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A Comparative Analysis of Approval Driving Tests in the Context of Carbon Dioxide Emissions on the Example of Selected Passenger Cars

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1. Introduction

The global progress of civilization, which has been observed over recent decades, apart from technological development, also has negative effects, largely on the natural environment. Progressing urbanization, development of the energy, industry and transport have contributed to a significant deterioration in the quality of the ecosystems that surround us, including atmospheric air (Tritscher et al. 2020). The most serious and one of the priority problems is the excessive emission of carbon dioxide into the atmosphere, which contributes to an increase in the average temperature on Earth (Wang et al. 2020). The increased greenhouse gas emissions, including a large share of carbon dioxide – which accompanies virtually all fuel-to-energy conversion processes – are considered a major anthropogenic factor that deepens the greenhouse effect (Anderson et al. 2016).

From 1990 to 2019, global carbon dioxide emissions increased by over 60%. Table 1 summarizes the increase in global carbon dioxide emissions in the years 1990-2019.

The largest CO_2 emitters are China (approx. 27%), the United States (approx. 14.5%) and India (approx. 6.8%). Together, the EU-28 Community countries are responsible for around 10% of the gas discharge into the atmosphere. In 2017, Poland ranked 5th among the European countries with the highest CO_2 emissions. What is worse, the European Environment Agency has reported that our country has recorded the largest increase in carbon dioxide emissions compared to all EU member states (EEA Report No. 5 2018).

Table 1. Total global carbon dioxide emissions in 1990-2019

	CO_2 emissions [Mt]								
	22,182	23,007	24,559	29,255	33,067	35,463	36,153	36,573	36,810
Years	1900	1995	2000	2005	2010	2015	2017	2018	2019

Source: Author's own study based on: Global Carbon Atlas (1990-2019)
http://www.globalcarbonatlas.org/en/CO2-emissions

According to the Global Carbon Project (GCP), 36.81 billion tonnes of CO_2 ($GtCO_2$) were emitted into the atmosphere in 2019. It means an increase of only 0.24 $GtCO_2$ (0.6%) compared to 2018.

The increase in global emissions in 2019 was almost entirely caused by China. This country has increased its CO_2 production by 0.26 $GtCO_2$. The rest of the world has reduced its emissions by -0.02 $GtCO_2$. This was due to a reduction in coal consumption in the US and Europe, as well as a slowdown in the Indian economy compared to previous years (Friedlingstein et al. 2019).

Transport is responsible for approximately 25% of CO_2 emissions, of which 70% is road transport. This sector is closely connected with practically every branch of the economy, which translates into increased dynamics of its development. The number of motor vehicles and road networks is constantly increasing, which translates into increasing negative environmental effects. In 2016, passenger cars were responsible for about 60% of total emissions, while trucks and vans only for 38%. On the example of Poland, it can be seen that the increase in the number of passenger cars is significant. In 2012, the number of passenger cars in Poland was 18,744,400, while in 2017 this number increased to 22,569,900 (PZPM Report 2018, Central Statistical Office of Poland 2019). Therefore, an increase of over 20% was recorded. The numerous advantages of road transport and the increased demand for broadly understood mobility contribute to increasing the number of vehicles on the road. According to the data of the General Directorate for National Roads and Motorways (GDDKiA), the volume of traffic on national roads is also increasing. The general traffic measurement carried out in 2015 (this measurement is carried out every 5 years) showed an increase in traffic on national roads by 14%. The average daily traffic in 2015 for motor vehicles was 11,178 vehicles per day, compared to 9,888 vehicles per day in 2010 (Opoczyński 2016).

As early as 1992, the world already took action to reduce greenhouse gas emissions, including carbon dioxide, during the United Nations Framework Convention on Climate Change. The basic resolutions of the convention concerned national strategies for reducing greenhouse gas emissions – the preparation of such strategies and their consistent implementation, the inventory of emissions, the preparation of reports related to the implementation of the Convention's postulates as well as the commitment to conduct research in the field of climate change (United Nations Framework Convention 1992). Another important document was the Kyoto Protocol to the United Nations Framework Convention on Climate Change, drawn up at Kyoto in December 1997, which set binding quantitative and qualitative targets for reducing greenhouse gas emissions (Kyoto Protocol 1997).

The European Union has taken consistent action in the context of the fight against climate change by adjusting its environmental policy to global commitments (Fuss et al. 2020). On December 12, 2015, COP21 was held, which was a meeting of the parties to the United Nations Framework Convention on Climate Change. The international proceedings were concluded with an agreement on maintaining the average temperature rise on earth at 2°C, compared to the period before the industrial revolution (UN FCCC/CP/2015/L.9 2015). Therefore, the European Community has committed itself to reducing greenhouse gas emissions, including CO_2, by 40% compared to 1990 levels. The time horizon was set for 2030 (Schleussner et al. 2016). Such stringent reduction levels have an impact on all sectors, including road transport (Krause et al. 2020).

In the road transport sector, aspects of emissions from vehicles have been regulated by EURO standards (1-6) since 1993. Introduced by relevant European directives, they have set binding limits for individual chemical compounds for newly manufactured vehicles. To verify cars in terms of the amount of emitted substances, the NEDC (New European Driving Cycle) approval test was performed. The procedure was developed in the 1980's, while it was officially used since the early 1990's (Mock et al. 2014).

In its updated phase, the test was divided into 2 parts – the urban cycle and the extra-urban cycle. The urban part, which was supposed to reflect driving in agglomerations, lasted 13 minutes, during which time the vehicle covered a distance of about 4 km. In this part there were 4 consecutive phases of accelerating the vehicle to the speeds of 15, 32 and 50 kph, followed by a stop of the vehicle. After repeating this cycles four times, the extra-urban cycle followed, typical for non-residential areas and motorways. This part lasted 6 minutes and 40 seconds and the vehicle covered about 7 km at that time. It included accelerating the vehicle to the speeds of 70, 100 and 120 kph. This part was carried out once, without stops, only with a reduction of the speed to 50 kph.). Based on this test procedure, the fuel consumption and emission of individual exhaust components from the tested vehicle were determined (Barlow et al. 2009, Regulation No 83 of the UNECE 2012).

Unfortunately, this test was characterized by quite a generalization and at some point did not at all reflect the real road conditions or the dynamics of modern cars, which has changed a lot since the 1990's. Along with increasingly stringent environmental standards, it was necessary to introduce a new test procedure that would be reliably testing exhaust emissions of motor vehicles. From 2008, work began on a new approval test and from September 1, 2018, the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) approval procedure was introduced into widespread use for all newly manufactured vehicles to be driven within the territory of the European Union. The WLTP test distinguishes three categories of vehicles and the criterion is the power factor per vehicle mass [kW/t]. Currently, only cars from the third class are offered on the European market. The procedure includes 4 driving phases: low (average speed: 18.9 kph), medium (average speed: 39.4 kph), high (average speed: 56.5 kph) and very high (average speed: 94.0 kph). Stops are also included. The whole procedure lasts 30 minutes, during which time the car covers a distance of 23.25 km, which is more than twice as much as in the previous test. The WLTP also takes into account the equipment and tires mounted on the vehicle and is performed in more reliable temperature ranges, as for European conditions. In addition, the test will be different for each car because it takes greater account of its dynamics. All this is to be reflected in the precision of the results obtained and their compliance with real conditions on the road (Orynycz et al. 2020). Table 2 below summarizes the main differences between the two approval tests.

As seen in the above table, the tests differ significantly, which may have a large impact on the results obtained on their basis. In this paper, it was decided to compare both test procedures on the example of a passenger car powered by biofuels and diesel. The choice of the vehicle was dictated by its urban character as well as the variety of fuels with which it can be supplied. The value of emitted carbon dioxide was chosen as the assessment parameter, due to the increasing restrictions on its reduction. The research used a simulation model that reflects the movement of the vehicle according to the given test procedure.

Table 2. Differences in the NEDC and WLTP homologation test procedures

Parameter	NEDC	WLTP
Development/Introduction	Developed in the 1980's, introduced at the beginning of the 1990's.	Developed from 2008, introduced from 1 August 2018.
Driving cycles	Urban cycle 65% and extra-urban cycle 35%	Low, medium, high and very high cycles. Urban cycle share – 52%, extra-urban cycle share – 48%
Duration	20 min	30 min
Total distance	11 km	23.25 km
Average speed	34 kph	46.5 kph
Maximum speed	120 kph	131 kph
Gear shift	According to schedule, in specific points	Individually, depending on the vehicle being tested
Remarks	No distinction between versions of equipment, tyres installed or other factors	Allows for vehicle equipment, tyres installed and other factors affecting exhaust emissions

Source: Author's own study based on (https://wltpfacts.eu/, Mock et al. 2014, Kroyan et al. 2020)

2. Methodology

The simulation model was developed in the SciLab environment. It is an open source scientific software that enables one to perform complex numerical calculations and build computational algorithms in a user-friendly manner. The unquestionable advantage is the ability to create block diagrams, each of which is based on mathematical equations and becomes a small element of a large simulation system. It is possible for the program to solve complex differential equations, linear and nonlinear systems, and optimize the resulting algorithms, which makes it a useful tool, also for structurally complex models. To build a simulation model of carbon dioxide emissions from the vehicles in question, the Xcos package was used, which corresponds to the Simulink package of the competitive Matlab environment and employs block diagrams to reflect the vehicle operation and dependencies in its mechanical systems (Czemplik 2012, Jaroszyński et al. 2014). Those research methods, based on computer simulations, are characterized by numerous advantages such as repeatability of results, the possibility of quick and costless modification of data and the acquisition of large amounts of data in a relatively short time (Łatuszyńska 2011).

The simulation model used the technical parameters of a Fiat Panda 1.3 MultiJet passenger car with a diesel engine. The Fiat Panda, equipped with a modern diesel engine of 1.3 liters, reaches its maximum power of 55 kW at 4,000 rpm and the maximum torque of 190 Nm is already achieved at 1,500 rpm. Diesel engines have different working characteristics than gasoline engines and achieve maximum torque sooner and in the lower RPM range. Fuel consumption for this car, according to the catalog data, is respectively: in the urban cycle 4.7 [l/100 km], in the extra-urban cycle 3.5 [l/100 km], while in the mixed cycle the fuel consumption is 3.9 [l/100 km] (FCA POLSKA SA 2015). Table 3 below lists the technical parameters of the engine in question.

Table 3. Technical parameters of 1.3 MultiJet engine

Parameter	Unit	MultiJet II
Engine cylinder capacity, Vss	cm^3	1251
Cylinder layout	–	in-line
Number of cylinders, c	–	4
Diameter of cylinder, D	mm	69.6
Injection type	–	direct, multistage

Table 3. cont.

Parameter	Unit	MultiJet II
Compression ratio, e	–	16.8 : 1
Piston stroke, S	mm	82
Maximum engine power, Ne	kW	55
Engine speed at maximum power, nN	rpm	4000
Maximum engine torque, Me	Nm	190
Engine speed at maximum torque, nM	rpm	1500
Rotational speed on idle gear, nbj	rpm	850±20

Source: Author's own calculations based on (Zembowicz 2010, Ambrozik et al. 2012)

In order to properly conduct the test procedure, it was necessary to implement appropriate fuel parameters and their consumption characteristics. The following conventional fuel and its alternative substitutes were used in the simulation to additionally assess the reduction potential of popular biofuels: diesel, fatty acid methyl esters (FAME), butanol (butyl alcohol). These substances were tested as self-contained fuel as well as mixtures with diesel oil. Table 4 below lists the properties of the fuels mentioned.

Table 4. Parameters of fuels used in the simulation

	Combustion parameters		Elemental composition		
	Calorific value [MJ/kg]	Air demand [g_{air}/g_{fuel}]	Carbon content [%]	Hydrogen content [%]	Oxygen content [%]
Diesel oil (ON)	44	14.5	86.5	13.4	0.0
Rapeseed oil (RO)	38.0	12.5	77.6	11.7	10.5
FAME (FAME)	37.0	12.5	78.0	12.0	10.0
Butanol (B)	33	11.2	64.8	13.5	21.6

Source: Author's own study based on (Baczewski et al. 2004, Gwardiak et al. 2011, Jóźwiak et al. 2006, Żółtkowski et al. 2015)

The above fuel and engine parameters as well as the course of approval tests were input into the simulation model being developed, which was used to obtain the results of carbon dioxide emissions from individual vehicles powered by various fuels. The results obtained refer to direct emissions during the test. In order to be able to refer to the reference values specified in the EURO standards, it was necessary to convert them into a unit appropriate for the standard – gram per kilometer [g/km].

The diagram of the model used to perform the computer simulation has been presented in Figure 1.

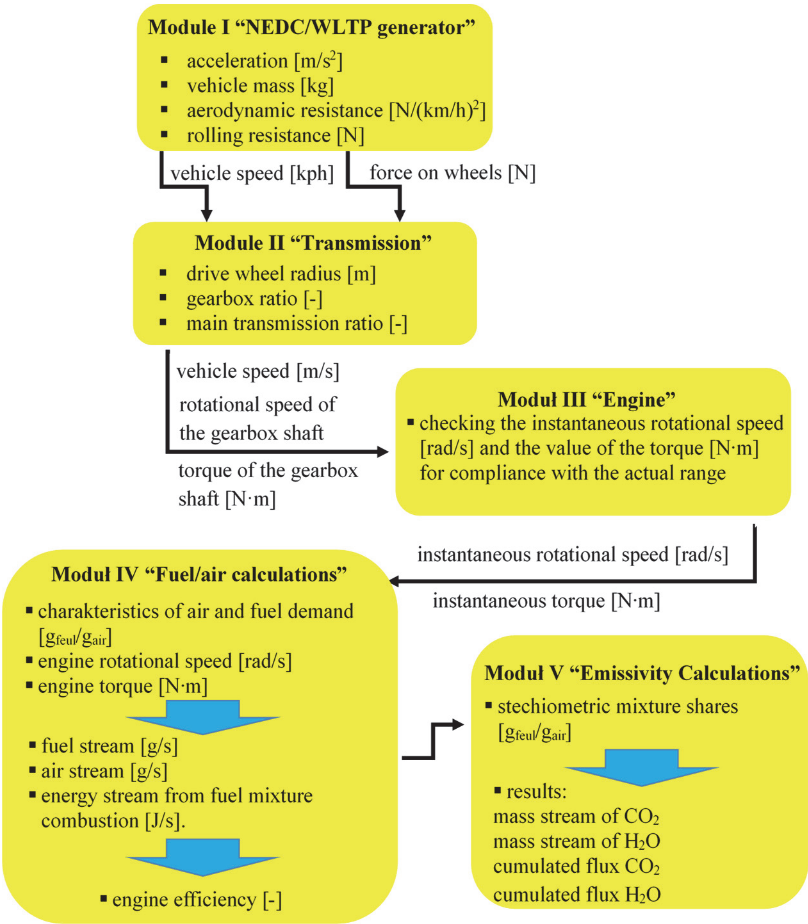

Fig. 1. Structure of the simulation model for CO_2 emissions from the NEDC and WLTP tests; Source: Author's own study

The model was divided into five modules, each of which was responsible for providing the results necessary to determine carbon dioxide emissions from the vehicles tested. Each of the modules presented in the diagram is described below:

- Module I "NEDC/WLTP generator" – Based on vehicle data such as mass, rolling resistance or aerodynamic resistance, the block provides the parameters characteristic for each driving test in the form of vehicle speed and wheel force.
- Module II "Transmission" – This block uses data on vehicle wheel size (dynamic diameter), transmission system ratios in relation to the rotational speed and ratios for the torque. On this basis, it generates signals such as: the speed at which the vehicle moves, the torque of the gearbox input shaft and its rotational speed.
- Module III "Engine" – Based on this module, the parameters obtained so far, such as the instantaneous speed and the instantaneous torque, are verified. It is essential that both of these factors should be within the designated ranges, allowed for a given engine. Any values that deviate from the acceptable ranges are directed to extreme parameter blocks and do not participate in further simulation stages.
- Module IV "Fuel/air calculations" – The block is based on the implemented hourly characteristics of the fuel and air demand and uses the torque and rotational speed values obtained in the previous block. It then calculates the fuel and air flow necessary to carry out the correct combustion process and the energy stream from the conversion of the fuel-air mixture.
- Module V "Emissivity calculations" – Taking into account the share of individual elements in the mixture, such as hydrogen, carbon and oxygen contained in the fuel mixture, mass streams of carbon dioxide and steam are determined and then their cumulative values are set.

3. Research results and discussion

The simulation model, developed according to the above scheme, renders it possible to map the movement of the vehicle according to the given driving test. It is therefore possible to carry out the experiment including the "start-stop" system installed in the vehicle and to determine the desired values of carbon dioxide emissions for fuels with different properties. Figure 2 below presents a summary of the charts obtained from module I and II, which reflect the values of individual parameters as the vehicle completes a given driving cycle. Part "A" refers to the NEDC test, while "B" refers to the WLTP. The parameters included here are: the vehicle speed (v [kph]), the distance traveled by the car (d [km]), resistance forces (F [N]) and the current gear ratio, i.e. the gear in which the vehicle is moving (p [-]).

The following comparison illustrates the significant difference between the two procedures in each of the aspects mentioned above. Even at first glance it can be inferred that the WLTP provides much more parameters than its predecessor and reflects the dynamics of the vehicle movement far more precisely. The courses of the speed of the car in each of the tests are consistent with the courses published in the available literature, which may lead to a conclusion that the model is working properly and provides reliable data. The further part of the results compares fuel consumption as a function of the additive share and carbon dioxide emissions as a function of the additive share. For these results, the functioning of the "star-stop" system was taken into account, which is fitted as standard equipment of the tested vehicle.

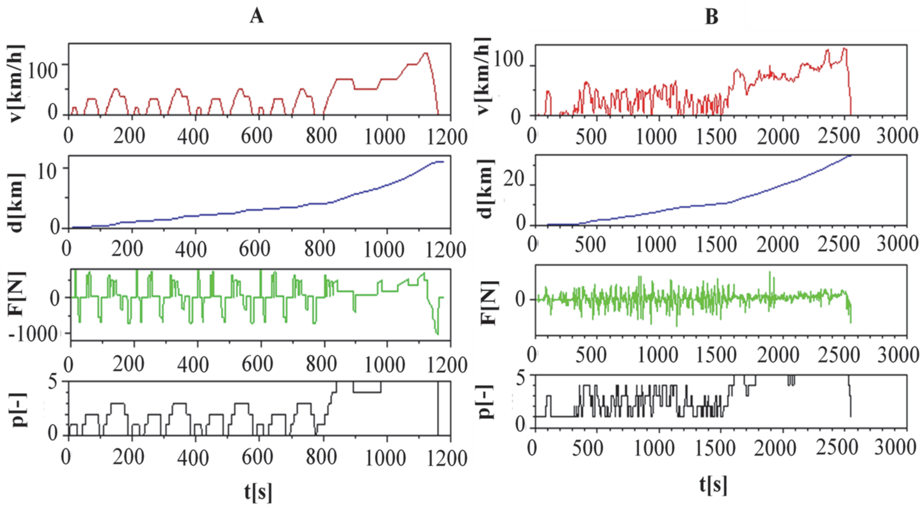

Fig. 2. Parameter courses obtained from modules I and II for NEDC (A) and WLTP (B) tests; Source: Author's own study

The vehicle under analysis has a five-speed gearbox. Therefore in figure 2 for p [-] the maximum value is 5. The figure shows the full range of changes of p [-] values.

3.1. Fuel consumption in the NEDC and WLTP tests – "start-stop" system disabled

Figure 3 summarizes the consumption of individual fuels and their mixtures [kg] by the vehicle in test A) NEDC and B) WLTP. This list does not include the operation of the system responsible for switching off the engine when the vehicle is idle (stationary).

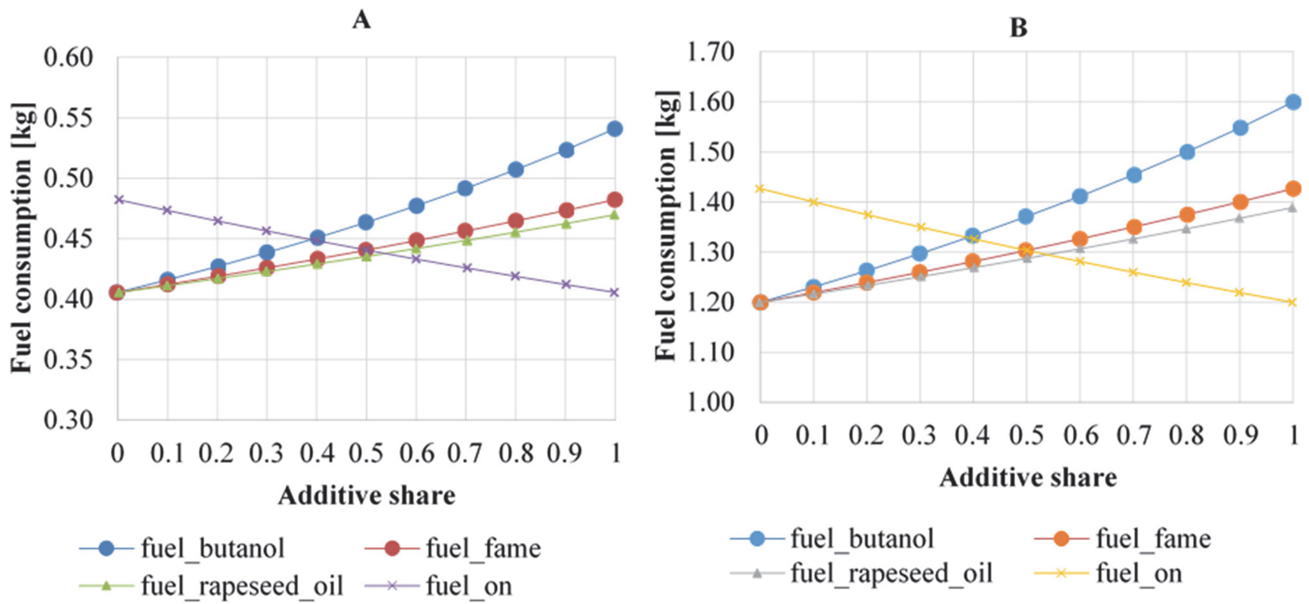

Fig. 3. Consumption of fuels and their mixtures in NEDC (A) and WLTP (B) tests ("start-stop" system disabled);
Source: author's own study

Based on the above graphs, a significant difference can be seen between the vehicle's consumption of individual fuels and their mixtures. Higher consumption in the WLTP test is correct though, due to the test distance being more than twice as long. Therefore, the difference obtained is obvious and the results obtained are correct. Both in the WLTP and NEDC tests, it can be seen that the increasing share of the additive in the mixture with diesel oil increases the consumption of the carrier and the highest values are achieved by biofuels as 100% powering fuel.

3.2. Fuel consumption in the NEDC and WLTP tests – "start-stop" system enabled

The Figure 4 shows the consumption of various fuels and their mixtures [kg] by the vehicle in the A) NEDC and B) WLTP tests while the "start-stop" system is enabled and shows its operation when the car is stationary.

With reference to the previous charts, a clear difference can be noticed in reducing the vehicle's fuel consumption. For pure butanol, the value of the carrier used in the NEDC test without the engine immobilization system is 0.54 kg, while with its participation it is merely 0.48 kg. The downward trend applies to all fuels and is a natural consequence of a break in the engine operation, therefore it does not combust fuel. In the WLTP procedure, a decrease in fuel consumption can also be seen, with the "start-stop" system running. However these differences are smaller due to the reduced number of stops and the longer test distance.

The following part presents the results of carbon dioxide emissions for individual fuels and test procedures, also taking into account the operation of the "start-stop" system in the vehicle.

3.3. Carbon dioxide emissions in the NEDC and WLTP tests – "start-stop" system disabled

Below (Fig. 5) are the results of carbon dioxide emissions for individual alternative fuels, and their mixtures with conventional diesel for the A) NEDC and B) WLTP test procedures. This option does not include the functioning of the "start-stop" system.

It can be seen that in the WLTP test emission values are about 4 times higher than for the NEDC test. When comparing the selected biofuels in both tests, butanol showed the lowest CO_2 emissions. Rapeseed oil gave intermediate results, while the highest concentration of carbon dioxide was provided by fatty acid methyl esters. This value increased along with the increase of this additive in a mixture with conventional diesel oil.

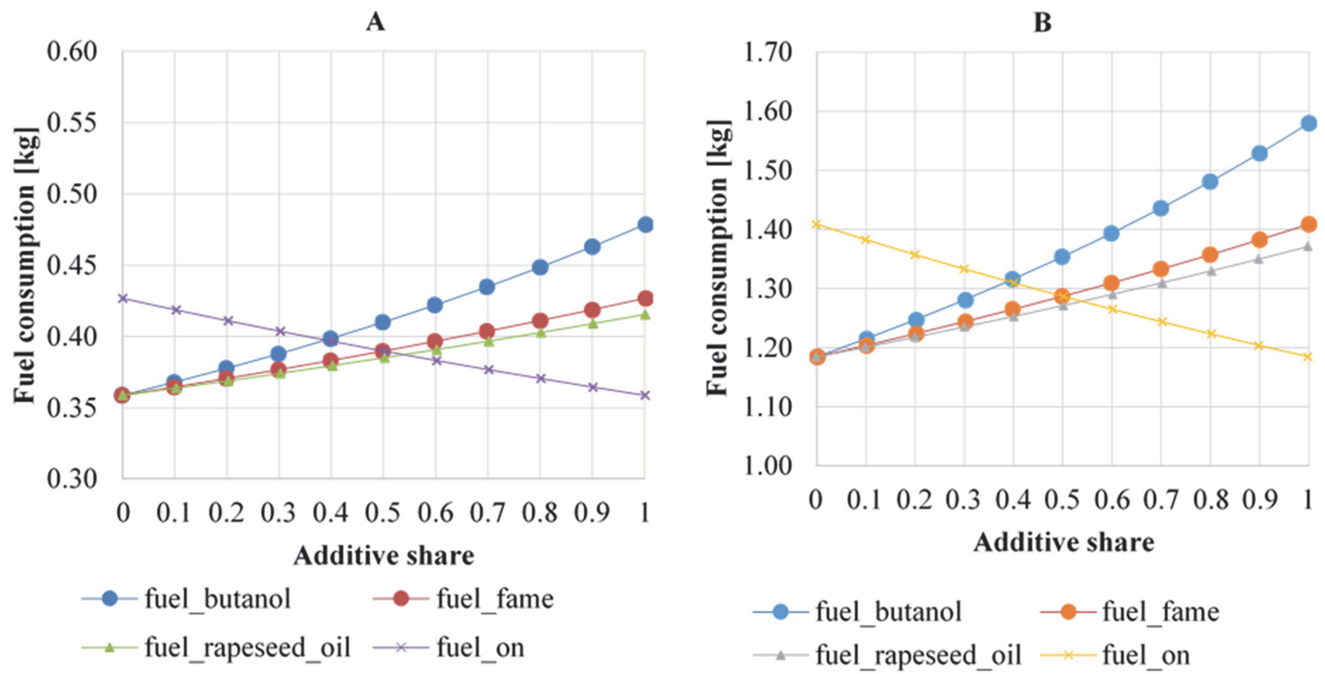

Fig. 4. Consumption of fuels and their mixtures in the NEDC (A) and WLTP (B) tests ("start-stop" enabled);
Source: author's own study

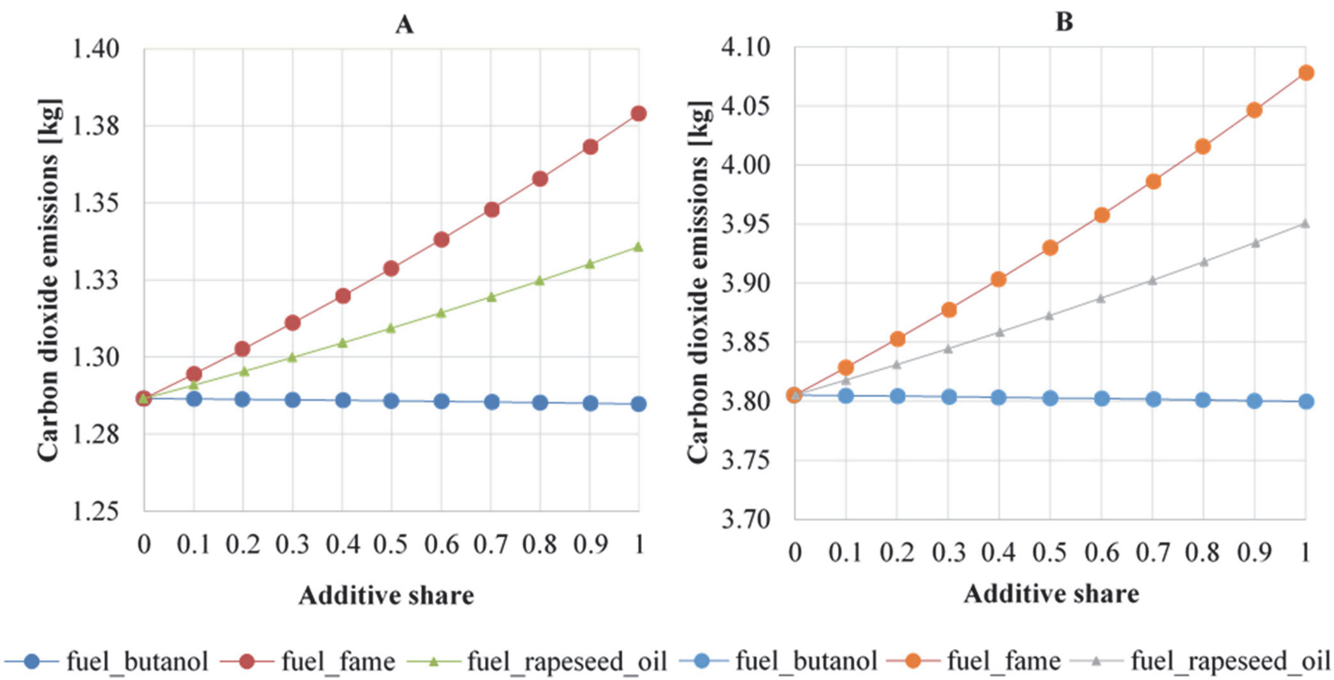

Fig. 5. Carbon dioxide emissions from individual fuels in the NEDC (A) and WLTP (B) tests (“start-stop” disabled); Source: author’s own study

3.4. Carbon dioxide emissions in the NEDC and WLTP test – "start-stop" system enabled

Fig. 6 summarizes the results of CO_2 emissions for selected A) NEDC and B) WLTP test procedures when the "start-stop" system is enabled.

It can be clearly seen that there is a favourable difference compared to not stopping the engine when the vehicle is stationary. In addition, as in the case of previous results, carbon dioxide emissions were much higher for the WLTP procedure than for the NEDC. This is obviously due to the vehicle's longer operation and fewer stops in the new test.

3.5. Summary of results

In the above form, it is impossible to objectively compare both methods due to the numerous differences in both schedules. As mentioned earlier, the new approval test has a much longer distance to be covered by the vehicle as well as different dynamics of movement. Therefore, Table 5 summarizes the results obtained for 100% fuels in both tests and converted them into a reference unit. This unit is strictly defined in EURO standards and is expressed as gram of substance per kilometer of road [g/km]. For the passenger car in question, the permissible value of carbon dioxide specified in the EURO standard is 130 g/km (Regulation (EC) No. 443/2009).

The above results show that no fuel exceeds the permissible level of carbon dioxide emissions in 100% content. It was evident in earlier graphs that alternative fuels as self-contained carriers show the highest emissivity, hence the values of emitted carbon dioxide for their pure forms were used for this comparison. With reference to the comparison of the values for both tests, it can be stated that:

- The values of carbon dioxide emitted for individual fuels depend on the functioning of the "start-stop" system.
- When engine sleep is off, this emission is lower for WLTP than NEDC.
- When the "start-stop" system is active, emissions in the new test procedure are higher. This may be related to the number of stops, of which are there are fewer in WLTP.
- In both tests, regardless of the system being on or off, the highest direct CO_2 emissions were attributed to FAME fatty acid methyl esters.
- Butanol was the fuel with the lowest emissions.

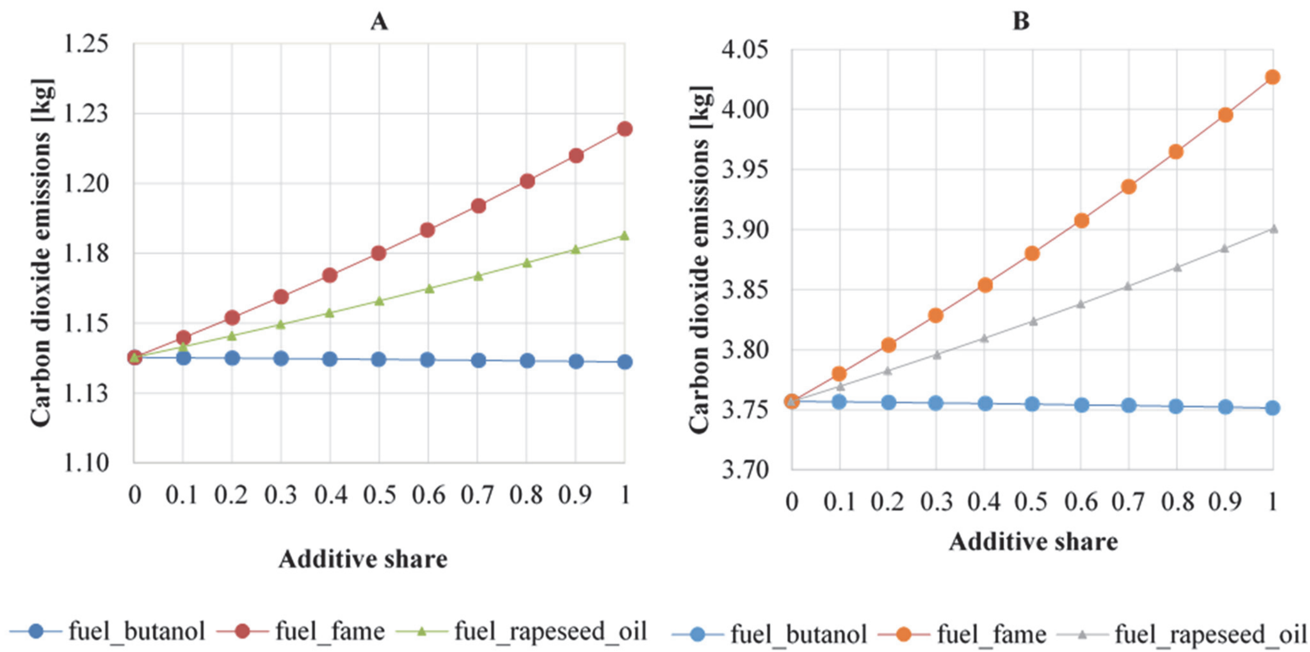

Fig. 6. Carbon dioxide emissions from individual fuels in the NEDC (A) and WLTP (B) tests ("start-stop" enabled);
Source: author's own study

Table 5. Summary of CO_2 emission results in NEDC and WLTP drive tests: Diesel oil (ON); Fatty Acid Methyl Esters (FAME), Rapeseed oil (RO); Butanol alcohol (B)

Driving test used	NEDC							
Distance in the test [km]	11.03							
Start/stop system	OFF	OFF	OFF	OFF	ON	ON	ON	ON
Fuel used	ON	FAME	RO	B	ON	FAME	RO	B
Carbon dioxide emission CO_2 [kg]	1.286	1.378	1.335	1.284	1.137	1.219	1.181	1.136
Reference unit [g/km]	116.591	124.932	121.034	116.410	103.083	110.517	107.072	102.992
Driving test used	WLTP							
Distance in the test [km]	34.68							
Start/stop system	OFF	OFF	OFF	OFF	ON	ON	ON	ON
Fuel used	ON	FAME	RO	B	ON	FAME	RO	B
Carbon dioxide emission CO_2 [kg]	3.805	4.078	3.95	3.799	3.757	4.026	3.900	3.751
Reference unit [g/km]	109.717	117.589	113.898	109.544	108.333	116.09	112.456	108.160

4. Summary

The deteriorating condition of the natural environment, including the air that surrounds us, influences the formation of climate policies of many countries and communities. Road transport, as a serious source of emissions, also in the field of carbon dioxide, is subject to increasingly restrictive regulations designed to limit its negative impact on ecosystems.

One example of changes in the transport sector was the introduction of a new approval procedure for motor vehicles to be put into service in the European Union. The comparative analysis of the new test with the previous procedure showed:

1. The new WLTP approval test should bring much more accurate results than the previous NEDC test, due to its assumptions in terms of time, distance, driving conditions and individual treatment of each vehicle
2. Research on carbon dioxide emissions from diesel oil and its alternative fuels has yielded equivocal results, depending on the activity of the vehicle's "start-stop" system.
3. For the engine sleep system turned on when the engine was idle, more emissions were recorded in the WLTP test.
4. For the switched off system, this emission was higher in the previous test procedure
5. When remaining within one test, it is clear that the "start-stop" system will reduce the amount of carbon dioxide emitted to the atmosphere.
6. It is worth mentioning that considering the results without a "start-stop" system is quite theoretical due to the fact that this system is in the basic equipment of the car, so it can be assumed that the WLTP test provided more objective results and the NEDC procedure simply lowers them.

The developed driving cycle test simulation tool uses data on actual fuel parameters (calorific value, chemical composition) and their mixtures. This allows for forecasting the change in exhaust gas emissions when using a different fuel mixture.

The simulation of engine operation takes into account the actual characteristics of specific fuel consumption as a function of speed and torque, which allows for the precise determination of momentary operating parameters and emissions under dynamic engine operation conditions during driving cycle tests. In the literature, the solutions used so far have mostly used averaged values resulting from vehicle exploitation.

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Abstract

This paper presents a comparison of two approval tests for a passenger car, both the current procedure and its predecessor. The car that was the subject of the study received a roadworthiness certificate based on the NEDC test, however, the emission results were compared with the new test procedure. The analysis showed the significance of the "start-stop" system in the conducted tests, however, assuming the original equipment of the car (active "start-stop" system), the WLTP test showed higher CO_2 emissions, which did not exceed the permissible emission standard for this model specified in the relevant regulation.

Keywords:
engine, CO_2 emission, NEDC, WLTP

Analiza porównawcza homologacyjnych testów jezdnych w kontekście emisji dwutlenku węgla na przykładzie wybranych samochodów osobowych

Streszczenie

Niniejsza praca przedstawia porównanie dwóch testów homologacyjnych dla samochodu osobowego, zarówno aktualnie obowiązującą procedurę jak i jej poprzednika. Samochód, który był obiektem badań, świadectwo dopuszczenia do ruchu otrzymał na podstawie testu NEDC, jednakże porównano wyniki emisji z nową procedurą testową. Dokonana analiza wykazała istotność systemu „start-stop" w przeprowadzonych badaniach, zakładając jednak oryginalne wyposażenie auta (aktywny układ start-stop) test WLTP wykazał wyższą emisję CO_2, jednakże nie przekroczyła ona dopuszczalnej dla tego modelu normy emisyjności określonej w stosownych przepisach.

Słowa kluczowe:
silnik, emisja CO_2, NEDC, WLTP