

# The Exhaust Emission from Passenger Cars using Portable Emission Measurement System

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## Abstract:

The paper presents the results of on-road exhaust emission tests of Passenger Cars fitted with diesel engines. Under such conditions the authors could determine the actual vehicle emissions. The tests were performed on a road portion of a hundred kilometers or so – these tests provide information on the on-road emissions and are a basis for their ecological evaluation. For the measurement of the exhaust emissions the authors used a Portable Exhaust Emissions System. The obtained data were used to calculate the relations that characterize the influence of the dynamic engine parameters on the exhaust emissions. These properties were taken into account indirectly using the whole range of speeds and accelerations of the vehicle for the preparation of the matrices of the emissions rate. The used data were averaged within individual speed and acceleration ranges thus obtaining the characteristics of the share of operation in individual ranges and the characteristics of the emission matrices of the individual emission components. The above results served for defining of the emission level indicator of the vehicles that can be used for classification of vehicle fleet in terms of their emission level).

## Keywords:

PEMS, On-road tests, Exhaust emissions, Ecology.

## 1. Introduction

Currently a trend has been seen of global treatment of the environmental perils from the automotive industry. The regulations permitting the vehicle to drive on roads (homologations and production conformity), periodical inspections of the vehicle technical condition and other legal acts directly or indirectly related to the production, use and disposal of used up civilization products treat the environmental issues in a complex way. In the previous years in individual countries there were different inspection and testing systems related to the exhaust emissions yet for some time now there has been a far reaching unification going on [3, 7, 9].

The growing number of vehicles in the world and the resultant natural environment pollution leads to a growth in the emission related requirements. Current level of technology advancement in all the fields of industry including transport results in a growth of the requirements for the emission measurement devices. In order for these requirements to be fulfilled to comply with the ever-changing regulations a concentration of industry became necessary in this matter. The exhaust emission tests are a sophisticated process. Modern analyzers of the emissions require special laboratory conditions and the homologation procedures comprise tests on chassis and engine dynamometers that do not entirely reflect the emissions under real operating conditions. The latest results of on-road tests show that in relation to some exhaust components the emission is higher by several hundred percent for both the gaseous compounds and [1-5, 15] particulate matter [6, 8, 10, 11]. Hence, we can see a trend attempting at a formalization and enforcement of the on-road emission testing.

## 2. Methodology of research

The aim of the tests was a verification of the emission level of Passenger Cars fitted with diesel engines, Euro 4/Euro 5 compliant under real traffic conditions. At the same time the tests were an attempt to develop an on-board exhaust emission measurement system. The determining of the on-road emission level and comparing it with the standards allowed a determination of the emission indicator. The obtained emission indicator served as an answer to the question whether the emissions under traffic conditions are comparable to the emissions obtained in the homologation tests. At the same time it is a verification of the conditions of the performance of the homologation test and the real traffic conditions.

The measurement of the on-road exhaust emission was performed under real traffic conditions: urban drive (share in the whole test – 13%), extra urban (42%), freeway (45%) in the province of Wielkopolska. The route profile differed in terms of elevation above the sea level and the maximum difference was 55 meters. Two vehicles were tested for which the drives were repeated three times. The differences in the values in the subsequent trials did not exceed 5% of the average value. The tests consisted in the measurement of the exhaust components (CO, HC, NO<sub>x</sub> and particulate matter for each vehicle) and then with the use of the GPS and OBD data the road emission of each exhaust component was determined.

The object of the investigations were vehicles (Fig. 1) whose drivetrain characteristics has been presented in Table 1. They are characterized with different emission standards, which resulted from the use of a DPF filter or its lack. Despite difference in the curb weight and engine capacity the common feature of the selected vehicles was the value of the volumetric power output indicator that amounted to approximately 50 kW/dm<sup>3</sup>.



Fig. 1. Exhaust emission analyzers fitted in vehicles A and B during the tests.

Table 1. Technical specifications of the vehicles used in the tests

Parameters	Vehicle A	Vehicle B
Type of engine	Diesel/turbocharged	Diesel/turbocharged
Capacity, dm <sup>3</sup>	2.2	2.0
Power output, kW/rpm	110/3600	103/4200
Torque, Nm/rpm	340/2000–2800	320/1750–2500
Vehicle curb weight, kg	1590	1550
Aftertreatment, Euro standard	oxycat, Euro 4	oxycat, DPF, Euro 5
Vehicle mileage, km	15,000	2000

For the measurement of the exhaust emissions the authors used a portable exhaust emissions analyzer SEMTECH DS by Sensors Inc. (Tab. 2). The analyzer enables a measurement of the concentrations of the exhaust components (CO, HC, NO<sub>x</sub>, CO<sub>2</sub>) and a mass flow of the exhaust gases. The exhaust gases introduced into the analyzer through a measuring probe maintaining the temperature of 191 °C are filtered out of the particulate matter (diesel engines only) and directed to the flame ionization detector where the measurement of hydrocarbons takes place. The exhaust gases are cooled down to the temperature of 4 °C and the concentration of nitric oxides is measured (non-dispersive ultraviolet-measuring both nitrogen monoxide and nitrogen dioxide). At the end the concentration of carbon monoxide and carbon dioxide (non-dispersive infrared method) and oxygen (electrochemical) are measured. The data from the GPS and OBD can be fed directly to the central unit of the analyzer.

*Table 2. Technical Specifications of the Portable Exhaust Emission Analyzer – SEMTECH DS [11]*

Parameter	Measurement method	Accuracy
1. Exhaust concentration		
CO	NDIR analyzer, range 0–10%	±3% of the range
HC	FID analyzer, range 0–10 000 ppm	±2% of the range
NO <sub>x</sub> = (NO + NO <sub>2</sub> )	NDUV analyzer, range 0–3000 ppm	±3% of the range
CO <sub>2</sub>	NDIR analyzer, range 0–20%	±3% of the range
O <sub>2</sub>	Electrochemical analyzer, range 0–20%	±1% of the range
2. Exhaust gas flow	Mass flow rate, T <sub>max</sub> : 700 °C	±2,5% range ±1% range
3. Warm up time	900 s	
4. Response time	T <sub>90</sub> < 1 s	
5. Diagnostic systems	ISO, CAN, VPW, PWM	

For the measurement of particulate matter the authors used a portable analyzer by AVL 483 (Micro Soot Sensor) that enables a continuous measurement of PM in diluted exhaust gases. The principle of operation of this device uses a photoacoustic method that allows a measurement of PM starting from the value of 5 µg/m<sup>3</sup>. The measurement of PM (the device measures the carbon part of the particle) with the photoacoustic method consists in a significant absorption of the laser light by the soot particles. This results in a periodical (interchanging) heating and cooling of the working gas (change in the pressure in the measurement chamber) and the generated sound wave is recorded by the microphones.

For the measurement of the particle size distribution (as a dependence of their diameter) a mass spectrometer by TSI Incorporated – 3090 EEPS (Engine Exhaust Particle Sizer™ Spectrometer) was used. The analyzer continuously measures the distribution of the PM size. It also measures the discrete range of particle diameter (from 5.6 to 560 nm) based on their different velocities. The range of the electrical motility of the particles changes exponentially and the measurement of the PM takes place with the frequency of 10 Hz.

### 3. Test conditions

In order to confirm the similarity of the drives the operating conditions of the vehicles were compared during real traffic operation (Fig. 2). The drives were done on the same route but they were done in different directions. For vehicle A the speed (Fig. 2a) in the individual parts of the test was as follows: urban area –  $V_{avg} = 30$  km/h, intercity roads –  $V_{avg} = 70$  km/h, expressway  $V_{avg} = 115$  km/h. For vehicle B similar values were recorded (the differences did not exceed 10%).

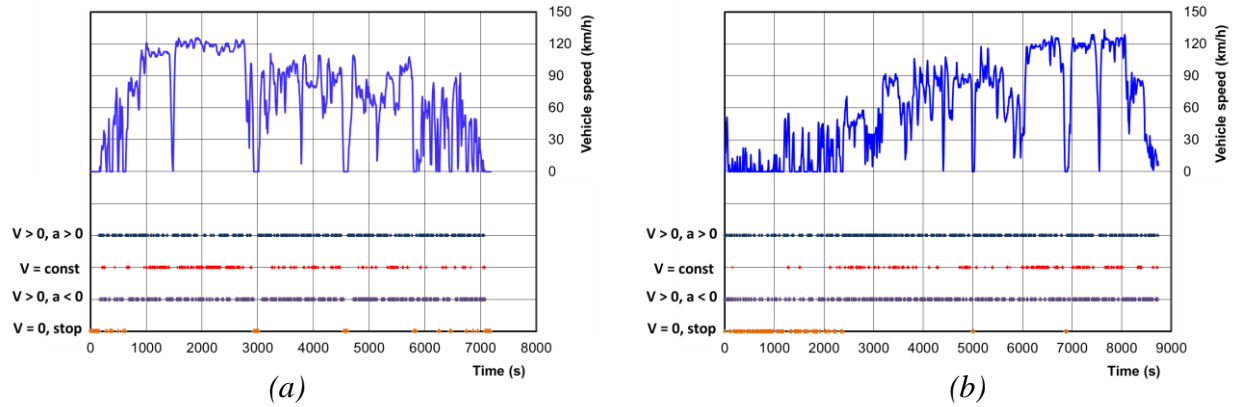


Fig. 2. Vehicle speed during the road tests: a) vehicle A no DPF fitted, emission standard Euro 4, b) vehicle B, DPF fitted, emission standard Euro 5.

From the comparison of the data presented in Fig. 2 it results that the drives were characterized by high similarity of the dynamic traffic conditions (the ranges of the occurrence of acceleration, steady vehicle speed, vehicle deceleration and coming to a full halt were compared). The results of the comparison shown in Table 3 indicate that in both drives (the one without DPF, Euro 4, vehicle A and the one with DPF, Euro 5 marked B) the differences in the parameters are maximum 25% (the test duration differs by approximately 19%, steady vehicle speed by 24%, acceleration time by 2.5%). The highest difference was recorded for the time when the vehicles were stationary— that amounts to 33%.

Table 3. The characteristics of the tests (for the vehicle A and B drives)

Test parameters	Vehicle A	Vehicle B	Relative difference
Total time, s	7183	8733	−19.5
Maximum speed, km/h	125	133	−6.2
Average speed, km/h	70.9	59.1	18.0
Length, km	142.6	143.4	−0.6
Share of the vehicle conditions, %:			
$V = 0$	9.0	12.7	−33.6
$V = \text{const}$	13.6	10.6	24.7
$a > 0$	39.6	38.6	2.5

It is noteworthy that an on-road test is a type of test where the lack of repeatability is not a disadvantage but a virtue that provides much more information as opposed to stationary tests. When comparing the emissions the authors did not attempt to precisely compare the vehicles but select the parameters for comparison that are objective and do not depend on the repeatability of the tests. Hence, the lack of the repeatability of the tests is characteristic of the real traffic conditions.

## 4. Analysis of the test results

The obtained data served to prepare the relations that characterize the influence of the dynamic engine properties on the exhaust emissions. Dynamic engine properties were indirectly taken into account, using the division of the whole range of speeds and accelerations under real traffic conditions to develop the matrices of emission intensity. The used data were averaged within the individual speed and acceleration ranges thus obtaining the characteristics of the share of engine operation and the characteristics of the matrices of the individual exhaust emissions. The greatest share of the engine operation under the tested traffic conditions falls in the area of idle speed and medium speeds (20–40 m/s) for a constant acceleration ( $a = 0 \text{ m/s}^2$ ) (Fig. 3).

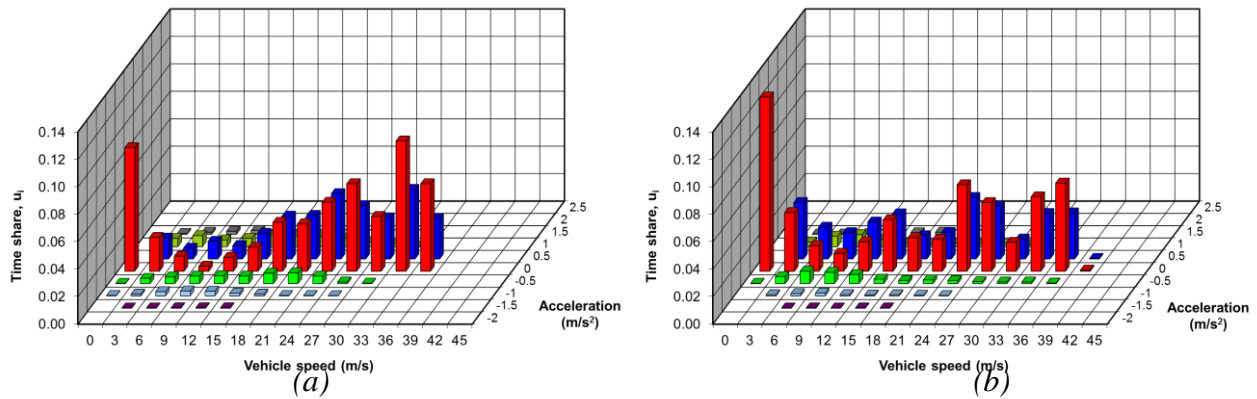


Fig. 3. The characteristics of the operating time share in the ranges of speeds and accelerations during the road tests: a) vehicle A, b) vehicle B.

The lack of the repeatability of the drives is seen with a greater share of idle speed for vehicle A – the share of this state in the whole tests amounts to approximately 10% (for the vehicle it is approximately 12%). The distribution of the operating time share for higher vehicle speeds is also alike; for vehicle A it oscillates around 17–39 m/s and for vehicle B this distribution is more even starting from the speed of 15 m/s.

The maximum carbon monoxide emission rate (Fig. 4) given in milligrams per second falls within the area of all used vehicle speeds and its accelerations within the range of  $-1$  do  $2 \text{ m/s}^2$ . These values are correlated with the vehicle acceleration: as the acceleration grows the emission of carbon monoxide grows as well. For vehicle A, however, (Euro 4) these are values several times higher than for vehicle B (Euro 5). For vehicle B the emission of carbon monoxide strongly depends on the vehicle speed and such a clear maximum (for vehicle average speeds and maximum acceleration) is not observed as in the case of the previous vehicle.

For comparison, in the graphs the values of the emission rates of each exhaust component have been given that result from the NEDC test – normative emission of CO amounts to 500 mg/km (for Euro 4/5); after converting into the average emission per second we obtain a result of 4.66 mg/s.

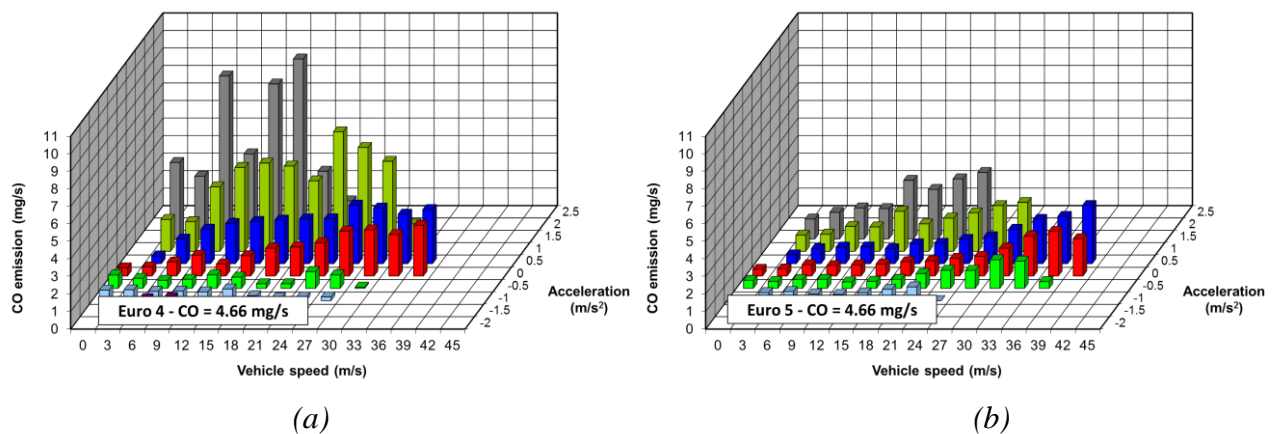


Fig. 4. The characteristics of the emission of carbon monoxide in the speed and acceleration ranges during the road tests: a) vehicle A, b) vehicle B.

The area of an increased nitric oxide emission rate of vehicle A (Fig. 5a) falls in the range of increased vehicle speeds and significant acceleration, hence high engine load. This is related to the increase in the fuel dose and the increase in the engine speed. For vehicle B twice-lower emission of nitric oxides was observed (approximately 50 mg/s) and at the same time this emission was higher for the maximum used speed (Fig. 5b).

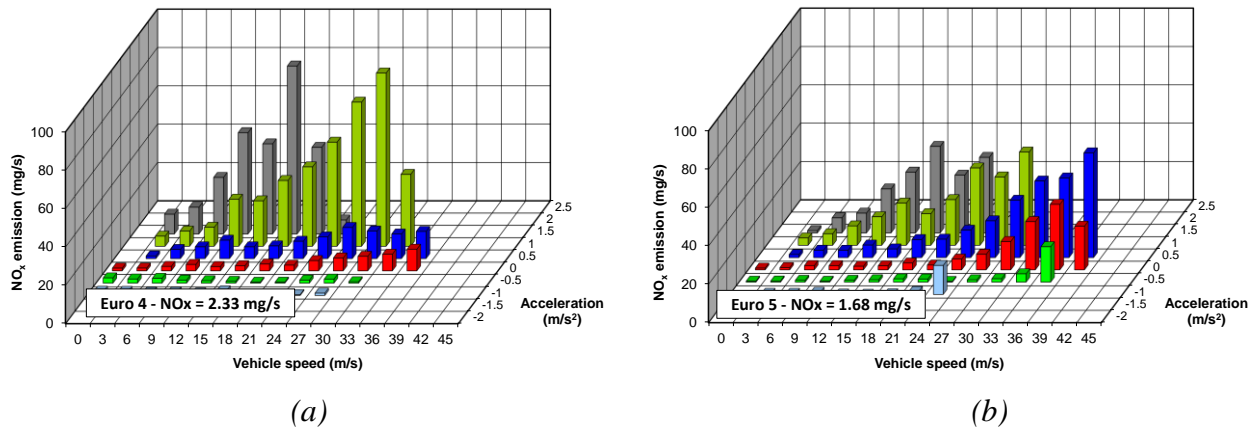


Fig. 5. The characteristics of the emission of nitric oxides in the speed and acceleration ranges during the road tests: a) vehicle A, b) vehicle B.

The emission of particulate matter is of different nature for vehicles A and B (Fig. 6). Vehicle A not fitted with DPF is characterized by a much larger emission of PM than vehicle B (Fig. 6a). The values of the emission in individual ranges are different approximately 20 times. DPF is an efficient method of the reduction of mass emission of PM, which is commonly applied in modern Euro 5 engines. The emission of carbon dioxide (Fig. 7) is similar for the tested vehicles: it grows as the vehicle speed and acceleration grow. The maximum values are comparable for both vehicles – they amount to approximately 10,000  $\text{g/s}$  and at idle this emission is approximately 500–800  $\text{mg/s}$ .

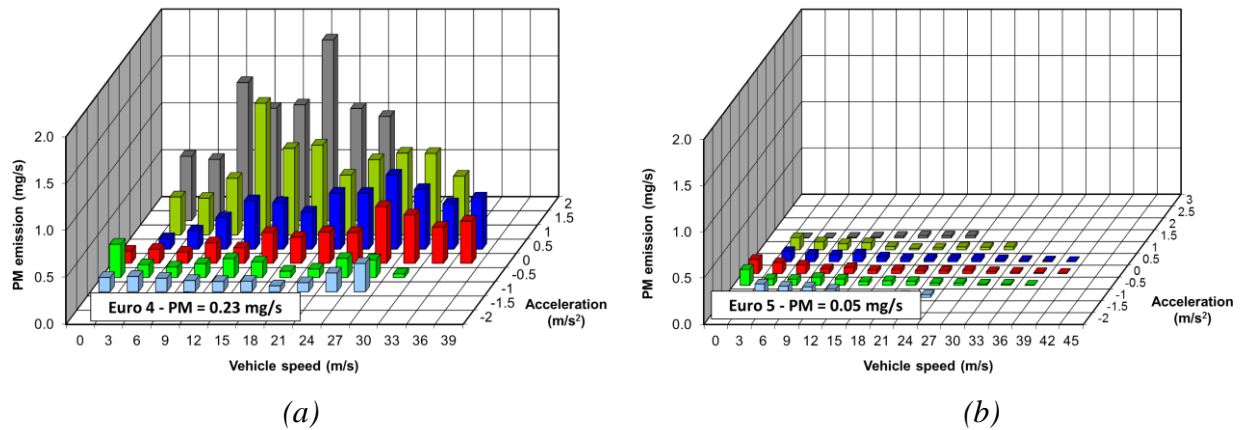


Fig. 6. Excess of the emissions of PM in the speed and acceleration ranges during the road tests: a) vehicle A, b) vehicle B.

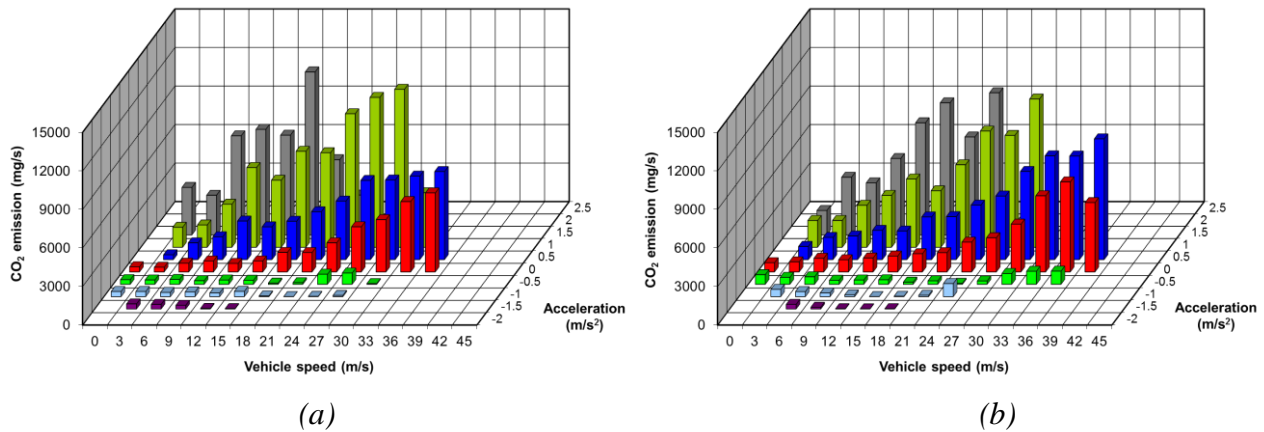


Fig. 7. The characteristics of the emission of carbon dioxide in the speed and acceleration ranges during the road tests: a) vehicle A, b) vehicle B.



## 5. The characteristics of the PM emission in terms of their size

Additionally within the on-road tests in real traffic a size-related analysis of the PM was performed. For the comparison the ranges of engine operation were used that are most frequently utilized under real traffic conditions. They correspond to three areas of operation (Fig. 8): 1 – idle speed, 2 – medium engine speed–medium load, 3 – high engine speed–high engine load. The vehicles were fitted with different powertrains, hence the selected ranges of operation do not overlap (similar areas were compared: as a criterion of similarity the relative engine speed and relative engine load were selected referred to the maximum values).

For such distinguished characteristics of the area of engine operation the size-related analysis of PM was performed falling within a given range of PM diameter (for vehicle A not fitted with the DPF – Fig. 9):

- range 1 (idle speed) – PM in the diameter range 10–150 nm is distributed evenly with the particles of diameter 30–60 nm prevailing; the concentration of the PM for the assumed work area in each size range amounts to  $5.0\text{--}6 \times 10^6 \text{ 1/cm}^3$ ; this results from a high air excess coefficient and a sufficient time for the combustion of a minimum fuel dose;
- range 2 (medium engine speed–medium load) – particles in the range 20–200 nm where the maximum falls within approximately 40 nm; the concentration of particles for these size ranges is  $6\text{--}7.5 \times 10^6 \text{ 1/cm}^3$ ; the values similar to the values of idle speed are a result of a high air excess coefficient (supercharged engine) and high fuel injection pressure (approximately 1300 bar);
- range 3 (high engine speed–high load) – the particles in the range 30–180 nm; the maximum falls within the range of 80–100 nm; the concentration of particles for this size range amounts to  $8\text{--}9 \times 10^6 \text{ 1/cm}^3$ ; the particle diameter characteristics values of this operating range refer to the larger particles than in previous cases– this results from a greater fuel dose, lower air excess coefficient and shorter time of fuel dose combustion.

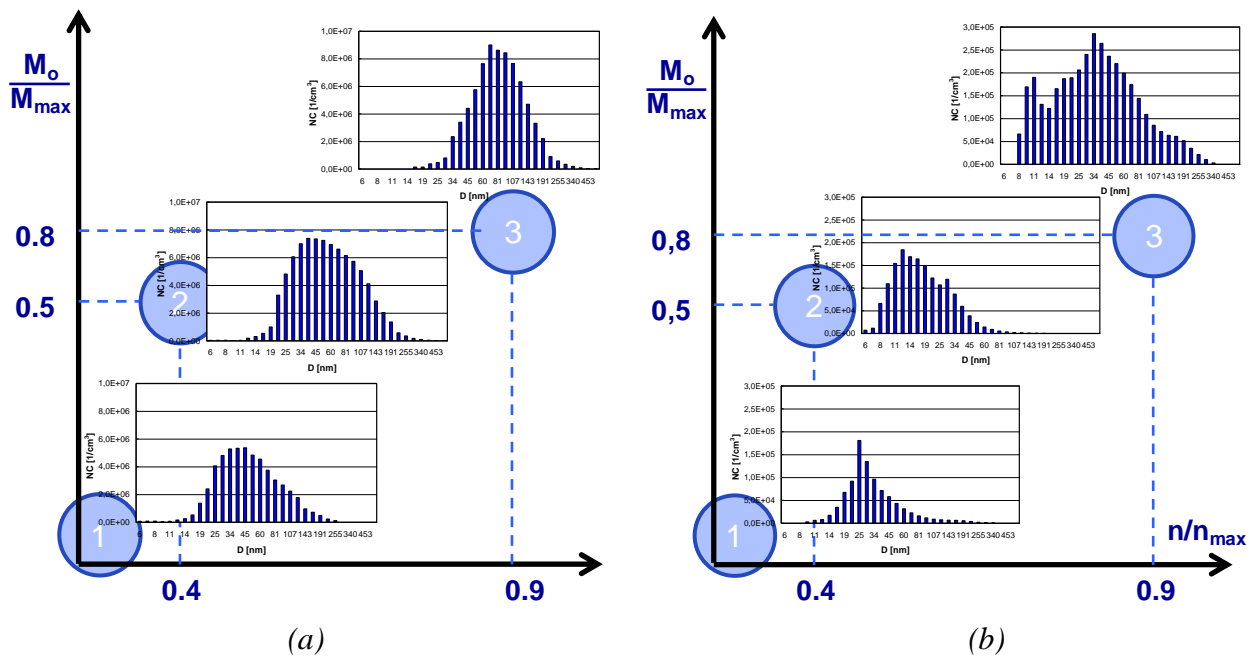


Fig. 8. Engine operating conditions in the coordinates of engine speed – engine load in the on-road tests and PM size distribution: 1 – idle speed, 2 – medium engine speed–medium load, 3 – high engine speed–high load; a) vehicle A, b) vehicle B.

For vehicle B fitted with DPF the size related analysis of PM (Fig. 8b) is different in terms of size and concentration (here we have lower values of particle count in most of the size ranges):

- range 1 (idle speed) – the characteristic diameter of the particles (particles highest in number) is the range of approximately 30 nm; the concentration of PM for this range is  $1.8 \times 10^5$  1/cm<sup>3</sup>;
- range 2 (medium engine speed–medium load) – particles in the range 10–30 nm, the maximum falls within the range of approximately 12 nm; the concentration of PM for this range is  $1.5\text{--}1.8 \times 10^6$  1/cm<sup>3</sup>;
- range 3 (high engine speed–high load) – particles in the range 10–100 nm; the maximum falls within the range of approximately 40 nm; the concentration of PM for this ranges is approximately  $3 \times 10^5$  1/cm<sup>3</sup>.

During the road tests for vehicle B fitted with DPF, Euro 5 compliant, the authors also observed the process of DPF regeneration that took place under the conditions of expressway traffic at the speed of approximately 120 km/h (Fig. 9).

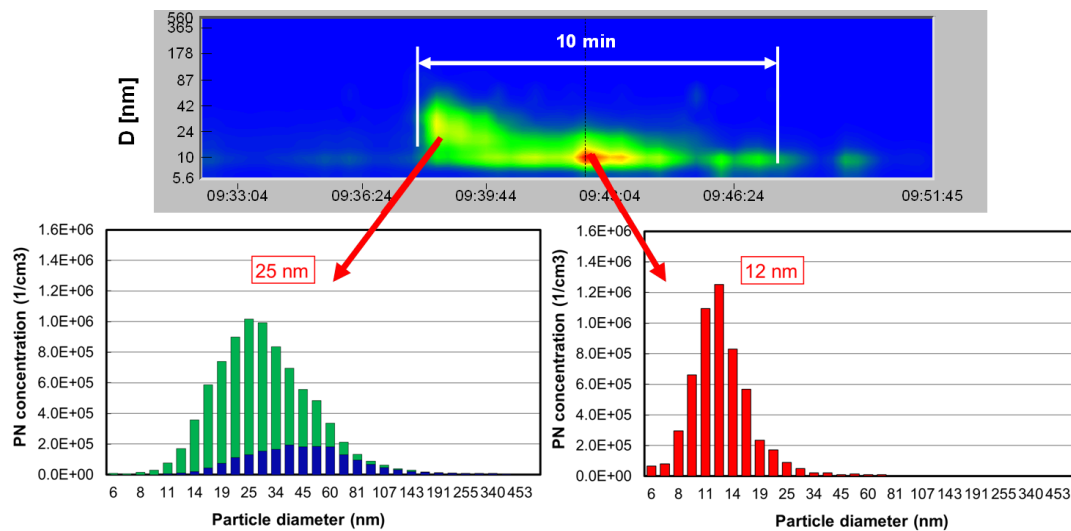


Fig. 9. The recorded process of DPF regeneration, vehicle B.

This was the process of full regeneration (total duration approximately 10 min). The size-related analysis of the PM emission shows a significant emission of PM during this process: the onset of the regeneration is characterized by an increased emissions of PM of the size of 20–30 nm (ok.  $8 \times 10^5$  1/cm<sup>3</sup>) and in the final phase (approximately  $1.3 \times 10^6$  1/cm<sup>3</sup>), the highest number of PM smaller in diameter is observed of the diameter of approximately 10 nm.

In terms of the total number of particles the regeneration process increases this value approximately 10 times: under steady states of expressway drive the total concentration of particles was approximately  $0.5\text{--}1 \times 10^5$  1/cm<sup>3</sup> (dilution level excluded) and during the regeneration process this value increased to  $4\text{--}5 \times 10^5$  1/cm<sup>3</sup>.

The first period of regeneration (initial 3–4 min) is characterized with a greater range of the emitted PM (15–60 nm) and in the subsequent period (4–10 min) – PM of smaller diameter variability range occur (7–20 nm). It is noteworthy that no significant mass growth of PM was recorded in this period. The normative values of the PM emission determined by the Euro 5 standard allow for the regeneration of the DPF filter hence the limit value cannot be exceeded irrespective of the fact whether the process occurs in the vehicle or not.



## 6. Quantitative emission indicators

The obtained results of the duration of the road tests served for the verification of the hypothesis on the fulfillment or non-fulfillment of the normative regulations on the on-road emissions. Such a comparison served to determine the value of growth or reduction of the on-road vehicles emissions as opposed to the homologation tests.

From the presented results of the emission rate (marked red on the figures) of any given component we can calculate the multiplicity of the growth or reduction in the on-road emissions as opposed to the normative values. This multiplicity was defined as an indicator of the vehicle emission (for each given exhaust component):

$$k_j = \frac{\sum_0^t E_{real,j}}{E_{normative,j}}, \quad (1)$$

where:  $j$  – exhaust component, for which the emission indicator was determined,  $E_{real,j}$  – on-road emission under real traffic from the start of the test (g/km),  $E_{normative,j}$  – normative on-road emission according to Euro 4/5 (g/km).

If we have an indicator determined in this way we can calculate its value:

- instantaneous (in figures marked green) – characterized by high variability, as it is calculated in each second of the test;
- incrementing while the test is performed; it is calculated as the on-going on-road emission of a given exhaust component (from the start of the test) as compared to the normative value; this value is marked blue in the figures;
- related to the whole test as a ratio of the on-road emission under real traffic to the normative emission.

The emission indicator of a given exhaust component can assume values from the range of  $<0, \infty$ ). This means that if the vehicle emission does not exceed the normative values, the indicator has a value lower than 1 and when the normative value is exceeded the indicator is greater than 1. If the values are equal (on-road and normative) the indicator is 1.

In the graphs from Fig. 10 for each exhaust component (for which the normative limit is fulfilled) the change of the emission indicator has been presented (gray). Despite high momentary variability of the emission indicator its value determined in an incrementing way is characterized as follows:

- for carbon monoxide – abrupt growth during engine start and then lowering of its value; under traffic conditions in a short time a reduction of this emission is obtained below the required standard for both vehicle A and B; the indicator values are similar for both tested vehicles (Fig. 10a);
- for hydrocarbons – the course of the changes of the indicator is similar to that recorded for carbon monoxide but vehicle A required a shorter distance (approximately 2 km) to reach the value of the indicator below 1, for vehicle B this distance was approximately 10 km (Fig. 10b);
- for the nitric oxides – no normative requirement fulfilled – this results from the fact that there is a difference in the engine operation under the NEDC test and in the real traffic; a small distance in the test results in an incomplete warming up of the engine, which leads to a small emission of the nitric oxides for both vehicles A and B. The value of the emission indicator is greater than 1 (Fig. 10c);
- for the particulate matter – the course of the changes of the emission indicator is different for the two vehicles: vehicle A was characterized by a very quick reaching of the indicator  $k < 1$  (PM limit for Euro 4 is 25 mg/km) and for vehicle B the indicator lower than 1 was reached after approximately 40 km despite the fact that the vehicle was fitted with DPF; this is due to a very low value of the limit for the Euro 5 standard (5 mg/km);

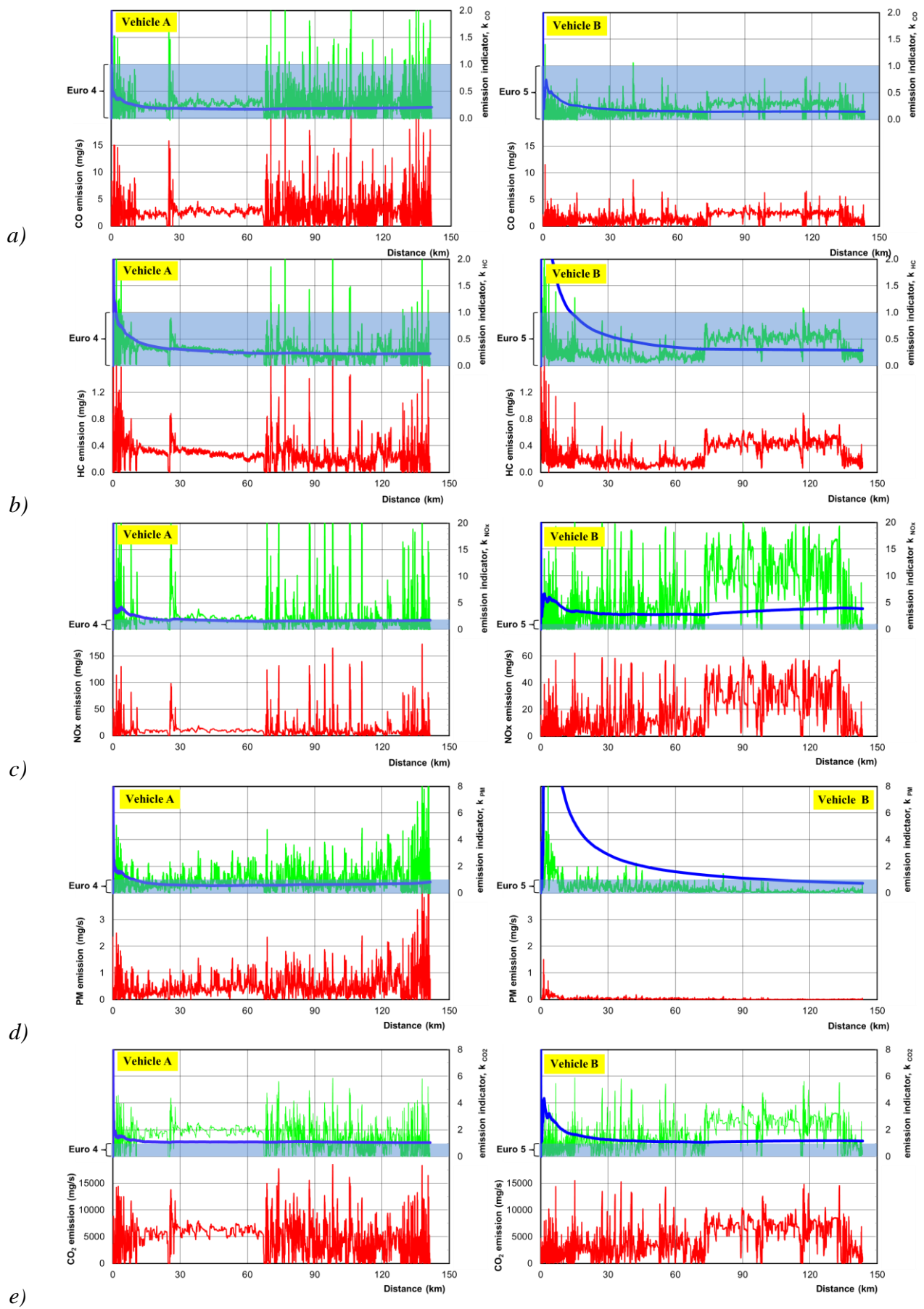


Fig. 10. The characteristics of the on-road exhaust emissions: a) CO, b) HC, c) NO<sub>x</sub>, d) PM, e) CO<sub>2</sub> for vehicles A and B as functions of the covered distance.

- for carbon dioxide – a normative value was assumed for comparison that amounts to 160 g/km (average value of the emission from vehicles in 2012 even though it is not determined for a single vehicle); the value of the CO<sub>2</sub> emission indicator was more than 1 under real traffic conditions due to a high capacity of the tested engines (2.0 and 2.2 dm<sup>3</sup>).

The obtained emission indicators for the whole test (for vehicles A and B) characterize the vehicle on-road emission level against the emission standards that applied to a given vehicle (Fig. 11). The emission indicator of carbon monoxide ( $k_{CO} = 0.1\text{--}0.2$ ), hydrocarbons ( $k_{HC} = 0.2\text{--}0.3$ ) and PM ( $k_{PM} = 0.7\text{--}0.9$ ) for the tested vehicles confirms that the vehicles do not exceed the average emissions in the on-road operation against the emission standards. The situation is quite contrary for the nitric oxides: for vehicle A, Euro 4 compliant, the emission indicator is 1.8, which confirms a much higher emission against the emission standard; for vehicle B this indicator is 3.9 – the average emission is several times higher against Euro 5. For comparison the authors also determined this indicator for carbon dioxide – it exceeded the standard values during the on-road tests by 10–20% (the assumed value 160 g/km corresponds to a fuel consumption of approximately 6.5 L/100 km).

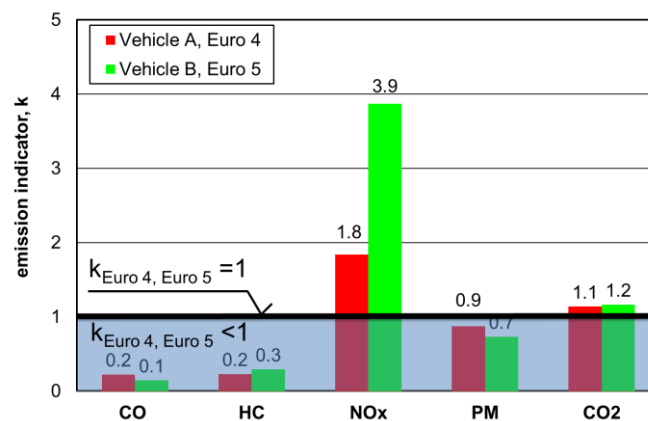


Fig. 11. The comparison of the emission indicators from passenger cars meeting different Euro emission standards.

## 7. Conclusions

From the analysis of the data it results that the normative emission values for the tested SUV vehicles meeting different Euro emission standards and the on-road exhaust emission vary. These differences in the case of some exhaust components under analysis are significant – these are as follows:

- For the Euro 4 compliant vehicle: the CO emission is lower by 80%, the HC emission is lower by 80%, the NOx emission is higher by 80%, the PM emission is lower by 10%, and the CO<sub>2</sub> emission is higher by 10%,
- For the Euro 5 compliant vehicle: the CO emission is lower by 90%, the HC emission is lower by 70%, the NOx emission is four times higher, the PM emission is lower by 30%, and the CO<sub>2</sub> emission is higher by 20%.

The analysis of the world trends in environment protection shows that in order to effectively reduce environment pollution a measurement of exhaust emissions in real road operating conditions is a necessary step to take. The institute owns a system of portable analyzers that enables the measurement of vehicle emission levels not only in stationary but also in dynamic conditions e.g. during engine start, transient conditions between two processes (diesel particulate filter regeneration). The system of analyzers is a set enabling a complex on-board measurement of exhaust emissions in real time under real road operating conditions of vehicles fuelled with different fuels (gasoline, diesel oil, LPG, CNG, E85 etc.). A complement to the existing system is an opacimeter and a PM measuring unit having the capacity to measure the PM mass and size (PM counter and mass spectrometer).

The on-road emission tests indicate that in relation to some of the exhaust components the emission is several times higher. Hence, a trend is seen to legalize and enforce the on-road exhaust emission measurement in Europe.

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