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Jacek PIELECHA
Kinga SKOBIEJ
Marek SIEROŃ

Combustion Engines
Polish Scientific Society of Combustion Engines

Evaluation of RDE exhaust emission indicators of Euro 6 passenger cars using classical and window averaging methods

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The article presents a comparison of exhaust emission results obtained in on-road tests using the latest legislative proposals relating to passenger cars. The results were analyzed with reference to the classical method (considering all measurement data) and the measurement window averaging method, also referred to in the literature as the EMROAD method. In this approach, measurement windows are defined (based on carbon dioxide emission data from the WLTC test), and the corresponding on-road emissions are determined for the RDE test. The study included Euro 6c vehicles equipped with gasoline engines and diesel engines. The gasoline engines featured direct fuel injection, while the diesel vehicle was equipped with a particulate filter and a selective catalytic reduction system to reduce nitrogen oxide emissions. In on-road tests, the correction factors depended on the applied technical solutions. For direct-injection gasoline engines in the Euro 6 class, the values remained below 1. A characteristic feature was that the correction factors were higher in the urban part of the test and lower for the entire RDE cycle. A different pattern was observed for diesel vehicles: in on-road tests, the correction factors were higher for the entire test than for the urban part of the RDE test. The conducted research and the determined emission indices made it possible to evaluate the environmental performance of vehicles from different emission classes and, at the same time, to provide a basis for proactive measures aimed at reducing selected pollutants from passenger cars.

Key words: *exhaust emissions, conventional vehicle, combustion engines, Euro 6*

1. Introduction

The need to determine real-world vehicle emissions arose from efforts to reduce the gap between laboratory test results and those obtained under actual driving conditions [2, 33]. Numerous scientific studies indicate that laboratory procedures, particularly type approval tests, are not the most reliable solution for assessing emissions and fuel consumption [22]. Laboratory results are often significantly lower compared to those measured during real-world vehicle operation [21]. Portable emission measurement systems are already widely available, and their use will soon become a legal requirement in the EU [34]. However, many open issues remain regarding the correlation between real-world emissions and those determined in laboratory conditions. In addition, despite recent legislative changes, several legal and technical aspects of RDE testing still remain, at least to some extent, unresolved [9].

These factors guide research and development towards the design of low-emission vehicles, the use of alternative fuels [10, 29], the introduction of new and more environmentally friendly engine types, as well as the improvement of the efficiency of existing engines. Consequently, emission tests involving gravimetric particle measurements, particle number counting, the determination of carbon dioxide mass, the assessment of fuel consumption, and the evaluation of the effectiveness of emission control systems have become more important than ever from both an industrial and scientific perspective. Advanced methods of emission measurement can provide valuable insights into the processes of pollutant formation and transport originating from exhaust gases.

The determination of exhaust gas emissions from any vehicle can be carried out using several methods:

– based on chassis dynamometer tests [27], where exhaust emissions are determined under a defined driving cycle. In accordance with standards and regulatory frameworks, it is also possible to determine the road emissions of a given exhaust component [g/km; g/test]
– based on on-road tests [23–26], where the concentrations of gaseous components as well as the mass and number of particles are determined. When the exhaust flow rate is taken into account, the road emissions of these components can also be calculated.

The emission values of exhaust gases from vehicles (mopeds [15, 31], tractors [28], or rail machinery [12]), determined on the basis of the methods presented above, cannot be directly compared. The procedures and conditions under which the tests are carried out differ, which results in a lack of standardisation among these methods. In this article, it is assumed that exhaust gas emission and fuel consumption measurements will be conducted both on a chassis dynamometer and using a mobile system for measuring exhaust gases, PEMS (Portable Emission Measurement System). Such a system enables the measurement of all engine and vehicle operating parameters. To determine load values (torque) and engine speed, vehicle speed, fuel flow rate, and coolant temperature, data from the vehicle's control unit are used. Regulations require that these data be provided by the control unit and read and recorded by PEMS-type systems. It should be noted that exhaust gas emission results obtained during on-road tests represent real values for a given type of vehicle and reflect specific road conditions [30]. Such conditions make it possible to estimate the environmental performance of the tested vehicles and their engines during typical operation (eg. temperature [1]).

2. Literature review

Exhaust gas emission standards are established to control the pollutants emitted by vehicles worldwide. In most regions, limits on carbon dioxide emissions have also been set, as they are directly related to fuel consumption [32]. Exhaust gas values are measured under laboratory conditions (for passenger cars on a chassis dynamometer) in a defined type-approval test [14]. This part of the vehicle certification process determines its "environmental performance" and is identical for all passenger cars. The driving cycle is designed to represent the "most probable" road conditions, and the uniform testing procedure for all vehicles allows direct comparison of exhaust gas results [4]. However, increasing emphasis is now placed on on-road testing (already reflected in proposed European Union regulations), referred to as RDE, which is carried out using mobile measurement equipment of the PEMS type [3].

The latest studies on exhaust gas emissions from vehicles under real-world driving conditions, conducted using mobile measurement systems, reflect the actual environmental performance of vehicles [5]. The primary focus is on the potential use of such tests for powertrain calibration, in order to reduce exhaust gas emissions not only during the certification test but also across the entire operating range of engines. The authors of publication [16] indicated that future on-road testing, currently simulated in various research procedures, may lead to increased on-road emissions of nitrogen oxides from vehicles. To mitigate this, they proposed essential modifications in vehicle control unit software, noting that these changes are likely to be effective only for vehicles equipped with gasoline engines. Vehicles with diesel engines [11], on the other hand, will require additional financial investments in improving the effectiveness of exhaust aftertreatment by applying new methods for reducing nitrogen oxide concentrations.

Similar conclusions were reached by the authors of the article [13], in which road exhaust gas emissions under real driving conditions were compared using PEMS-type analyzers and the COPERT program [17]. It was found that, within the speed range of 20–120 km/h, calculations performed with the COPERT program were approximately 10% higher for parameters such as fuel consumption and on-road hydrocarbon emissions. In contrast, with respect to on-road nitrogen oxide emissions, the values obtained from the COPERT program were underestimated by about 30%.

Comparative studies of exhaust gas emissions from Euro 5 class vehicles, carried out in a laboratory on a chassis dynamometer [8] using various driving cycles, also confirmed the results described earlier. The authors applied tests in which the characteristics of speed variation reflected real driving conditions. It was found that, for vehicles with gasoline engines, on-road carbon monoxide emissions did not exceed 1 g/km (the permissible Euro 5 limit is also 1 g/km). On-road hydrocarbon emissions did not exceed 10% of the limit value (0.1 g/km), while on-road nitrogen oxide emissions corresponded to approximately 20% of the limit value (0.06 g/km). The authors indicated, however, that vehicles equipped with diesel engines significantly exceeded the permissible nitrogen oxide emission limits – the values obtained were approximately four times higher than the standard (the permissible Euro 5 nitrogen oxide emission value is 0.18 g/km).

In on-road studies, significant particulate emissions have been observed, particularly in the range of nanoparticles from combustion engines powered also by alternative fuels (eg. natural gas) [19]. The authors highlighted the high mileage of vehicles powered by alternative fuels, which consequently results in up to an eightfold increase in particulate number emissions for vehicles with a mileage of around 500,000 km compared to those with a mileage of 75,000 km. The article further confirmed, based on RDE tests under different traffic intensity conditions, that vehicles fueled with compressed natural gas emit higher amounts of nitrogen oxides compared to vehicles equipped with gasoline engines.

With regard to the accuracy of measurements during real-world driving, the final result depends on the operating conditions of the vehicle and the engine (including vehicle speed, road surface, driver characteristics and driving style, as well as other factors determining traffic conditions). These conditions are unpredictable and can significantly affect the outcome of exhaust gas emission measurements. Data presented in publications [7, 35] indicate that the most influential factors on the measured exhaust gas emissions are: the thermal state of the vehicle (engine), the average driving speed and dynamics, and the road gradient.

The impact of road conditions on exhaust gas emission results was the main subject of the article [20], in which sport utility vehicles (SUVs) with both gasoline and diesel engines were tested under varying road gradients. The authors attempted to estimate the change in on-road exhaust gas emission values of individual components as a function of road slope angle. They demonstrated that a 10% change in road gradient caused a twofold change in on-road emissions for vehicles with gasoline engines and a 1.5-fold change for vehicles with diesel engines.

The review of the current state of research highlights both the limitations of laboratory-based procedures and the importance of on-road testing supported by mobile measurement systems. It also demonstrates the significant influence of vehicle technology, driving conditions, and road gradients on the measured values of exhaust gas emissions. Against this background, the aim of the present article is to compare the results of on-road exhaust gas emission tests for passenger cars with the latest legislative proposals. The analysis includes both the classical method, which accounts for all measurement data, and the measurement window averaging method (EMROAD). This approach makes it possible to assess the environmental performance of Euro 6 vehicles with different powertrain technologies and to provide guidance for further reduction of selected exhaust components in real driving conditions.

3. Research methodology

3.1. Research objects

The objects of the study were passenger cars, the characteristics of whose powertrains are presented in Table 1. The vehicles were equipped with gasoline and diesel engines, all meeting the Euro 6 emission standard. Despite differences in engine displacement and type, a common feature was their comparable curb weight. The aim of the study was to determine the relationship between on-road exhaust gas emissions of specific compounds for both gasoline and diesel engines separately.

Table 1. Technical characteristics of the engines and vehicles used in the study

Parameter	Gasoline	Diesel
Engine		
Number and arrangement of cylinders	4, in-line	4, in-line
Engine displacement [cm3]	1984	1968
Emission standard	Euro 6	Euro 6
Maximum engine power [kW] at [rpm]	169/4700-6200	135/4000
Maximum engine torque [Nm] at [rpm]	350/1500–4400	380/1750–3000
Fuel supply	TSI	Common Rail
Drive		
Drive type	front-wheel drive	front-wheel drive
Gearbox type and number of gears	automatic, 6	automatic, 6
Weight		
Curb weight [kg]	1349	1354
Performance		
Top speed [km/h]	250	230
Acceleration 0–100 km/h [s]	6.4	7.1
Fuel consumption		
Combined cycle fuel consumption [dm³/100 km]	6.4	4.2
CO_2 emissions [g/km]	139	109

3.2. Research equipment

Exhaust gas emission measurements were carried out under real driving conditions, in accordance with the methodology presented, among others, in studies [1, 18, 20]. This approach required the installation of an exhaust sampling system on the vehicle in a manner that allowed its normal operation. For this purpose, an exhaust sampling line was constructed, which, when connected to the exhaust flow measurement system, formed a complete exhaust sampling setup for the measurement analyzers.

For the measurement of harmful compound concentrations in exhaust gases, a Semtech DS mobile analyzer from Sensors Inc. was used. It enabled the measurement of harmful components such as CO, NO_x, and CO_2. Additional data were supplied to the central unit of the analyzer directly from the vehicle's onboard diagnostic system, along with a GPS location signal. Information presented in publications concerning the use of mobile exhaust analyzers combined with data recorded from onboard diagnostic systems confirms the validity of assessing exhaust gas emissions under real driving conditions using the described measurement configuration.

3.3. Research route

On-road emission measurements were carried out under real traffic conditions (detailed characteristics – Table 2). The test route included urban, highway, and rural sections (Figures 1 and 2) and was performed for vehicles with different powertrain configurations (gasoline and diesel engines). Each test was repeated three times; the partial results presented are given as examples, while the final results represent the average of all measurements obtained.

Table 2. Test route characteristics

Test conditions	Vehicle A (gasoline engine)	Vehicle B (diesel engine)	Relative difference $\frac{(A-B)\times100\%}{\frac{1}{2}(A+B)}$
Total time [s]	5349	5209	2.65
Maximum speed [km/h]	147.9	133.3	11.36
Average speed [km/h]	33.73	34.51	–2.28
Distance [km]	50.11	49.93	0.43
Share of vehicle operating conditions			
V = 0 [%]	34.71	33.02	4.99
V = const [%]	9.24	9.58	–3.61
a > 0 [%]	29.51	30.20	–2.31

Fig. 1. Test route

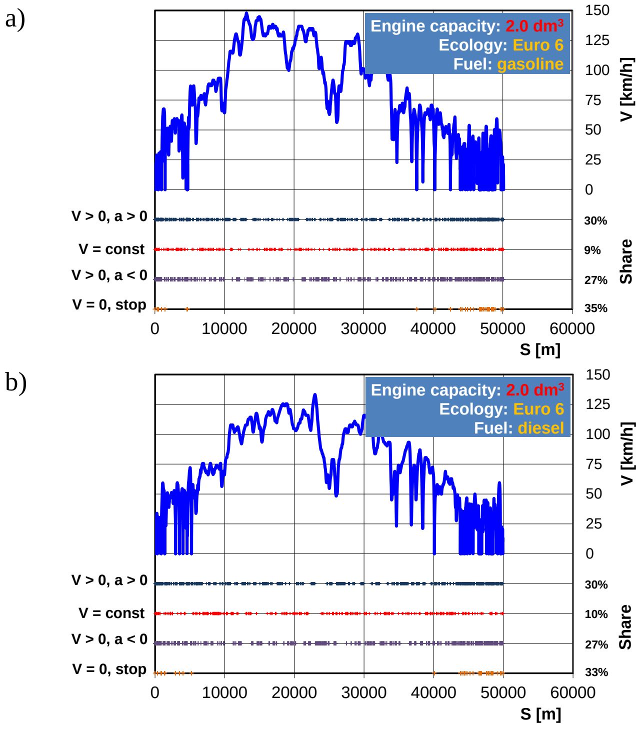

Fig. 2. Characteristics of the test drive: vehicle with gasoline engine (a) and diesel engine (b)

The test route was selected to cover diverse driving conditions, taking into account different topographies: urban, rural, and highway, in order to assess their impact on the exhaust gas emission values of gaseous components.

On-road studies are characterized by an inherent non-repeatability, which should be regarded not as a limitation but as a source of valuable information. In the analysis of exhaust gas emissions, the objective was not to perform a precise comparison of individual vehicles, but rather to select measures that are objective and independent of test variability. Therefore, non-repeatability should be considered an essential attribute of studies conducted under real operating conditions.

4. Measurement results

4.1. Gasoline engine vehicle

During the tests of the vehicle with a gasoline engine, measurements were taken of CO, NO_x, and CO_2 concentrations in the exhaust gases, as well as engine speed and load, which were recorded from the vehicle's diagnostic system. The figures present the time traces of the recorded harmful compounds. The carbon monoxide concentration along the analyzed section of the route was mostly below 0.05%, which consequently resulted in a carbon monoxide emission rate not exceeding a few mg/s (Fig. 3).

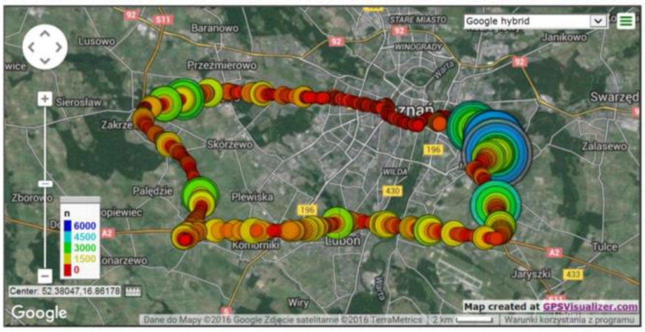

Fig. 3. CO concentration recorded during tests for the gasoline engine vehicle (visualized along the test route)

The concentration of the next gaseous component – nitrogen oxides – remained at a very similar level throughout the entire test. The concentration values, within the range up to 100 ppm, were the result of exhaust aftertreatment devices applied to reduce this compound. The nitrogen oxides emission rate did not exceed 1 mg/s for most of the test (Fig. 4). The observed variability of the results reflected normal engine operation, while the recorded increases in emission rate occurred during acceleration and highway driving conditions, where the emission rate significantly exceeded the previously reported values.

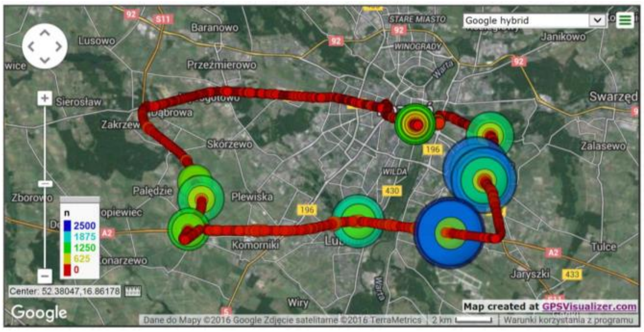

Fig. 4. NO_x concentration recorded during tests for the gasoline engine vehicle (visualized along the test route)

The carbon dioxide concentration presented in Fig. 5 reached a maximum of 13%. This is the peak value corresponding to an air-fuel equivalence ratio equal to one. For values of the equivalence ratio greater than one, lower concentrations of this compound were recorded (only during engine braking). During the tests, the carbon dioxide emission rate did not exceed 7000 mg/s (highway conditions), while the average value was approximately 1000 mg/s. Larger fluctuations were observed in the middle phase of the test under highway driving conditions.

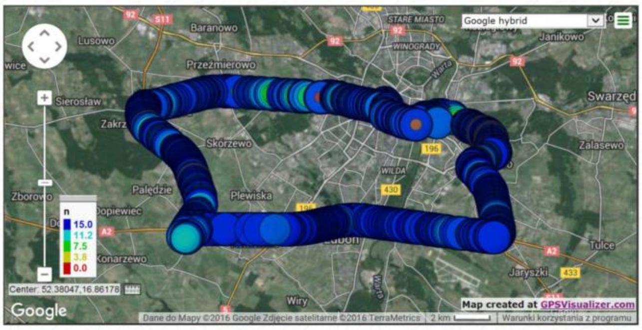

Fig. 5. CO_2 concentration recorded during tests for the gasoline engine vehicle (visualized along the test route)

The recorded variations in engine speed and load are presented in Fig. 6, where the largest operating range of the engine corresponds to medium loads and medium rotational speeds. The concentration profiles of exhaust constituents obtained during the tests made it possible to identify relationships that characterize the influence of the engine's dynamic properties on exhaust emissions, taking into account the results from the entire measurement route. The dynamic properties of the engine were considered indirectly by dividing the full range of engine speed and load under real driving conditions to generate concentration maps of selected exhaust constituents. These data were then presented on engine characteristics plotted in the coordinates of engine speed and load.

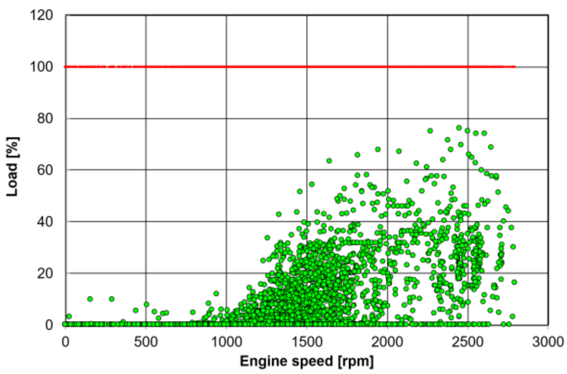

Fig. 6. Engine operating conditions in engine speed–load coordinates (gasoline engine)

The recorded emission rates of exhaust constituents, when related to engine speed and load, allowed the identification of characteristic dependencies for the tested engine, which are defined by the following values:

– the maximum emission rate of carbon monoxide (Fig. 7a) is approximately 20 mg/s and occurs at an engine speed of around 2800 rpm and a load in the range of 40–50%

– the maximum emission rate of nitrogen oxides (Fig. 7b) is approximately 70 mg/s and occurs at an engine speed of 2200 rpm and a load in the range of 60–70%
– the maximum particle number emission rate (Fig. 7c) reaches approximately $15–20 \cdot 10^{13}$ 1/s, occurring at an engine speed in the range of 1200–1300 rpm and a load of 20–30%.

a)
b)
c)

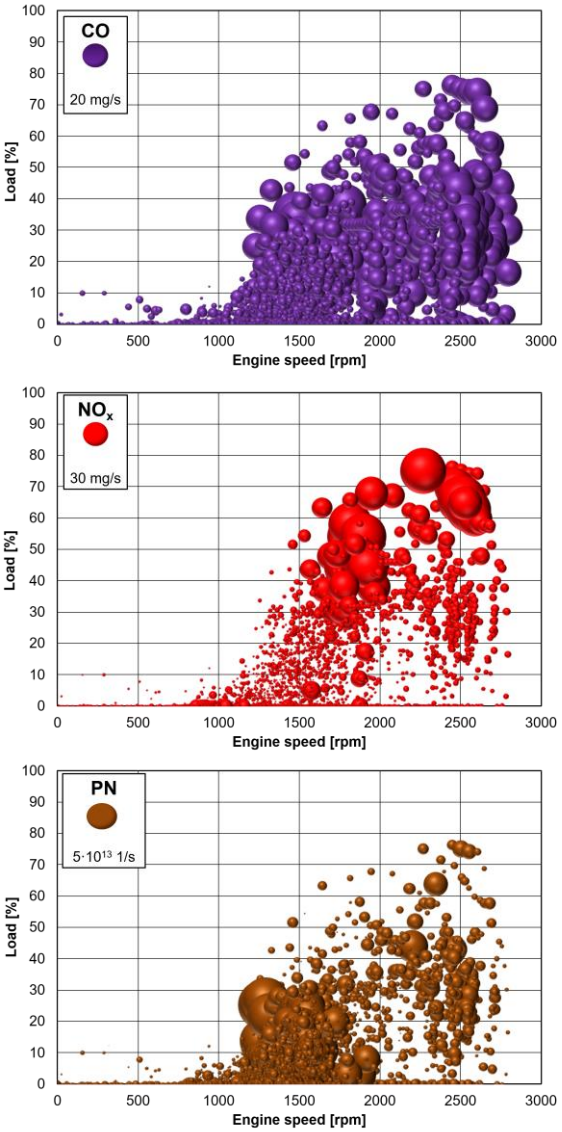

Fig. 7. Emission rates of CO (a), NO_x (b), and PN (c) related to engine operating parameters in vehicle speed–acceleration coordinates during tests for the gasoline engine vehicle

The analysis of the gasoline engine vehicle confirmed generally low levels of CO and NO_x emissions under real driving conditions, with emission peaks observed mainly during acceleration and highway operation. The highest variability was recorded for CO_2 and PN, reflecting the influence of engine dynamics on emission characteristics. These results highlight the importance of considering both transient conditions and engine load when evaluating the real-world environmental performance of gasoline engines.

4.2. Diesel engine vehicle

Figure 8 presents the recorded variations in engine speed and load, with the largest operating area corresponding to medium loads and medium rotational speeds. Based on the recorded concentration profiles of exhaust constituents, it was possible to develop relationships describing the influence of the engine's dynamic properties on exhaust emissions, considering the results from the entire measurement route. To account for engine dynamics indirectly, the full range of engine speed and load under real driving conditions was divided into intervals to generate concentration maps of selected exhaust constituents. These data are shown on the engine characteristics plotted in engine speed–load coordinates.

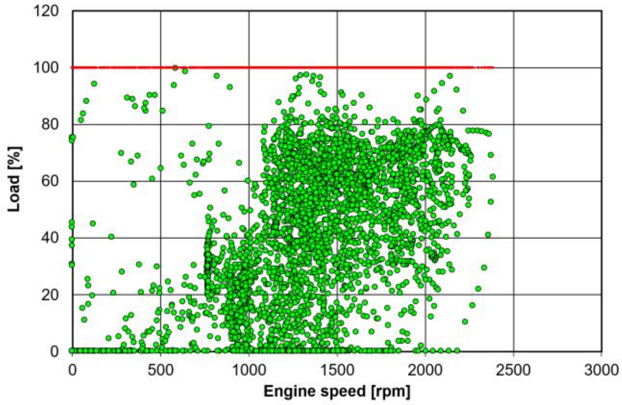

Fig. 8. Engine operating conditions in engine speed–load coordinates (diesel engine)

Relating the emission rates of exhaust constituents to engine speed and load made it possible to determine characteristic patterns for the tested engine, which are defined by the following values:

– the maximum emission rate of carbon monoxide (Fig. 9a) is approximately 70 mg/s and occurs at an engine speed in the range of 1500–2000 rpm and a load in the range of 20–40%
– the maximum emission rate of nitrogen oxides (Fig. 9b) is approximately 120 mg/s and occurs at an engine speed in the range of 2000–2500 rpm and a load in the range of 60–70%
– the maximum particle number emission rate (Fig. 9c) is approximately $2.5 \cdot 10^{13}$ 1/s and occurs at an engine speed in the range of 1500–2000 rpm and a load in the range of 30–50%.

The analysis of the diesel engine vehicle revealed considerably higher emission levels compared to the gasoline case, particularly for NO_x and particulate matter. The highest CO and PN emission rates were observed at medium engine speeds and loads, while NO_x reached peak values at higher loads and engine speeds. These results confirm the strong influence of engine operating conditions on real-world exhaust emissions and underline the challenges of meeting stringent emission limits for diesel engines.

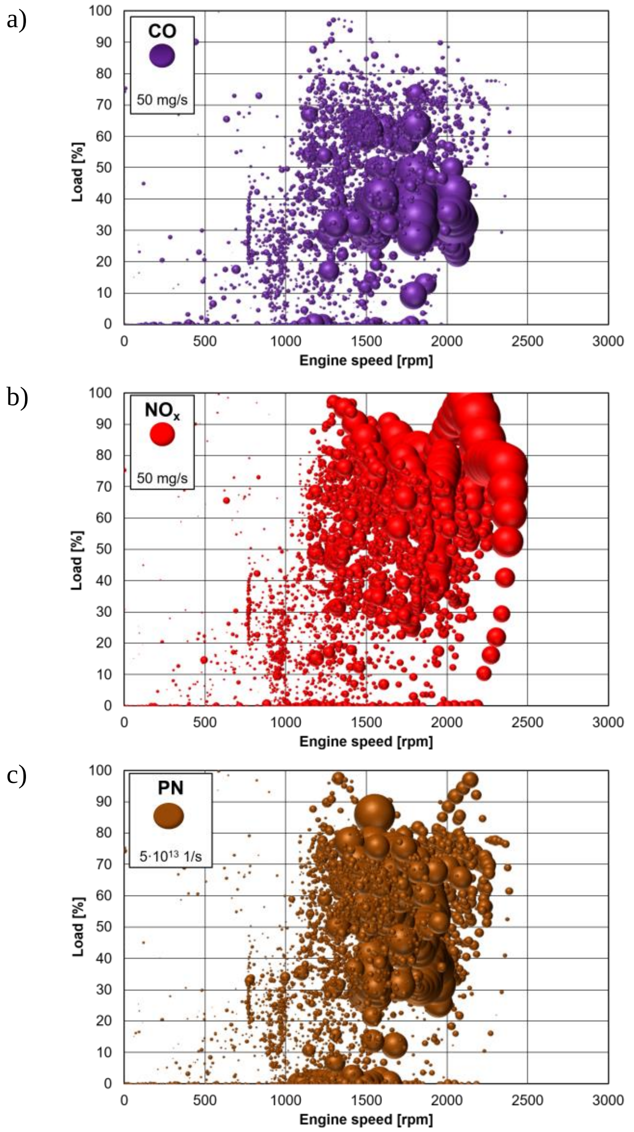

Fig. 9. Emission rates of CO (a), NO_x (b), and PM (c) recorded for the diesel engine vehicle during tests

5. On-road emission factors of exhaust constituents in RDE tests

5.2. Gasoline engine vehicle

Based on the previously obtained emission rate values and the known distance traveled by the vehicle, instantaneous emission indicators, CF (Conformity Factor), were determined. They are defined as the ratio of the on-road emission of a given constituent to the corresponding on-road emission limit specified by the standard ($CF = b_{RDE}/b_{norm}$).

The following values were obtained for the respective exhaust constituents:

– the emission index value for carbon monoxide (Fig. 10a) does not exceed 1, with the final value being less than 0.2
– the initial emission index value for nitrogen oxides (Fig. 10b) exceeds 2, while the final value is also around 1
– the instantaneous emission index value for particle number (Fig. 10c) exceeds 1, whereas the final value remains below 1.

The on-road emission values for the gasoline engine vehicle obtained during the test route are as follows:

– on-road carbon monoxide emission: 216 mg/km
– on-road nitrogen oxides emission: 56 mg/km
– on-road particle number emission: $5.8 \cdot 10^{11}$ 1/km
– on-road carbon dioxide emission: 117 g/km.

Compliance of on-road emissions with the Euro 6 limit values was observed for all analyzed constituents (Fig. 11):

– the emission index for carbon monoxide was 0.22
– the emission index for nitrogen oxides was 0.89
– the emission index for particle number was 0.68.

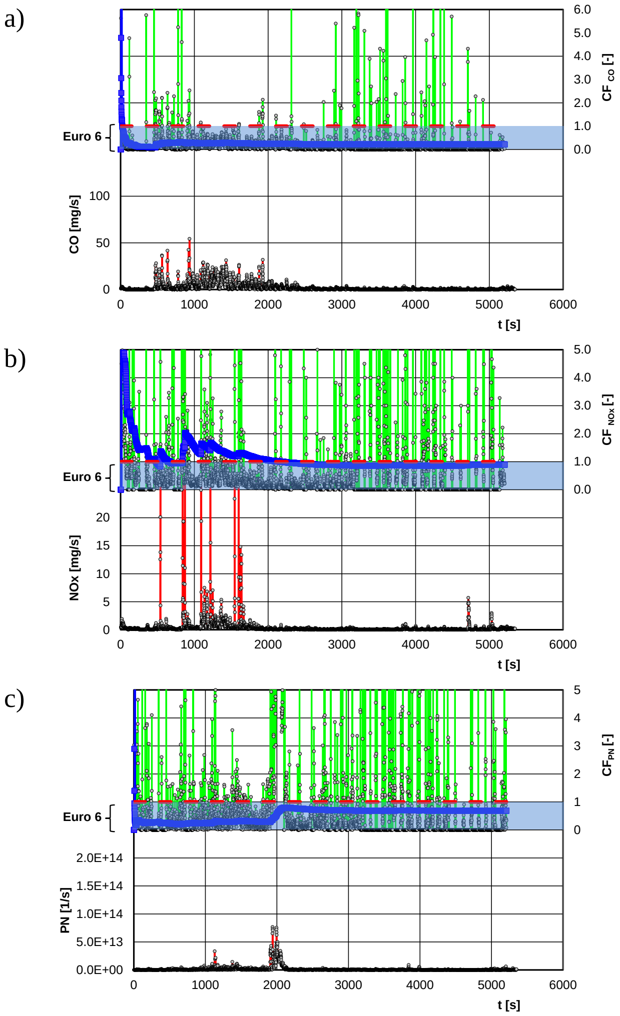

Fig. 10. Emission index of CO (a), NO_x (b), and PN (c) – instantaneous and cumulative values during the test for the gasoline engine vehicle

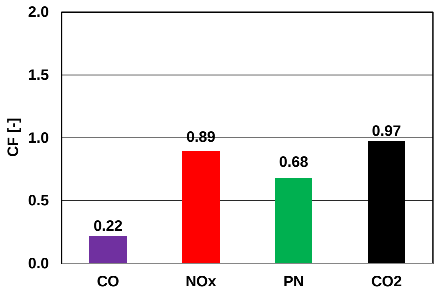

Fig. 11. Emission index determined during on-road tests for the gasoline engine vehicle

The data analysis shows that the on-road emission values obtained under real operating conditions do not exceed the permissible limits for vehicles with gasoline engines.

5.2. Diesel engine vehicle

For the individual exhaust constituents, the following values were obtained:

- the emission index value for carbon monoxide (Fig. 12a) does not exceed 1, with the final value being less than 0.5
- the instantaneous emission index value for nitrogen oxides (Fig. 12b) exceeds 1, while the final value is also around 1
- the emission index value for particle number (Fig. 12c) does not exceed 1 in the first part of the test.

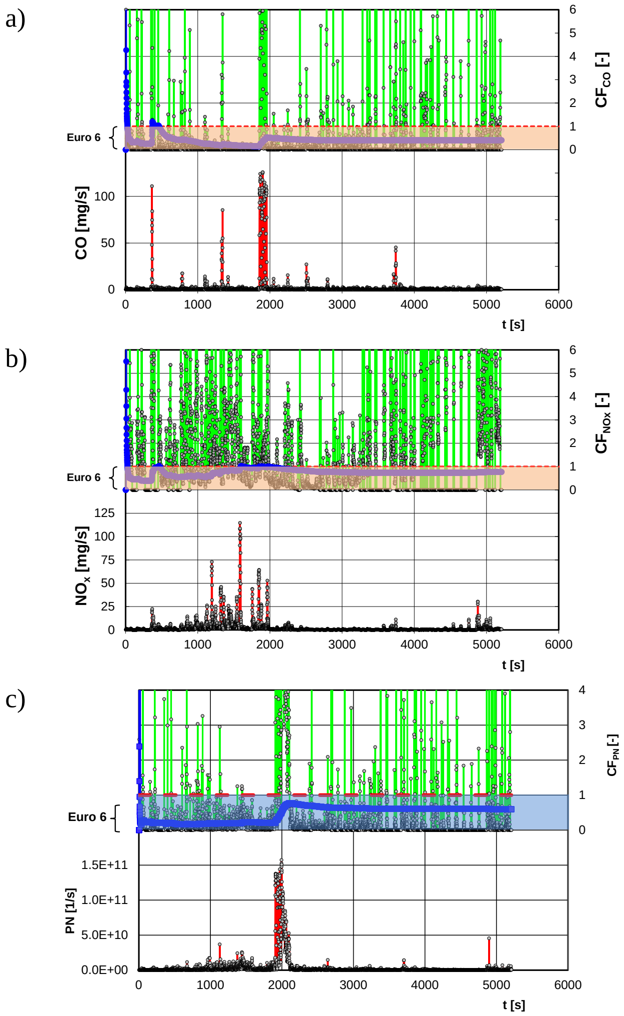

Fig. 12. Emission index of CO (a), NO_x (b), and PN (c) – instantaneous and cumulative values during the test for the diesel engine vehicle

The on-road emission values determined for the diesel engine vehicle during the test route are as follows:

- on-road carbon monoxide emission: 204 mg/km
- on-road nitrogen oxides emission: 66 mg/km
- on-road particle number emission: $3.6\cdot10^{11}$ 1/km
- on-road carbon dioxide emission: 148 g/km.

The emission indices determined for the diesel engine vehicle show a similar pattern to those of the gasoline engine. No exceedances were recorded with respect to the Euro 6 limit values. The indices were as follows (Fig. 13):

- carbon monoxide emission index: 0.41
- nitrogen oxides emission index: 0.82
- particle number emission index: 0.60.

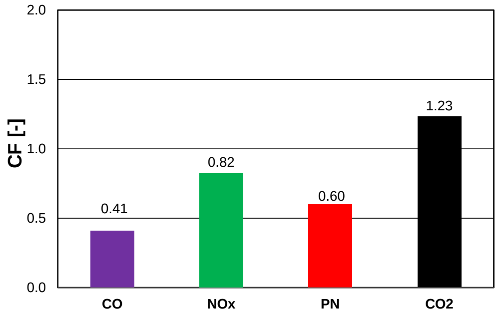

Fig. 13. On-road emissions of exhaust gas constituents determined during tests for the diesel engine vehicle

6. On-road exhaust emission indices in RDE tests – measurement window averaging

The first stage in determining on-road emission values according to the RDE testing procedure is the verification of the test validity. The following data were taken into account for the gasoline engine:

- test distance, which must be at least 48 km (divided into three parts of 16 km each); in the conducted test, the obtained values were 16.58, 11.54, and 23.18 km, giving a total distance of 51.30 km (one value does not meet the test requirement)
- test duration, which must range from 90 to 120 minutes; in the study, the duration was 90 minutes
- test duration during which the engine is not warmed up to its normal operating temperature; in the study, the value obtained was 5 minutes (requirement met)
- share of individual phases of the test in the total emission test: urban driving must account for 29–44% of the total test time (value obtained: 32.33%), rural driving must account for 23–43% (value obtained: 22.49%), highway driving must account for 23–43% (value obtained: 45.18%); all obtained values meet the test requirements (differences are very small)
- average speed in urban driving must be between 15 and 40 km/h; in the study, the value obtained was 14.69 km/h (requirement met – very small difference)
- share of driving at speeds exceeding 145 km/h on the highway section; in the study, this speed was not exceeded (requirement met)
- duration of driving at speeds above 100 km/h during the highway section must be at least 5 minutes; in the study, the value obtained was 9.5 minutes (requirement met)
- share of stop time in the urban part must range from 6% to 30%; in the study, the value obtained was 28.7% (requirement met)
- altitude difference between the start and end of the test must be less than 100 m; in the study, the result obtained was 7.1 m (requirement met).

With all test requirements fulfilled, it was considered justified to perform a comparison of emissions determined by two methods, since the obtained measurements were derived from the same test drive. The plot of on-road carbon dioxide emissions as a function of the average speed in the measurement windows shows that the on-road emissions of this constituent were lower in the test than in the type-approval test (Fig. 14).

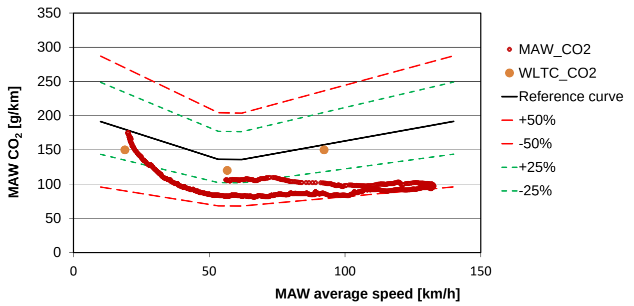

Fig. 14. Relationship between on-road carbon dioxide emissions and average speed in the measurement windows (gasoline engine vehicle)

The on-road emission results for carbon monoxide, nitrogen oxides, and particle number were determined in accordance with the procedure presented in [26, 27]. The following values were obtained:

- on-road carbon monoxide emission: 430 mg/km in the urban section, 150 mg/km in the rural section, and 110 mg/km in the highway section; the total value for the entire test was 230 mg/km (Fig. 15a)
- on-road nitrogen oxides emission: 22.4 mg/km in the urban section, 43.6 mg/km in the rural section, and 71.9 mg/km in the highway section; the total value for the entire test was 45.7 mg/km (Fig. 15b)
- on-road particle number emission: $4.9 \cdot 10^{11}$ 1/km in the urban section, $4.3 \cdot 10^{11}$ 1/km in the rural section, and $5.8 \cdot 10^{11}$ 1/km in the highway section; the total value for the entire test was $5.0 \cdot 10^{11}$ 1/km (Fig. 15c).

As in the previous case, the validity of the test procedure was also verified for the diesel engine vehicle. The following data were obtained:

- test distance; in the conducted test, the values were 17.16, 16.69, and 20.83 km, giving a total distance of 51.68 km (values meet the test requirements)
- test duration, which must range from 90 to 120 minutes; in the study, the duration was 92 minutes (requirement met)
- test duration during which the engine was not warmed up to normal operating temperature; in the study, the value obtained was 5 minutes (requirement met)
- share of individual phases of the emission test: urban driving – 33.20%, rural driving – 26.49%, highway driving – 40.31% (all values meet the test requirements)
- average speed in urban driving must be between 15 and 40 km/h; in the study, the value obtained was 16.09 km/h (requirement met)
- share of driving at speeds exceeding 145 km/h on the highway section; in the study, this speed was not exceeded (requirement met)
- duration of driving at speeds above 100 km/h during the highway section must be at least 5 minutes; in the study, the value obtained was 9.28 minutes (requirement met)
- share of stop time in the urban part must range from 6% to 30%; in the study, the value obtained was 28.32% (requirement met)
- altitude difference between the start and end of the test must be less than 100 m; in the study, the result obtained was 7.6 m (requirement met).

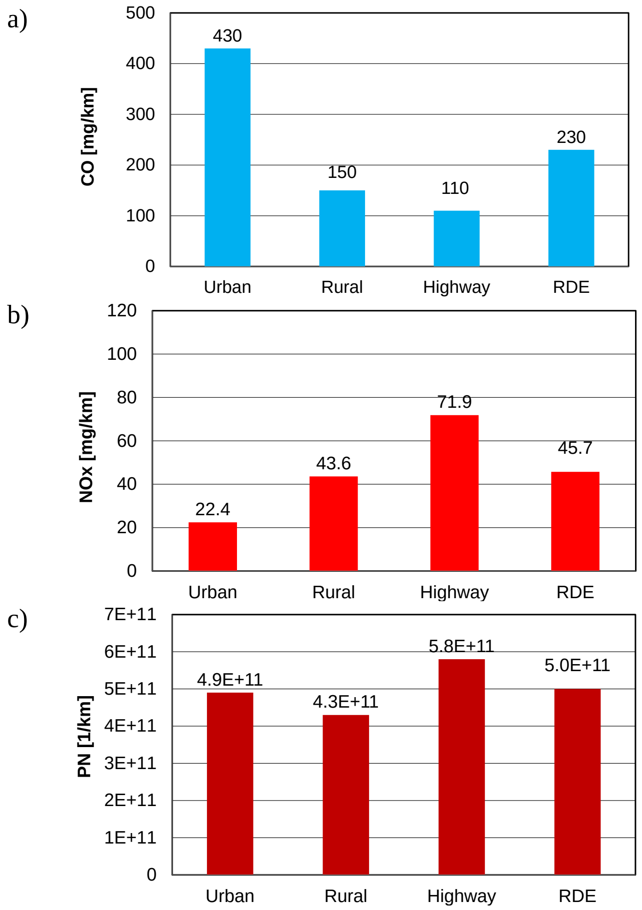

Fig. 15. On-road emissions of CO (a), NO_x (b), and PN (c) obtained in individual parts of the test and the average value for the entire test (values determined using measurement window averaging) for the spark-ignition engine vehicle

The plot of on-road carbon dioxide emissions as a function of average speed in the measurement windows shows that the on-road emissions of this constituent were lower in the test than in the type-approval test (Fig. 16).

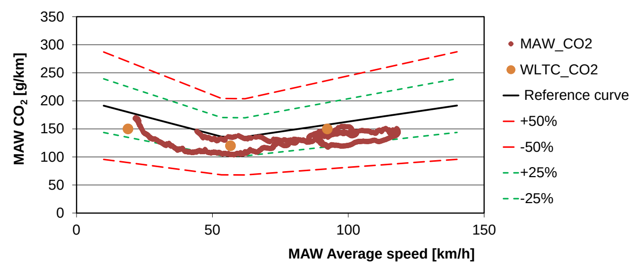

Fig. 16. Relationship between on-road carbon dioxide emissions and average speed in the measurement windows (diesel engine vehicle)

The on-road emission results for carbon monoxide, nitrogen oxides, and particle number were determined in

accordance with the RDE procedure. The following values were obtained:
– on-road carbon monoxide emission: 100 mg/km in the urban section, 87.1 mg/km in the rural section, and 328 mg/km in the highway section; the total value for the entire test was 171 mg/km (Fig. 17a)
– on-road nitrogen oxides emission: 31.1 mg/km in the urban section, 35 mg/km in the rural section, and 117.1 mg/km in the highway section; the total value for the entire test was 61.1 mg/km (Fig. 17b)
– on-road particle number emission: $4.2 \cdot 10^{11}$ 1/km in the urban section, $4.6 \cdot 10^{11}$ 1/km in the rural section, and $6.3 \cdot 10^{11}$ 1/km in the highway section; the total value for the entire test was $5.0 \cdot 10^{11}$ 1/km (Fig. 17c).

a)
b)
c)

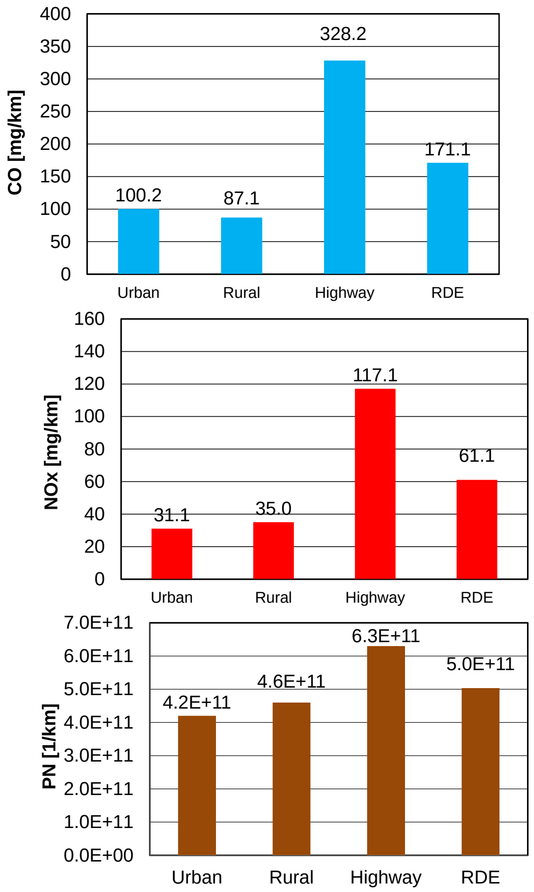

Fig. 17. On-road emissions of CO (a), NO_x (b), and PN (c) obtained in individual parts of the test and the average value for the entire test (values determined using measurement window averaging) for the diesel vehicle

7. Summary

The obtained on-road emission results for the tested vehicles are presented for carbon monoxide, nitrogen oxides, and particle number. When comparing the procedures for determining on-road emissions in RDE tests, it can be concluded that using all measurement data from the entire test drive provides comparable exhaust emission results:
– for the gasoline engine vehicle: for on-road carbon monoxide emissions, the difference is approximately 5% (with values of 216 mg/km and 227 mg/km, respectively); for on-road nitrogen oxides emissions, the difference is approximately 20% (values of 56 mg/km and 46 mg/km, respectively); for on-road particle number emissions, the difference is approximately 16% (values of $5.8 \cdot 10^{11}$ 1/km and $5.0 \cdot 10^{11}$ 1/km, respectively)
– for the diesel engine vehicle: for on-road carbon monoxide emissions, the difference is approximately 17% (values of 204 mg/km and 171 mg/km, respectively); for on-road nitrogen oxides emissions, the difference is approximately 27% (values of 66 mg/km and 182 mg/km, respectively); and for on-road particle number emissions, the difference is approximately 35% (values of $3.6 \cdot 10^{11}$ 1/km and $5.0 \cdot 10^{11}$ 1/km, respectively).

The comparison of emission index (CF) values in RDE tests provided the following results:
– for the gasoline vehicle: the on-road carbon monoxide emission index values were 0.23 and 0.43 (for the entire RDE test and the urban section, respectively); the nitrogen oxides emission index values were 0.76 and 0.90 (for the entire RDE test and the urban section, respectively); and the particle number emission index values were 0.67 and 0.87 (for the entire RDE test and the urban section, respectively) – Fig. 18a
– for the diesel vehicle: the on-road carbon monoxide emission index values were 0.34 and 0.20 (for the entire RDE test and the urban section, respectively); the nitrogen oxides emission index values were 0.76 and 0.39 (for the entire RDE test and the urban section, respectively); and the particle number emission index values were 0.84 and 0.70 (for the entire RDE test and the urban section, respectively) – Fig. 18b.

a)
b)

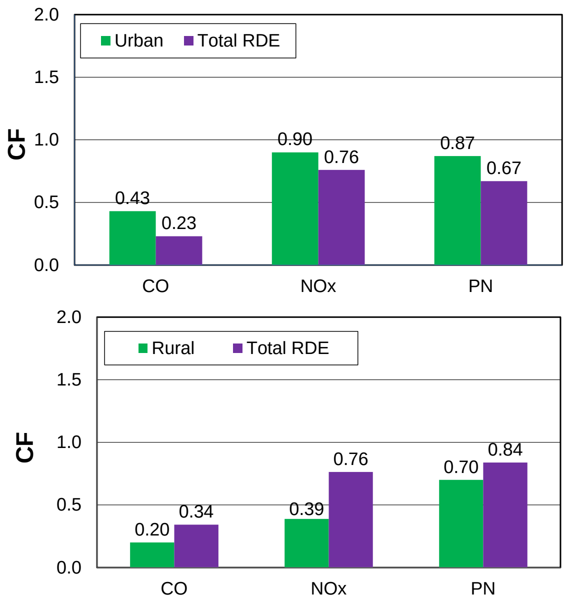

Fig. 18. Comparison of on-road emission indices of carbon monoxide, nitrogen oxides, and particle number in road tests: a) gasoline engine vehicle, b) diesel engine vehicle

Based on the obtained on-road emission results and emission indices, it can be concluded that the emission indices of CO, NO_x, and PN do not exceed the permissible limits for conventional Euro 6 passenger cars equipped with gasoline and diesel engines. Future work is expected to focus on testing hybrid vehicles of the latest emission class, as well as on durability studies, in which exhaust gas emissions will be monitored during several years of vehicle operation. The comparison of the classical and EMROAD methods demonstrated their mutual consistency, which confirms their suitability for assessing the environmental performance of Euro 6 passenger cars. The observed differences between gasoline and diesel vehicles highlight the greater challenges associated with diesel powertrains, particularly regarding NOx and PN control. These insights provide valuable input for both legislative development and the design of more effective emission reduction strategies.

Nomenclature

CF	conformity factor
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
EU	European Union
FC	fuel consumption
NO_x	nitrogen oxides
PEMS	portable emission measurement system
PN	particle number
RDE	real driving emissions
SI	spark ignition
SUV	sport utility vehicle
WLTC	Worldwide Harmonized Light-duty Vehicles Test Cycles

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Prof. Jacek Pielecha, DSc., DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *jacek.pielecha@put.poznan.pl*

Kinga Skobiej, DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.
e-mail: *kinga.skobiej@put.poznan.pl*

Marek Sieroń, MEng. – Volkswagen Rzepecki Mroczkowski, Poland.
e-mail: *marek.sieron@rzepeckimroczkowski.pl*