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Modelling of CO_2 Emissions in Driving Tests on the Example of a Compression Ignition Engine Powered by Biofuels

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Abstract: Climate change, environmental degradation and the introduction of increasingly restrictive legal regulations mean that the automotive industry is facing tremendous challenges. The paper presents a computer tool that uses the results of tests carried out on a chassis dynamometer for a Fiat Panda 1.3 Multijet, to simulate driving tests. As a result of the work of a computer tool, the impact on CO_2 emissions was analysed in the context of CADC – Artemis (Common Artemis Driving Cycles) road tests for the following fuels: diesel oil, FAME (Fatty Acid Methyl Esters), rapeseed oil and butanol. Mass consumption of fuels and CO_2 emissions were analysed in driving tests for the vehicle in question. The highest mass consumption of fuel and carbon dioxide emissions occurred in the case of FAME (respectively 2.283 kg and 6.524 kg).

Keywords: engine, CO_2 emission, CADC

1. Introduction

Climate change and the deteriorating condition of the natural environment are currently the leading problems for the countries of the European Union and the world (Fekete et al. 2021, Capros et al. 2018, Jacyna et al. 2018). With the constant development of economic industrialization, it is necessary to introduce an appropriate environmental policy so that further technological progress does not pose a threat to health and life in developing areas (Tutak et al. 2021). The new strategy of the European community, also known as the "European Green Deal", is an action plan that aims to make Europe a neutral continent in terms of greenhouse gas emissions by 2050, while maintaining a competitive, modern and sustainable economy (Gunfaus et al. 2021). The possibilities of implementing the plan are pursued in all economic and social areas, including, to a large extent, the transport sector which is currently responsible for about ¼ of greenhouse gas emissions (Zhao et al. 2020). By 2050, emissions from transport are expected to be reduced by around 90%. For this purpose, integrated and consistent actions are required, through cleaner and healthier solutions that can replace current conventional technologies (Olabi et al. 2021, Pyza et al. 2018). It is not possible to completely switch to electric mobility, therefore, for internal combustion engines, an increase in the share of biofuels and biocomponents that can reduce CO_2 emissions from these vehicles is expected, in addition to more stringent exhaust emission standards (Puricelli et al. 2020, Commission Regulation (EU) No 407/2011, Regulation No 85 of the Economic Commission for Europe of the United Nations (UN/ECE), Regulation No 101 of the Economic Commission for Europe of the United Nations (UN/ECE)). Further research on alternative fuels is therefore recommended, which will be used in the implementation of the reduction targets set (Javed et al. 2020).

From the point of view of the development of infrastructure and services in the field of transport and mobility, the transport behaviour of urban residents and the assessment of mobility in urban areas are also important issues (Chamier-Gliszczyński et al. 2016, Chamier-Gliszczyński et al. 2016).

This article focuses on vehicles with a compression ignition engine. For cars of this type, diesel fuel can be replaced by fatty acid methyl esters, vegetable oils with appropriate parameters as well as alcohols with properties similar to those of conventional fuel. These substances are usually used as additives, but some could be self-contained propellants. Fatty acid methyl esters (FAME), rapeseed oil and butanol were selected for the analyses carried out in the study. FAME fuel is a substance produced from vegetable oils or animal fats in the process of trans-esterification of fatty acids (Bemani et al. 2020). Depending on the climatic conditions and the crops grown, the basis can be rapeseed oil, e.g. in Germany or Poland, sunflower oil, e.g. in Spain or soybean oil, e.g. in the United States. Methyl esters have better lubricating properties than diesel oil, which extends the life of the engine, and has a more favourable carbon dioxide emission balance (Alves-Fortunato et al. 2020). Butanol is also known as butyl alcohol – which is an organic chemical compound from the group of alcohols (Bharathiraja et al. 2017). On a massive scale, it is obtained from fossil fuels, but it can also be obtained by fermentation, e.g. of plant biomass. As a result, it supports the EU's policy of promoting alternative energy sources, whether as an additive or a standalone fuel. Its advantage is the possibility of direct application without the need for additional actions to modify the properties to make them even more similar to conventional fuel. Raw rapeseed oil is mainly used for food purposes. It could however, under certain conditions, replace classic diesel oil, due to the similarity of some physicochemical characteristics (Mikulski et al. 2020). This would be advantageous as there would be no need to carry out costly and energy-consuming technological operations required to transform the oil into e.g. esters.

In order to assess the possibilities of reducing carbon dioxide emissions for the indicated alternative fuels, computer simulations were carried out using the physicochemical properties of these substances. The simulation was performed according to the CACD (Common Artemis Driving Cycles) test procedure (Sileghem et al. 2014). It is a test procedure carried out on a chassis dynamometer, whose formula was defined as a result of the international research project called Artemis. The program improved European methods for estimating and inventorying emissions from the transport sector. About 50 participants (laboratories, project teams and institutions) from 17 countries took part in the project. As a result, a test procedure was obtained that reflects the real movement of vehicles in road traffic and thus produces reliable emission results from these vehicles. The CADC consists of three main parts: the urban cycle, the extra-urban cycle, and the motorway cycle (Common Artemis Driving Cycles 2021).

As a result of the simulations, the results of fuel consumption and carbon dioxide emissions from the vehicle were obtained when running on the indicated fuels. However, to assess the functionality of alternative fuels, the power, torque and mechanical energy value generated during the test were also compared.

2. Methodology

As part of the project, a quantitative model was prepared of specific fuel consumption as a function of rotational speed and torque of a compression ignition engine, on the basis of data published by EPA (Environmental Protection Agency). The publications on which the simulations were based included studies of a compression ignition engine (Ambrozik et al. 2012, Ambrozik et al. 2016).

Then, simulations of the operation of the selected vehicle in driving tests were carried out in order to obtain the amount of CO_2 emissions and fuel demand for the fuels used (diesel oil, FAME, rapeseed oil and butanol). It was assumed in the developed model that, at a given simulation point of the engine resulting from the instantaneous rotational speed and instantaneous torque for various fuels, the efficiency of this engine is the same.

Table 1 summarizes the basic properties of the fuels used (Kordylewski et al. 2008, Baczewski et al. 2008, Gwardiak, et al. 2011, Regulation of the. Minister of Economy of 9 October 2015, PN-EN 590+A1:2017-06, PN-EN 16942+A1:2021-08).

Table 1. Parameters of the fuels used in the research for CADC driving tests

Parametr	Diesel	FAME	Rapeseed oil	Butanol
Carbon content [%]	86.5	78.0	77.4	64.8
Hydrogen content [%]	13.4	12.0	11.4	13.5
Oxygen content [%]	0.0	10.0	11.2	21.6
Air demand [g_{air}/g_{fuel}]	14.5	12.5	12.5	11.2
Lower heating value [MJ/kg]	44.0	37.1	37.5	33.0

The parameters of a 2014 Fiat Panda 1.3 Multijet II from were used to develop a simulation model for driving tests under the CADC standard (Fiat 2021). Table 2 below presents the most important technical parameters of the vehicle and the factors necessary to be used in driving tests and programs generating the required waveforms. The values of the "n/v coefficient" factor for individual gears were calculated on the basis of the following dependence:

$$\text{Ratio n/v} = \mathrm{n_{engine}} / \mathrm{v_{vehicle}} \; [\mathrm{h/(km \cdot min)}] \qquad (1)$$

where:

η_{engine} – measured value of the engine rotational speed [min^-1],

$v_{vehicle}$ – vehicle speed for the given gear number [km/h].

Table 2. Parameters of the vehicle used in the research for CADC driving tests

Parameter	Description	Unit
Vehicle (MY, Make, Model)	Fiat Panda 1.3 Multijet II 16V	–
Equivalent test mass	1170	Kg
Rated power (declared)	55	kW
Rated engine speed (declared)	4000	min^{-1}
Idling engine speed (declared)	800	min^{-1}
Max vehicle speed(declared)	168	km/h
Number of gears	5	–
Ratio n/v_1, gear 1	121.9	h/(km·min)
Ratio n/v_2, gear 2	64.10	h/(km·min)
Ratio n/v_3, gear 3	41.32	h/(km·min)
Ratio n/v_4, gear 4	29.49	h/(km·min)
Ratio n/v_5, gear 5	21.97	h/(km·min)
Target Coeff f0	86	N
Target Coeff f1	0.1694	N/(km/h)
Target Coeff f2	0.03202	$N/(km/h)^2$

Generating the required waveforms as part of the CADC simulation used data which enabled the determination of the characteristics of the maximum engine power as a function of rotational speed. The characteristic of the demand for fuel (diesel oil) as a function of rotational speed and torque was determined (Fig. 1).

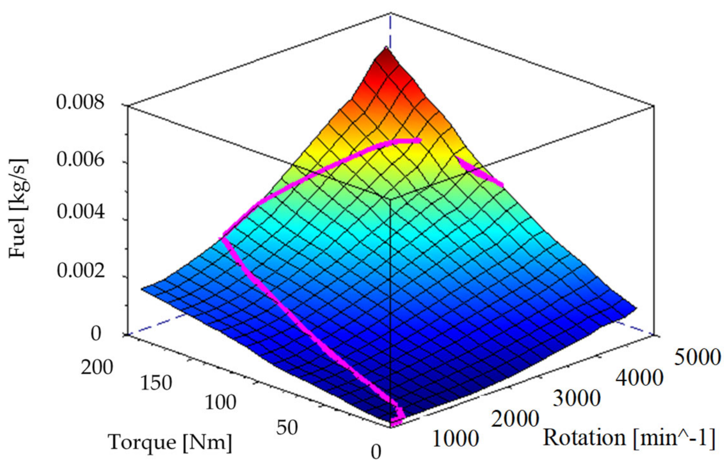

Fig. 1. A fuel consumption (Diesel) as a function of engine rotational speedand engine torque

The above fuel and engine parameters as well as the course of approval tests were input into the simulation model under development, which was used to obtain the results of carbon dioxide emission of the analysed vehicle powered by various fuels (Fig. 2).

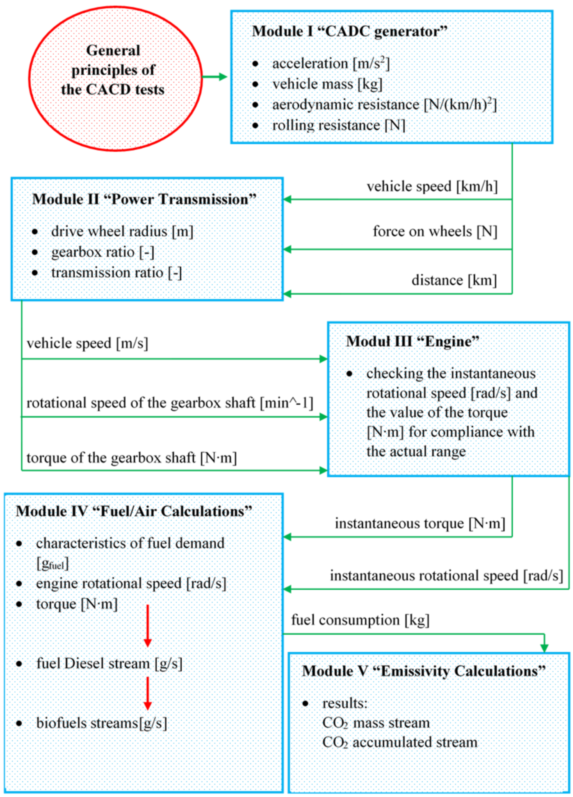

Fig. 2. Structure of the simulation model

In the developed computer simulation, the instantaneous values of the vehicle speed calculated in m/s and km/h units are available in parallel.

In module 1, using the instantaneous value of the vehicle speed, the differentiating element and the vehicle computational mass, the dynamic force is calculated:

$$F_{Dyn} = \frac{dv}{dt} m \text{ [N]} \tag{2}$$

where:

m – mass of the vehicle [kg].

The values of the rolling resistance forces were calculated from the rolling coefficients assumed for the vehicle using the relationship:

$$F_{Sta} = f0 + f1 \cdot v + f2 \cdot v^2 \text{ [N]} \quad (3)$$

where:
v – vehicle speed [km/h],
$f0, f1, f2$ – target coefficient (Table 2).

In module II, on the basis of the instantaneous speed of the vehicle and the instantaneous values of the "Ratio n/v" coefficients resulting from the gear ratio, the instantaneous value of the rotational speed of the gearbox shaft is calculated according to the relation:

$$n_{engine} = (\text{Ratio n/v}) \cdot v \text{ [1/min]} \quad (4)$$

where:
v – vehicle speed [km/h],
Ratio n/v – coefficient (Table 2).

The instantaneous torque value at the engine crankshaft is then calculated:

$$T_{engine} = \frac{(F_{Sta} + F_{Dyn}) \cdot v}{\omega_{engine}} \text{ [N} \cdot \text{m]} \quad (5)$$

where:
v – vehicle speed [m/s],
ω_{engine} – instantaneous rotational speed [rad/s].

In module IV the fuel flux is calculated on the basis of fuel demand characteristics (Fig. 1), instantaneous values of engine rotational speed and engine crankshaft torque according to the relation:

$$\dot{Fuel}_{Diesel} = Fun(n_{engine}, T_{engine}) \text{ [kg/s)]} \quad (6)$$

where:
n_{engine} – engine rotational speed [1/min],
T_{engine} – engine crankshaft torque [N·m].

In the case of using a fuel other than diesel the instantaneous flux of this fuel is calculated according to the relation:

$$\dot{Fuel} = \dot{Fuel}_{Diesel} \frac{Cal_{Diesel}}{Cal} \text{ [kg/s)]} \quad (7)$$

where:
Cal_{Diesel} – calorific value for diesel fuel [J/kg],
Cal – calorific value for another fuel [J/kg].

Then, in Module V, the carbon dioxide emission stream is calculated according to the relation:

$$\dot{CO_2} = 3.664 \cdot \dot{Fuel} \cdot C \text{ [kg/s]} \quad (8)$$

where:
C – mass fraction of carbon in the fuel [kg/kg].

In the subsequent calculations in this module, the carbon dioxide emissions are calculated on the basis of:

$$CO_2 = \int \dot{CO_2} \, dt \text{ [kg]} \quad (9)$$

where:
$\dot{CO_2}$ – mass flux of carbon dioxide emissions [kg/s].

3. Research results and discussion

The results of independent simulations of the selected Fiat Panda 1.3 Multijet vehicle in the applied driving tests with change of fuel (Diesel, FAME, rapeseed oil, butanol) are presented below.

Figures 3-6 show the simulation results for the Fiat Panda 1.3 Multijet vehicle powered by diesel fuel: waveforms of instantaneous vehicle speed values; waveforms of the instantaneous values of the rotational speed of the vehicle engine; waveforms of the instantaneous values of the torque of the engine of the vehicle; waveforms of the instantaneous values of the engine power of the vehicle.

Figures 7 and 8 show the results of the developed computer simulations of the waveforms of instantaneous values of mass streams and the waveforms of the instantaneous values of mass consumption.

Figures 9 and 10 show the results of the developed computer simulations of the waveforms of the instantaneous values of carbon dioxide streams and the waveforms of the instantaneous values of carbon dioxide emissions for the CADC drive tests for the Fiat Panda 1.3 Multijet vehicle, with the use of diesel fuel, FAME, rapeseed oil and butanol.

Figures 11-13 and Figures 14-16 show the obtained simulation results concerning fuel consumption and carbon dioxide emissions with the use of various types of fuel in the analysed driving tests.

3.1. Simulation results for CADC tests of vehicle operating parameters

The figures below (Fig. 3-6) show the results of the developed computer simulations of CADC driving tests (urban, extra-urban and motorway cycles): course of instantaneous vehicle speed values; the waveforms of the instantaneous values of the rotational speed of the vehicle engine; the waveforms of the instantaneous values of the torque of the engine of the vehicle; the waveforms of instantaneous values of the engine power of the vehicle. The basis for the development of the computer simulations were the results of the driving tests carried out on a chassis dynamometer for the Fiat Panda 1.3 Multijet diesel powered vehicle.

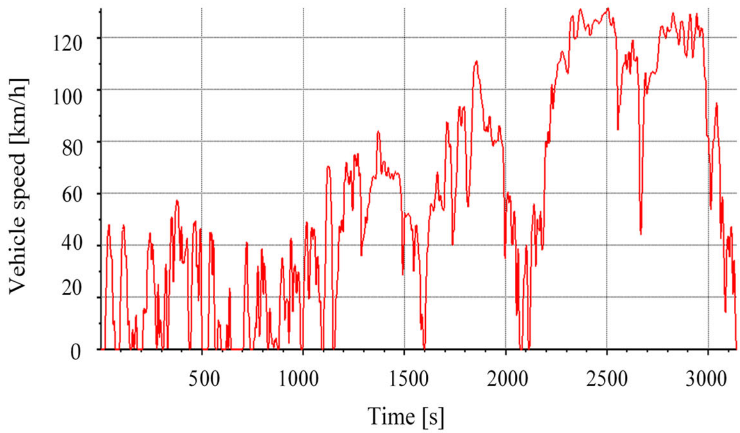

Fig. 3. The waveforms of the instantaneous vehicle speed values obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

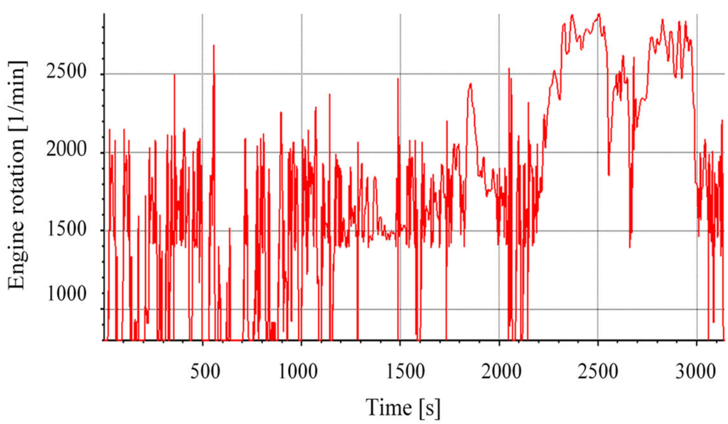

Fig. 4. The waveforms of the instantaneous values of the engine rotational speed obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

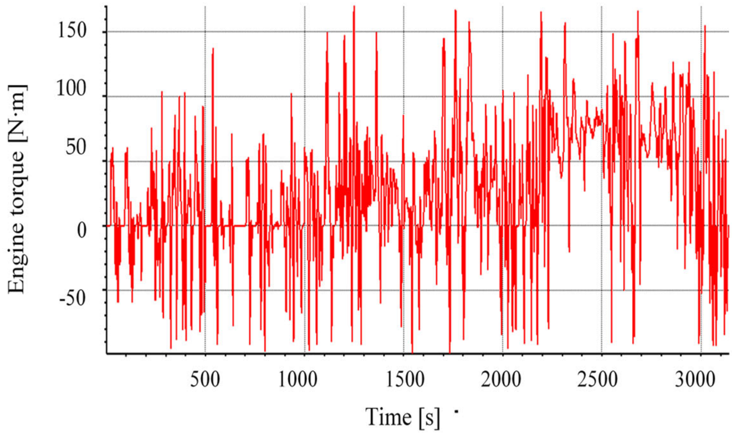

Fig. 5. The waveforms of the instantaneous values of the torque of the vehicle engine obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

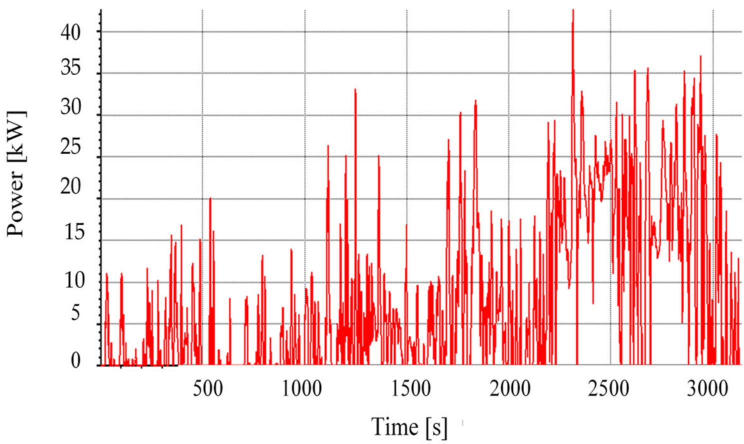

Fig. 6. The waveforms of the instantaneous values of the power of the vehicle engine obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.2. Simulation results for CADC fuel consumption tests

Below are the results of the developed computer simulations of CADC driving tests (urban, extra-urban and highway cycles) for the Fiat Panda 1.3 Multijet for the fuels used (diesel oil, FAME, rapeseed oil and butanol): the waveforms of the instantaneous mass stream values and the waveforms of the instantaneous mass consumption values.

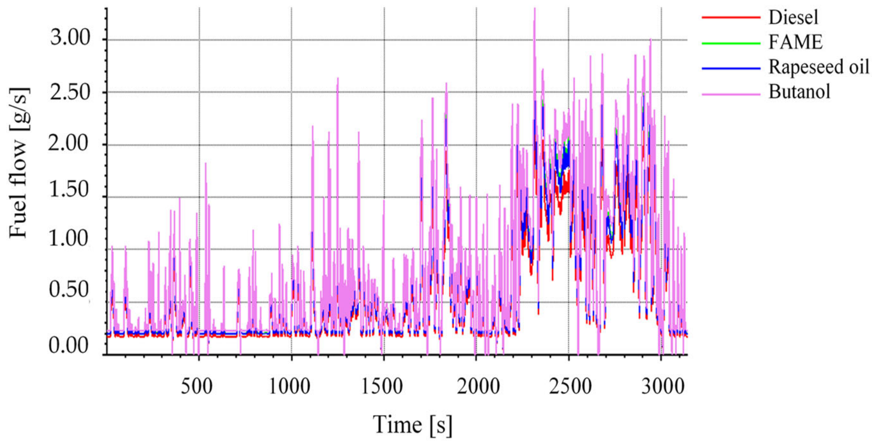

Fig. 7. The waveforms of the instantaneous values of mass streams [g/s] for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

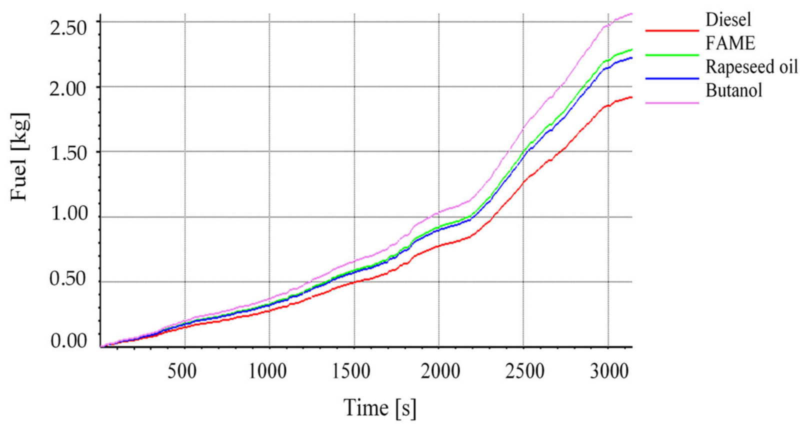

Fig. 8. The waveforms of the instantaneous values of mass consumption [kg] for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.3. Simulation results for CADC carbon dioxide emission tests

Figures 9 and 10 show the results of the developed computer simulations of the waveforms of the instantaneous values of carbon dioxide streams and the waveforms of the instantaneous values of carbon dioxide emissions for CADC driving tests (urban, extra-urban and motorway cycles) – Fiat Panda 1.3 Multijet vehicle, used fuels: diesel oil, FAME, rapeseed oil and butanol.

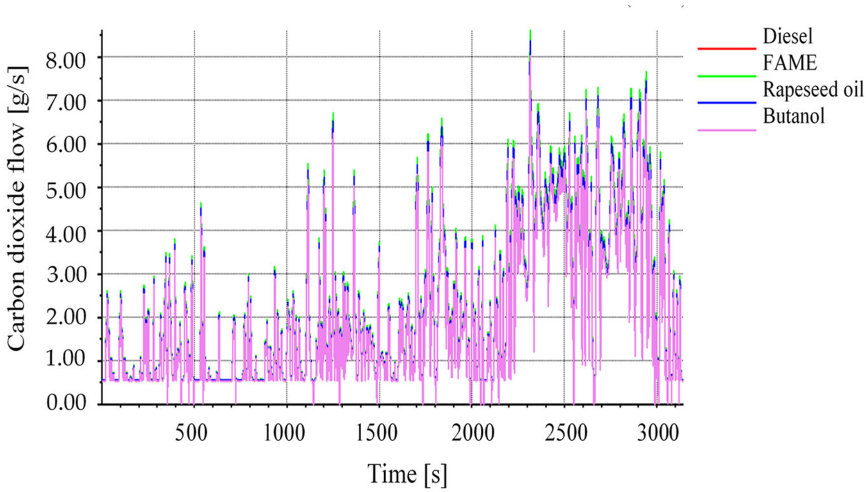

Fig. 9. The waveforms of the instantaneous values of carbon dioxide fluxes for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

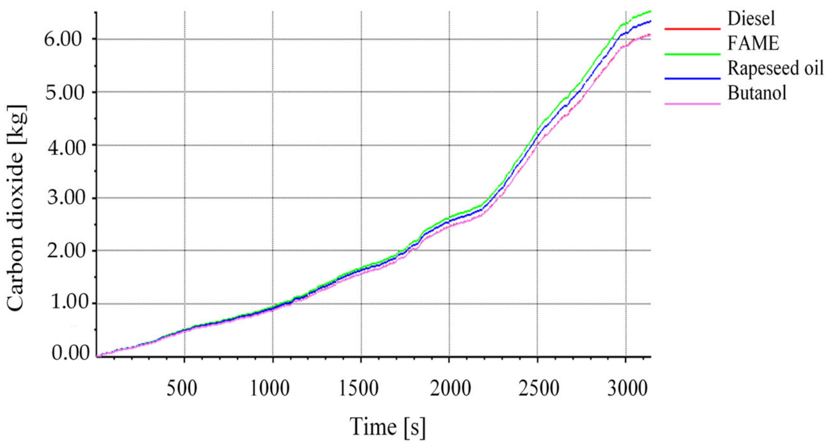

Fig. 10. The waveforms of the instantaneous values of carbon dioxide emissions for selected fuels, obtained from the simulation of the CADC drive test including urban, extra-urban and motorway cycles

3.4. Simulation results for CADC carbon dioxide emission tests

The figures below show a summary of the simulation results for the CADC tests of fuel consumption and carbon dioxide emissions. Sample parameters of the developed simulations of the CADC test variants are presented in Table 3.

Table 3. Summary of the results obtained from various variants of the CADC test: test duration, distance, mechanical energy

Parameter	CADC full	CADC urban	CADC extra urban	CADC motorway
Duration [s]	3142	992	1082	1068
Distance [km]	50.887	4.874	17.275	28.738
Mechanical energy [MJ]	24.139	1.865	6.156	16.118

3.4.1. Summary of simulation results for CADC fuel consumption tests

The figures below (Fig. 10-12) show the results of fuel mass consumption, fuel mass consumption per kilometre and fuel mass consumption per 1 MJ for various variants of the CADC test.

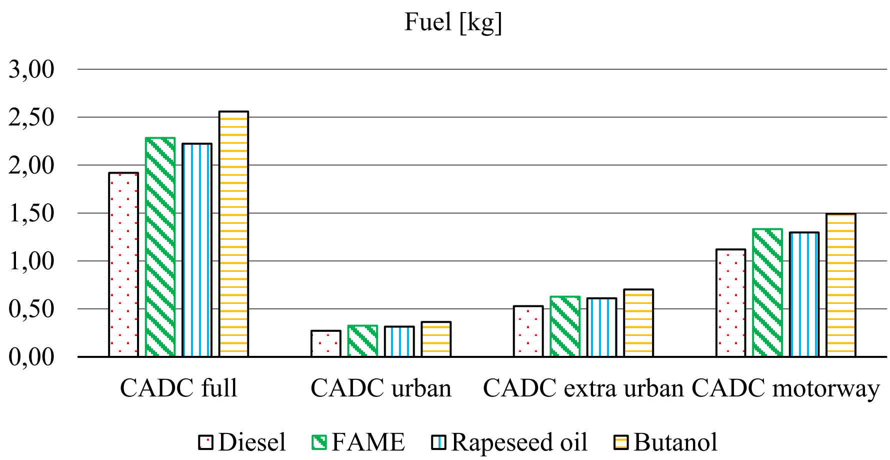

Fig. 11. Summary of fuel mass consumption results for selected fuels, obtained from different variants of the CADC test

Based on the test results shown in Figure 11, it can be concluded that in the driving test analysed, the highest fuel consumption [kg] was with butanol, while the lowest was for Diesel fuel. This is due to the calorific value of these fuels. Diesel fuel provides more energy per unit mass than butanol. To meet the energy requirements to cover the same distance, more of a lower calorie carrier must be provided. The highest consumption of all fuels was for the motorway cycle. It is related to the route and duration of this part of the driving test. The motorway cycle compared to the urban and extra-urban cycle is over 60% longer.

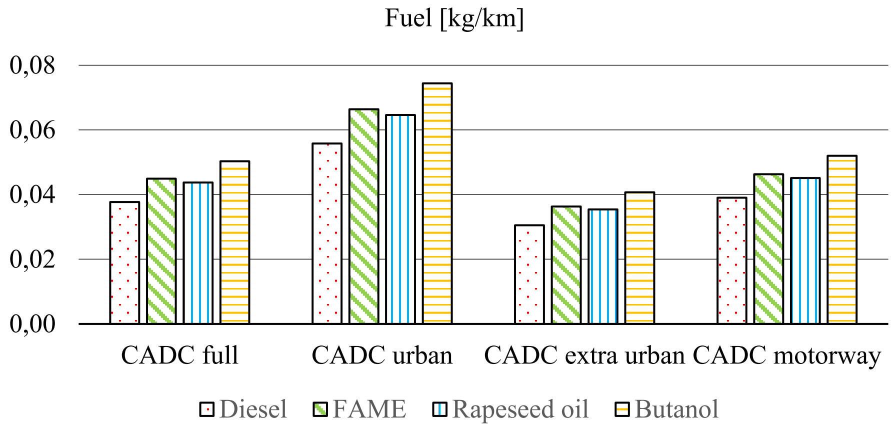

Fig. 12. Summary of the results of mass fuel consumption per 1 kilometre for selected fuels, obtained from different variants of the CADC test

The figure above shows the mass fuel consumption per 1 km for each part of the driving test. The highest amount fuel is consumed in the test's urban cycle (regardless of the type of fuel used). The vehicle does not move at a constant speed, and its dynamic changes significantly contribute to increased fuel consumption. The motorway cycle is in second place in terms of fuel economy. However, this consumption is clearly lower than in urban cycle. This is related to the characteristics of moving a vehicle through a metropolitan area.

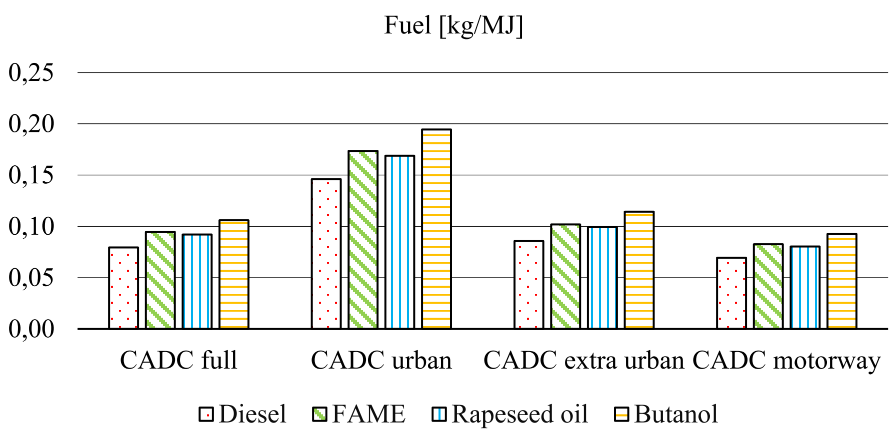

Fig. 13. Summary of the results of fuel mass consumption per 1 MJ for selected fuels, obtained from different variants of the CADC test

From the perspective of mass fuel consumption per 1 MJ of energy, most fuel is consumed in the urban cycle. The fuel whose consumption is the highest is butanol, which results from its physical and chemical properties.

3.4.2. Summary of simulation results for CADC carbon dioxide emission tests

The figures below (Figure 13-15) show the results of carbon dioxide emissions for selected fuels, obtained from different variants of the CADC test.

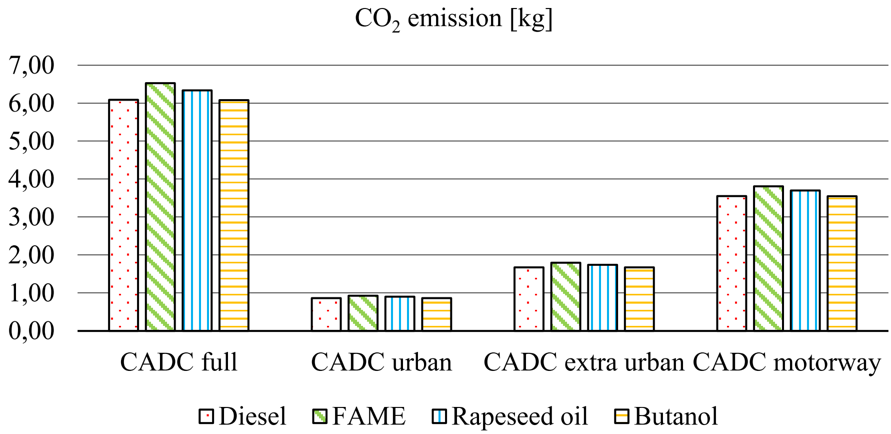

Fig. 14. Carbon dioxide emission results for selected fuels, obtained from different variants of the CADC test

As with mass fuel consumption carbon dioxide emissions also proved to be highest for the motorway cycle (Fig. 14). This is due to the largest mass consumption of energy carriers due to the largest distance travelled. In this figure, no reference to kilometres driven (as in Figure 15) is included, so that, emissions are determined directly by the amount of fuel conversion.

The consideration of the specificity of moving the vehicle in the urban cycle is well shown in Figure 15. Considering the number of kilometers driven in a given driving cycle test, CO_2 emissions will be highest for the urban cycle, followed by the motorway cycle.

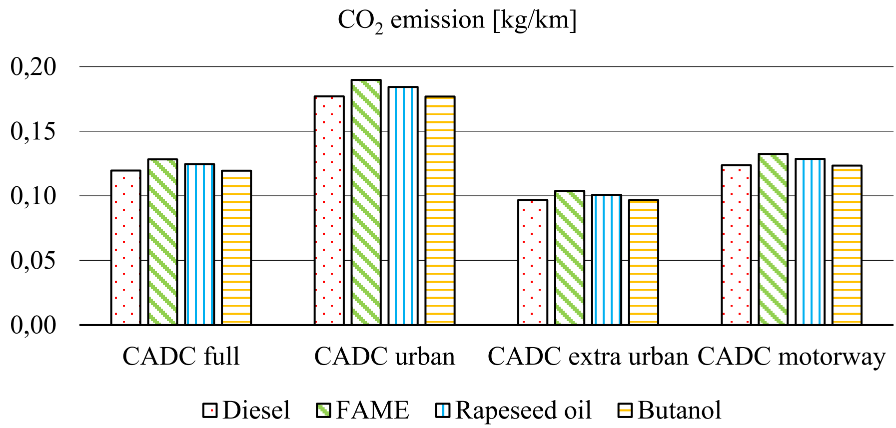

Fig. 15. Summary of the results of carbon dioxide emissions per kilometer for selected fuels, obtained from different variants of the CADC test

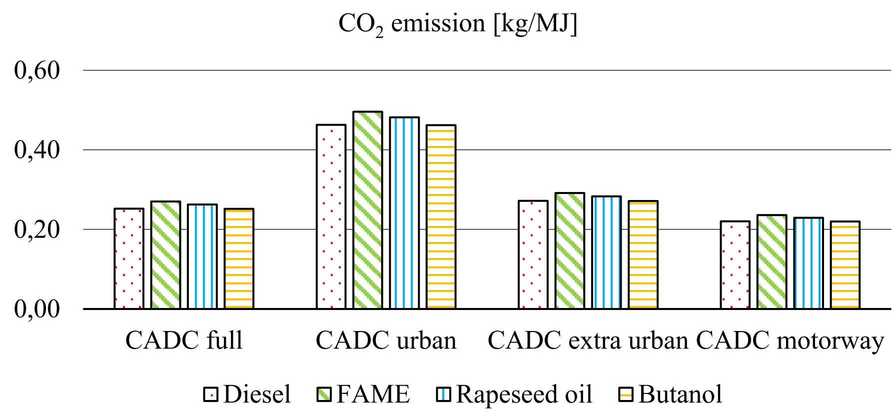

Fig. 16. Summary of the results of carbon dioxide emission per 1 MJ for selected fuels, obtained from different variants of the CADC test

On the basis of Figure 16 it can be stated that in the whole test, the highest CO_2 emission from 1 MJ of energy was characteristic for FAME fuel, while the lowest for butanol and diesel fuel. It should be noted that the differences in emission values are not significant. The fuels used in the analysis differ in the content of carbon hydrogen, sulphur and oxygen in their elemental composition and in their calorific value.

4. Summary

The driving cycle is currently the only standardised way to record vehicle movement. Vehicle approval tests, during which exhaust emissions from the exhaust pipe are collected and analysed, are performed on chassis dynamometers. During the test, it is checked that the permissible limits of pollutant emission into the atmosphere are not exceeded.

Fuel economy tests for new vehicles vary depending on the region of the world and the driving conditions associated therewith. Therefore, taking into account the migration of car brands in the world, it is important to develop computer tools that will make it possible to determine the amount of pollutants emitted into the atmosphere from vehicles.

The aim of the project was to build a computer tool using tests carried out on a chassis dynamometer to simulate driving tests. The built driving test simulator determines the amount of CO_2 emissions and fuel demand, including the parameters of the analysed vehicle for the given input parameters and the type of fuel (diesel oil, FAME, rapeseed oil and butanol).

On the basis of the tests carried out with one CADC, it is concluded that:

1. the highest mass consumption of fuel for the CADC full test occurred for FAME (2.283 kg) and butanol (2.559 kg);
2. in the case of mass fuel consumption per kilometre and fuel consumption per 1 MJ for the CADC full test, the lowest values were recorded for diesel fuel (0.0377 kg/km and 0.0795 kg/MJ respectively);
3. the highest carbon dioxide emissions occurred for FAME (6.524 kg) and rapeseed oil (6.336 kg);
4. when analysing carbon dioxide emissions per kilometre and carbon dioxide emissions per 1 MJ, the lowest values were noticed for butanol (0.1194 kg/km and 0.2518 kg/MJ).

The parameters of the fuels used had undoubtedly influenced the obtained results of computer simulations.

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