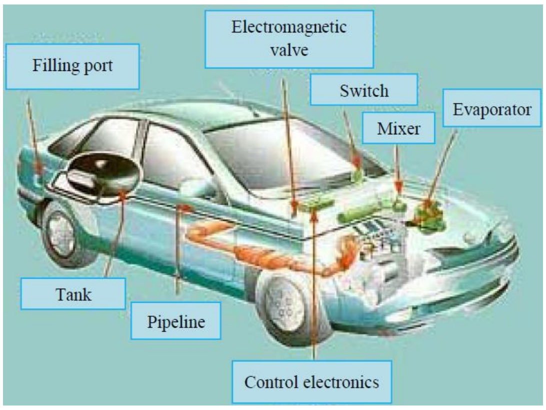

Fig. 3 Basic parts of the supply installation of LPG engines, [1]

Gas tank is usually of cylindrical shape and it is placed in the luggage compartment of the vehicle. Tank capacity is selected according to the type of vehicle and possibility of placing it. The most commonly used tanks are of capacity from 35 to 120 liters. By installing the tank, about 20 ÷ 30% of storage space in the luggage compartment is lost. There are also so called toroidal tanks that can be stored in the spare wheel well. They take up less luggage space, but the problem of the place for the spare wheel remains. Placement of the tank and the loss of usable space are the major aggravating factors in switching to LPG operation. In some vehicles it is possible to place the tanks outside, as well.

Tank connection is an assembly that allows refilling of LPG tank and it is usually placed at the rear bumper or beside the petrol filling port. From the connection, LPG is brought to the tank by insulated copper pipes. From the tank, LPG is guided by special insulated copper pipes towards the evaporator placed in the engine compartment of the vehicle. The pipes are properly secured to the vehicle floor. To prevent possible damage, all connections to the tank, as well as the safety valve, are placed in the appropriate housing which is an integral part of the tank.

The key part of the installation is the evaporator which, as its name suggests, is used for turning LPG from liquid to gaseous state. For this process, it is necessary to provide heat, because during the evaporation process, each liquid takes heat from the environment. For this purpose, the coolant of the engine is used. The evaporator is connected to the engine cooling system by hoses, so that hot water from the engine continuously flows around it and heats the liquid gas that evaporates. From the evaporator, the gas is supplied to the so-called mixer, which is located at the throttle or intake manifold in front of the butterfly valve. From there, the gas is sprayed into the carburetor and the intake manifold, and mixture of fuel and air is formed after that.

For engines that are equipped with modern electronic fuel injection systems, the installation for the supply of LPG contains additional electronic module that switches the drive from petrol to gas and vice versa. This module has the task to emulate the signal of the butterfly valve position and lambda probe signal, and necessary quantity brought to the intake manifold is determined on the basis of this.

The first generation of the systems on gas drive is applied to carburetion engines. Figure 4 shows a simplified scheme of such a system.

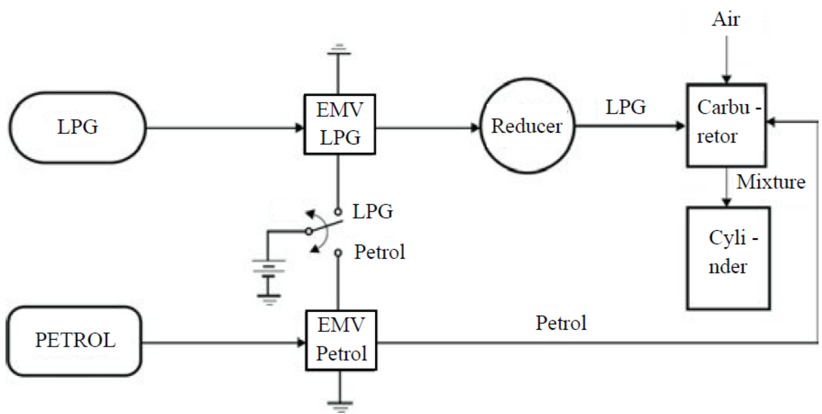

Fig. 4 Basic concept of the system for propulsion of LPG carburetor engine, [2]

The presented system allows the operation of engine with petrol or LPG, with the choice of fuel used to run the engine is made by switch (Pr) with manual or automatic activation in the operational mode of the engine. In case when the engine is gas-powered, electromagnetic valve (EMV) for petrol interrupts the supply of fuel into the float bowl and EMV for LPG opens the passage of gas from the tank into the reducer-evaporator and mixer that is placed in the zone of where the velocity of carburetor streaming is the greatest (diffuser).

In the LPG tank, gas is in liquid and vapour phase, wherein the pressure therein is equal to the pressure of saturated vapours of propane and butane at a given temperature. The values of this pressure depend on the ambient temperature and the level of fullness of the tank and they are within the range of 6 to 10 bar. As LPG tank could be destroyed, due to the expansion of the liquid phase at higher temperatures, the tank can be filled up only up to the maximum of 80% of its nominal volume.

Reducer-evaporator is usually a two-stage device. In the first stage, there is a significant lowering of temperature as a result of lowering of the pressure and evaporation of the liquid phase. To prevent glaciation, this stage is heated by the medium from the cooling system of the engine. Further, controlled reduction of the pressure to a value approximately equal to environment pressure is done in the second stage.

The mixer is made as a diffuser (venturi) of constant (eg. Landi Renzo), or variable cross section of passage (Impco) and it is placed in the main stream of air flow in the carburetor. In the mixer with constant cross section of passage, the change of underpressure in its narrowest section, which is a function of number of revolutions of the engine and the position of the butterfly valve, is transferred to the outlet of the second stage of the evaporator and it causes movement of its membrane, which changes the flow of gas into the mixer. Dosage of gas in these systems depends on the design of the evaporator, its adjustment, the design of the mixer and the flow of air through its narrowest section. Systems with mixers with variable cross-section passage operate by changing the cross-section passage in the function of underpressure in the intake system of the engine, which changes the flow of gas as well, while the pressure at the exit of the second stage of the evaporator remains approximately constant.

As the regulations on the emission of toxic components became stricter, there was a need to introduce electronic-controlled fuel injection systems with spark ignition engines (EFI - Systems), which inevitably led to corresponding changes in the system to power these engines with gas.

The simplest possible version of such a system is certainly a concept with a reducer-evaporator and mixer of constant cross-section passage as used in carburetor engines. In this case, the mixer is installed in the intake line in front of the butterfly valve, in order to ensure normal operation of electronic control unit (ECU), the emulator is placed in the system, whose role is to simulate the operation of injectors. Previously emphasized imprecision of dosage of gaseous fuel of this system and the inability to use ECU management map is a significant lack that makes its use not rational.

In order to eliminate the above shortcomings in these systems, it is common to use an electronically controlled gas valve and actuators that are placed between the evaporator and mixer (systems: Eurogas Landi Renzo, AG Autogas ALC, BRC LPGas Koltec et seq.). Operation of the valves is controlled by a special ECU, which is connected to ECU for operation with petrol, in order to use signals from the respective sensors: number of revolutions, lambda probe, butterfly valve position, the pressure in the intake line and other sensors essential for optimal management of gaseous fuel dosage.

The greatest opportunities in terms of the complexity of managing the composition of mixture and other important engine parameters are provided by systems with gas injection, analogous to petrol injection systems, can be made in versions of central injection (SPI) and injection on all cylinders (MPI).

MPI systems can be made as a continuous, time-simultaneous and sequential. Most of these systems are designed to inject LPG in gaseous state, but some manufacturers (Vialle, Tartarini), offer systems with the injection of gas in the liquid phase. In addition to precise electronic regulation and management in closed contour, a significant advantage of such systems is the ability to be mono fuel or bi-fuel/dual fuel system.

3. Reduction of Exhaust Emissions of Liquefied Petroleum Gas in Vehicles

Environmental requirements to be met by vehicles using liquefied petroleum gas in its propulsion system are defined only in 1996, as a part of the ECE Regulation no. 49 (Supplement 2 to the 02 series of amendments) for vehicles used for transportation of passengers and goods, and in 1998 as a part of the ECE Regulation no. 83 (Supplement 1 to the 03 series of amendments) for passenger vehicles.

Liquefied petroleum gas is currently commercially acceptable alternative fuel that meets all the rigorous standards on the limitation of emissions from motor vehicles, and thus it immediately offers concrete solutions to improve air quality, especially in urban areas.

Regardless of the poorer accuracy of fuel dosage, systems of the first generation of the gas propulsion of engines had significant advantages in relation to carburetor engines with respect to the emission of toxic components (Table 3).

Table 3 Components in the exhaust gases of petrol and LPG operated engines [3]

	HC g/km	CO g/km	NOx g/km	CO (idle) g/km
Petrol	1,4	16,6	1,6	1,8
LPG	0,9	1,3	1,3	0,1
Difference	-38%	-92%	-22%	-95%

Table 4 shows the values of content of basic toxic components in the exhaust gases of engines in cases when system GTI (Gas Injection Technologies ûGuildford NSW Australia) is used, made in version MPI-sequential and petrol propulsion.

Table 4 Components in the exhaust gases of petrol and GTI LPG operated engines [3]

	HC g/km	CO g/km	NOx g/km	CO_2 g/km
Petrol	0,14	1,49	0,03	334,5
GTI LPG	0,01	0,05	0,02	263,5
Difference	-93%	-97%	-33%	-21%

LPG combustion in motor vehicles, compared to modern petrol vehicles equipped with an oxidation catalytic converter, emits [4]:

- 10% less carbon dioxide,
- 40% less nitrogen oxides,

- 85% less hydrocarbons,
- 75% less carbon monoxide and
- significantly reduced content of sulfur dioxide.

Compared to low-sulfur diesel, LPG emits [4]:

- 90% less nitrogen oxides,
- 90% less hydrocarbons,
- 85% less particles and
- 60% less carbon monoxide.

When comparing emissions of so called "non-standardized" substances that pollute air, such as aldehydes, benzene, toluene and xylene with the emissions of petrol and/or diesel fuel, health and environmental benefits of LPG are much higher. Numerous tests of the impact of harmful exhaust gases from motor vehicles conclusively show that LPG as an engine fuel, if compared to petrol/diesel, has the lowest potential risk for cancerous diseases.

Studies showed that the same motor vehicle meets the requirements of Euro 3 standard when it uses petrol, whereas it meets the requirements of Euro 4 standard when it uses LPG.

4. Advantages and Disadvantages of Use of LPG as Propulsion Fuel in Vehicles

From the above mentioned facts, advantages and disadvantages of use of LPG as propulsion fuel in vehicles can be summed up as follows.

Advantages of use of LPG as fuel are:

- high heating value,
- high octane and methane number,
- lower price of LPG when compared to petrol,
- exhaust emissions are lower from the aspect of unburned hydrocarbons, carbon monoxide, aroma additives, benzene and polycyclic compounds,
- better lubrication of the engine (LPG does not wash off the cylinders and does not dilute oil),
- the equipment of vehicle is known and there should be no problems in that field,
- defined international standards (ECE R 67/01 and ECE 115),
- burning of mixture of gas and air is better, which is explained by better homogenization of the mixture; due to this, total efficiency ratio is slightly increased,
- with regard to better burning and significantly smaller quantity of solid particles (soot), quantity of deposits on pistons, valves and engine head is smaller, which extends life of pistons and piston rings,
- service life of the catalyst is extended because clogging, burnout or destruction of noble metal layer are less likely to happen,
- service life of oil in the engine is extended, because the oil is less diluted, longer preservation of total base number of oil (due to smaller quantity of acids) and significantly less deposit in the oil,
- relatively soft operation of the engine, without detonations, turns into general improvement of working conditions for bearings, crankshaft and other parts in the system, which enables longer service life of the engine,
- the risk of fire due to uncontrolled expiration or leakage is minimized, given the narrow flammability range.

Disadvantages of use of LPG as fuel are:

- harmful exhaust emissions of nitrogen oxides are slightly higher than those of petrol engines, which is explained by the higher temperature of combustion as a result of more homogeneous mixture,
- this fuel does not belong to the group of renewable fuels, regardless of the fact that it can be obtained by synthesizing coal; its use in the future will be quite limited,
- engine power is by 10÷15% lower when compared to the power of engine that uses petrol as a fuel,
- due to lower engine power, the time of the acceleration of the car is slightly longer (i.e. acceleration is worse), and the maximum speed is lower by about 5%,
- LPG usage is not recommended in engines with low compression ratio (under 8), in which valves do not have stellite coating on the valve heads and seats (basically, those include all of the older generation engines and engines with cast heads),
- in engines with low compression ratio, which use premium petrol, ignition timing would have to be subsequently adjusted when LPG is the fuel.

Despite these shortcomings in the implementation, developed countries have long been systematically working on massification of the LPG use for propulsion of road vehicles. In large cities, with great intensity of traffic, public transport buses, as well as taxis, use LPG widely. Austria has the longest tradition in this regard; almost all public buses in Vienna have been using LPG for 30 years. The situation is similar in other European countries, in Japan and the United States. In addition to public transportation, special tax incentives encourage the use of LPG in passenger vehicles (EU countries subsidize the change to gas propulsion, by participating with about 30% in the expenses). Incentives for the implementation of LPG in the EU countries refer to the possibility of parking of vehicles using LPG in places where it is not allowed to park vehicles powered by petrol.

From their production lines (Renault, Vauxhall, Ford, Volvo, Fiat, Daimler Crysler, GM, Rover) the world's leading car manufacturers deliver vehicles which already have factory implemented LPG system; these are so-called bi-fuel versions of vehicles that can use both petrol and LPG. Car manufacturers Nissan and Toyota produce mono fuel autogas version for taxi service vehicles. In addition to the aforementioned passenger vehicles, development in the field of heavy vehicles, i.e. buses that use LPG as fuel (DAF-Holland, OAF-Austria, etc.) is also prominent.

5. CONCLUSION

Extensive application of alternative fuel for propulsion of internal combustion engines is primarily caused by their good environmental characteristics, distribution of natural resources, favorable price, satisfactory driving performances, relatively simple modification of existing motor vehicles and the possibility of use in versions of mono fuel and bi-fuel systems. In recent years, the application of liquefied petroleum gas has been particularly important.

The paper presents the characteristics of the propulsion of engines with LPG, with the aim to critically analyze the trend of their development, compliance with the requirements for engines and possible improvements of their performances. What this paper irrefutably demonstrates is the fact that the use of liquid petroleum gas in motor vehicles significantly reduces exhaust emissions compared with fossil fuels.

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UPOTREBA TEČNOG NAFTNOG GASA KAO POGONSKOG GORIVA U MOTORNIM VOZILIMA

Brzi razvoj motorizacije, sve stroži ekološki zahtevi, kao i činjenice da su rezerve fosilnih goriva ograničene, neminovno je doveo i do preispitivanja koja vrsta goriva za motorna vozila, pored dobro poznatog benzina i dizela, može zadovoljiti sve oštrije ekološke i bezbedonosne zahteve i tako omogućiti prihvatljiv dalji razvoj drumskog saobraćaja. Pod alternativnim gorivom u širem smislu, smatraju se goriva koja su u stanju da zamene postojeća klasična goriva za pogon motornih vozila, kao što su motorni benzin i dizel gorivo. Već niz godina istražuju se nove vrste goriva za motore sa unutrašnjim sagorevanjem. Istražuju se goriva kojih će u dužem periodu vremena biti dovoljno, po prihvatljivoj ceni i sa povoljnim ekološkim osobinama. Pažnja se usmerava na različite alternative, a jedna od njih je smeša propan-butana, u javnosti poznatija kao tečni naftni gas. Ekonomska kriza, posebno u zemljama u tranziciji, kao i potreba za zaštitom životne sredine razlog je da se sve više tečni naftni gas koristi kao pogonsko gorivo u motornim vozilima. U radu je analiziran tečni naftni gas kao alternativno gorivo za pogon motornih vozila. Analizirani su, takođe, osnovni pokazatelji motora (snaga i ekološke karakteristike) pri pogonu na tečni naftni gas, koji potvrđuju da je ovo gorivo ekološki čistije od benzina i dizel goriva.

Ključne reči: *tečni naftni gas,* izduvni gasovi, *zaštita životne sredine*