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ORIGINAL RESEARCH

Study of dynamic and ecological properties of automotive bi-fuel engine

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Abstract
Gaseous fuels are increasingly used to power internal combustion engines. Spark-ignition engines are fuelled with liquefied petroleum gas. Engines powered by gaseous fuels are characterized by good ecological properties due to the emission of pollutants. The paper presents the results of empirical tests of two passenger cars with spark-ignition engines powered alternatively: with gasoline and LPG fuel. The engines were equipped with fifth generation LPG fuelling systems. The tests were performed on a chassis dynamometer in tests used in approval procedures in Europe (NEDC test) and in the United States of America (FTP-75 test). These tests were the basis for determining the average specific distance emission of pollutants (carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide) during the tests. The engines were also tested in the conditions of the external speed characteristics while accelerating the car in third gear. It was found that the type of fuelling the engines with both fuels has little influence on the dynamic properties of the engine due to the effective power. The tests clearly showed a decrease in specific distance emission of carbon monoxide and carbon dioxide. The relative reduction in specific distance emission of carbon monoxide was in the order of (45–65)%, and carbon dioxide—about 10%. For hydrocarbons, there was an increase in specific distance emission of hydrocarbons for the fuelling of engines with LPG, while for hydrocarbons, there was a large difference in the value of the relative specific distance emission difference for both tests. (The relative difference was from 25 to 175%.) Specific distance emission of nitrogen oxides turned out to be significantly higher when running engines with LPG. The reason for this is leaning of the fuel mixture at high rotational speed during acceleration of the car, which may result from insufficient conversion efficiency of engine control algorithms in the LPG fuel mode.

Keywords Traffic ecology · Exhaust gases emission · NEDC test · FTP-75 test · Engine performance · LPG · Spark-ignition engines

Introduction

Fuel installations for unconventional fuels in IC engines have not yet been readily adapted by automotive OEM's. There are at least five generations of LPG fuel supply systems where the first generation was based on a mixer that was responsible for spraying the vaporized LPG fuel before it was mixed with air before the throttle.

The second generation differed from the first one that it had a step motor-driven valve on the LPG fuel inlet to the mixer.

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The third generation was the improved version of the second generation. In this case, instead of the fuel mixing before the throttle, the vaporized LPG was vacuum supplied to the spigots screwed to the intake manifold pipes.

The fourth generation was based on multipoint injection of vaporized LPG into the pipes of an intake manifold of the engine.

The fifth generation differs significantly from its predecessors, because in this case to each pipe of the intake manifold, the LPG fuel is injected in a liquid phase, which means that instead of a less vaporized mixture, a pressure-regulated mixture was supplied. Another difference is the addition of a fuel pump inside the LPG fuel tank.

The sixth generation is the improvement of the fifth one, but it rather results from a need to supply the engines with gasoline direct injection by LPG in a liquefied phase.

LPG also known as liquefied petroleum gas is among the more prevalent gas fuel and is stored in the condensed phase at a pressure of approximately (0.3 ÷ 0.5) MPa, thereby effectively reducing cost as high pressure tanks are invariably not required (see [1–4]).

LPG fuel is a mixture of liquefied hydrocarbon gases, especially $C3–C4$ (hydrocarbons having 3 and 4 carbon atoms) (see [1, 3–6]). LPG has a fuel density in the range of (500–600) kg/m^3 (see [1, 3, 4]). The calorific value of LPG is about 46 MJ/kg (see [1, 3]), and the research octane number reaches the value 102–108 (see [1, 3, 4]).

Petroleum gas is obtained mainly by degassing natural gas, stabilizing crude oil in the crude oil field, distillation of crude oil, catalytic cracking and hydrocracking, thermal processing, reforming, isomerization, butadiene production and ether production [4, 7, 8].

Low production costs and as a consequence a low market price along with a high calorific value and the possibility of obtaining low emissions compared to the use of conventional liquid petroleum fuels has led to a rapid increase in the use of LPG as a fuel.

Fuel LPG is mainly used to supply the SI engines. These are therefore dual-fuel engines (see [2, 5, 6, 8–14]). Engine starting and warming are based on gasoline input. Also, the engine can work only on gasoline and only on LPG with periodic injection of gasoline to cool the combustion chamber and improve the lubricating properties of the gas fuel. There is also a possibility for spark-ignition engines to be only LPG powered—such solutions are used primarily for large combustion engines used for the propulsion of heavy vehicles [2, 15].

Mostly self-ignition engines are upgraded to spark-ignition engines fueled with LPG. However, this solution is applied more often for natural gas. Spark-ignition engines fueled with LPG have good properties due to their emission (see [5, 6, 8–14, 16, 17]). For applications of all gaseous fuels, a reduction in emission of carbon monoxide and usually hydrocarbons is the prime target, which mainly results from the fact that the emission is from a much more uniform combustible mixture as compared to the combustion of liquid fuels. The results of emissions measurements of nitrogen oxides are ambiguous. Sometimes the higher temperature of the gaseous fuel combustion causes an increase in nitrogen oxides emission as seen in the case of spark-ignition engines with direct fuel injection using LPG for a sixth generation fuel supply system. In case of the engines with direct fuel injection, an injector is used for injection of gasoline or LPG fuel in liquid phase. The process of supplying LPG via direct injection causes a reduction in emissions as the mass and the number of particles emitted is drastically reduced (see [5, 13]). Research results presented by [5] confirm very high influence of LPG fuel in case of direct injection spark-ignition engines and a substantial decrease in the emission of nanoparticles especially those harmful to health [18].

There is also the possibility of using LPG fuel to supply CI engines (see [6, 19, 20]). In this case; mixed ignition is carried out inside the cylinders. Firstly, it is the compression of diesel fuel and then spark ignition of LPG-air mixture. By supplying LPG as fuel to CI engines, we observe a reduction in emissions of carbon monoxide, hydrocarbons, nitrogen oxides and particulates. Also, to be seen is a significant reduction in noise [18].

Apart from the obvious advantage of using LPG for IC engines, there are also some disadvantages. The most significant problem is the rise in thermal load of the combustion chamber because of higher combustion temperature by light hydrocarbons and practically no gas lubricity. This may cause an increased wear of certain components, such as the plates of exhaust valves and exhaust valves seats.

Another disadvantage is that most of OEM's do not produce an engine run by LPG. Therefore, it is necessary to install an additional LPG supply system in automobiles. In comparison to the present state of technical precision of mass manufacturing of automobiles, this solution is deeply unprofessional, even if there are procedures to formally authorize LPG supply system mounting. Objections to the professionalism of the modification of supply systems also stem from the fact that the decisive factor for succeeding in properly working LPG-powered engines is the price of additional systems. In this case, these are usually the simplest technical solutions. For example, the method of LPG dose control where the only modification is the change in the algorithm of gasoline injection control. Modernization of the original power supply systems also causes adverse effects in the area of security. For this reason, it is often forbidden to park cars equipped with LPG in underground garages, since LPG fuel is more volatile than gasoline.

A more practical issue relevant to operation is the sensitivity of the vapor pressure of LPG fuel to the ambient temperature. Due to the possibility of the existing differences in the composition of the fuel, the saturation vapor strongly decreases with increasing number of carbon atoms in each homologous series, for example, in alkanes (see [1, 4]).

LPG is the most common fuel used to power the dual SI engines and therefore mainly used for passenger cars and small light commercial vehicles, the so-called delivery vans.

Despite critical evaluation using LPG as a fuel source, one must say with indiscretion that there is a lot of scope for development still. In fact, it is justifiable to say that LPG powered IC engines can significantly reduce emission and thereby increase efficiency and performance.

This article focuses mainly on the pollutant emissions and dynamic properties of a dual-fuel LPG combustion engine compared to an original gasoline engine.

The literature is dominated by information mainly on the results of pollutant emission tests in standard type approval tests. Even if the properties of the engine in dynamic states are considered, they are usually limited—apart from standard tests in homologation drive tests—to the assessment of the acceleration time of the car to a certain speed.

Article [6] reviews unconventional fuels for spark ignition and compression ignition engines in terms of physicochemical properties, sources and technological aspects of production. Currently, the most commonly used fuels are natural gas, LPG fuel and biofuels such as transesterified vegetable oils and alcohols (mainly bioethanol).

Work [12] presents the results of operational tests of the LPG fuelling system due to the risk of icing of the injector in the LPG injection system in the liquid phase. Design guidelines for injectors have been proposed based on the icing characteristics of a conventional injector. The considerations were supported by the results of empirical research.

Work [16] presents the results of simulation tests of the processes and properties of a compression ignition engine fuelled with LPG fuel. The results of the simulation tests made it possible to generalize the results of empirical tests, confirming the benefits of using LPG fuel, mainly in terms of reducing pollutant emissions.

In [21], the properties of a spark-ignition engine turbocharger powered by LPG were investigated. The results of thermodynamic analysis and empirical research are presented.

Work [22] presents the results of comparative tests of a spark-ignition engine powered by gasoline and LPG fuel. Lower useful power of the LPG fuelled engine was found, but at the same time lower emission of carbon monoxide, hydrocarbons and carbon dioxide.

Paper [11] presents the results of research on pollutant emissions from a spark-ignition engine powered by gasoline and LPG. The tests were performed on a chassis dynamometer in the NEDC test. The greatest benefit in terms of pollutant emissions was found for high engine load in the Extra Urban Cycle test for nitrogen oxides—reduction of average specific distance emission by 77%.

Paper [23] presents the results of ammonia emission tests from a spark-ignition engine powered by LPG in connection with the use of the TWC reactor in the exhaust gas cleaning system. The study showed that in the case of high temperature of the catalytic reactor and periodic enrichment of the mixture, the emission of ammonia may be increased. The studies were carried out in the WHTC test.

Work [24] reviews the use of LPG fuel to power internal combustion engines. Tangible benefits were found in the reduction of pollutant emissions from a spark-ignition engine powered by LPG fuel compared to gasoline. The considerations were supported by the results of empirical tests, mainly in the approval procedures.

Article [25] presents the results of modeling the emission of nitrogen oxides in a dual-fuel engine powered by diesel oil and LPG fuel. Simulations were carried out for various doses of LPG fuel at various engine loads. The empirical verification of the model showed good agreement with the simulation results. Simulation tests enable the optimization of the mixture composition (diesel fuel—LPG) with regard to the emission of nitrogen oxides.

The World LPG Association (WLPGA) publishes studies on the market development and application of LPG fuel. Study [26] presents an extensive analysis of the possibilities of using LPG fuel in heavy-duty engines, showing great benefits in terms of pollutant emission, especially in terms of particulate matter and nitrogen oxides.

The authors decided to supplement this state of knowledge. Firstly, it was decided to carry out the research in various tests, which makes it possible to assess the sensitivity of the test results to the vehicle traffic conditions. Secondly, it was decided to test the properties of the internal combustion engine in the most extreme dynamic state, i.e., with acceleration at full engine control settings. These properties concern both the energy properties, such as the effective power and torque, as well as the emission of pollutants—in this range, the emission intensity was studied, as it is the original quantity in the time domain, which in the case of tests in dynamic states is of fundamental importance. The presented research results are completely original and in most cases incomparable with the knowledge available in the literature on the subject.

Object, program of research and test rig

The outline of the research consisted testing two passenger automobiles equipped with 4-cylinder SI engine with a displacement volume of 1100 cm^3. Also, the engine is equipped with a LPG fuel supply system of the fifth generation using sequential fuel injection method where liquid is given as an input to the intake ports and dosing valves are controlled electronically [2]. A lambda sensor is integrated in the system to control the composition of the mixture. This works in relation with the engine after—management system which is equipped with a multifunctional catalytic converter. Algorithms of LPG supply are controlled using an electronic control unit. The described LPG fuel system is approved for all components in accordance with the regulations ECE / ONU67-01, ECE/ONU 10-02, D95 / 54 [15]). The cars were equipped with a gearbox with five gears and the reverse gear.

The outline of the research program is described below:

1. Research is done on the evaluation of dynamic properties of the engine and emissions for external engine speed characteristics during car acceleration in 3rd gear.

Also, to evaluate the dynamic properties of the engine, the effective power is calculated in terms of acceleration at full fuel dose. There were six iterations performed.

2. Calculating emissions for the NEDC (New European Driving Cycle) driving test ([15]). The study was performed four times.
3. Research on emissions for the FTP-75 (Federal transient procedure) driving test ([15]). The study was performed four times.

Note: All tests were performed on an engine heated to a stable temperature.

The study was conducted on a chassis dynamometer at the Automotive Industry Institute in Warsaw. The chassis dynamometer type EMDY 48 Schenck-Komeg is equipped with a roller having a diameter of 48 inches. For gas sampling and analysis, the CVS—7300 Horiba (with constant flow intensity) is used. To measure the concentrations of exhaust components diluted by air, a set of Horiba MEXA 7200 analyzers is used. The testing program and data acquisition were carried out by the Horiba VETS—7000 system. The equipment used in the tests meets all the requirements of the approval procedures for testing passenger cars and light duty vehicles.

The approach of the author's research about automobiles equipped with LPG differs from the information found in the literature. It was based on the investigation of an engine in the transient state depending on the increase in dosage of fuel supply, ideally for the condition when the throttle is fully opened. Engine properties are usually investigated by fuel consumption and exhaust gas emission by road tests, mainly homologation tests (see [6, 7], 12]) or by testing engine working conditions [17] in a static state, while the vehicle is being driven at a constant velocity. Research on fuel consumption and exhaust emission in conditions of vehicle acceleration with full fuel dose corresponds to the extreme operating conditions of the engine in a dynamic state.

Research results

Figures 1 and 2 depict engine speed characteristics of effective power and torque for automobiles engines No. 1 and No. 2 at full fuel dose and being powered by petrol and LPG fuel during acceleration of the vehicle. The sets of points from six series of measurements were approximated using a sixth-degree polynomial.

Comparing engine speed characteristics of automobile engines No. 1 and No. 2, there are no significant differences when comparing the two fuels, especially in case of car No. 2 during acceleration.

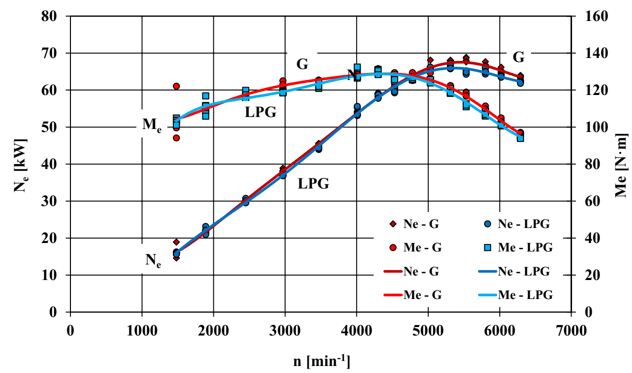

Fig. 1 Engine speed characteristics of effective power and torque of automobile engine No. 1 for full fuel dose, powered by petrol and LPG fuel

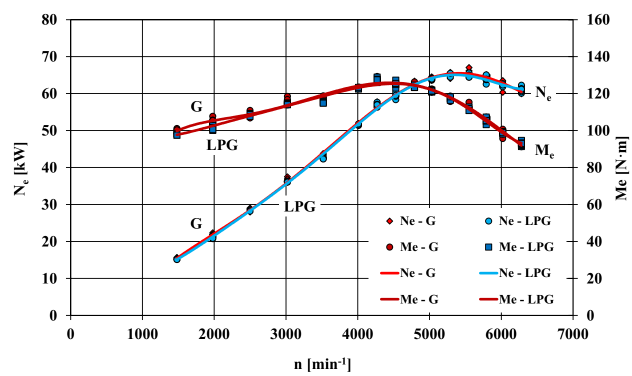

Fig. 2 Engine speed characteristics of effective power and torque of automobile engine No. 2 for full fuel dose, powered by petrol and LPG fuel

To assess the influence of applied fuel on the engine power, the relative difference of the average effective power during vehicle velocity increase was determined (see Eq. (1)). In this case, engine rotational speed varied from 1500 to 6500 min^{-1}.

$$\delta N_{\text{eAV}} = \frac{\int_{n_1}^{n_2} N_{\text{e G}}(n)\ \text{dn} - \int_{n_1}^{n_2} N_{\text{e LPG}}(n)\ \text{dn}}{\int_{n_1}^{n_2} N_{\text{e G}}(n)\ \text{dn}} \tag{1}$$

where $N_{\text{e G}}(n)$—effective power of engine supplied by gasoline as a function of rotational velocity n, $\text{N}_{\text{e LPG}}(n)$—effective power of engine supplied by LPG fuel as a function of rotational velocity n, $n_1 = 1500\ \text{min}^{-1}$, $n_2 = 6500\ \text{min}^{-1}$.

Figure 3 depicts the relative difference of average effective power between engine rotational speed from 1500 to

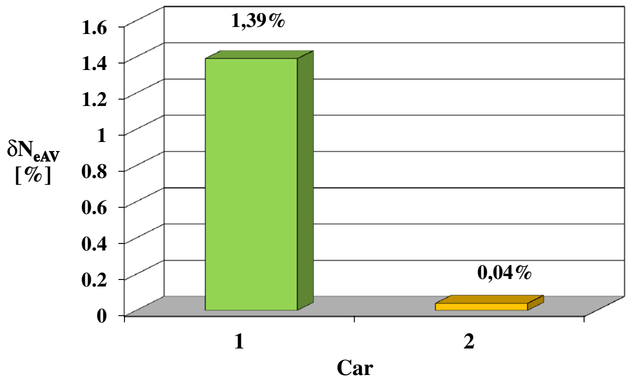

Fig. 3 Relative difference of average effective power between engine rotational speed from 1500 to 6500 min-1 for car No.1 and No. 2 for gasoline and LPG fuel

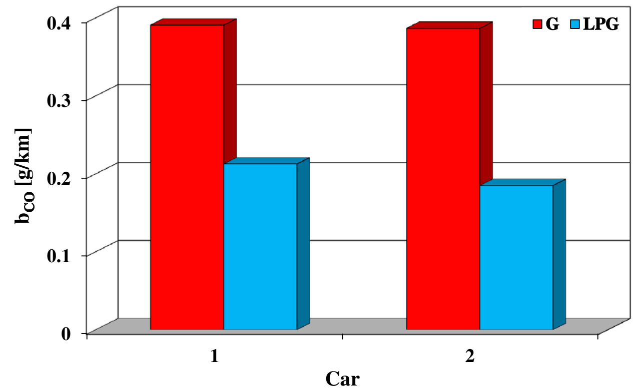

Fig. 4 Average specific distance emission of carbon monoxide in NEDC test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

6500 min^{-1} for gasoline and LPG-powered engines during vehicle acceleration.

The results shown in Fig. 3 confirm the assessment of the engine speed characteristics for engines of both cars. In case of car engine No. 1 power output and torque are slightly higher when the engine is fueled with gasoline.

These slight differences in torque and effective power for supplying engines with petrol and LPG fuel result mainly from the use of LPG fuel supply system of the fifth generation. The volumetric efficiency does not decrease when injection of LPG is in a gaseous state as compared to the liquid state.

These results confirm slight differences, first of all, in the calorific value of gasoline (about 44 MJ/kg) and LPG fuel (about 46 MJ/kg). The possibility of practically no loss of power by the engine when fuelled with LPG fuel results from the fact that the tested cars were equipped with fifth generation fuel supply systems, in which the fuel is injected in the liquid phase. Therefore, there is no deterioration of the cylinder charge filling, as is the case with LPG fuel dosing in the gas phase, as is the case in older generation systems with mixers.

As a consequence of examining the energy properties of internal combustion engines in a dynamic state, corresponding to acceleration at full control settings, it can be concluded that the fuel supply system used has practically no effect on these properties.

In Figs. 4, 5, 6 and 7, the specific distance emission of exhaust gases for an input of gasoline and LPG fuel sampled during the NEDC test for engines of cars No. 1 and No. 2 is presented.

To assess the difference between gasoline and LPG fuel supply system, a relative difference of suitable parameters is obtained according to Eq. (2):

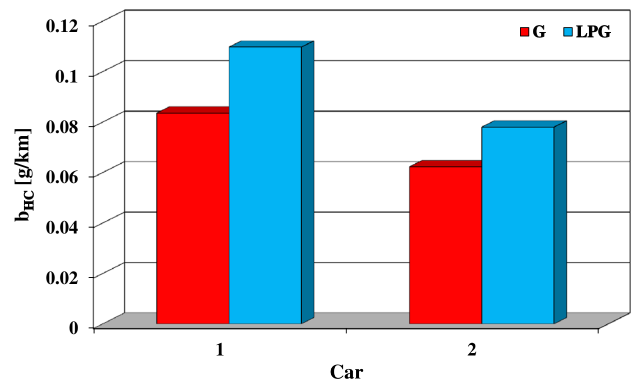

Fig. 5 Average specific distance emission of hydrocarbons in NEDC test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

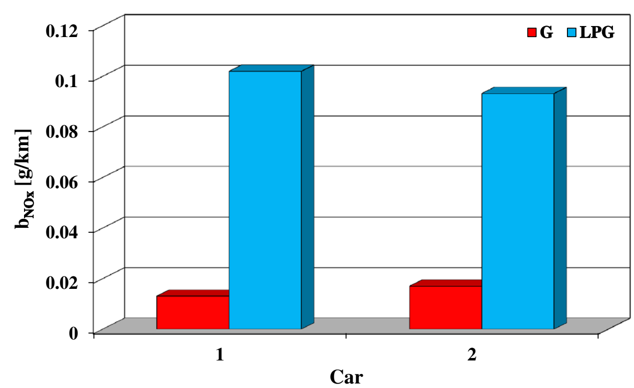

Fig. 6 Average specific distance emission of nitrogen oxides in NEDC test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

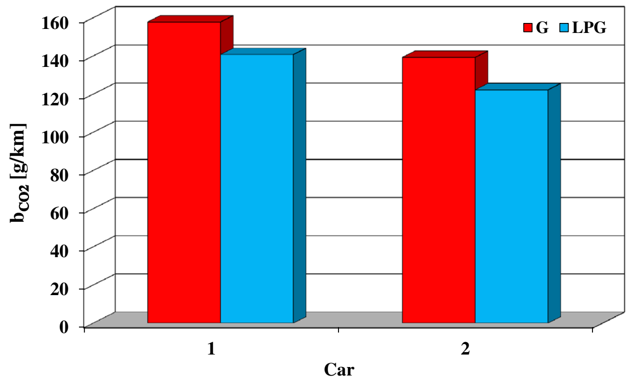

Fig. 7 Average specific distance emission of carbon dioxide in NEDC test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

$$\delta x = \frac{|x_G - x_{LPG}|}{x_G} \quad (2)$$

where x investigated parameter, x_G investigated parameter for gasoline supplied engine, x_{LPG} investigated parameter for LPG supplied engine.

Considering emission of carbon monoxide and carbon dioxide for engines of both cars, specific distance emission is lower for the LPG-powered engine. A relatively high difference is observed for carbon monoxide (car No. 1: 45.6%; car No.2: 52.2%), and as for carbon dioxide, the relative difference of specific distance emission is lower (car No. 1: 10.8%; car No. 2: 12.2%).

Considering hydrocarbons and nitrogen oxide emission for engines of both cars specific distance emission is significantly higher for an LPG-powered engine. For hydrocarbons, the relative difference of the specific distance emission for car No. 1 equaled 31. 3% and for car No. 2: 25.2%. In case of oxides of nitrogen, the specific distance emission for car No. 1 is 678.3% and for car No. 2 is 447.5%.

The reduction in specific distance emission of carbon monoxide is due to the combustion of lighter hydrocarbons in LPG than in gasoline and the formation of a more homogeneous mixture when mixing with air. In the case of road emissions of hydrocarbons, it is possible to increase it when fuelling the engine with LPG. This is possible mainly due to the relatively low reactivity of propane, especially methane, which is present in LPG fuel in a small amount. The increase in specific distance emissions of nitrogen oxides mainly results from the depletion of the mixture when dosing LPG fuel. This is due to the fact that the LPG fuel dose control algorithms in the version of the tested vehicles function in such a way that they process control signals from the original gasoline dosing controllers for the purposes of LPG fuel dosage. The signal processing algorithms are not always fast enough, and this may lead to a depletion of the mixture when accelerating. In the case of carbon dioxide specific distance emission, there are no big differences for both fuel systems.

Figures 8, 9, 10 and 11 show an average specific distance exhaust emission for FTP-75 test engines in cars No. 1 and No. 2 powered by gasoline and LPG fuel. To be precise, four series averaged measurements results are shown.

Results of exhaust emission investigation in FTP-75 tests were similar to the NEDC test. Comparing emissions of carbon monoxide and carbon dioxide for engines of both cars, emission is lower for LPG supplied engine. The major difference is in the emission of carbon monoxide (car No. 1: 63.9%; car No. 2: 59.0%), and for carbon dioxide, the relative difference of specific distance emission is lower (car No. 1: 8.4%; car No. 2: 10.0%). Specific distance emission of hydrocarbons and nitrogen oxides is significantly higher for the LPG-powered engine.

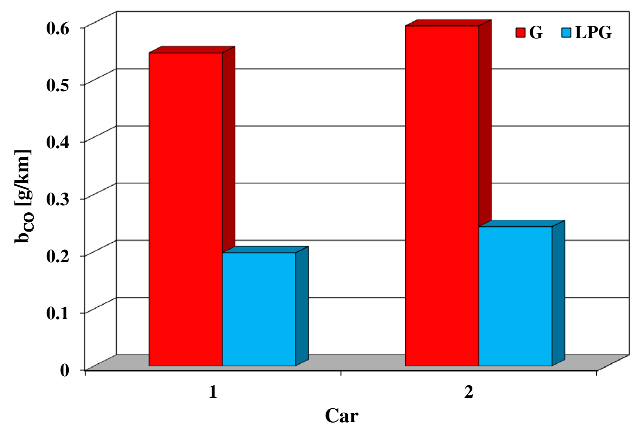

Fig. 8 Average specific distance emission of carbon monoxide in FTP-75 test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

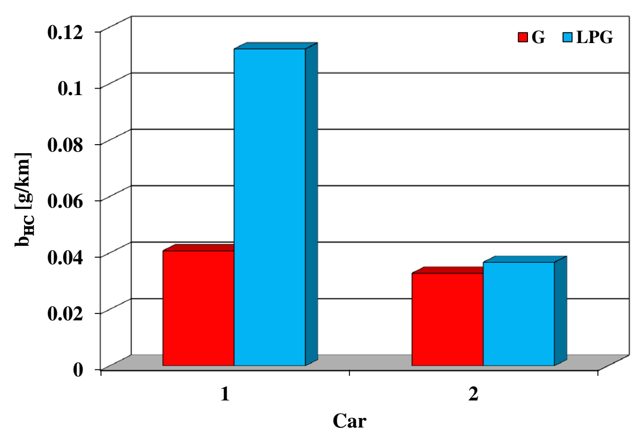

Fig. 9 Average specific distance emission of hydrocarbons in FTP-75 test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

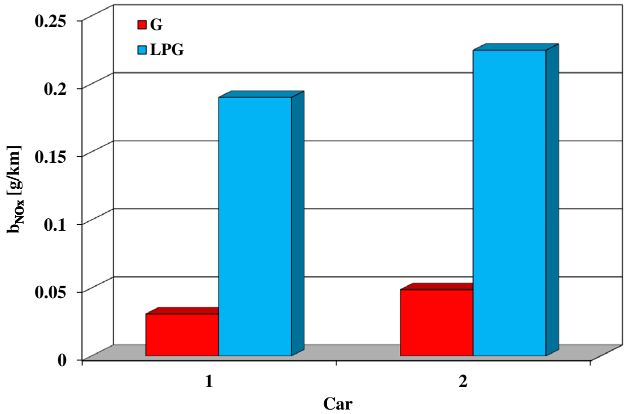

Fig. 10 Average specific distance emission of nitrogen oxides in FTP-75 test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

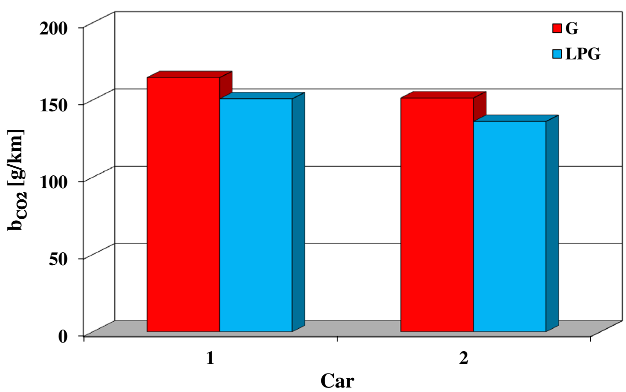

Fig. 11 Average specific distance emission of carbon dioxide in FTP-75 test for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

A characteristic difference is seen in the result of hydrocarbon emissions. The specific distance emission for car No. 1: 175.2% and for car No. 2: 11.7%. Average difference of nitrogen oxide specific distance emission for car No. 1 is 514.2% and for car No. 2 engine is 360.4%.

A comparison of the results of specific distance emissions of exhaust fumes in various tests shows that the influence of the fuel supply system used is not strongly sensitive to the engine operation states, both static and dynamic, as these states may differ significantly in the case of the NEDC and FTP-75 tests.

The comparison of the results of pollutant emission tests obtained by the authors with the results available in the literature shows large discrepancies. Only in the case of carbon dioxide specific distance emission is compliance—a relative reduction of specific distance emission by 10% [10, 11]. In the case of specific distance emission of carbon monoxide, there is a large dispersion of test

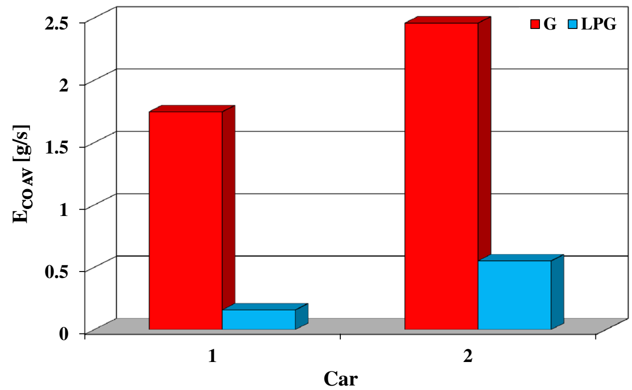

Fig. 12 Average emission intensity of carbon monoxide for engine rotational velocity between 1500 and 6500 min-1 for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

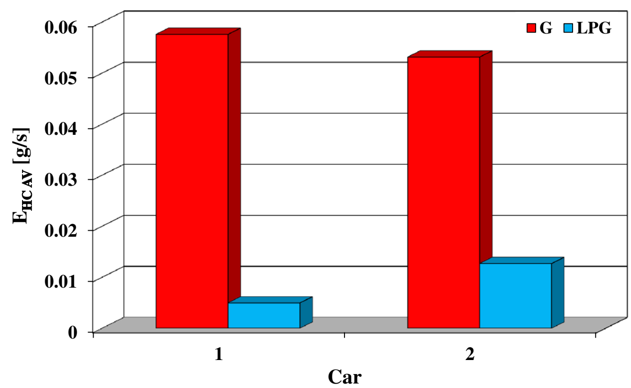

Fig. 13 Average emission intensity of hydrocarbons for engine rotational velocity between 1500 and 6500 min-1 for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

results—the relative reduction of specific distance emission is from 6% [11] to 94% for a motorcycle engine [10]. For hydrocarbons, the test results show even differences in the tendency of the influence of LPG fuelling in relation to gasoline fuelling. The relative reduction of specific distance emission according to [11] is 23%, and according to [13], there is a relative increase in specific distance emission by 5%. In this study, an increase in specific distance emission of hydrocarbons was also found, as in the case of nitrogen oxides, while according to [11], there is a relative decrease in specific distance emission of nitrogen oxides by (30–50)% [11, 13].

Also investigated was the exhaust emission for engines working on external speed characteristics during acceleration on the third gear. Figures 12, 13, 14 and 15 show the average value of exhaust emission from engines of car No. 1 and car No. 2, supplied by gasoline and LPG, when the range of engine rotational velocity is 1500 to 6500 min^{-1}. Results averaged from six measurement attempts are depicted.

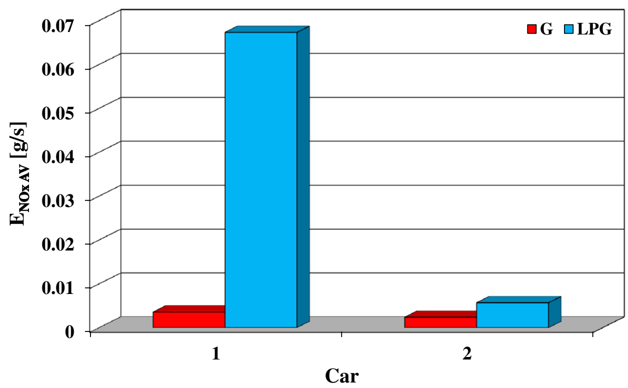

Fig. 14 Average emission intensity of nitrogen oxides for engine rotational velocity between 1500 and 6500 min-1 for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

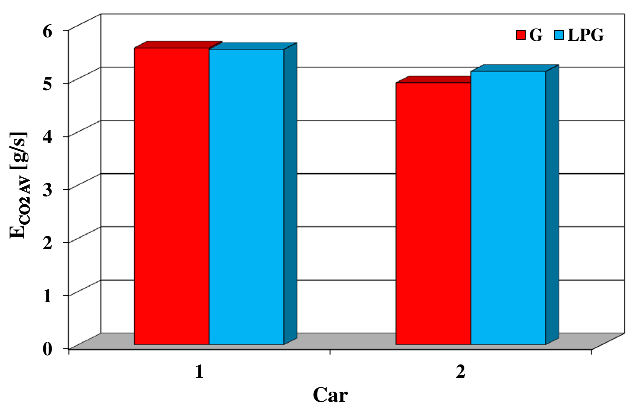

Fig. 15 Average emission intensity of carbon dioxide for engine rotational velocity between 1500 and 6500 min-1 for engines of cars No. 1 and No. 2, gasoline—G and LPG fuel supplied

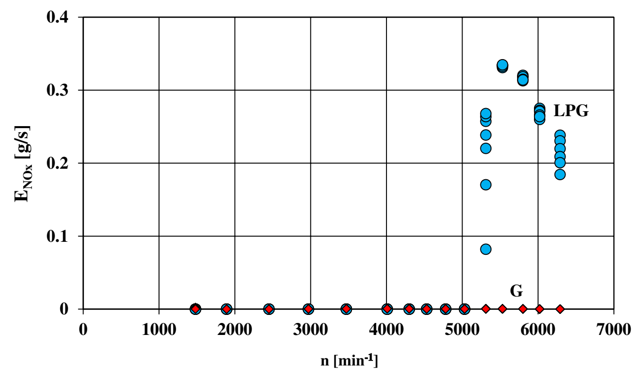

Fig. 16 Engine speed characteristics of intensity of nitrogen oxides emission for engine of car No. 1, supplied by gasoline—G and LPG fuel: a set of six attempts of measurements

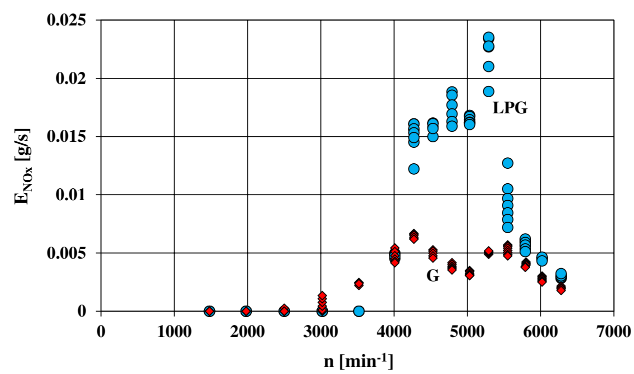

Fig. 17 Engine speed characteristics of intensity of nitrogen oxides emission for engine of car No. 2, supplied by gasoline—G and LPG fuel: a set of six attempts of measurements

There is a very significant reduction in the average intensity of emission of carbon monoxide and hydrocarbons. For carbon monoxide, specific intensity of emission equals 90.9% for the engine of car No. 1 and 77.6% for the engine of car No. 2. For hydrocarbons, specific intensity of emission equals 91.4% for engine of car No. 1 and 76.1% for engine of car No. 2.

Significant increase in the average value of intensity of emission of nitrogen oxides is differentiated for engines of both cars. Namely, for engine of car No. 1, the relative difference of the intensity of emission equals 1786.1% and for engine of car No. 2 equals 136.6%. There is also a difference in case of the average intensity of carbon dioxide emission. For engine of car No. 1, the average value of intensity of carbon dioxide emission is slightly lower for an engine supplied by LPG fuel (relative difference: 0.5%) and slightly higher for the engine of car No. 2 (relative difference: 4.4%).

The reason being the fact that during acceleration at high rotational velocity, the mixture becomes lean as less amount of LPG fuel is supplied. This is depicted by speed characteristics of intensity in nitrogen oxide emission from engines in Figs. 16 and 17.

In case of the engine of car No. 1, the effects are precisely clear when the mixture becomes lean. The reason for this may be the fact that the LPG electronic control unit is not a stand-alone. It only modifies the LPG fuel injection period in relation to the information from the gasoline fuel electronic control unit. Hence, the injection and ignition timing are adjusted in the same manner as for gasoline fuel.

This lean combustible mixture of LPG which is needed during acceleration of the car 1 results in a much higher decrease in torque and power output than compared to car No. 2.

For engines supplied by LPG integrated with an individual electronic control unit (new versions of 5th LPG fuel supply systems generation [2]), a risk of a highly lean mixture for higher rotational velocities during vehicle acceleration can result in a negative torque.

Conclusion

Based on performed tests, it is possible to conclude the following.

Comparing vehicles used for testing that are equipped with gasoline and LPG fuel supply systems, the LPG fuel supply system slightly influences the dynamic properties of the engine. The rated difference between the effective power of an engine supplied by gasoline and LPG is slightly higher than one percent. These were investigated as transient states (acceleration and maximum dose of fuel).

Results of exhaust emission measurement according to homologation procedures (for member countries of the United Nations Economic Commission for Europe—NEDC test, in United States of America—FTP-75 test) are not fully compatible with the knowledge enclosed in the literature.

The reduction of carbon monoxide specific distance emission for LPG fuelling is clearly confirmed—the relative reduction of carbon monoxide specific distance emission was in the order of (45–65)%.

In the case of hydrocarbons, an increase in specific distance emission of hydrocarbons was found, but there was a large difference for both tests — the values of the relative difference of specific distance emission of hydrocarbons for the FTP-75 test are higher (relative increase in specific distance emission up to 175%), which is characterized by stronger dynamic properties than the NEDC test.

The information on the tendency to increase specific distance emission of nitrogen oxides as a result of fuelling engines with LPG fuel is confirmed.

The type of engine fuelling did not have a significant impact on the specific distance emission of carbon dioxide (relative reduction of specific distance emission by 10%), and therefore also —as a consequence— on fuel consumption.

Investigation of exhaust emissions for vehicle acceleration with maximum fuel dose indicates that there is a significant effect of a strong and lean mixture on the measurement results. Therefore, LPG fueled engines emit on average a smaller number of hydrocarbons.

Based on the conducted research is that it is justified to continue the steps that support the development of the LPG fuel systems. These steps, whose results can already be seen in the fifth generation of LPG systems, include the use of independent LPG spark-injection control systems with newly designed algorithms. Regarding the sixth generation LPG systems that are applied to the engines with direct fuel injection into the combustion chamber, there are integrated electronic control units for gasoline and LPG fuel supply systems, where a kind of fuel is identified. Individual control algorithms differentiated for gasoline and LPG would allow minimizing the influence of fuel change on the engine's dynamic properties.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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