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Calculation of the production of exhaust emissions in the laboratory conditions

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Abstract. In the past, the type approval of road vehicles with regard to the production of pollutants was carried out exclusively in the form of laboratory tests. Laboratory tests determined the course of the vehicle's driving cycle and the methodology for quantifying pollutants depending on the distance passed. The revision of EU legislation in 2016 brought changes in the field of type approval, in particular a change in the driving cycle and an additional driving test in the form of real drive emission. The paper discusses a matter of the possibility of using Commission Regulation (EU) 2017/1151 for the purpose of calculating emissions of road vehicles in their operation by applying the methodology of real drive emission. The research task was performed on a roller dynamometer on two vehicles in the simulation of the original New European Driving Cycle (NEDC) in laboratory conditions with the application of the methodology for calculating emissions from real drive emission. During the test, the method of calculating the exhaust flow by sensing the amount of fuel consumed and the amount of intake air was used. Significant data, such as mass air flow, air temperature, engine speed, vehicle speed was recorded via the electronic control unit. Recorded data obtained from emission tester, roller dynamometer and On Board Diagnostic (OBD) tool must be synchronised. Test results should be used in the field of comparison of the type approval emission level and the emission level in operation.

1. Introduction

The measurement of the exhaust emissions of passenger cars and light-commercial vehicles is one of the key tests required for the type-approval of a vehicle which may have an influence on the protection of the environment [1]. At present, the current framework for the type approval of motor vehicles in Europe Directive 2007/46 / EC is still in force. This framework regulation is still being implemented by Regulation (EC) No 715/2007. It determines how vehicle testing is performed for type-approval purposes and sets limits for Euro 5 and Euro 6 vehicles [2,3]. Testing is performed in laboratory conditions by simulating the NEDC driving cycle. Due to the large difference in the results achieved between real values and laboratory values of emissions and fuel consumption, new EU legislation was adopted in 2017. Commission Regulation (EU) 2017/1154, Commission Regulation (EU) 2017/1151 and Commission Regulation (EU) 2018/1832 brought about a comprehensive change to vehicle testing for exhaust emissions [4,5]. The New European Driving Cycle (NEDC) has been replaced by the



Worldwide Harmonised Light Vehicles Test Cycle (WLTC), which is considered to be more realistic in form and its results are intended to reduce the difference between laboratory and real emissions and fuel consumption values. Among other things, these regulatory acts introduce the obligation to measure real drive emission. The aim of this paper is to apply selected parts of the EU Commission Regulation 2017/1151 for the purpose of the mass quantification of CO (carbon monoxide), CO₂ (carbon dioxide), THC (total hydrocarbons), NO_x (nitrogen oxides) and O₂ (oxygen) emission of two vehicles with different emission systems [6,7,8]. By comparing the measurement results during the simulation of the NEDC driving cycle, it is possible to illustrate the differences between the type-approval limits of the relevant Euro standards with the values of the results from the approval tests and the results of the author's measurements [9,10].

2. Methodology

Laboratory emission tests of two passenger cars were performed in the laboratories of the Department of Road and Urban Transport. During the tests, data were recorded from the vehicle's roller dynamometer, exhaust gas analyser and vehicle diagnostics electronic systems communicating via the OBD connector. The test stand scheme is shown in the figure 1.

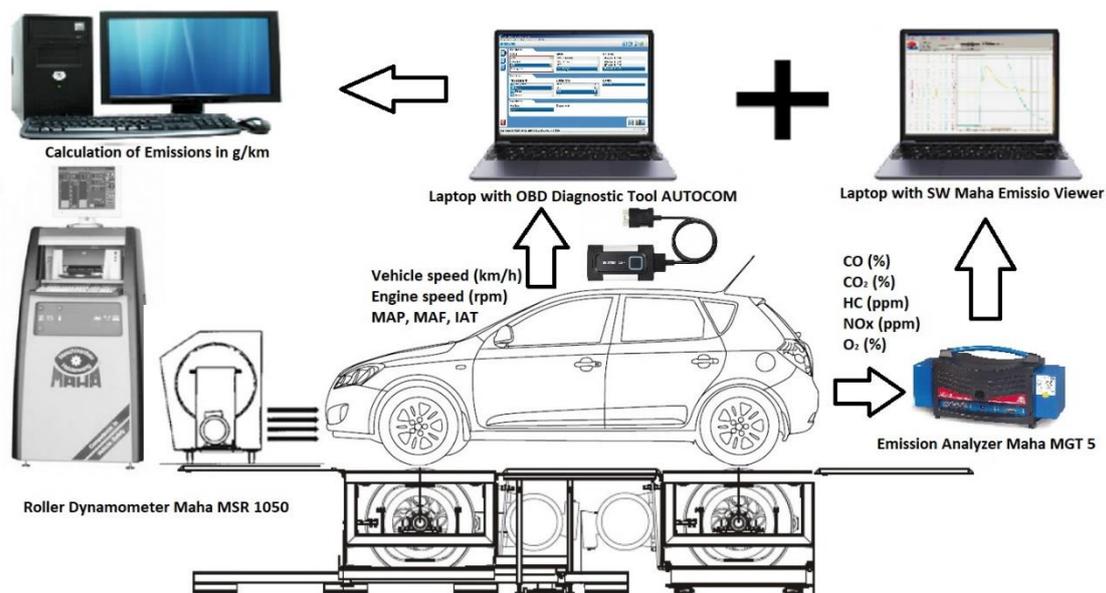


Figure 1. The test stand scheme.

Afterwards, the data was collected in three files with different data ranges and different sampling frequencies. It was necessary to synchronise these data for the purpose of their subsequent use for the calculation of exhaust emissions [11,12,13]. Driving tests were performed with the vehicles according to the NEDC driving cycle and after synchronisation, the data formed a series of 1180 seconds intervals. The courses of driving cycles for Kia Ceed and Volkswagen Golf Plus are shown in the figure 2 and figure 3.

3. Tested vehicles

For the purposes of this research task, two measuring vehicles with different types of fuel were used. These vehicles were passenger cars with a comparable engine cylinder capacity. For both vehicles it was necessary to perform coast-down driving tests due to the correct setting of the roller dynamometer. Basic parameters of tested vehicles are in Table 1. These vehicles are subject to the different emission standards, Kia Ceed is subject to the Euro 4, while VW Golf is subject to Euro 5 emission standard.

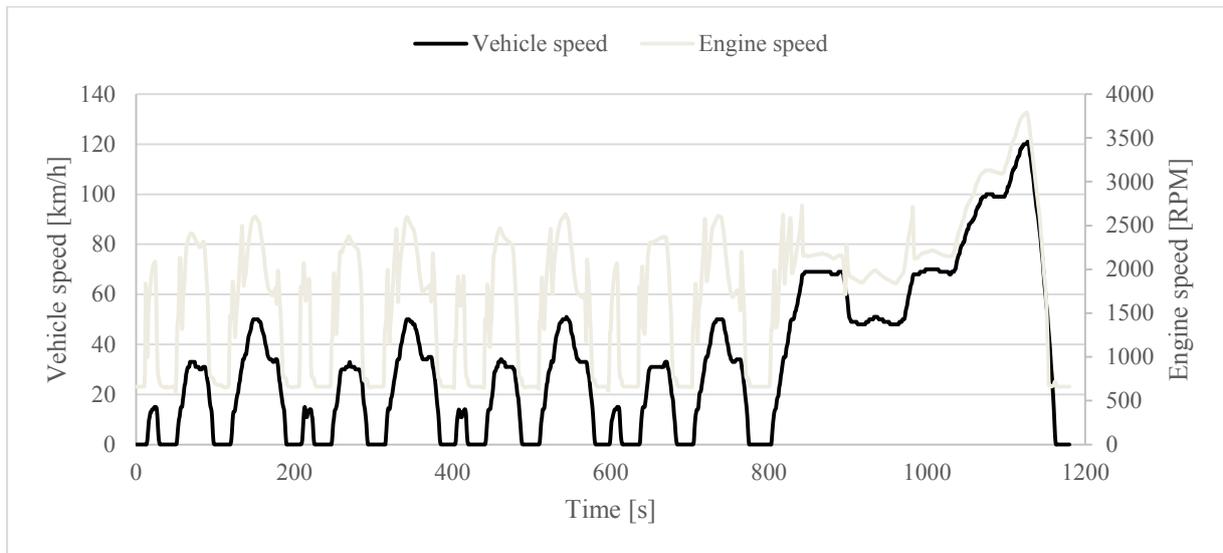


Figure 2. The course of driving test Kia Ceed.

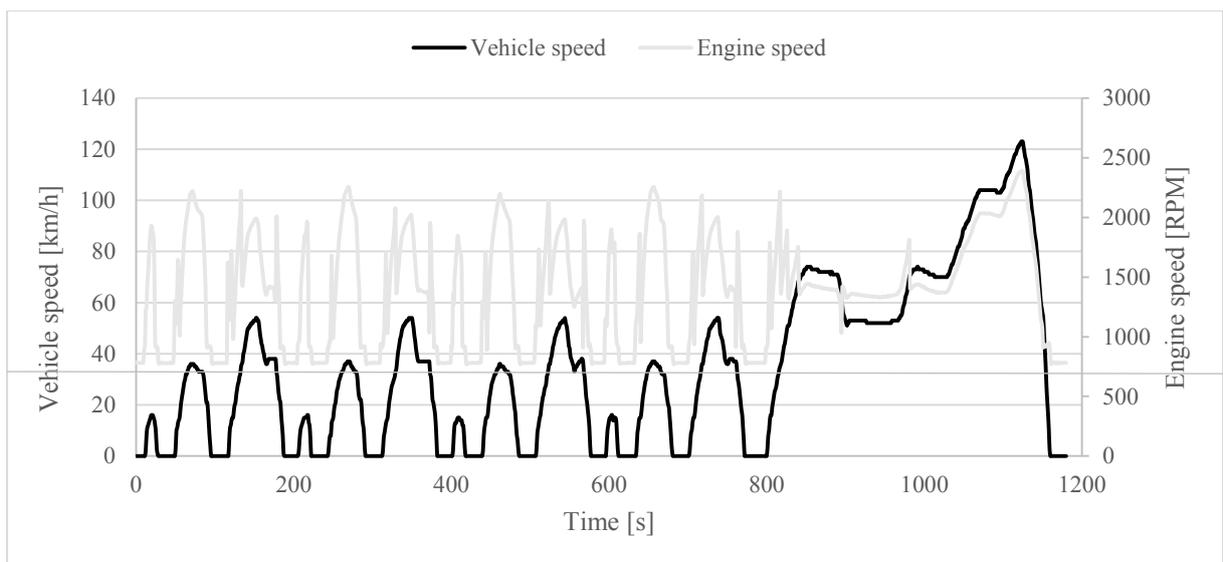


Figure 3. The course of driving test Volkswagen Golf Plus.

4. Measuring equipment

The main measuring device for the purpose of emission calculation is the Maha MGT 5 exhaust gas analyser. This gas analyser is designed to measure THC, CO, CO₂, O₂ and NO_x emissions. The analyser operates via selective absorption which means that each component of the exhaust is assessed in the infrared range. The tested exhaust gases are conducted from a vehicle exhaust pipe to an exhaust probe that is connected to the analyser by a hose. At first, H₂O water vapor is separated from exhaust gases, which then are led to the measuring chamber. The infrared light beam in the direction of the measuring element is weakened by the gas. The amount of attenuation of this light beam is manifested by a different wavelength depending on the type of gas. Such a method is used to measure amount of THC, CO and CO₂. On the other hand, O₂ and NO_x are measured by electrochemical detection. The measured data from the emission analyser is evaluated on a portable computer with Maha Emission Viewer software, which allows emissions to be recorded during whole driving of the vehicle [14, 15, 16].

Table 1. Basics parameters of tested vehicles.

	Kia Ceed	Volkswagen Golf Plus
Emission legislation	70/220*2003/76B (EURO 4)	715/2007*692/2008A (EURO 5)
Cylinder capacity	1591 cc	1598 cc
Engine type	In-line 4 cylinder	In-line 4 cylinder
Bore x stroke	77.0 x 85.4 mm	79.5 x 80.5 mm
79,5 x 80,5 mm	10,5 :1	16,5 :1
Fuel	Petrol	Diesel
Max. power	90 kW	77 kW
RPM	6200	4400
Max. torque	154 Nm	250 Nm
RPM	4200	1500
Valve control	DOHC	DOHC
Fuel system	multipoint injection	common rail

Single Roller Dynamometer MSR Maha 1050 is a roller test bench (performance testing device) with inter-axle control regulation which is taken from the industrial laboratories. One roller on the tire allows for carrying out the long-term tests without the risk of tire damage. During the testing, the vehicle is substantially higher than the laboratory floor and this fact allows for better cooling air flow. On this device, following types of measurement can be carried out, depending on the level of equipment: engine performance measurement (continuous, or discretely); load simulation (constant tractive force, constant speed, ride simulation, constant engine speed); engine flexibility measurement; tachometer monitoring.

In addition, AutoCom was used as a tool for communication with the vehicle's electronic system. It allows communication with all available control units in the vehicle. For measurement purposes, it was used to record data from the engine control unit. The vehicle speed, engine speed, amount of intake air (intake air pressure) and intake air temperature were recorded. During the Kia Ceed test, the intake air pressure (MAP sensor) and the intake air temperature were recorded as a parameter evaluating the amount of intake air. These values were then calculated for the amount of intake air in (g / s) according to the methodology given in [17]. During the test of the VW Golf vehicle, the parameter the amount of intake air in g / s was recorded from the MAF sensor.

5. Processing of measurement results

After obtaining data from the performed measurement, it was necessary to calculate from these data the real number of individual components of emission produced by vehicles. The calculation of emission components was carried out based on the Commission Regulation of the European Union 2017/1151 from 1 June 2017 [18, 19]. The calculation of emissions is described in Appendix 4 to Annex IIIA to this Regulation.

The calculation of the instantaneous masses of the individual emission of the gaseous components was determined for each second from the recorded series of data according to the formula:

$$m_{gas,i} = u_{gas} * c_{gas,i} * q_{mew,i} \quad (1)$$

where:

$m_{gas,i}$ is the mass of the exhaust component gas [g/s],

u_{gas} is the ratio of the density of the exhaust component gas and the overall density of the exhaust gas,

$c_{gas,i}$ is the measured concentration of the exhaust component gas in the exhaust [ppm],
 $q_{mew,i}$ is the measured exhaust mass flow rate [kg/s].

The values of the density ratio of the exhaust component gas and the overall density of the exhaust gases for each component of the exhaust gases were required to calculate the instantaneous mass emission components (Table 2). These values are specified in the regulations for different types of fuels. For the purpose of evaluating the measurement, the values of the individual emission components for diesel and E10 petrol were needed [18,20,21,22,23,24].

Table 2. The density ratio of the exhaust component gas and the overall density of the exhaust.

	NO _x	CO	THC	CO ₂	O ₂
E10 petrol	0.001587	0.000966	0.000499	0.001518	0.001104
Diesel	0.001586	0.000966	0.000482	0.001517	0.001103

The instantaneous exhaust mass flow rate can be calculated from the air mass flow rate and the air-to-fuel ratio described in the regulation as follows:

$$q_{mew,i} = q_{maw,i} * \left(1 + \frac{1}{A/F_{st} * \lambda_i}\right) \quad (2)$$

where:

$q_{mew,i}$ is the measured exhaust mass flow rate [g/s],
 $q_{maw,i}$ is the instantaneous intake air mass flow rate [g/s],
 A/F_{st} is the stoichiometric air-to-fuel ratio [g/g],
 λ_i is the instantaneous excess air ratio.

The stoichiometric air-to-fuel ratio is calculated as follows:

$$A/F_{st} = \frac{138,0 * \left(1 + \frac{\alpha}{4} * \frac{\varepsilon}{2} + \gamma\right)}{12,011 + 1,008 * \alpha + 15,9994 * \varepsilon + 14,0067 * \delta + 32,0675 * \gamma} \quad (3)$$

where:

α is the molar hydrogen ratio (H/C),
 β is the molar carbon ratio (C/C),
 γ is the molar sulphur ratio (S/C),
 δ is the molar nitrogen ratio (N/C),
 ε is the molar oxygen ratio (O/C).

These coefficients are given for each fuel type. In our case, the stoichiometric ratio of air and fuel had to be calculated in the Table 3 for diesel and petrol E10.

Table 3. The values of coefficients for examined fuels.

Fuel	α	β	χ	δ	ε
diesel	1.92	1	0	0	0,03
E10	1.8	1	0	0	0

The instantaneous excess air ratio calculates as follows:

$$\lambda_i = \frac{\left(100 - \frac{C_{CO} * 10^{-4}}{2} - C_{HCW} * 10^{-4}\right) + \left(\frac{\alpha}{4} * \frac{1 - \frac{2 * C_{CO} * 10^{-4}}{3,5 * C_{CO_2}} - \frac{\varepsilon}{2} - \frac{\delta}{2}}{1 + \frac{C_{CO} * 10^{-4}}{3,5 * C_{CO_2}}}\right) * (C_{CO_2} + C_{CO} * 10^{-4})}{4,764 * \left(1 + \frac{\alpha}{4} * \frac{\varepsilon}{2} + \gamma\right) * (C_{CO_2} + C_{CO} * 10^{-4} + C_{HCW} * 10^{-4})} \quad (4)$$

where:

- C_{CO_2} is the dry CO_2 concentration [%],
- C_{CO} is the dry CO concentration [ppm],
- C_{HCw} is the wet THC concentration [ppm],
- α is the molar hydrogen ratio (H/C),
- γ is the molar sulphur ratio (S/C),
- δ is the molar nitrogen ratio (N/C),
- ε is the molar oxygen ratio (O/C).

6. Results

As these are vehicles using different types of fuel and with different ways of preparing the fuel mixture, it is clear that the instantaneous values of some important parameters will be different. In particular, the parameters of the amount of intake air and the air-fuel ratio (AFR) differ diametrically during the tests. This fact has a significant impact on the results and the comparison of the individual components of the exhaust emissions of the two vehicles. As a representative of a vehicle with an atmospheric engine, Kia Ceed operates using a stoichiometric mixture. During operation, it rather maintains the air-fuel ratio (AFR) close to 1. The Volkswagen Golf with a supercharged diesel engine works with a high excess of air. The figure 4 shows that Volkswagen Golf AFR is only up to the value of 25 due to the legibility of the course of Kia AFR. Its theoretical values approach 150 in some operating states. Normal operating value of AFR is in the range from 3 to 5 (figure 4).

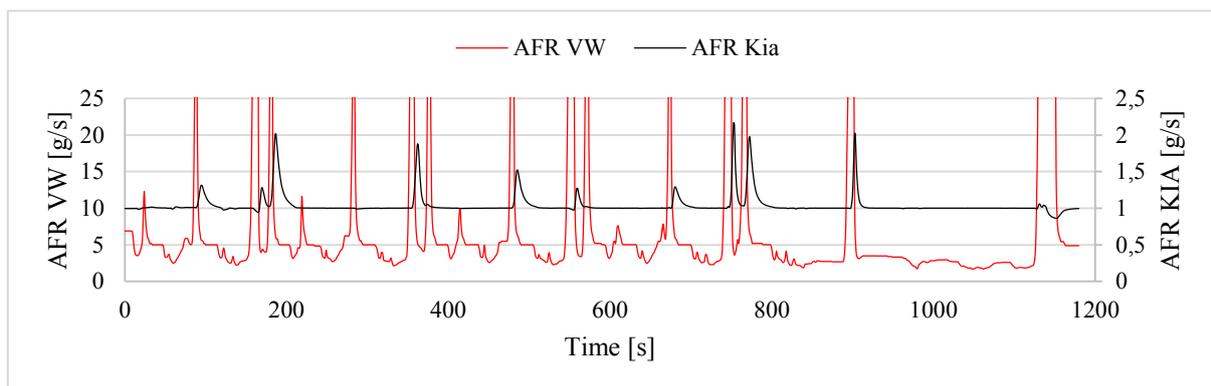


Figure 4. The comparison of air fuel ratio (AFR) for VW Golf and Kia Ceed.

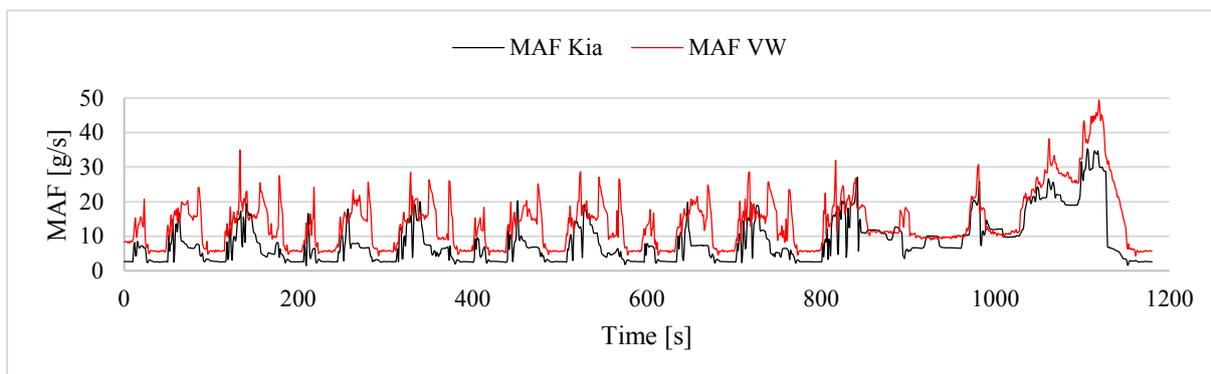


Figure 5. The comparison of the amount of intake air for VW Golf and Kia Ceed.

The measured values of the amount of intake air also result from the principle of different activities of the examined engines (figure 5). During the measurements, the values of the amount of intake air reached during the identical 1180 seconds drive were significantly different (Kia Ceed 9918.66 g air;

VW Golf 16455.76 g air). These two operating parameters of the engines significantly affect the result of the composition of selected components of the exhaust gases.

After the application of the mentioned methodology, the total and relative emissions of CO₂, CO, THC, NO_x and O₂ were calculated from the measured data. The different course of the recorded volume of CO₂ in the exhaust gases is caused by difference in operation of the diesel and petrol engines (figure 6). The supercharged VW Golf engine produced about 6 kg of exhaust gas more than Kia Ceed petrol engine during the NEDC driving cycle. However, majority of the exhaust gas of VW Golf consists of unburned O₂. The exhaust gases of the tested diesel engine contained more than 2.7 kg of O₂ during the test. Since the petrol engine works with a stoichiometric mixture, its O₂ production in the exhaust gases is exceptionally low.

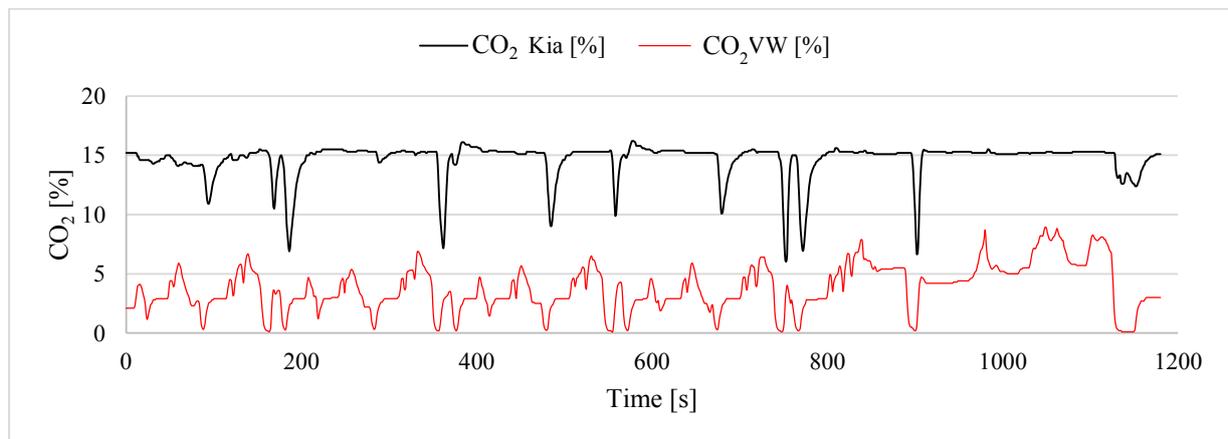


Figure 6. The comparison of CO₂ for VW Golf and Kia Ceed.

The total production of individual components of the exhaust gases of examined vehicles is processed in figure 7 and figure 8. The petrol engine produced a significantly larger amount of CO₂, resulting from the volume of CO₂. The petrol engine produced 11.8 g of CO gas and the diesel engine 6.882 g of CO. There is a significant difference in the amount of NO_x produced. In this case, a larger amount of NO_x is produced by the diesel engine than by the petrol one.

The maximum values of individual gases are determined by EU legislation depending on the type approval time of the given vehicle. The vehicles examined have not only a different type of fuel, but also the relevant Euro standard. The limits in these regulations are set in g / km for passenger cars. In Table 4 it is possible to observe the difference in the values specified by the relevant Euro standard, the declared values from the type approval tests (COC value) and the values measured in the course of conducted for the purpose of this paper studies.

Regulation 2003 / 76B (EURO 4) sets limits for the Kia Ceed for the exhaust gas components CO, HC and NO_x. The measured CO value at 1.086 g / km is just above the limit of the Euro 4 standard. The manufacturer declares the value of CO at the level of 0.433 g / km. The THC values measured in the test are significantly below the limit and also below the value from the type-approval tests. An almost identical NO_x value was measured (0.0215 g / km) comparing to the manufacturer's type-approval result (0.023 g / km).

For Volkswagen Golf Plus with diesel engine, the limits are set according to 692 / 2008A (EURO 5) for the exhaust gas components CO, NO_x and THC + NO_x. In this case, only for the CO component, the measured values are exceeding, in comparison with the limit of the relevant Euro standard. The CO produced during testing reached a value of 0.627 g / km, as compared to the value of 0.5 g/km set by the Euro standard as a limit. The amount of NO_x produced is almost identical to the value given by the manufacturer from the vehicle type-approval tests.

Table 4. The comparison of emission measured values, values specified by the relevant emission Euro standard and values from type-approval tests.

		CO	CO ₂	THC	NO _x	THC+NO _x
		[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
	EURO 4 limit	1.000	-	0.1000	0.0800	-
Kia Ceed	Measured	1.086	222.54	0.0145	0.0215	-
	COC value	0.433	152	0.038	0.023	-
	EURO 5 limit	0.500	-	-	0.1800	0.2300
VW Golf	Measured	0.627	98.61	0.0090	0.1449	0.1539
	COC value	0.182	126	-	0.1470	0.174

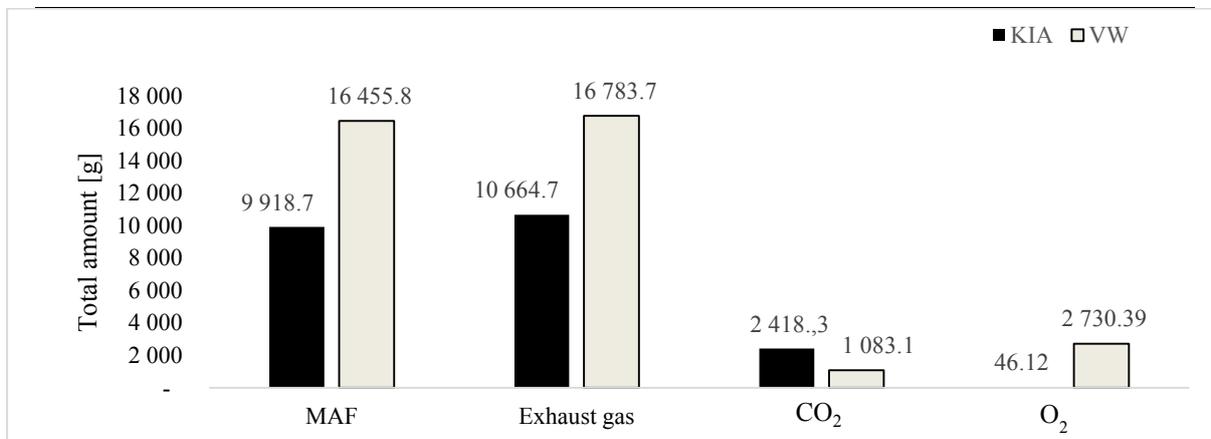


Figure 7. The comparison of individual components of the exhaust gases.

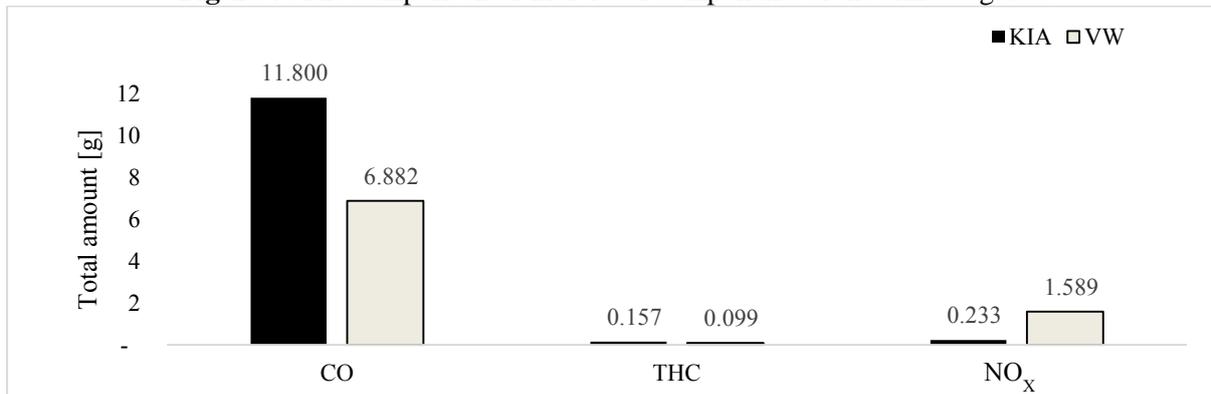


Figure 8. The comparison of individual components of the exhaust gases.

7. Conclusion

The issue of measuring the production of exhaust emission is very extensively examined nowadays. It is possible to use several available methodologies to quantify them. For the purpose of analysing the differences in the approach of calculating the amount of intake air, two vehicles with different emission systems and types of fuel were selected. The difference in the calculation is mainly in the method of calculating the amount of intake air (MAP and MAF sensor). Also, due to the difference in fuel, the ratio of density of the exhaust component gas and overall density of the exhaust are used differently. In the case of this paper, a simple 5-component exhaust emission analyser was used. It recorded the volume composition of the exhaust gases. For the purposes of the above measurements,

the EU Commission Regulation 2017/1151 was used due to the calculation of the amount of exhaust gases produced. This type of measurement is suitable not only for laboratory conditions, but such a set of measuring devices can replace PEMS systems. The disadvantage of this type of calculation is the complexity of evaluating of selected components of the produced exhaust gases. The process of calculation included the need for calculation or measuring the amount of intake air. This parameter can be recorded by OBD diagnostics, but the evaluation method may differ depending on the type of sensor in the engine intake system (MAP or MAF sensor). It is also necessary to synchronise all recorded data with respect to the course and measurement time. In the case of the presented results, the records from the vehicle roller dynamometer, exhaust gas analyser, and OBD diagnostics had had to be synchronised. The mentioned constants of density of the exhaust component gas and overall density of the exhaust gases and the constants of individual fuels also entered into the process of calculation. In the future, it would be appropriate to compare the presented method with PEMS devices used in Real Drive Emission (RDE) tests. For the purposes of comparison of different vehicles, determination of the effects on vehicles in normal operation and in scientific research, however, this method can be considered appropriate and inexpensive in view of the necessary test and diagnostic techniques.

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