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Research on the influence and the methodology of the calibration process for Diesel-LPG dual fuel supply systems

The paper raises the problem of the lack of a methodology for how to calibrate the Diesel-LPG dual fuel system in the literature and the lack of information about the impact of calibration method on reducing the amount of consumed Diesel. Its purpose is to study such a system in which a part of Diesel is replaced by a mixture of propane and butane and to establish methodology of choosing the calibration parameters to ensure the maximum reduction in the amount of burned Diesel while keeping the engine durability. The results of the research done on the road and chassis dynamometer, carried on the van type vehicle, allow to conclude that the reduction in the amount of consumed Diesel may vary by up to 25% between different calibration methods.

Key words: *compression-ignition engine, dual fuel supply, LPG, calibration*

1. Introduction

The fuel market is a dynamic one. Despite of a recent sharp drops in fuel prices, due to political reasons, during prolonged periods the fuel prices tend to rise. During the last decade fuels prices increased by approx. 50% (Diesel from 3.3 to 4.9 zł, premium unleaded gasoline (95) from 3.5 to 5 zł). In the same period, the price of LPG increased by 25% (from 2 to 2.5 zł). As a result, even users of cars with Diesel engines, which are known for small consumption, started to look for solutions that would help to reduce exploitation costs. Because dual fuel systems for petrol engines are known to achieve great financial and environmental benefits, a concept of similar system for Diesel engines was put into practice.

At first one should consider why have dual fuel systems for petrol engines became so popular? LPG is a fuel, that has a higher calorific value than gasoline and Diesel (respectively: 46 MJ / kg to 44 MJ / kg and 43 MJ / kg) and higher octane rating (approx. 102), what in theory translates into an increase in engine efficiency. Other advantages are associated with the combustion process: easiness of obtaining a homogeneous mixture and the prolonged life of engine due to lack of dissolved gas in the engine oil. However, beside all these advantages, the autogas is used mainly for one reason: the low price. In petrol engines, in which it is possible to replace up to 98% of gasoline with LPG, it allows to achieve significant savings.

When it goes to the adaptation of Diesel engine there is one major problem. In petrol engines the ignition source is a spark from the spark plug. Diesel engines don't have one, and the ignition source is the auto-ignition of Diesel under high thermodynamic parameters in the combustion chamber. Therefore, two approaches were considered: intervention in the engine block and installation of additional spark plugs, or leaving Diesel as a source of ignition and reducing the amount of fed fuel only to the amount that allows it to perform as it. Mainly because of the simplicity (and therefore lower cost) and lower engine failure possibility, the second solution is widely used.

The purpose of this paper is to analyze such dual fuel system, in which a part of Diesel is replaced by a mixture of propane and butane, and to establish a methodology of choosing the calibration parameters of LPG system, to ensure maximum reduction of the Diesel consumption. Vehicle with dual fuel system must meet all the requirements set for such a system, which are to be determined later in the paper. These calibration parameters will also be tested on road, to determine combined fuel cost.

2. Methods for the dual fuel system calibration after installation

The most important step in the assembly process of the dual fuel system is the calibration. The paper will discuss two main calibration methods currently used: “on the road” and on a chassis dynamometer. In both methods the beginning is the same: one should connect to the LPG electronic control unit (LPG ECU).

The program used during studies is Dual Fuel Elpigaz I MP48DF version 3.0.1.23. Other programs available on the market may vary visually, but the basic function of the program, that is to determine gas injection and pressure emulation maps, must be contained.

During the calibration on a chassis dynamometer, the same as in the calibration on road, one is using two arrays (so called “maps”) that allow to enter values: "Map GAZ-G - Home" and "Map DIESEL-R - (pressure emulation by RPM)". Both maps are set depending on engine speed (RPM) (horizontal top row of the map) and the accelerator pedal position (far left column), parameters, that determine the engine load.

If one makes change on the map "map GAZ-G – Home”, for example, by increasing the value by 10 units, it will theoretical extend the opening of gas valves by 1 ms. At this point three important issues should be emphasized. First, the injection time is extended only theoretically by set unit of time. For example, adding 80 units does not actually increase opening time of the gas injectors by 8 ms. The time varies from the set one due to correction parameters. Second, even with the best currently available injector opening time should not be less than 2.5 ms. The time shorter than this doesn’t provide the operating element of the injector (plunger, membrane) enough time to return to the rest position and to cover of the outlet channel, resulting in the continuous outflow of the gas to the collector. The last issue is the gradual increase of injector opening time. In both the horizontal and the vertical ways this change should not be more than 35 units between cells. That makes it sure that the actual injection time does not change more than by 3.5 ms, which means more steady change of the engine’s operating point.

Changes on the map "Map DIESEL-R - (Cisne emulation by RPM)" are read by the ECU as a percentage change, where the level of 100 units is equal to no emulation. The higher the value above this level, the lower amount of Diesel is fed to the system (thus entering into the map a value of e.g. 130, will be read by the central unit of the vehicle as if the pressure in the power supply system rail was 30% greater than the actual pressure, and a corresponding reduction of oil feeding time will occur). It should be noted, that this does not mean that the dose of injected oil was reduced by a specified value (in this example 30%), and only the injection time was adjusted to a pressure read out the emulation. This allows to say that it was definitely reduced, but without further examination it cannot be determined by how much.

3. The essence of the calibration process

The calibration process comes down to finding the balance point between several parameters correlated with each other and the characteristics of the operating engine, so that for each point of the map all the requirements of properly calibrated installation (Table 1) are met. The goal of the process is to achieve the maximum reduction of fed Diesel, while still meeting all the requirements.

Unfortunately, all of the relationships between these parameters can not be represented by a single function, but to illustrate the complexity of the problem some correlations between them will be presented:

- providing autogas and increasing its injection time (at constant emulation level) results in a non-linear increase in

temperature, non-linear decrease in the air–fuel equivalence ratio, the initial growth of the vehicle's power, and after a certain point its decline and uneven operation of the engine;
- increasing pressure emulation in the rail (at constant gas injection time) causes a nonlinear increase of air–fuel equivalence ratio, non-linear increase of temperature, and after a certain point its decline, the initial growth of the vehicle's power, and after a certain point its decline and uneven engine operation.

Table 1. Requirements for properly calibrated gas installation

No.	Requirement
1	Obtaining the same air–fuel equivalence ratio (λ) for an engine running using only Diesel and the engine running on dual fuel supply.
2	Obtaining no more than approx. 30°C temperature rise at each of the cylinders after switching the supply system from Diesel to bi-fuel.
3	No noticeable increase in engine power after switching to bi-fuel.
4	No noticeable decrease in engine power after switching to bi-fuel.
5	Steady work of engine on dual fuel (no jerking).

Another element that hinders the process is the lack of simple relations in case of a simultaneous changes to both of the control parameters (gas injector opening time and the pressure emulation).

As a result, the calibration process can not be put in simple frameworks of mathematical relations or linear patterns.

4. Calibration on a chassis dynamometer

To summarize all of the information so far, the calibration methodology for a vehicle on a chassis dynamometer can be put in the following scheme:

i. Preparation of the vehicle for the calibration – connecting vehicle to the program;
ii. Preparation of the vehicle for the calibration - additional elements (thermocouple etc.);
iii. The division of the two maps into identical calibration areas (Fig. 1*a*);
iv. Setting the load on the chassis dynamometer that will allow the engine to operate in the range of loads included in a selected area of calibration;
v. Selecting a single calibration point in the area and then manipulating the engine to get into that point and remain at it;
vi. Specifying the number of units that will provide injector's opening time of no less than 2.5 ms;
vii. Increasing the level of pressure emulation in the rail until the engine runs unevenly;
viii. Increasing the amount of fed autogas until the identical resistive torque at the wheels on mono and bi-fuel supply will meet;
ix. Controlling the temperature changes on each of the cylinders and the λ in the transition of power from Diesel to bi-fuel;
x. Applying appropriate changes to the calibration parameters;
xi. Using the same calibration parameters for the whole calibration area;
xii. Random inspection of how bi-fuel system operates in other points than the original point inside the calibration area;
xiii. Random inspection of the dual fuel system operation in other than the original point of the field calibration area;
xiv. The amendment of the calibration parameters (if necessary) in the inspected points;
xv. Going to the next calibration area by repeating the procedures from step iv;
xvi. After calibrating the whole map end calibration (Figure 1*b*).

While the procedure itself does not seem complicated, it's true complexity is hidden in the tenth point. After the first nine stages of the procedure, the engine probably will not work properly. There are problems with achieving even operation of the engine or the applicable parameters (temperature, λ). It can therefore be assumed that obtained calibration is the starting point for further amendments. From this point the only option is searching for the best parameters by trial and error. It is a laborious process, but done properly allows to achieve a reduction unattainable in the “on the road” calibration process.

5. Calibration "on the road"

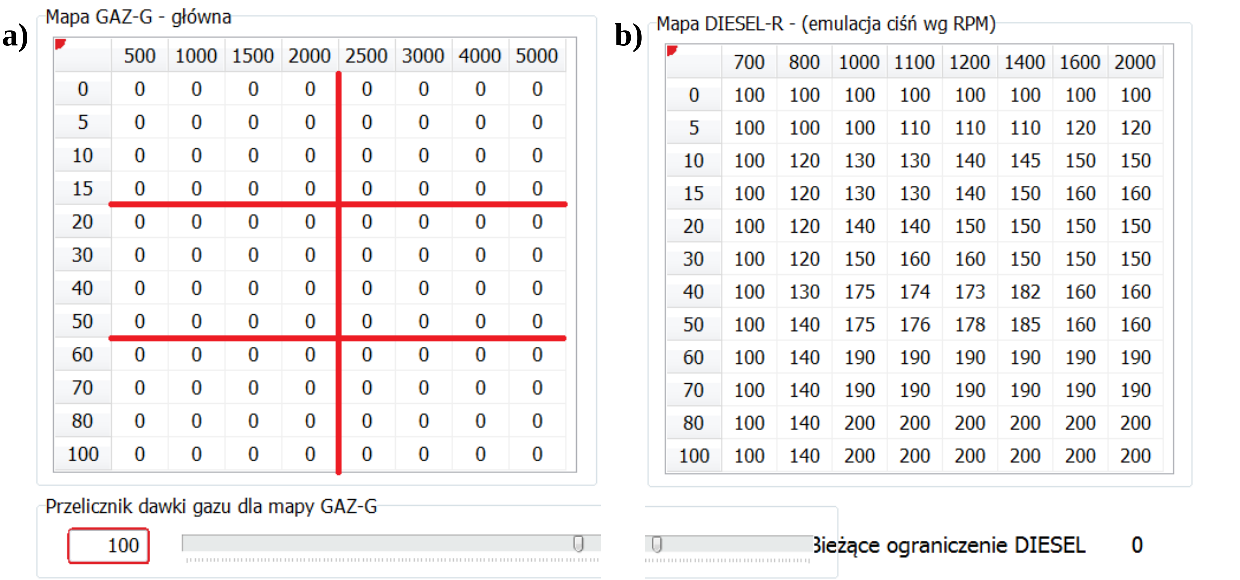
Calibration "on the road" is performed to establish a complete map of the bi-fuel system on the basis of data obtained by loading vehicle’s motor while driving on the road. During the calibration "on the road" it is much more difficult to determine whether some of the requirements (Table 1) are met, due to the dynamic nature of changes occurring in the process. Therefore, the maximum reduction of Diesel is often not achieved, but only a reduction that allows to say with certainty that the requirements have been met.

It is difficult in this case to indicate the specific methodology of the proceedings, but the beginning of the calibration scheme should be analogous to the calibration procedure in the case of a chassis dynamometer.

The biggest change is how the optimal calibration parameters should be determined. They should be gradually increased, all while examining the fulfillment of the requirements. As soon as the next step would not fulfil all of the requirements one should find closest parameters that do and from there proceed as from tenth point in the procedure.

6. Basic information about performed examination

From her on the paper is devoted to the research carried out on the van type vehicle (Table 2). The dual fuel system in the vehicle has been calibrated on the basis of the information contained in the theoretical part of this study. The aim of the research is to verify the correctness of presented calibration methodology and determine the economical differences between two presented calibration methods.



a) Mapa GAZ-G - główna

	500	1000	1500	2000	2500	3000	4000	5000
0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0

b) Mapa DIESEL-R - (emulacja ciśń wg RPM)

	700	800	1000	1100	1200	1400	1600	2000
0	100	100	100	100	100	100	100	100
5	100	100	100	110	110	110	120	120
10	100	120	130	130	140	145	150	150
15	100	120	130	130	140	150	160	160
20	100	120	140	140	150	150	150	150
30	100	120	150	160	160	150	150	150
40	100	130	175	174	173	182	160	160
50	100	140	175	176	178	185	160	160
60	100	140	190	190	190	190	190	190
70	100	140	190	190	190	190	190	190
80	100	140	200	200	200	200	200	200
100	100	140	200	200	200	200	200	200

Fig. 1. An example of a complete array of gas: a) before calibration sample indicating areas of calibration, b) after calibration

7. Basic information about performed examination

From her on the paper is devoted to the research carried out on the van type vehicle (Table 2). The dual fuel system in the vehicle has been calibrated on the basis of the information contained in the theoretical part of this study. The aim of the research is to verify the correctness of presented calibration methodology and determine the economical differences between two presented calibration methods.

8. Measurement on a chassis dynamometer

a) Characteristics of the test vehicle speed section when running mono fuel

Comparing the ratings of the vehicle (Table 2) with the data obtained during the measurements (Table 3) can be seen a large discrepancy in the value of maximum power speed (lower than 300 rev / min) and greater than rated maximum torque (more than 35 Nm). As a result, both offset each other and engine flexibility does not change significantly. The results are the basis for all subsequent comparative measurements.

b) Characteristics of the test vehicle speed section when running on dual fuel after "on the road" calibration

In order to verify the difference between "on the road" calibration and calibration on a chassis dynamometer measurements were also carried. As can be seen (Table 3), there has been an increase in the maximum power speed and a change in the point when maximum torque is reached (increase) and its value (decrease). As a result a significant decrease in the flexibility of the engine can be noticed. While driving the car could be characterized with lack of noticeable changes in power, but there has been a noticeable

c) Characteristics of the test vehicle speed section when running on dual fuel after calibration on a chassis dynamometer

The characteristic points (Table 3) of the obtained characteristics (Fig. 3), show a large increase in power (16.6%), the maximum torque (5.4%) and a large decrease in elasticity (10.4%) compared to a mono power. However, during the study it was not possible to notice. The car was characterized by noticeably good acceleration (better than when powered with Diesel) and noticeable power increase, what was acceptable in the terms of requirements for calibration increase in acceleration compared to mono fuel.

Table 2. Data of the examined vehicle

Vehicle manufacturer	Renault
Model	Trafic II
Engine type	1,9 dCi (four-cylinder row type compresion ignited)
Year of manufacture	2004
Vehicle category	N1
Body type	Van
Engine displacement	1870 cm^3
Maximum power	74 kW (100 KM)
The rotational speed of maximum power	3500 rev/min
Maximum torque	240 Nm
The rotational speed of maximum torque	2000 rev/min
Engine flexibility	2,08
Fuel system	Common Rail with turbocharger
LPG system type	LPG, Full Group, FG2 by Elpigaz

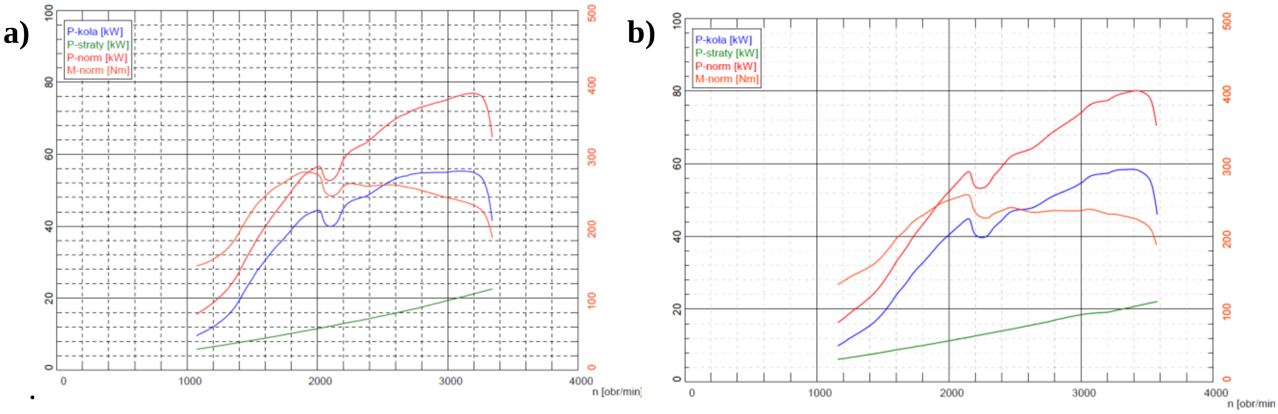


Fig. 2. Characteristics of the test vehicle speed section when running: a) mono fuel (Diesel), b) dual fuel after “on the road” calibration

Table 3. Characteristic points of the test vehicle speed characteristics when running base fuel and dual fuel “on the road” and chassis calibration

No.	**Parameter**	**Measurement (base fuel)**	**Measurement (dual fuel „on the road”)**	**Measurement (dual fuel chasiss)**
1	Maximum power at the wheels	55 kW	58,3 kW	61,9 kW
2	Maximum power on the motor shaft	76,1 kW	79,1 kW	88,7 kW
3	The rotational speed of maximum power	3190 rev/min	3420 rev/min	3225 rev/min
4	Maximum torque	275,2 Nm	257,2 Nm	290 Nm
5	The rotational speed of maximum torque	1910 rev/min	2130 rev/min	1950 rev/min
6	Engine flexibility	2,02	1,87	1,83
7	Meeting the requirements of the calibration	not applicable	Yes	Yes

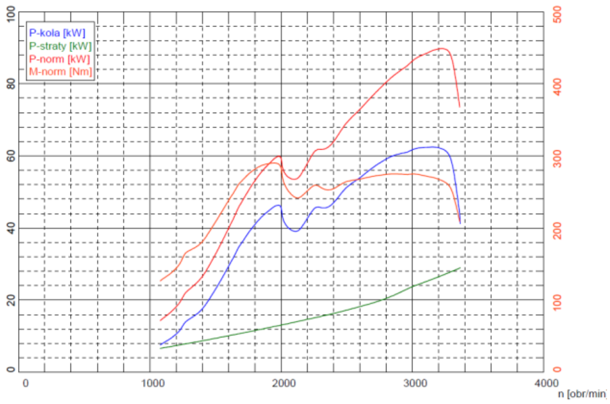


Fig. 3. Characteristics of the test vehicle speed section when running dual fuel after calibration on a chassis dynamometer

d) A series of measurement based on the calibration parameters change

Table 4 presents the results of a measurement series in which suitably described calibration parameters of the gas system were changed. Changes were introduced in the whole range of maps array by percentage (+ increase it by X%; - reduction of the parameter by X%).

Comparing all the measurements with the initial calibration (measurement #2 in Table 4) it can be seen that:
- the biggest increase in power beyond primary calibration obtained at 4, 8, 9, 10;
- the greatest loss of power obtained with the calibration 6, 7, 12;
- the largest increase in torque calibration obtained at 4, 8;
- the biggest drop in torque calibration obtained at 5, 7, 11;
- the largest increase in maximum power speed and torque calibration obtained at 3, 5, 9, 10. They are also calibrations, which have some of the largest engine flexibility. The largest increase occurred flexibility for calibration 8, and the biggest drop for calibration 11.

Table 4. Results of a series of measurements to optimize the calibration parameters of the gas system

Nr	Description of measurement	Maximum power at the wheels [kW]	Maximum power on the motor [kW]	The rotational speed of maximum power [obr/min]	Maximum torque [Nm]	Maximum torque speed [obr/min]	Engine flexability [-]	Meeting the requirements of the calibration
1	ON	55	76,1	3190	275,2	1910	2,02	Not apllicable
2	ON + LPG	61,9	88,7	3225	290	1950	1,83	Yes
3	LPG *+5%*	64,1	85,2	3420	279,7	2085	1,93	Yes
4	LPG *+10%*	63,9	87	3205	304,2	1965	1,91	No
5	LPG *-5%*	61	83,3	3440	272,7	2110	1,92	Yes
6	LPG *-10%*	60,1	81,5	3165	288	1965	1,89	No
7	EMULATION *+10%*	58,2	81,1	3180	274,8	1970	1,82	No
8	EMULATION *-10%*	64,6	88,9	3225	310,9	1955	1,95	Yes
9	LPG *+5%* EMULATION *-5%*	63,8	85,4	3425	283	2110	1,93	Yes
10	LPG *-5%* EMULATION *-5%*	63,3	85,3	3420	282,9	2100	1,93	Yes
11	LPG *+5%* EMULATION *+5%*	60,1	84,8	3180	275,8	1995	1,73	No
12	LPG *-5%* EMULATION *+5%*	59,4	82,6	3215	281,2	1960	1,88	No

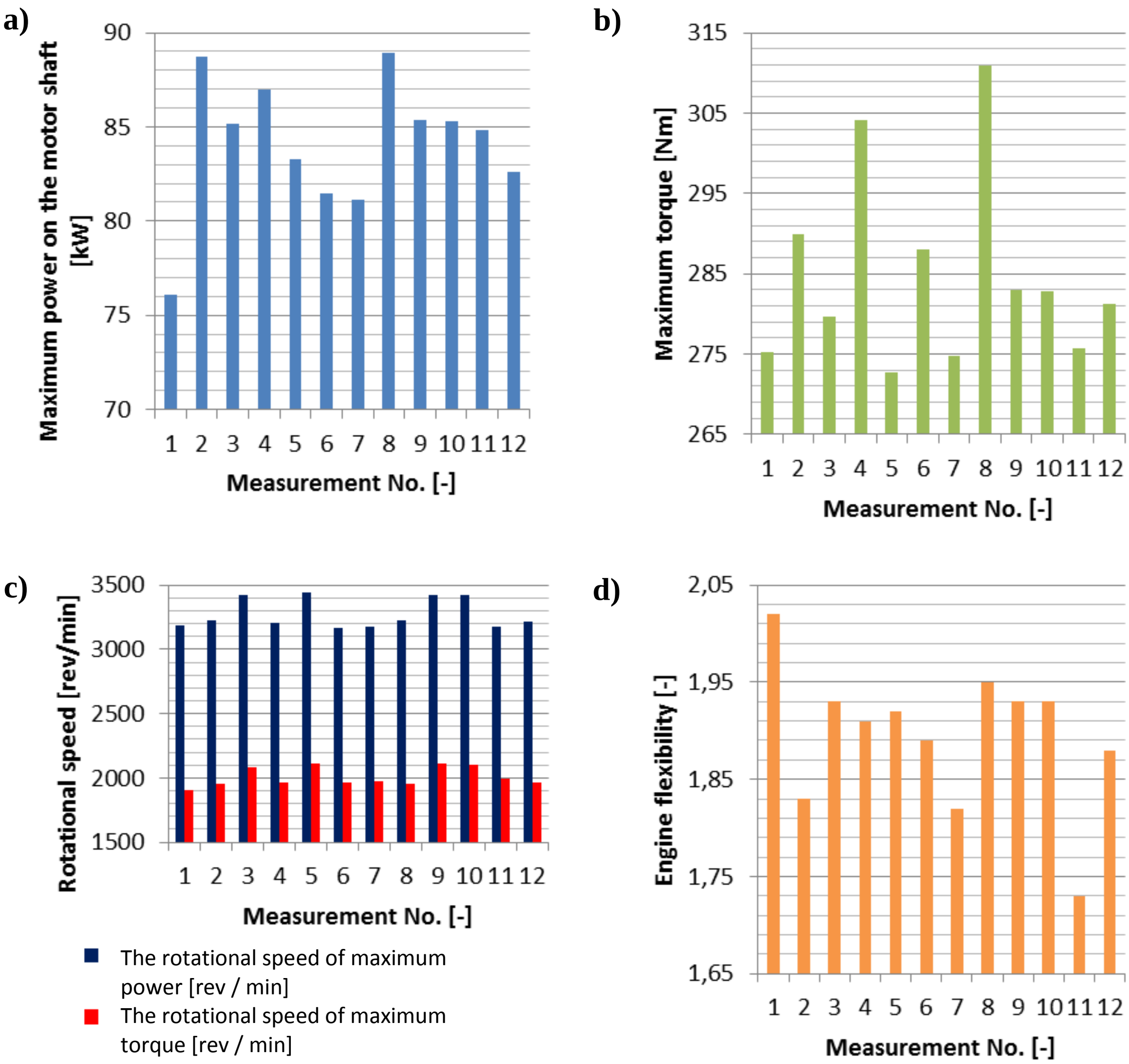


Fig. 5. Graphical presentation of the results of the series of measurements from Table 4: a) the measurement of maximum power on the engine, b) measurement of peak torque, c) the measurement of maximum power and maximum torque rotational speed, d) the resulting flexibility of the overall engine

9. Study of road fuel consumption

Fuel consumption test for each of the fuel supply systems was carried out through normal use of the car in urban conditions. The values in table 5 show the fuel consumption per 100 km due to the possibility of easier comparison.

10. Exhaust emissions measurement

Because of the test vehicle supply system defect, the nature of the measurement of environmental parameters (acceleration to maximum speed and maintaining that speed for a few seconds), and in regard of the user's safety, the

Table 5. Results of measurements of road fuel consumption

	Diesel consumption [l /100 km]	LPG consumption [l /100 km]	The level of substitution [%]
Diesel oil only	9,78	-	-
Dual fuel („on the road")	7,42	2,88	24%
Dual fuel (calibration on chasiss dynamometer)	6,84	3,24	30%

environmental tests were not conducted. However, given the data from the literature [2], [3] and the data made available by Elpigaz, sure enough it can be assumed that:

- there was a reduction in particulate emissions, there was a reduction in the level of smoke, was reduced emissions of nitrogen oxides,
- increased emissions of hydrocarbons.

In the case of increased emissions of hydrocarbons and carbon monoxide it should be noted that the likely relative increase of exhaust emissions of these components is significantly smaller than the reduction in emissions of oxides of nitrogen (Fig. 6). Also the type of emitted hydrocarbons changes, where the increase applies only to the emission of light hydrocarbons.

11. Conclusions

Summing up the paper and the results of the research, it can be stated that the final calibration ensures maximum use of LPG, at 30%, while complying with all requirements and providing the lowest cost of ownership of the vehicle. This allows to say that presented calibration methodology meets the requirements placed before her.

Calibration itself, as it was repeatedly highlighted over the work, is a complex process that requires knowledge and experience. It is important that it be done as best because its quality has a very large impact on the size of savings. Even achieving the highest levels of substitution does not mean that the system is optimally calibrated and ensures maximum savings. Following of some basic rules allows for satisfactory results, however, in order to achieve maximum savings it is required to perform a chassis dynamometer tests and analysis of results. This will not only help to achieve the greatest reduction of Diesel consumption but also minimalize the amount of additional LPG.

If the research was to be continued it would expand the range of studied types of vehicles, in order to determine whether the calibration methodology defined in the paper can also allow to achieve maximum savings for other types of vehicles.

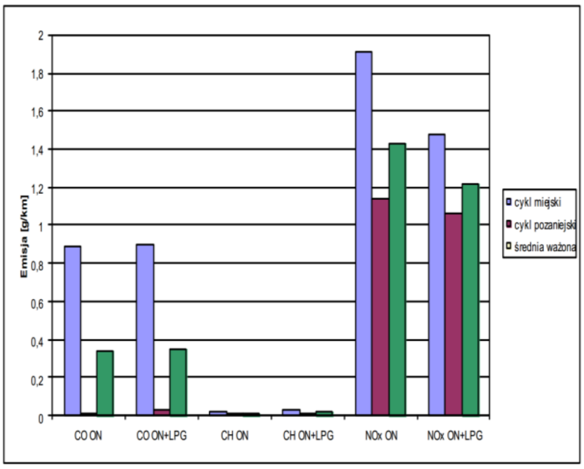


Fig. 6. Road toxic exhaust emissions at power ON or ON and LPG [1]

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