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ENGINE FLEXIBILITY FOR SI ENGINES FUELED BY LIQUID GAS WITH DIMETHYL ETHER BLEND

Summary. The aim of the study is to present the changes in the vehicle dynamics that occur in connection with the use of various fuels that power the engine. The article presents the effect of gaseous fuels being mixtures of LPG and BioDME on the flexibility of the vehicle. In previous studies, not much attention has been paid to the problem of changing the performance of the vehicle with the use of various fuels supplying the engine. It is a new approach that allows to determine the advantages and disadvantages of using alternative fuels, including mixtures using BioDME. The study was conducted for a four-cylinder SI engine with a displacement of 1.6 dm^3, installed in a passenger vehicle. The mixture of LPG and DME was assessed, and the results compared to the parameters obtained for the LPG-powered engine. Received results have been made it possible to determine changes in the value of the engine flexibility for selected engine loads and various DME shares in the mixture. The thesis that DME can be considered as an activator of the combustion process and may have an impact on the vehicle dynamics is confirmed.

1. INTRODUCTION

In view of the current socio-economic situation and confirmed climate change, obtaining the energy necessary to sustain the global economy is a key challenge. Climate change and the wide impact of conflicts on the global supply chain have a significant impact on the energy security of the region, therefore humanity faces a huge challenge to find alternative energy sources diversifying today's resources.

Wheeled transport, one of the most important areas of the economy, is based on the region's energy security. Currently, the shortages of traditional energy carriers (crude oil and natural gas) are becoming particularly acute. In the face of such problems, it becomes necessary to look for other energy sources, thus increasing energy security in the field of transport of goods and individual communication.

One of the many ways to obtain energy is the processing of biomass. Plants generate carbohydrates from water and carbon dioxide captured from the atmosphere during photosynthesis using sunlight. This chemical energy of carbohydrates is the source of biomass energy. Organic plant resources are called biomass and their energy is called bioenergy.

The most important feature of bioenergy from an environmental point of view is its zero carbon footprint. This means that bioenergy generated with the use of biomass will not introduce an excess of gases into the environment that contribute to global warming. Even the consumption of fuel made from bioenergy releases the carbon dioxide accumulated in the plant growth processes used to produce biomass. This causes the total balance of carbon dioxide emissions to be zero.

Zero excess carbon dioxide emissions in the production of bioenergy is also the reason why it is possible to obtain fuels and chemicals represented by DME. Table 1 shows the classification of

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biomass as different sources of bioenergy. The presented biomass has been divided into two categories: biomass as a product (energy of vegetation) and biomass from waste. Biomass as a product is primarily vegetation intended for energy purposes. An example is the sugar beet cultivation in Brazil, which is used to produce methanol used in motor vehicles.

World resources of dry biomass were determined to be 1.2 ÷ 2.4 trillion tons, which corresponds to the equivalent of 24 ÷ 48 x 1021 J of energy. Annually, around 1,300 billion tonnes of dry biomass are produced worldwide, which corresponds to 2,580 trillion J per year. There are seven or eight times the world's energy needs. If the production of biomass was kept at a level higher than its consumption, then sustainable bioenergy production would be achieved.

Since there are many sources of biomass on the market today, a wide variety of processes have been developed to obtain bioenergy. Conversion of biomass is possible thanks to thermochemical or biochemical processes.

Table 1

Biomass classification [1, 6]

Classification		Biomass resources examples
Plant biomass	Land	Sugar beets, corn, rape etc.
	Underwater	Marine vegetation, microorgasim etc.
Biomass from waste	Agriculture	Rice straw, straw, sugarcane residua
	Forestry	Wood waste, sawmill waste, demolition waste
	Fishing	Fish processing residues etc.
	Municipal waste	Excrement, meat residue etc.
	Household waste	Garbage, sewage sludge etc.

Thermochemical conversion is based on biomass combustion, thermal cracking and thus obtaining fuels, e.g. bio-diesel, in esterification processes. Further technological processing of the obtained biocomponent makes it possible to obtain and produce BioDME.

Thermochemical technology by gasification of biomass requires the use of air, water vapor and oxygen as gasifying agents and a mixture of hydrogen and carbon monoxide. The biggest challenge is the proper selection of process parameters to obtain the minimum amount of tar. Currently, more than 200 technologies are available, differing in pressure and temperature in the reactor, gasifying agents and the type of furnace. This study is devoted to the possibilities of using BioDME to power the SI engine. As mentioned earlier, due to its physicochemical properties, feeding the SI engine fully with DME fuel is impossible, therefore the use of dimethyl ether as an additive to liquefied petroleum gas (LPG) was considered. The analysis of the use of various configurations of fuels supplying the internal combustion engine will allow for the selection of the fuel from this group causing the smallest decrease in the dynamics of the vehicle powered by such fuel.

Research on the use of DME as an engine fuel has shown that the use of DME is an effective way to improve the efficiency of chemical energy conversion and reduce the content of exhaust components. These currently significant advantages have become the basis for assessing the impact of using a DME-LPG mixture as fuel for SI engines from the point of view of vehicle performance.

2. STATE OF KNOWLEDGE

Current literature studies do not pay attention to the considerations related to the use of BioDME to power diesel engines. From the point of view of the author of this study, this technology will allow for a few or over a dozen percent diversification of LPG gas fuel.

The authors of articles on the possibility of using the LPG-BioDME mixture focus on three main areas of discussion. The first area is the analysis of the possibilities of using DME in road transport [4, 14, 18]. The authors of these studies provide examples of the use of LPG-DME technology as a power source for an internal combustion engine. The second area presents the results of emission tests of internal combustion engines fueled with the LPG-DME mixture [11, 12, 15, 21]. The essence of these studies is to indicate the impact on the natural environment and to present the ways to further reduce the negative emission of toxic compounds into the atmosphere. The last group of works related to the possible use of LPG-DME fuel and derivatives is the determination of the impact of the use of such fuel on the combustion process [5, 16, 8, 13, 10, 17]. This study is part of the third group of studies, extending the knowledge of the impact of the dynamics of the movement of a motor vehicle powered by alternative fuels, including the LPG-BioDME mixture.

Much attention is given in the literature to other fuels that can reduce the use of fossil fuels [9, 19, 20]. As alternative fuels in the above studies, such energy sources as LPG, biodiesel, electricity, BioMethane and ethanol were considered.

3. FUEL PROPERTIES AND MEASUREMENT SET-UP

The currently used engine fuels are a mixture of hydrocarbons with a very wide range of boiling points. Table 1 presents a comparison of conventional (petrol and diesel) and alternative fuels (methane, LPG and DME). Low boiling point fuels are methane and a mixture of petroleum gases (LPG), both currently used to power SI engines. Both of these gaseous fuels correspond to two others with a similar explosive limit, like dimethyl ether (DME). DME has a boiling point corresponding to a mixture of petroleum gases, but its high cetane number allows it to be used to power CI engines [1, 6].

Table 2

Physicochemical properties of chosen fuels [1, 6]

Specification	DME	Propane	Methane	Hydrogen
Chemical structure	CH_3OCH_3	C_3H_8	CH_4	H_2
Molecular weight [g/mol]	46,07	44,09	16,4	2,02
Liquid density [kg/m^3]	661	500	415	71
Boiling point [°C]	-24,9	-42	-162	-251,9
Octane number	-	105	130	>130
Cetane number	55÷60	5	-	-
Mass heating value [MJ/kg]	28,8	46,30	50,2	121
Stoichiometric A/F [kg/kg]	9,0	15,88	17,2	34,2
Ignition temperature [°C]	350	470	540÷650	400
Combustion speed [cm/s]	42,9÷61	45,0	30÷33,8	min.271
Wobbe index [MJ/m^3]	52	81	54	48
C/H/O	52/13/35	82/18/0	75/25/0	0/100/0

Similar properties regarding the storage of LPG and DME fuels, it is necessary to use DME as an additive to liquefied. Assuming the use of DME as an additive, consider how to introduce the ingredient into LPG. Application of the DME additive may be considered, e.g. at the stage of LPG bottling plant, where it is possible to introduce the assumed dose of ether during or before loading. It is also possible to make a mixing system and implement it at a refueling station. Diagram of the installation, designed and made at the Faculty of Transport and Aviation Engineering, Silesian University of Technology, and shown in the Fig. 1.

The fuel supplied to the engine of the test object was created with the use of the presented apparatus. Thanks to this research, it was possible to evaluate the combustion efficiency of the mixture of LPG and DME fuel.

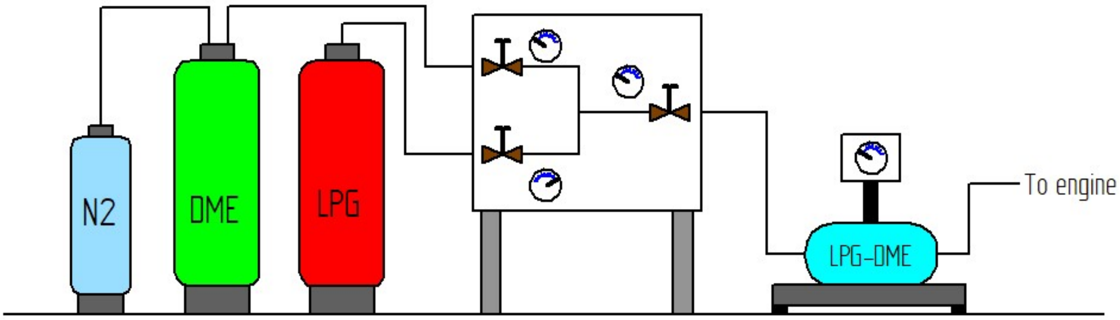

Fig. 1. LPG-DME Mixture prepared system

Using the apparatus presented above, tests were carried out on the impact of DME admixtures on the dynamic parameters of the engine and finally - the car. Research has been done, it was possible to assess the efficiency of LPG and DME fuel mixture combustion.

In the conducted research, mixtures were used, gas mixing was carried out in a strictly defined sequence, thus preparing LPG and DME mixtures with the following mass fractions:

- 7% DME, 93% LPG,
- 11% DME, 89% LPG,
- 14% DME, 86% LPG,
- 17% DME, 83% LPG,
- 21% DME, 79% LPG,
- 26% DME, 74% LPG,
- 30% DME, 70% LPG,
- 100% LPG (propane – butane mixtures with 40/60).

The mixtures prepared in this way were introduced into a properly configured supply system, which was a system of additional equipment for the tested car (Fig. 2). This system delivered the vaporized gas mixture to the inlet channels of the tested engine. The influence of DME share on engine operation was assessed for three loads: 21%, 48% and 100%.

The object of the research was a OPEL ASTRA car powered by a SI engine with a capacity 1600 cm^3, adapted to be powered by an alternative gas fuel. The main data characterizing the engine and drive system of the tested car are presented in Table 3.

The operating parameters of the car engine were determined by analyzing its characteristics, which were obtained using a Bosch chassis dynamometer, for previously prepared mixtures with a different mass fraction of DME. During the tests on the dynamometer, the acquisition of engine characteristics was possible for the 4th gear in the gearbox. A simplified diagram of the stand is shown in Fig. 2.

The test stand was equipped with transducers and sensors ensuring identification of the engine operating state. Basic control and measurement systems, ensuring continuous recording of the engine operation status, were, among others, measuring devices:

- In-cylinder pressure,
- Crank angle with TDC,
- Wheel power,
- Intake manifold pressure,
- Gas exhaust temperature,
- Gaseous fuel mass flow delivered to the engine.

Table 3

Main data of the researched engine and drive system

Manufacturer:		Opel	Top speed:	170 km/h
Model:		Astra F	Gearbox: Transmission type:	manual
Traction:		FWD (front-wheel drive)	Number of gears:	5
Engine type: Fuel type: Cylinders alignment:		spark-ignition 4-stroke	Gear ratios (overall): I II III IV V	 3.727 (13,94) 2,136(7,99) 1.414 (5.29) 1,121 (4,19) 0.890 (3.33)
Horsepower net:	gasoline (petrol)		Final drive ratio std:	3,74
	Line 4			
	1598 cm^3	1475 mm		
	55 kW (ECE)	2517 mm		
Top speed:		170 km/h		
Tire size		175/70 R13		

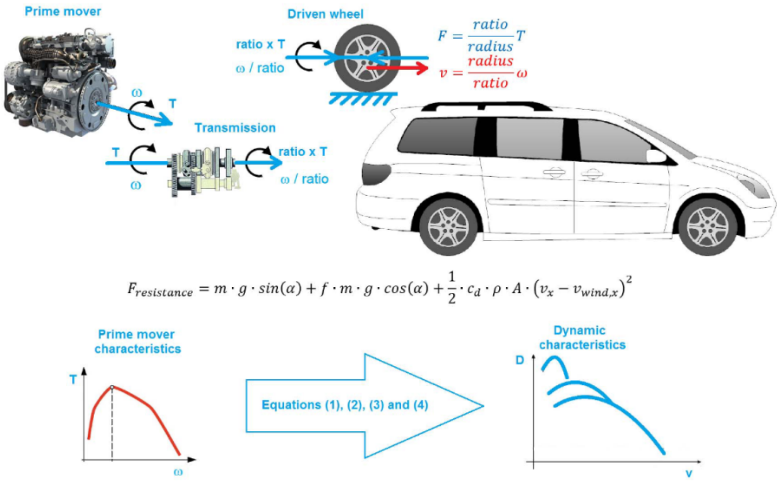

Fig. 2. Scheme of testing stand [7]

The in-cylinder pressure was measured using a piezoelectric pressure sensor type 6121 connected to 5011 charge amplifier from KISTLER. The position of the crankshaft and its RPM were determined using the KISTLER 2613B crankshaft position marker.

Additionally, the signal from the absolute pressure transducer in the engine intake manifold was measured and recorded. The transducer is an integral part of the gasoline fuel injected to the intake manifold of the tested car's engine. The mass flow of gaseous fuel flowing into the engine supply system was measured with a precision strain gauge. All measured parameters were recorded and visualized using the NI PCI-6143 data acquisition card and a proprietary program developed in the environment LabView 7.1.

4. RESULTS AND DISCUSSION

4.1. Torque and power measurement

For the above-mentioned gas fuel mixtures, the engine power and torque were measured. Measurements were carried out for three assumed engine loads: 100%, 48% and 21%. The measurement results are presented in the Table 4.

The presented results show that there is a change in the dynamic parameters of the engine. The maximum power and torque values are reduced compared to the reference value (100% LPG) only for higher DME contents (above 26%). At full engine load (100%), for LPG fuel blended with 7%, 11%, 17%, 21% and 26% DME blend, the torque value increased, and the engine power was maintained at a comparable value. In the case of partial loads (48% and 21%), the maximum power and torque values are lower (than LPG fuel) for all DME shares in the mixture. However, for the 14%, 17% and 21% DME shares, the power values are close to the power values were corresponding to the base fuel (LPG).

Table 4

Results of the dyno measurement

Fuel	Engine load [%]					
	100%		48%		21%	
	Power [kW]	Torque [Nm]	Power [kW]	Torque [Nm]	Power [kW]	Torque [Nm]
7% DME, 93% LPG	57,6	129,6	43,3	122,0	17,9	89,2
11% DME, 89% LPG	57,2	126,3	43,6	119,1	15,6	81,8
14% DME, 86% LPG	55,1	126,3	49,0	125,3	18,8	93,5
17% DME, 83% LPG	57,0	129,6	47,8	126,6	24,0	103,0
21% DME, 79% LPG	58,3	131,1	48,3	125,8	21,4	98,4
26% DME, 74% LPG	58,6	124,6	44,2	119,8	23,1	97,8
30% DME, 70% LPG	56,8	120,6	43,9	116,2	24,9	94,0
100% LPG	56,5	129,1	49,5	123,4	25,6	104,3

Dynamometer charts with power and torque waveforms are presented in Figs. 3, 4 and 5.

4.2. Engine flexibility during alternative fuel feeded (LPG-DME)

The shape of the torque curve significantly affects the dynamics of the vehicle's movement. The design work related to internal combustion engines is reduced to obtaining a torque curve where the maximum value is constant over a broad or, preferably, over the entire engine speed range, i.e. from idle to maximum rotational speed. Such a torque curve will guarantee constant dynamics of the vehicle motion in every rotational speed range. Current designs of motors allow to obtain a constant value of maximum torque in certain ranges of rotational speeds. Vehicles equipped with such engines are characterized by high acceleration but only in the range of maximum torque. The assessment of the dynamics of motion, referred to as flexibility, can be made by using simple relationships between the values of the maximum torque, the value of the torque at maximum power and their rotational.

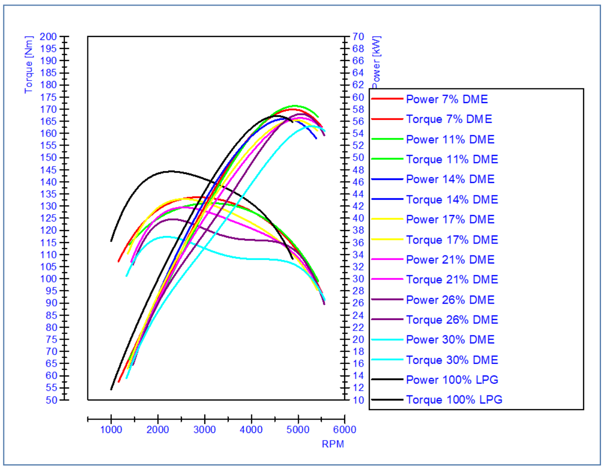

Fig. 3. Power and torque for different DME blends and 100% loads

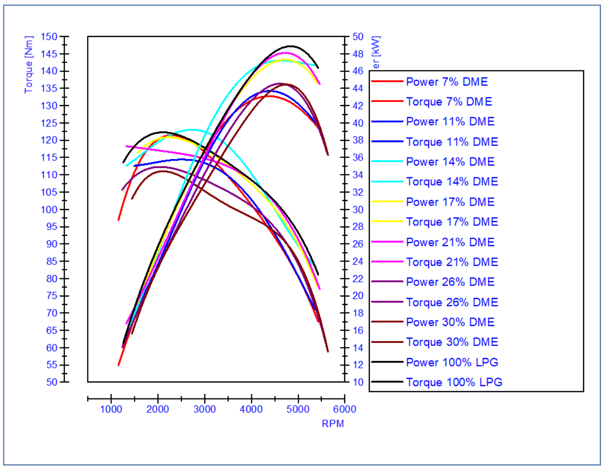

Fig. 4. Power and torque for different DME blends and 48% loads

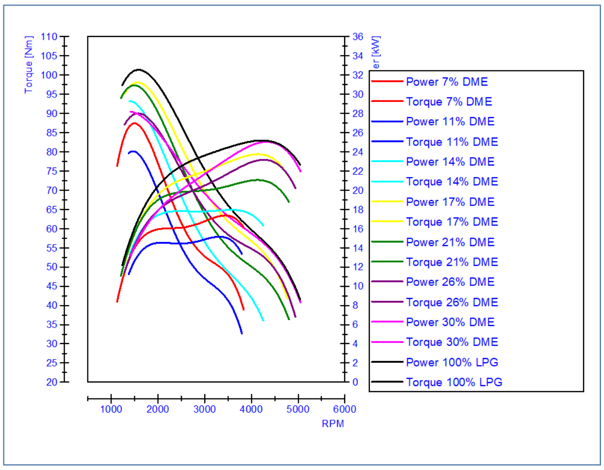

Fig. 5. Power and torque for different DME blends and 21% loads

The shape of the torque curve and the speed range between the rotational speed corresponding to the maximum torque and the speed corresponding to the maximum power rotational speed, determine the ability of the engine to adapt automatically to the actual driving conditions of the vehicle (load). The adaptation of the motor is the more pronounced the greater the slope of the torque characteristic, and more specifically, obtaining the greatest possible span between the maximum torque M_{omax} and the torque corresponding to the maximum power M_{Nmax} is crucial. Motors characterized by a large range M_{omax} and M_{Nmax}, and a large range of rotational speeds (n_{Mo} and n_N) are considered flexible. The torque spread e_M is presented in the:

$$e_M = \frac{M_{omax}}{M_N} \tag{1}$$

where: M_{omax} – maximum torque; M_N – torque value at maximum power

The range of rotational speeds e_n is described by the following relationship:

$$e_n = \frac{n_N}{n_M} \tag{2}$$

where: n_N – RPM at maximum power; n_M – RPM at maximum torque

The flexibility of the engine was defined as the product of the coefficients presented in the above relationships and is called the elasticity coefficient E:

$$E = e_M \cdot e_n \tag{3}$$

The calculated values of the elasticity coefficient, torque spread, and speed range are presented in the diagrams below. The charts have been compiled according to the engine load values (100% - Fig. 6a, 48% - Fig. 6b, and 21% - Fig. 6c).

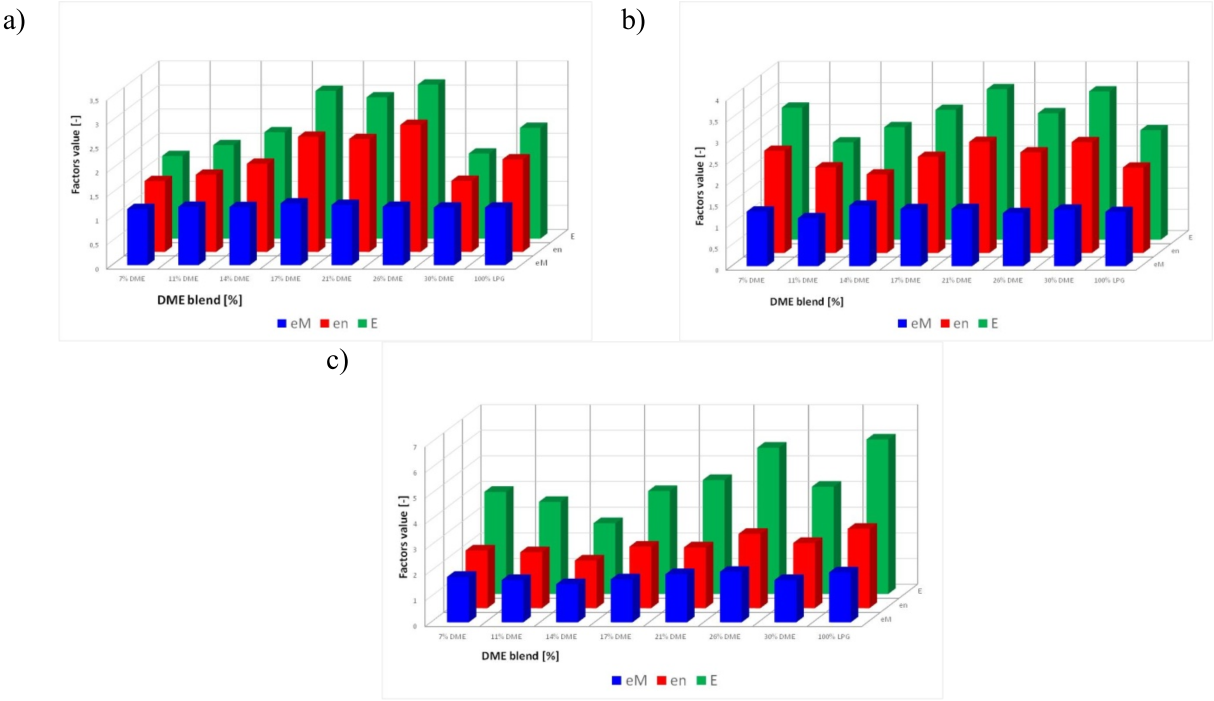

Fig. 6. Flexibility E for different DME blends and loads: a) 100%, b) 48%, c) 21%

In the case of the LPG and DME mixtures accepted for testing and the maximum load, the most favorable elasticity coefficient was obtained for the shares of 17% and 26% of DME. The increase in the elasticity coefficient for these fuels is very clear.

In the case of partial loads, the most favorable values of the elasticity coefficient vary depending on the value of the load. This allows the conclusion that DME can be considered as an activator of the combustion process and, in certain ranges, by changing its share, improve the course of the combustion process. Consequently, the engine operating parameters, including power and torque, are improved.

4.3. Estimation of CO_2 participations for LPG and LPG-DME mixtures fueled car

An issue often discussed in the scientific and technical space is the issue of CO_2 emissions from internal combustion engines. The use of alternative fuels seems to have some potential for reducing emissions. This study presents changes in emissions only for the combustion process, although a very important issue is the assessment of CO_2 emissions for the entire process from the start of fuel production through its distribution until the fuel is supplied and burned in the engine cylinder.

From the point of view of carbon dioxide emissions, the production methods that allow obtaining DME from biological material (biomass) should be of greatest interest. These methods significantly reduce the carbon footprint and, consequently, reduce the global CO_2 emissions related to the functioning of internal combustion engines. The production of DME itself binds CO_2 by carrying out the reforming reaction, so it can be assumed that the use of ether to power the engine not only reduces emissions, but also uses the previously formed carbon dioxide to produce an alternative fuel.

Graphs (Figs. 7 ÷ 9) present the results of model tests determining CO_2 participation for the alternative fuel adopted in this study with a different DME share.

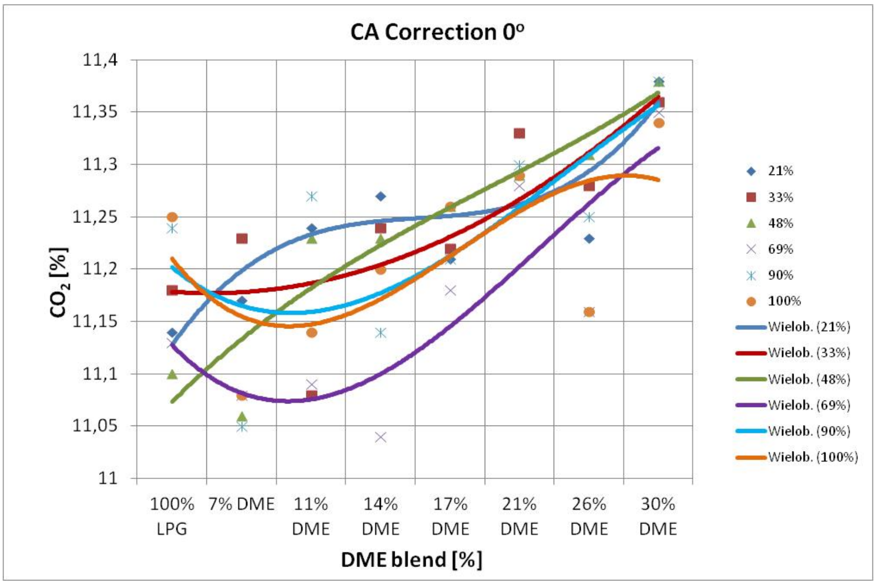

Fig. 7. Participations change CO_2 for LPG-DME fueled engine (RPM = 3000 min^{-1} T_{advcor} = 0°CA)

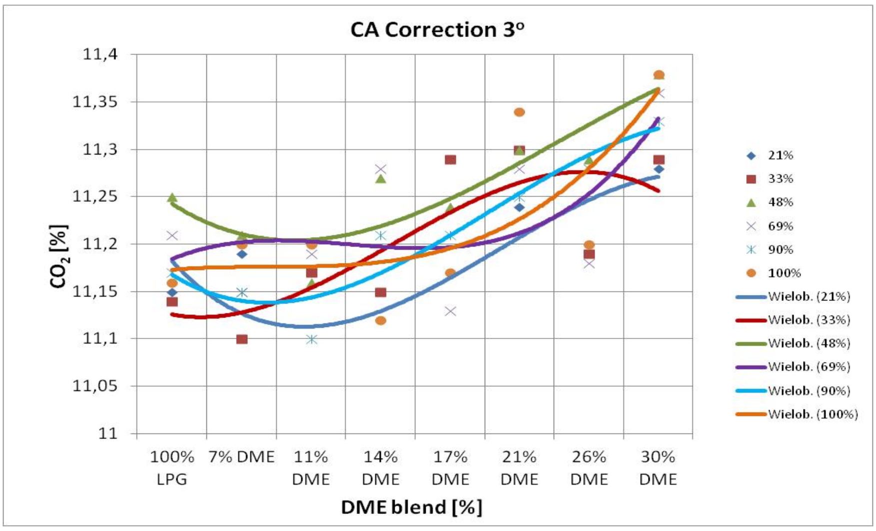

Fig. 8. Participations change CO_2 for LPG-DME fueled engine (RPM = 3000 min^{-1} T_{advcor} = 3°CA)

The above charts reveal that carbon dioxide participations are lower for small proportions of DME in the mixture (7% - 14%) when comparing the participations to the reference fuel (LPG). As the share of DME in the mixture increases, the level of emissions also increases. This situation slightly changes in the case of an additional correction of the ignition advance angle (CA). As the correction increases (0° → +3° → +6°) the nature of the curve is very similar, i.e., lower DME shares are characterized by lower CO2 emissions, higher shares, and higher emissions. However, it should be observed that introducing a correction of the ignition advance angle as a whole results in a reduction of carbon dioxide emissions, i.e. the emission curves register lower values.

5. CONCLUSIONS

Visualization of the power and torque characteristics of the engine may make it difficult to infer about the change in the dynamics of the vehicle motion. The row maximum power and torque data do not directly determine the dynamics of the vehicle motion, especially in real operation conditions. Information on how the vehicle can behave, and in particular how the dynamics of the vehicle movement changes, will be provided by the analysis of the mutual relations between power and torque and the speed range of these parameters. Such mutual relations of rotational speed, maximum power and maximum torque values are described by the flexibility parameter. In general, and popular science literature, authors often mistakenly define flexibility as the ability of a vehicle to accelerate. In fact, flexibility, as expressed by defined relationships, is a deeper form of analysis of the mutual position of the maximum torque and maximum engine power.

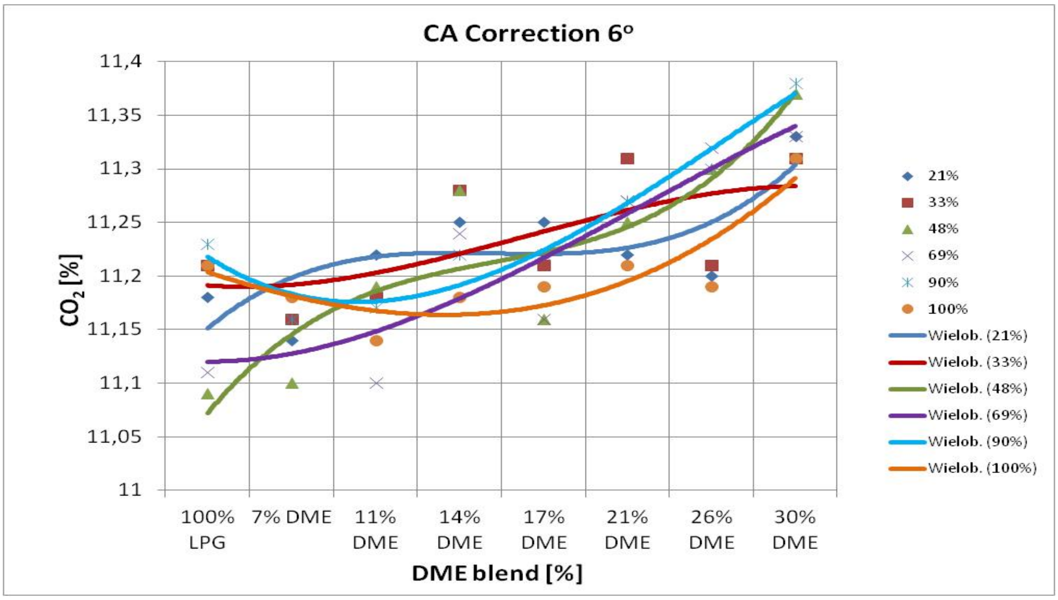

Fig. 9. Participations change CO_2 for LPG-DME fueled engine (RPM = 3000 min^{-1} T_{advcor} = 6°CA)

When analyzing the flexibility coefficient, changes in the position of the maximum torque and maximum power as well as the rotational speed of the engine were taken into account. This approach to the problem allows for the detection of changes in the width of the useful field, for which a change in the dynamics of the vehicle movement may occur. The use of different fuels to power the engine allowed for the determination of such characteristics that not only do not deteriorate the vehicle dynamics, but also cause a positive change in them. Detailed analysis of the flexibility coefficient allows for the conclusion that the most favorable change occurs for the fuel with the share of 17% and 26%. The fuel with such a share is characterized by the most favorable increases in the flexibility coefficient also in relation to the reference fuel. In the case of these fuels (17% and 26% DME in the mixture), the elasticity coefficient reaches even higher values of the flexibility coefficient. Therefore, it can be assumed that the application of the DME additive increased the dynamics of the vehicle motion powered by a mixture of ether and LPG.

From the analysis of the share of CO_2 in the exhaust gas, it can be concluded that the concentration of carbon dioxide is lower for low DME shares in the mixture (7% - 14%). Especially if we compare it to the reference LPG fuel. As the proportion of DME in the mixture increases, the proportion of CO_2 also increases. Considering individual types of fuel and modifying the ignition timing, the situation changes slightly. However, it should be observed that introducing a correction of the ignition advance angle as a whole results in a reduction of carbon dioxide emissions, i.e. the emission curves register lower values.

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