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EFFECT OF LPG GAS FUEL INJECTORS ON THE PROPERTIES OF LOW EMISSION VEHICLES

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Abstract

Modern spark-ignition engines used for the propulsion of low emission vehicles are fuelled by injection systems in which the fuel is individually metered to each cylinder by a single injector (multipoint injection). For the proper engine operation, it is necessary that the injectors are similar to each other and stable in respect of the fuel dosage during the whole engine operation. This requirement is satisfactorily met by petrol injectors used by OEM. In contrast to petrol injectors, gas injector used in LPG-fuelled vehicles, in particular for the retrofit, are still in the development phase and therefore their quality and production consistency are often regarded as unsatisfactory from the standpoint of view of the proper engine operation. The injector-to-injector variation in the fuel dosage results in air-fuel mixture maldistribution in the cylinders, which, in turn, affects vehicle emission characteristics.

The paper presents results of an investigation of inconsistency of gas injectors used in LPG vehicles in respect of their dosage. The method of measurement of the dosage uniformity is described.

On the basis of the measurement, three sets of injectors differing in respect of injector-to-injector variation were selected for further vehicle tests. Tests were conducted on a passenger Euro 4 car. The emissions of limited pollutants were measured over the NEDC type-approval cycle and cycle's representative for the real world driving under Polish driving conditions. The paper presents results of the conducted tests and discusses the effect of injector-to-injector variation on the pollutant emissions.

Keywords: *road transport, liquid fuels, LPG, combustion engines, air pollution, environmental protection*

1. Introduction

One of the leading activities of MTI is testing the exhaust emissions of internal combustion engines used in vehicles. For the purposes of the certification tests, they are conducted under standardized conditions. However, the particular importance has studies of emissions from vehicle exhaust system examined in real conditions exploitation. Executed works concern problems of determining the emission properties of the vehicles. One group of tested vehicles is passenger vehicles equipped with spark-ignition engines, adapted for LPG fuel supply.

As part of the realized work [1-3] it was found that emissions from the exhaust system of a vehicle powered by LPG has an increasing trend compared to the same vehicle powered by gasoline. The work to identify sources of this phenomenon was completed by continuing the studies of vehicles running on LPG [4].

In order to gather data, there were planes for an experiments series that determine how the elements of gas installations works and their influence on the emission parameters of limited exhaust gas components of vehicles running on LPG.

In the first phase, the dose uniformity tests were performed on a sample of 19 LPG injection rails. Then, on the basis of the collected data prepared bi-fuel vehicle, equipped with a gas installation. There were prepared the injectors, differing in quality control, with characteristics corresponding with injectors from the sample and subsequently assembled them in a test vehicle. On the vehicle, prepared in this way, were carried out measurements of emissions from the exhaust system.

2. Methodology of dosage uniformity assessment of LPG injector

Measurements of average expenditure of injectors were made using a device to measure gas injectors flow in conditions simulating the real conditions of the injector work.

On the measuring device, the injector is supplied with compressed air with regulated pressure. The opening of the injector is controlled by electrical impulses from the current limit. This allows for change the duration of injector opening and change the frequency of its work. Control of each injector in fuel rail takes place in a sequential series 1-3-4-2, simulating the operation of injector mounted in a four-cylinder engine of the vehicle. Comparison of average flow rate of each injector is realized based on the pressure drop on measuring nozzles and the pressure reading can be made using four liquid pressure gauges. The device indications have been validated on the basis of the indication of the gas meter. The measurements were performed in the room temperature. The injectors were on a device table during the measurements.

The research involved LPG gas fuel injectors mounted in sets in the fuel rail. In this article, the set will be called the fuel rail.

Determination of the fuel rail contains the type and a serial number, for example, IG1-III means is an injector number three, type IG1. The same designation is used for the figures.

Fig. 1. Measuring device used to measure the flow rate of injectors

Fig. 2. Measuring device used to measure the flow rate of injectors

Fig. 3. Measuring device used to measure the flow rate of injectors

Control the operation of the injector is characterized by the duration of the injector control signal and the frequency of the resulting engine speed. Each measurement was performed at constant parameters of the injector supply pressure and the frequency and time of the opening in certain conditions, marked with letters from A to D, and given in Tab. 1.

Before measuring, the injectors were conditioned for not less than 5 minutes to stabilize the flow.

Tab. 1. Gas injector operating conditions applied during the flow test

marking working conditions	injector operating frequency corresponding to the engine speed [rpm]	impulse time [ms]
A	1000	4
B	2000	5
C	3000	8
D	4000	6

To assess the nonuniformity of injectors work the ratios Δ and K were introduced. Injector error rate Δ is determined based on the formula 1:

$$\Delta_{ij} = \frac{p_{ij} - Wsr_j}{Wsr_j}, \quad (1)$$

where:
Δ – injector error rate,
p – volume flow rate of single injector,
Wsr – (average flow rate of fuel rail,
i – (injector number in the fuel rail),
j – (work conditions due to Tab. 1).

Ratio Δ determines the relative deviation of single injector‘s flow rate with respect to the average value of flow through the injectors of fuel rail. This parameter allows for the assessment of dosage of single injector in reference to the average value for the researched fuel rail in the certain work conditions.

Error rate K of fuel rail is calculated based on the formula 2. It is calculated as the difference between the highest and lowest flow rate of a single injectors in the fuel rail in reference to the average value of flow rate for all injectors of tested fuel rail:

$$K_j = \frac{W_{j\max} - W_{j\min}}{Wsr_j}, \quad (2)$$

K – fuel rail error rate,
$W_{\max}$ – maximum value of flow rate of single injector determined for tested fuel rail,
$W_{\min}$ – minimum value of flow rate of single injector determined for tested fuel rail,
Wsr – average flow rate for injectors from fuel rail,
j – work conditions due to Tab. 1.

This ratio was adopted as a measure of dose uniformity of LPG fuel by researched fuel rail.

3. Injectors research

Selection of injectors for testing was made on the basis of their incidence in vehicles. The research involved nine brand-new type of fuel rails type IG1 and 10-fuel rails type FH02 (Fig. 4 and 5).

The coefficients Δ and K by the formulas (1) and (2) were determined for each fuel rail.

Specify the Δ ratio allows for assessing the error trends of each injector with respect to the average expenditure. For fuel rail IG1-VII (Fig. 6) the ratio Δ designated for injectors 1 and 2 has negative values, for injector 3 positive values, and for the injector 4 is consistent with the value of the average flow injectors of researched fuel rail.

Research on fuel rail IG1-III shows that in the sample there are elements that have determined Δ ratios and are subject to significant change depending on the test conditions. Injector 3 in fuel rail IG1-III has a tendency to decrease, and the injectors 2 and 4 to increase the flow rate with increasing work frequency of injectors. This results in a change of K ratio, depending on test conditions.

This has an impact also on the value of the error rate of fuel rail K. The maximum value of K ratio is determined for the fuel rail IG1-VII and injector IG1-III shows a similar maximum values

Fig. 4. Fuel rail type IG1

Fig. 5. Fuel rail type FH02

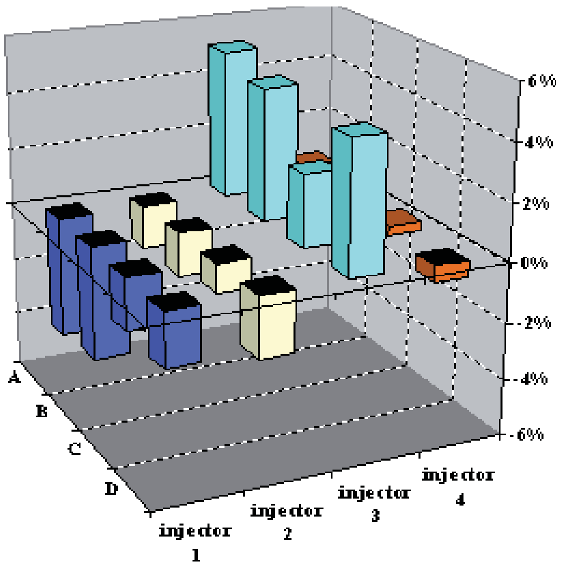

Fig. 6. Injector terror ratios Δ mounted in fuel rail IG1-VII

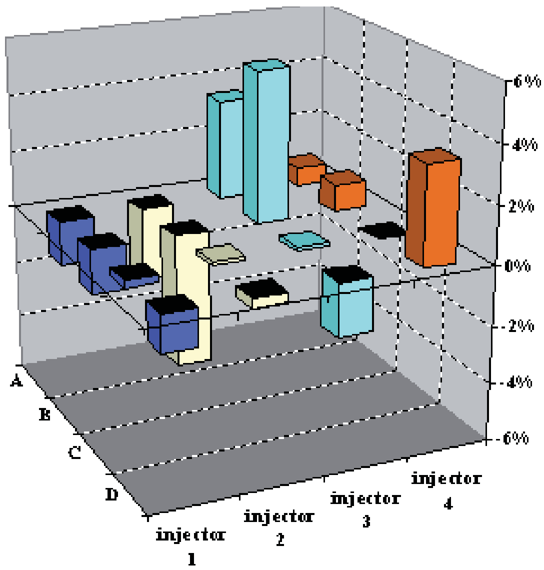

Fig. 7. Injector terror ratios Δ mounted in fuel rail IG1-III

of 9.4% and 9.9% respectively, while the minimum between 4.2% and 0.3% (Fig. 8 and 9).

The total results of K_{min} and K_{max} rations, chosen as the minimum and maximum value among the set of coefficients K_A, K_B, K_C and K_D are shown in Fig. 10 and 11.

Ratios of uniformity of fuel rail dosage ranged from 0.4 to 15% for type IG1 fuel rail and suitably from 0.4 to 15.1% for the fuel rail type FH02.

Fuel rails of the same type, same manufacturer and from the same batch are vary in uniformity of dosage. The error rates Δ of the injectors for the two types IG1 is shown in Fig. 12 and 13.

In the sample there are fuel rails, which injectors has incorrectly adjusted expense. However, after appropriate adjustment of injectors can be reduced dose nonuniformity ratio of fuel rail to be ± 5%. In the sample also found the presence of the injectors, which characteristics hampered the proper regulation because of the unequal impact of changes in injectors operating conditions of the injectors for fuel rail. Optimisation of fuel rail work with these characteristics in the selected operating conditions can have an adverse effect in other areas of operation.

Ratios Δ and K changes values depending on the frequency of operation and control, so in practice uneven fuel delivery to engine cylinders is the variable value, depending on engine speed and load.

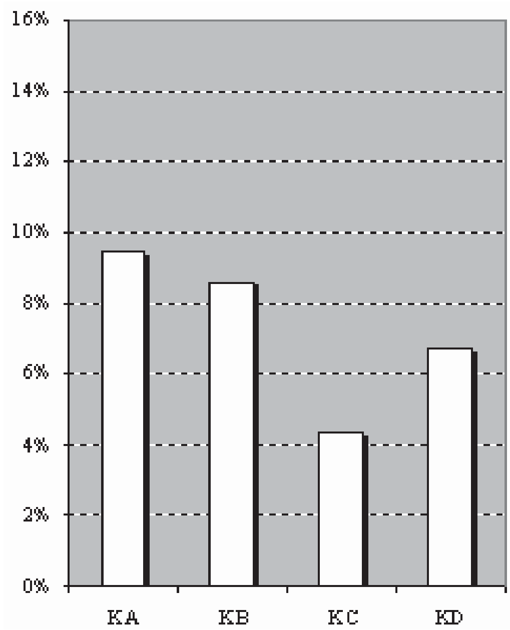

Fig. 8. Error rations of fuel rail IG1-VII

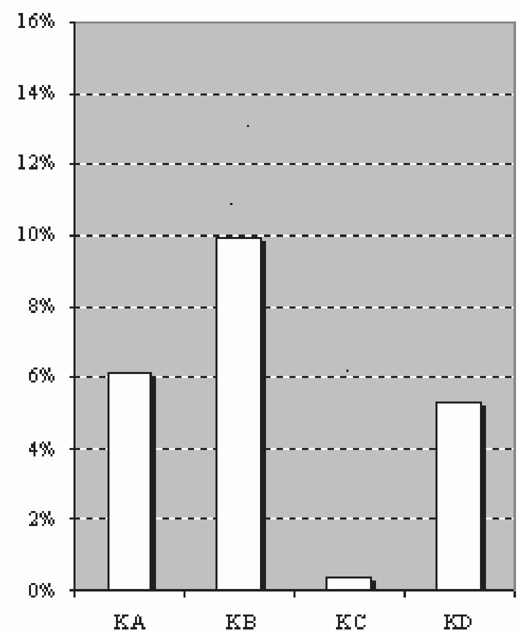

Fig. 9. Error rations of fuel rail IG1-III

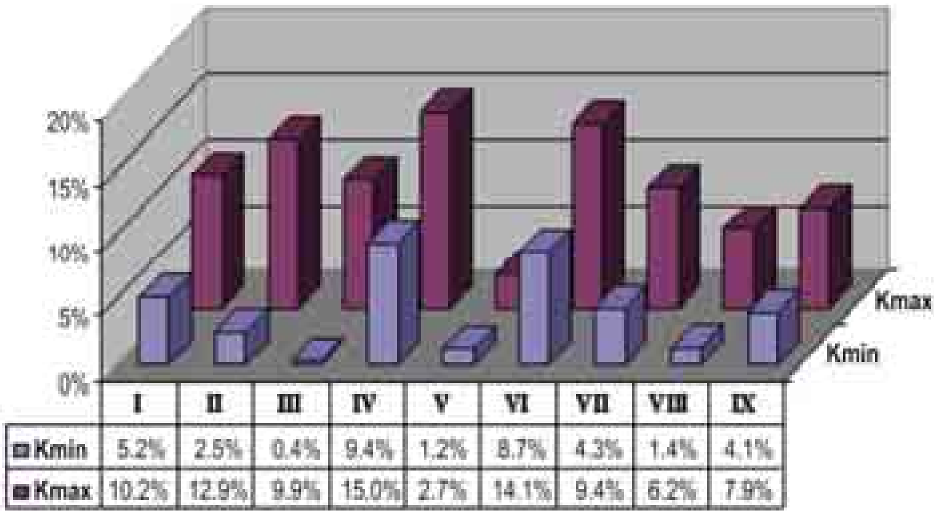

Fig. 10. Summary of minimum and maximum values of K ratio for researched population of 9 injectors type IG1

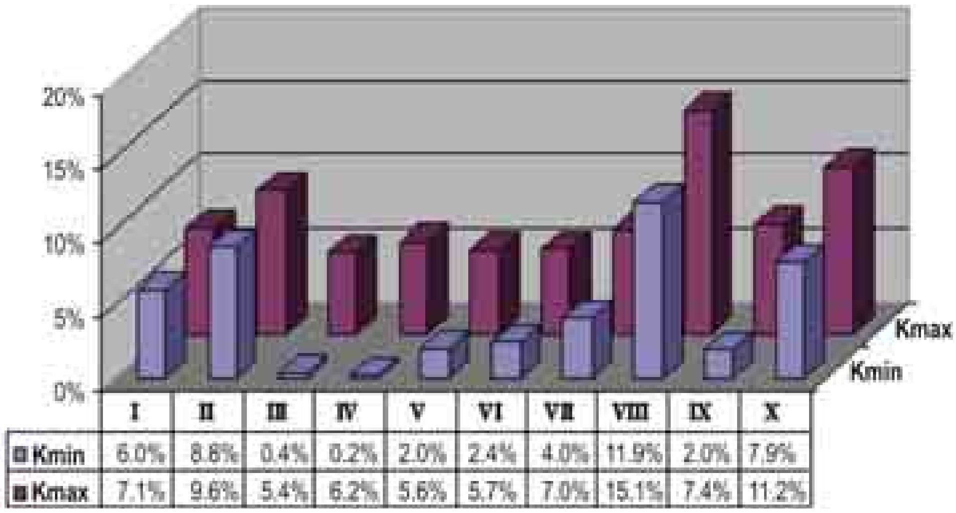

Fig. 11. Summary of minimum and maximum values of K ratio for researched population of 10 injectors type FH02

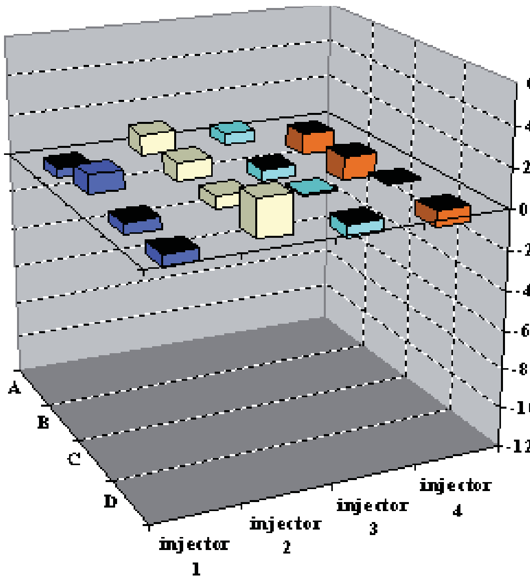

Fig. 12. Selected results of the ratio Δ research for fuel rails tyle IG1-V with the lowest dosage uniformity

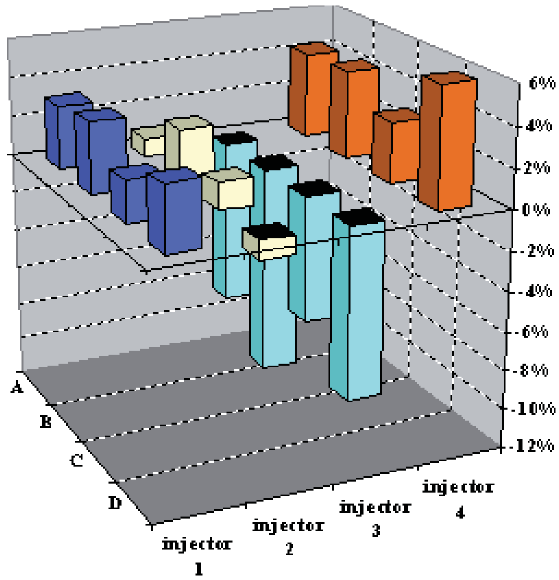

Fig. 13. Selected results of the ratio Δ research for fuel rails tyle IG1-VIII with the highest dosage uniformity

Preparing the injectors for the emission tests

Based on the tests results three-fuel rails type IG1 were prepared. It was assumed that the error rate of fuel rail should be 0%, 15% and 25% with a work frequency of 25 Hz corresponding to the engine speed n = 3000 rpm, and duration of 5 ms signal without changing the mean flow injection mouldings. The above conditions (n = 3000 rpm, t = 5 ms) are defined later in the text in terms of regulation and marked with R index.

For fuel rails, prepared this way, coefficients Δ and K were specified in conditions A, B, C and D (see Tab. 1). The results are shown in Fig. 14 and 15.

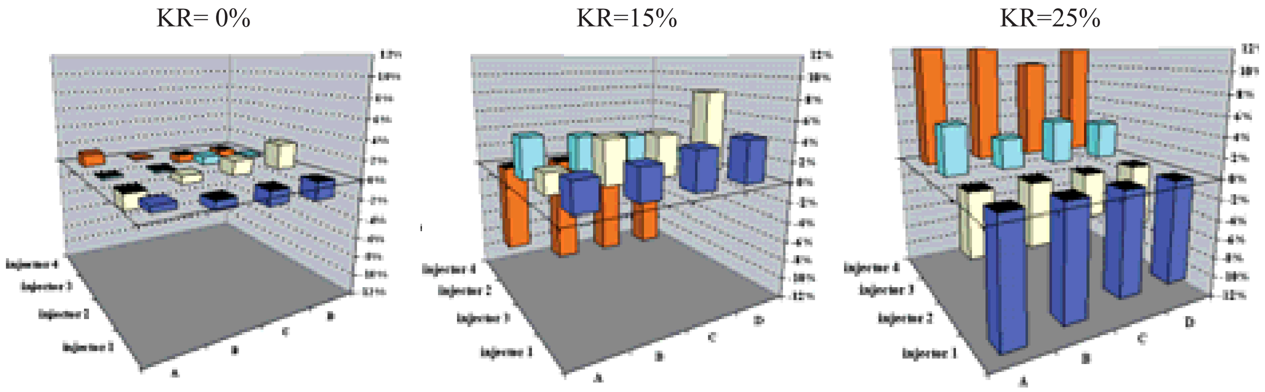

Fig. 14. Coefficients Δ specified in conditions A, B, C i D for several injectors prepared for measurements

Vehicle selection

For the study was used the passenger car, which meet the emission requirements of EURO 4 with LPG retrofit system. The indicated mileage of the vehicle was about 110 000 km, to the course of 104 000 km it was operated only on gasoline.

The vehicle was prepared for emissions testing by the manufacturer of the gas installation. The exhaust gases aftertreatment system was featured with a new, original catalytic reactor and other components were replaced such as coils, spark plugs, and lambda sensors, whose correct operation is essential to achieve good emission properties. Despite considerable progress, the

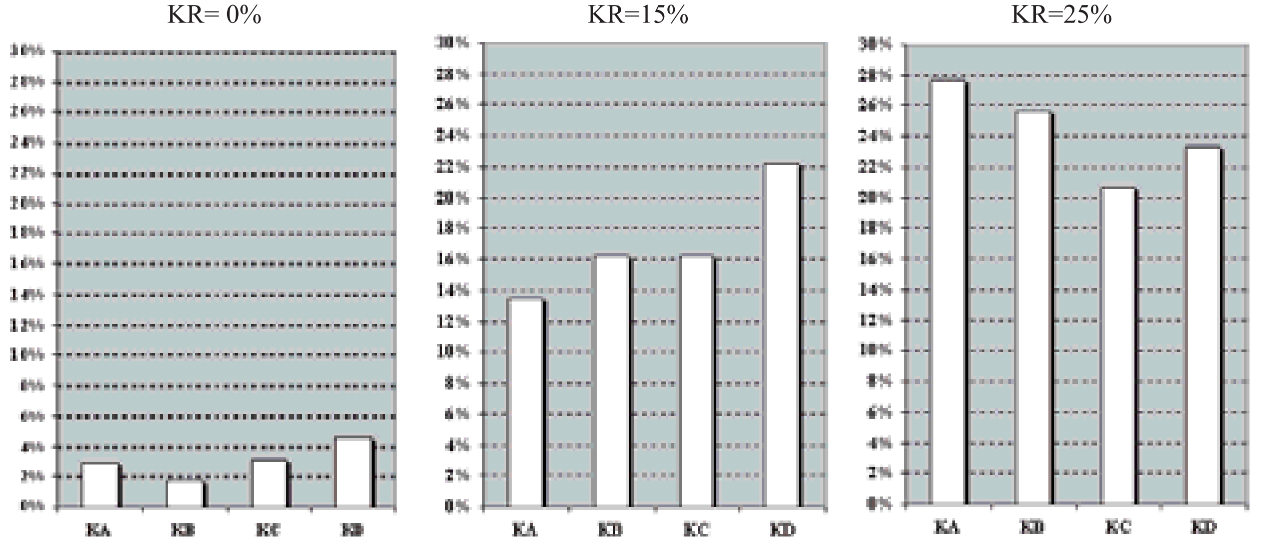

Fig. 15. Coefficients K specified in conditions A, B, C i D for each prepared fuel rails, respectively KR=0%, 15% and 25%

emissions from the vehicle contained the limits acceptable of the Regulation 83.04 (EURO 4) for the emissions at petrol supply, as well as LPG gas fuel supply. The K coefficient of originally used fuel rail of gaseous fuel should not exceed 5%.

Vehicle traffic conditions

Driving cycles conducted on the chassis dynamometer were prepared based on the research of real traffic conditions. The basic parameters characterizing the real cycles are shown in Tab. 2, thus the research of velocity as a function of time – in Fig. 16.

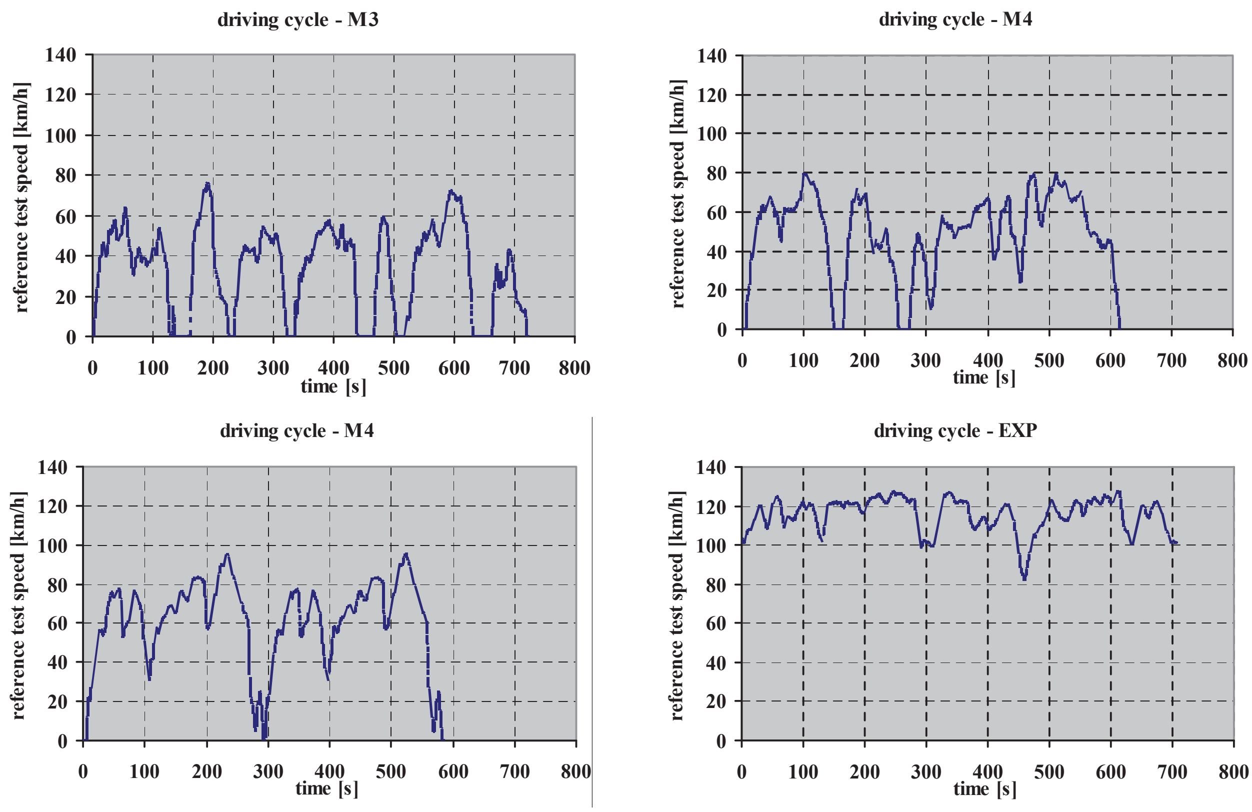

Fig. 16. Parameters of cycles used for stimulation of real traffic conditions

Tab. 2. Parameters of cycles used to simulate the real traffic conditions

cycle identification	time [s]	distance [m]	average speed [km/h]	type of traffic
M3	725	6 746	33.5	rapid urban traffic
M4	617	8 382	48.9	suburban road
M5	587	9 943	61.0	suburban road
EXP	706.5	22 706	115.7	expressway

Emissions tests

Emission tests were performed in the driving cycles described above. The research concerns vehicle brought to the thermal stability by driving at pseudo-constant speed in the range 60-80 km/h. Then there were conducted the emissions test of limited exhaust gas components such as carbon monoxide (CO), nitrogen oxides (NOx) and hydrocarbons (CH) during supply the motor engine by gasoline. Then tests were made, using LPG fuel using injectors previously prepared (see Fig. 14 and 15).

Comparison of results during gasoline supply and LPG supply and fuel rail at the lowest coefficient of LPG dosage uniformity equal to Kr=0% shows, that gas fuel supply compared to gasoline supply cause increasing the carbon dioxide emission from 158% for EXP cycle up to 9700% for M5 cycle with decreasing the nitrogen oxides in M3, M4 i EXP cycles and increasing in M5 cycle (Tab. 3 and Fig. 17). Such large increase of CO was due to that the tested vehicle was prepared to emission tests with gas supply. The nitrogen oxides emission is a greatest problem in type-approval tests according to ECE Regulation 115 for vehicles of EURO 4 category. Therefore shifting the composition of the mixture toward the rich mixtures has a purpose to reduce the tendency of vehicle powered by gas fuel to increase emissions of nitrogen oxides at the expense of an increase in emissions of carbon monoxide. The increase of carbon monoxide emission with LPG fuel supply is therefore the factor of purpose activity, typical during vehicle preparation for emissions test.

Tab. 3. Influence of the fuel and fuel rail calibration on the carbon monoxide emission [CO]

test cycle identification	M3	M4	M5	EXP
fuel / fuel rail	[g/km]	[g/km]	[g/km]	[g/km]
gasoline	0.042	0.008	0.003	0.424
LPG, Kr=0%	0.789	0.160	0.291	0.672
LPG, Kr=15%	0.246	0.262	0.246	0.609
LPG, Kr=25%	0.010	0.006	0.053	0.181

Changing the fuel rail for rail with K_R=15% causes a reduction of CO emissions in cycles M3, M5, EXP and increase in M4. While the emission of nitrogen oxides is reduced in the M3 and M5 cycles, the increases for EXP cycle and remain constant for the M4.

Changing the fuel rail for rail with K_R=25% causes a reduction of CO emissions in all cycles under results obtained for other injectors, and in three cycles M3, M5, EXP under the level of carbon monoxide emission with gasoline supply.

The value of emissions of nitrogen oxides using LPG injector at Kr = 25% significantly increase for cycles M3, M4 and M5. At the same time for EXP cycle, measured emissions of nitrogen oxides decreases below the measured value at gasoline supply (Tab. 4, Fig. 18).

Tab. 4. Influence of the fuel and fuel rail calibration on the nitrogen oxides emission [NO_x]

test cycle identification	M3	M4	M5	EXP
fuel / fuel rail	[g/km]	[g/km]	[g/km]	[g/km]
gasoline	0.012	0.014	0.008	0.011
LPG, Kr=0%	0.010	0.007	0.017	0.009
LPG, Kr=15%	0.006	0.007	0.006	0.019
LPG, Kr=25%	0.023	0.038	0.026	0.004

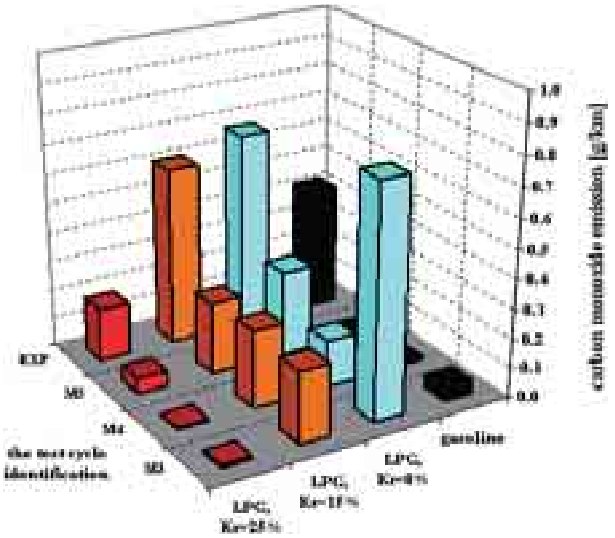

Fig. 17. Influence of the fuel and fuel rail calibration on the carbon monoxide emission [CO]

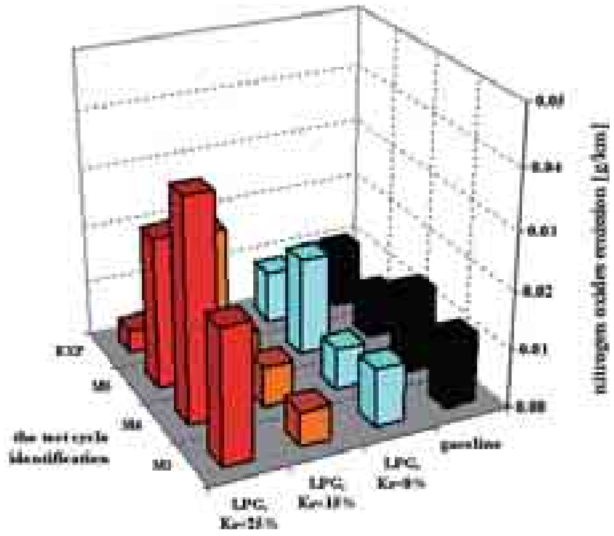

Fig. 18. Influence of the fuel and fuel rail calibration on the nitrogen oxides emission [NO_x]

In studied case, the results for cycles M3, M4 and M5 exhibit similar trends. The emission of carbon monoxide increases with the change of the fuel to the gas. The values of the supply of LPG for fuel rail with K_R=15% aren‘t differ from the values obtained for the fuel rail of K_R=0%. The application of the fuel rail of K_R=25% results in drastic reduction of CO emissions. In the case of NOx, the trend is reversed. When replacing the fuel rail of K_R=0% for fuel rail of KR = 15% there are no significant differences. Whereas changing the fuel rail for the one of KR = 25% causes a significant increase of emissions.

In the case of EXP cycle, these trends are not so clear. There is a reduction in carbon monoxide emissions, but there is no increase of NOx emissions like in other cycles.

Differences in emissions of hydrocarbons are less reproducible. This is mainly because of very small values contain in the range 0.000 - 0.017 g/km. According to the experience of laboratory, the uniqueness of the measurements of hydrocarbon emissions resulting from the uniqueness of the research object as well as the uniqueness of the conducted cycles are larger than the measured values. However, the characteristics of emission changes is consistent with the characteristics of changes in carbon monoxide emissions. In cycles M3, M4 and M5 the lowest emission is obtained at LPG fuel engine supply and fuel rail at K_R=25% (Tab. 5, Fig. 19).

Tab. 5. Influence of the fuel and fuel rail calibration on the hydrocarbon emission [HC]

test cycle identification	M3	M4	M5	EXP
fuel / fuel rail	[g/km]	[g/km]	[g/km]	[g/km]
gasoline	0.005	0.005	0.003	0.020
LPG, Kr=0%	0.013	0.004	0.006	0.013
LPG, Kr=15%	0.013	0.009	0.013	0.017
LPG, Kr=25%	0.002	0.002	0.000	0.016

Conclusions

- The results of measurements of nineteen brand new fuel rails from two batches showed, that the various copies differ from one another in terms of uniformity of dosage. The maximum values of specified error rates of fuel rails K for the studied population of fuel rails are in the range from 2.7% to 15.1%.
- The degree of dose nonuniformity of injectors, specified by coefficient K varies with changing test conditions. Thus, during the operation of a gaseous fuel engine running on gas

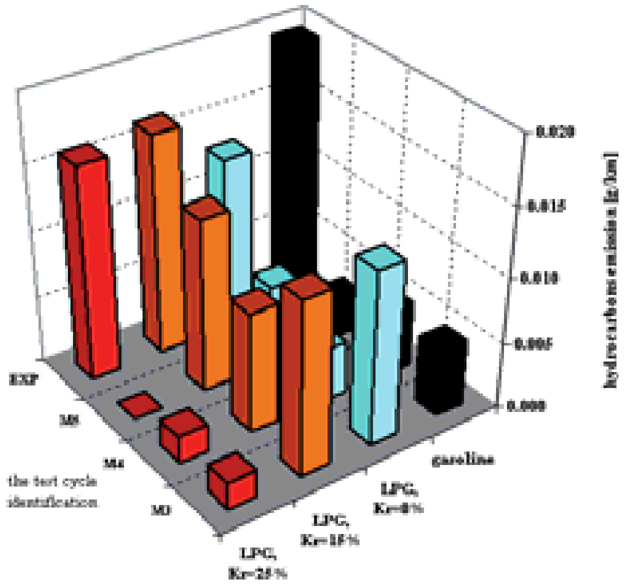

Fig. 19. Influence of the fuel and fuel rail calibration on the hydrocarbon emission [HC]

fuel, the degree of inequality of fuel delivery to the cylinders varies with the change of load and engine speed.

– According to the tested vehicle growth of the rate of fuel rail of error is a factor favouring the growth of emissions of nitrogen oxides by reducing emissions of carbon monoxide and hydrocarbons.

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