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## Measurement of rail vehicles exhaust emissions

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The basic problem in terms of measuring exhaust emissions is the approval tests of traction vehicles, which are carried out on engine dynamometers. Therefore, it is impossible to obtain reliable results concerning their actual impact on the natural environment. It is therefore advisable to carry out the tests in real operation conditions, as is the case for road vehicles for which RDE (Real Driving Emissions) tests are carried out. The latest Stage V emission standards push for the introduction of this type of test, but no limit values for toxic exhaust gases have been established and no test guidelines have been defined for assessing actual emissions. This article describes the issues related to the legislative guidelines for non-road vehicles in force in Europe, as well as the measurement tools used, such as mobile equipment for measuring emissions of PEMS (Portable Emissions Measurement Systems) and newly developed emission gates. Additionally, the paper presents examples of locomotive exhaust emission tests in real operating conditions. The aim of the measurements was to assess the emission of toxic compounds against the relevant standards. The subject of the research was a diesel locomotive type T448.P equipped with a modernized internal combustion engine.

Key words: *exhaust emission, rail vehicles, RDE, PEMS, NRMM*

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### 1. Introduction

Despite efforts to electrify vehicles used in road and rail traffic, vehicles with internal combustion engines still constitute a significant part of rail vehicles used in Poland (Fig. 1). The planned modernization works and purchases of new vehicles announced by Polish railway operators indicate that the future of vehicles with internal combustion engines on Polish tracks seems to be safe for the next several years or even a decade. Freight carriers have planned investments in 167 locomotives with the financial value of approximately PLN 930 million for the years 2017–2023 [19]. This situation may be influenced by the degree of electrification of the Polish railway network, which has changed slightly over the years and in the years (2003–2018) increased from 59.8% to 61.8% [11–14]. This means that in 2018, 7341 km of tracks in Poland were not available for electric rolling stock.

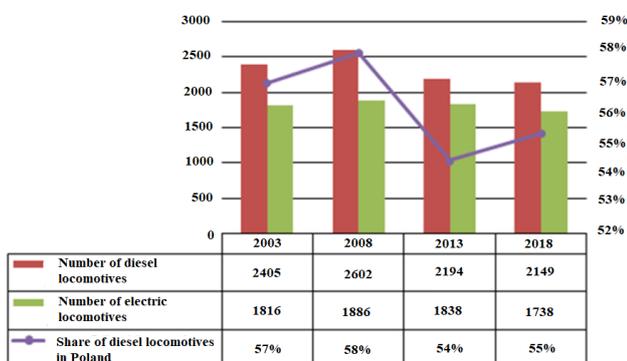


Fig. 1. The structure of the rolling stock in Poland in 2003-2018 [11–14]

### 2. Exhaust emission standards for rail vehicles used in Poland

The development of measuring technology and research on the harmful effects of substances emitted in exhaust

gases meant that several decades ago, increasing awareness began to appear regarding the risks associated with the emissions from internal combustion engines. As a consequence, exhaust emission standards for rail vehicle engines were developed and put into place. The ORE B13 report is the oldest form of formal recording of exhaust emission limits for vehicles used in Poland. Based on this document a twenty-nine-phase test was carried out (Fig. 2), from which four evenly distributed operating points were selected for the calculations.

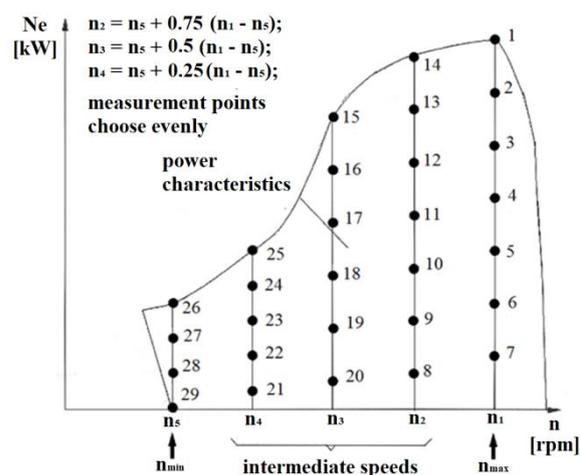


Fig. 2. The ORE B13 test measurement points [6]

Along with the above-mentioned test, emission limits for such compounds as: CO, HC and NO<sub>x</sub> were introduced (Table 1). The standards for off-road vehicles provide the maximum value of the specific emissions for each exhaust component, i.e. expressed in the mass of substance emitted in the process of generating a unit of work. The most recent version, introduced in 1997, assumed a fourfold reduction

in carbon monoxide emissions, a fivefold reduction in hydrocarbon emissions and a twofold reduction in nitrogen oxides emissions compared to the first stage. At the same time, the opacity of the exhaust gases was to remain at the same level all the time.

Table 1. Exhaust emission limit value according to ORE B13 [1]

Applicable	CO	HC	NO <sub>x</sub>	Opacity k
	g/kWh			m <sup>-1</sup>
Until 31.12.1981	12	4.0	24	1.6–2.5
Since 01.01.1982	8	2.4	20	1.6–2.5
Since 01.02.1991	4	1.6	16	1.6–2.5
Since 01.02.1997	3	0.8	12	1.6–2.5

Poland's accession to the European Union resulted in the entry into force of the EU standards for the NRMM (Non-Road Mobile Machinery) vehicle category. On the basis of successive regulations of the European Parliament, newer and more stringent exhaust emission standards were introduced. Particular attention should be paid to the following standards: Stage IIIA (2006), Stage IIIB (2011) and Stage V (2019). Each of these stages divides the engines of off-road vehicles into categories depending on the power, type of ignition and the vehicle on which the engine is installed (Table 2). The standard provides for limits on such toxic compounds as CO, HC, NO<sub>x</sub>, total HC and NO<sub>x</sub> emissions, as well as PM mass (Fig. 3).

Table 2. Railway vehicle engine categories in stages: IIIA, IIIB and V [4, 18]

Norm	Stage IIIA	Stage IIIB	Stage V
Types of vehicles	Railcars RC A P < 130 kW	Railcars RC B P < 130 kW	Railcars RLR, CI/SI; P > 0 kW
	Locomotives RL A 130 kW < P < 560 kW	Locomotives R P > 130 kW	Locomotives RLL, CI/SI P > 0 kW
	Locomotives RH A P > 560 kW		
RC A – railcar engines, from 31.12 2005 RL A – locomotive engines, from 31.12 2006 RH – locomotive engines from 31.12 2008 RC B – railcar engines, from 31.12 20011 R B – locomotive engines, from 31.12 20011 RLR – railway railcars, from 31.12 20020 RLL – railway locomotives, from 31.12 20020			

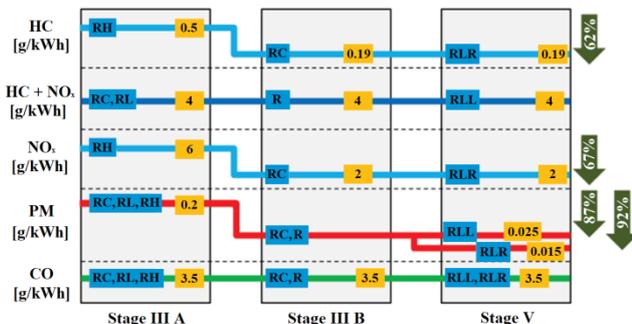


Fig. 3. Exhaust emission limits for Stages IIIA, IIIB and V [3]

As a result of these regulations, the latest designs of rail vehicle engines are equipped with modern solutions known mainly from passenger cars and trucks, such as the Common Rail injection system or the SCR (Selective Catalytic Reduction) reactor. With Stage V, there is a requirement to test NRMM vehicles under real operating conditions. However, the limit values for the individual toxic exhaust gases have not yet been defined.

### 3. Rail vehicle emission testing

Emission tests for NRMM category vehicles are governed by ISO 8178. The measurement cycles are carried out in the Stage I, II, IIIA, IIIB, IV and V standards for diesel engines with a net power of 19 kW ≤ P ≤ 560 kW, which run at constant or variable speed. The test procedure consists of a series of eleven measurements at different speed and torque values that characterize the typical operation of the vehicle engine. The different modes and their weighting factors are presented in Table 3. Weighting factor is the weight of the operating point for the calculation of the resulting emission. The test is performed under steady-state operating conditions, so it ignores transient conditions important from the emissivity point of the engine, when the drive unit has to adapt to the changing load.

Table 3 Test weight factors according to ISO 8178 [21]

Phase number	Torque [%]	Engine speed [rpm]	Non-road vehicles		Constant engine speed		Locomotives
			C1	C2	D1	D2	F
1	100	Rated	0.15	–	0.30	0.05	0.25
2	75		0.15	–	0.50	0.25	–
3	50		0.15	–	0.20	0.30	–
4	25	Medium range	–	0.06	–	0.30	–
5	10		0.10	–	–	0.10	–
6	100		0.10	0.02	–	–	–
7	75	Idle	0.10	0.05	–	–	–
8	50		0.10	0.32	–	–	0.15
9	25		–	0.30	–	–	–
10	10		–	0.10	–	–	–
11	0		0.15	0.15	–	–	0.60

C1 – test cycle for C.I. engines operated under intermittent speed  
 C2 – test cycle for S.I. engines operated with a power > 20 kW  
 D1 – test cycle for auxiliary engines operated under constant speed  
 D2 – test cycle for C.I. engines operated under constant speed  
 F – test cycle for locomotives engines

Examination of exhaust gas composition is important in the context of engine diagnostics and its functional systems such as: catalytic converters, DPF filters (Diesel Particulate Filter) and SCR reactors [9]. Diagnostics of the wear of these elements in specific vehicles or entire series of engines may be an important step in the development of further technical solutions reducing the emission of toxic compounds. There are tests performed at the stage of research and development of structures and control tests, which are divided into:

- homologation (NTA – new type approval),
- conformity of production (tests of vehicles drawn randomly from series production to confirm compliance with approval),
- periodic tests at motor vehicle diagnostic stations.

Approval tests in accordance with ISO 8178 are a time-consuming and complicated process. They are carried out in stationary conditions, often with the use of generator brakes. Control tests, performed after installing the engine on the vehicle, are carried out after an appropriate period of operation at a diagnostic station (Fig. 4) equipped with, among others, water resistor [3].



Fig. 4. Diagnostic station for measuring operational parameters and emissions of rail vehicles [20]

The concentrations of the individual exhaust components are measured by specific exhaust gas analyzers. The exhaust gases are supplied to them thanks to the use of a probe placed in the exhaust system. Engine operating parameters, including power, are regulated from the driver's cab. Testing emissions only under steady-state conditions leads to significant discrepancies between the results of the approval tests and the emissions under real conditions [2, 15, 16]. Hence the idea of a real driving test (RDE) for road vehicles. Such measurements have already been included in the WLTP (World harmonized Light-duty vehicles) Test Procedure tests. It is possible to develop a methodology of such tests for rail vehicles and to add their results to the test according to ISO 8178 thanks to the use of PEMS devices.

#### 4. The use of PEMS devices in the testing of the emissions of rail vehicles combustion engines

The use of PEMS equipment allows for testing vehicle emissions in real engine operating conditions (Fig. 5). Devices of this type measure the concentrations of: CO, CO<sub>2</sub>, HC, NO<sub>x</sub> and the mass, number and size of solid particles. The engine operating parameters are taken from the CAN (Controller Area Network) bus. In order to facilitate the comparison of RDE test results with approval tests, the CF (Conformity Factor) has been introduced.[10]:

$$CF_i = \frac{E_{r,i}}{E_{WHTC,i}} \quad (1)$$

where: i – compounds for which the concordance factor is determined, E<sub>r,i</sub> – emission under real operating conditions, E<sub>WHTC,i</sub> – emission in the WHTC test.

Determining the maximum value of the CF coefficient makes it possible to take into account the difference between the operating conditions in RDE and type-approval tests and the tolerances of the devices used. Measurements

with PEMS equipment can be particularly useful when comparing emissions before and after rolling stock upgrades. The assessment of the emission change and the determination of environmental benefits may be the basis for making a decision to carry out further modernization works. In addition, tests carried out in various conditions can be the basis for the assessment of emission tests and their compliance with the actual performance of vehicles.

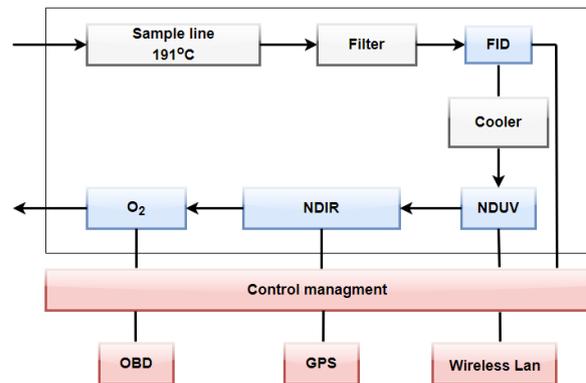


Fig. 5. Scheme of PEMS analyzer based on Semtech DS [12] FID (Flame Ionization Detector), NDUV (Non-dispersive Ultra Violet), NDIR (Non-dispersive Infrared), OBD (On-Board Diagnostics), GPS (Global Positioning System), LAN (Local Area Network)

#### 5. Research on the emission of toxic compounds with use of remote-sensing technology

Testing in laboratory conditions and PEMS measurements do not meet all the expectations of today's exhaust emission testing. Therefore, there was a need to develop methods that would allow the measurement of vehicle emissions at a reduced cost and time-consuming research. This possibility is provided by remote-sensing technology. They are currently used to assess the emissions of road vehicles. China and the USA are the leaders in work on such solutions. The Republic of China was the first country to introduce emission standards for measurements using this method.

Two development paths can be distinguished among the developed gate solutions [7]:

- open – path, based on absorption spectroscopy to study the concentrations of harmful compounds in the exhaust gas (Fig. 6a),
- extractive, where the exhaust gas sample is collected and analyzed by laboratory analyzers (Fig. 6a).

Both methods base their results on the relation of the concentrations of toxic compounds to the concentration of carbon dioxide in the exhaust gases. In most cases, the system measures nitrogen monoxide (NO), carbon monoxide (CO), hydrocarbons (HC) and carbon dioxide (CO<sub>2</sub>). It is also possible to determine the concentrations of nitrogen dioxide (NO<sub>2</sub>) and ammonia (NH<sub>3</sub>). The measurement of particulate mass (PM) is possible indirectly from the exhaust blackness. Open – path uses the laws of optics and light absorption by exhaust gas components to determine their concentrations. So far, the results of the measurements are used to select vehicles with the highest emissivity, in order to refer them to further tests, e.g. PEMS. Determining the vehicle's emissivity on the basis of such measurements

is easier for SI (Spark Ignition) engines than for CI (Compression Ignition) engines. The reason is the operation of diesel engines on lean mixtures with variable oxygen concentration. With properly operating SI engines, the CO<sub>2</sub> concentration is usually around 15%. In diesel engines, this value can vary from 1 to 13%, and even 15% during regeneration of cleaning systems.

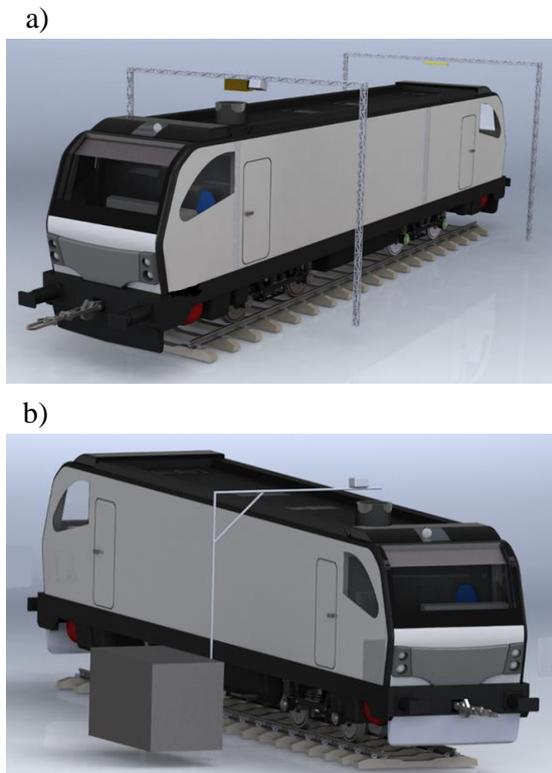


Fig. 6. Emission gate for the evaluation of type rail vehicles a) open – path, b) extractive

The issue that constitutes the greatest difficulty in the wide application of remote-sensing technology is the difficulty in unambiguously comparing their results with the

maximum emission values introduced by the standards. The remote-sensing technology does not allow the measurement of the exhaust gas intensity, so it is impossible to determine the road [g/km] or specific emission [g/kWh]. Road emissions relate the mass of the pollutant to the distance traveled by the vehicle, while the specific emission relates to the useful work performed by the vehicle engine. To improve the information carrying capacity of the results, three methods of comparing the results to the maximum values were proposed. The first one is based on the estimation of CO<sub>2</sub> concentration on the basis of dynamic properties and characteristics. The second method is to test the amount of oxygen versus carbon dioxide in the exhaust cloud close to the end of the exhaust system. Unfortunately, there is no technology yet that would allow such measurements to be made. The third way is to define emission factors based on CO<sub>2</sub> emissions or fuel consumption. The assessment of the toxicity indicators, which refer individual compounds to CO<sub>2</sub> emissions, is presented in [17]. This approach seems to be the most developmental at present. A method of converting the concentrations of toxic compounds into road emissions has been developed, while maintaining certain dependencies.

## 6. Examples of tests in real operating conditions

The tests in real operating conditions were carried out on an unloaded T448.P diesel locomotive (Fig. 7, Table 4).

Table 4. Basic technical data of the research object (according to the operation and maintenance documentation [5])

Type of work	four-stroke cycle
Injection	direct
Top-up	turbocharging
Layout	V90°
Cylinder liner diameter [mm]	165
Piston stroke [mm]	185
Number of cylinders	12
Displacement volume [dm <sup>3</sup> ]	47.5
Compression ratio	13.6:1
Maximum power [kW]	680
at rotational speed [rpm]	1300
Torque at 40°C coolant temperature [Nm]	560



Fig. 7. General view: I – diesel locomotive T448, II – diesel engine 12V396

The aim of the measurements was to assess the emission of toxic compounds, taking into account the histograms of the load of locomotives under typical operating conditions in the light of the requirements of the relevant standards, directives and regulations [4, 6, 8, 18]. The locomotive was equipped with a 12-cylinder combustion engine with a displacement of 47.5 dm<sup>3</sup>. It had a maximum power of 680 kW at a rotational speed of 1,300 rpm. The diagram of the performed measurements is shown in Fig. 8.

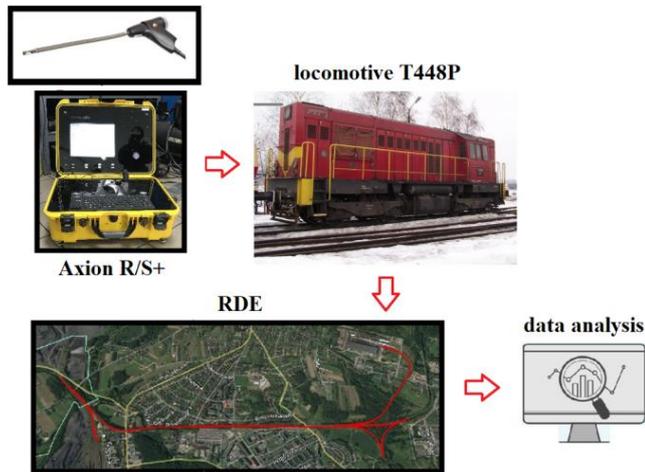


Fig. 8. Diagram of the performed tests

The tests were carried out using the Micro PEMS Axion R/S+ mobile analyzer manufactured by Global MRV. The device measures the concentration of gaseous toxic compounds with the use of: a non-dispersive infrared analyzer – NDIR (CO<sub>2</sub>, CO, HC) and an electrochemical analyzer (NO). The equipment also allows you to measure PM concentration using a method based on Laser Scatter, in which the speed of particle movement is measured (taking into account the values assigned to PM10).

Based on the recorded parameters during the tests, the characteristics of the time density as a function of velocity – acceleration (V–a) were determined (Fig. 9). The area defined by the ranges (0 m/s; 8 m/s> and (–0.5 m/s<sup>2</sup>; 0.5 m/s<sup>2</sup>>) had the highest share of working time – 68%. The highest values for a single operating point (17.5%) were obtained while for speed (4 m/s; 6 m/s> and acceleration 0 m/s<sup>2</sup> and for idling (17.4%). It is also worth noting that the share of operating time from a run by a locomotive with zero acceleration was 61%. was 4.5 km with an average speed of 14.5 km/h, the locomotive during this test achieved a maximum speed of 54 km/h.

The intensity of CO<sub>2</sub> emissions (Fig. 10) of the tested object is closely related to the speed and acceleration of the vehicle, which can be seen in the entire range of vehicle operation. It is closely related to the fuel consumption of the locomotive. The highest emission intensity occurred in the following ranges (14 m/s; 16 m/s> i (0 m/s<sup>2</sup>; 0.5 m/s<sup>2</sup>> (117 g/s) and (12 m/s; 14 m/s> and (0 m/s<sup>2</sup>; 0.5 m/s<sup>2</sup>> (115 g/s). The average emission intensity remained at 34 g/s. The area with the highest values is described by the speed ranges (6 m/s; 16 m/s). > and acceleration (0 m/s<sup>2</sup>; 1 m/s<sup>2</sup>>. While idling, the vehicle emitted 17.4 g/s CO<sub>2</sub>.

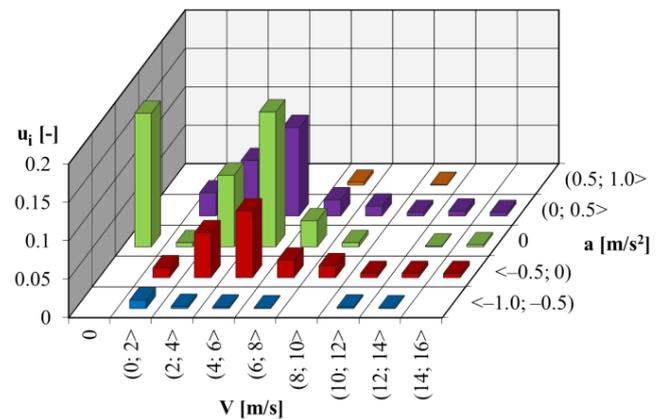


Fig. 9. Operating time density graph in real operating conditions expressed in speed and acceleration intervals

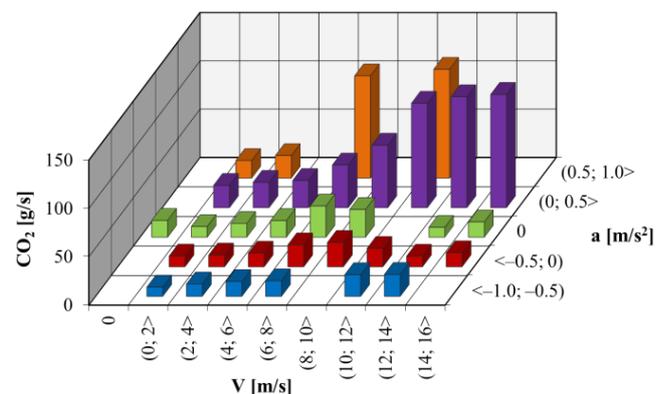


Fig. 10. CO<sub>2</sub> exhaust emission intensity of the tested vehicle in speed and acceleration intervals

As in the case of carbon dioxide, the obtained CO values depended on the speed and acceleration of the vehicle, but in this case their distribution was more even (Fig. 11). The highest values were obtained for the area of (6 m/s; 16 m/s> and (0 m/s<sup>2</sup>; 1 m/s<sup>2</sup>>, with the maximum value for a single operating point (6 m/s; 8 m/s> and (0.5 m/s<sup>2</sup>; 1 m/s<sup>2</sup>> was 2.44 g/s. The average value of carbon monoxide for the entire test was 0.56 g/s. At the point characterized by the lack of speed and acceleration, the vehicle was characterized by a value of 0.39 g/s.

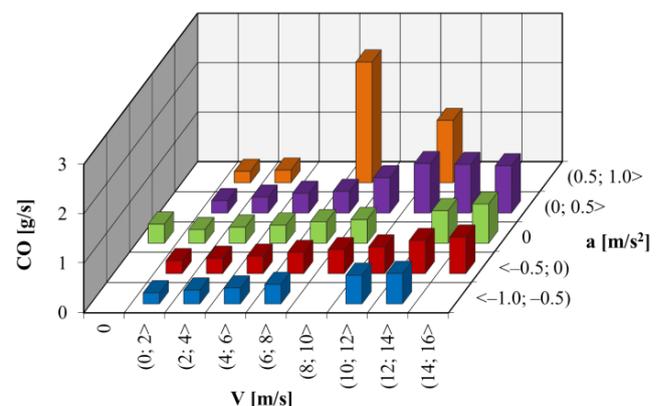


Fig. 11. CO exhaust emission intensity of the tested vehicle in speed and acceleration intervals

The values of HC emission intensity increased with increasing vehicle speed, and its average value was equal to 0.06 g/s. The highest values occurred in the area (10 m/s; 16 m/s> for the entire vehicle acceleration range. A single operating point characterized by the maximum value (0.1 g/s) occurred at the speed (14 m/s; 16 m/s> and acceleration (0 m/s<sup>2</sup>; 0.5 m/s<sup>2</sup>>. For idling the obtained value was close to the average value from the whole test.

The presented characteristics of the NO<sub>x</sub> emission intensity (Fig. 13) showed that the highest values occurred in the following ranges (6 m/s; 16 m/s> and (0 m/s<sup>2</sup>; 1 m/s<sup>2</sup>>, where the maximum value was 2.84 g/s) was obtained at the operating point determined by the intervals (14 m/s; 16 m/s> and (0 m/s<sup>2</sup>; 0.5 m/s<sup>2</sup>>. The average value obtained during the tests was 0.6 g/s. For the point 0 m/s and 0 m/s<sup>2</sup>, the emission rate was below 0.2 g/s.

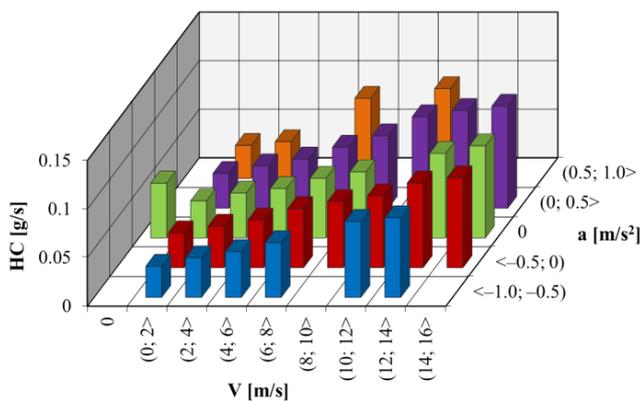


Fig. 12. HC exhaust emission intensity of the tested vehicle in speed and acceleration intervals

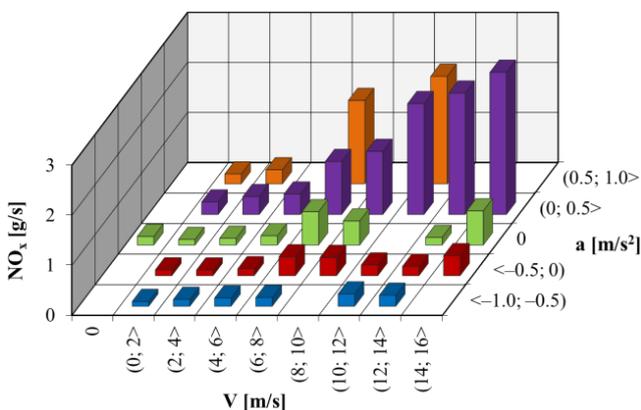


Fig. 13. NO<sub>x</sub> exhaust emission intensity of the tested vehicle in speed and acceleration intervals

As in the case of NO<sub>x</sub>, the PM emission intensity (Fig. 14) showed that the highest values occurred in the ranges (6 m/s; 16 m/s> and (0 m/s<sup>2</sup>; 1 m/s<sup>2</sup>>. Maximum value 0.34 g/s was obtained at a single operating point characterized by the speed ranges (6 m/s; 8 m/s> and acceleration (0.5 m/s<sup>2</sup>; 1 m/s<sup>2</sup>>. The average value of the PM emission rate was 0.04 g/s, while the value for idling did not exceed 0.01 g/s.

The next stage of the research was the measurements of the specific exhaust emissions of the tested object and comparing them with the exhaust emission standards applicable

in the years of its production, included in the ORE B13 Rp 22 report, introduced in 1991. During the measurements, the locomotive obtained the specific emission of carbon monoxide at the level of 7.8 g/kWh. It was the only compound that did not meet the limits (4.0 g/kWh) established in the standard. On the other hand, the locomotive met the requirements for HC and NO<sub>x</sub>, their values were respectively 1.12 g/kWh and 8.4 g/kWh. The limit values were 1.6 g/kWh for hydrocarbon and 16 g/kWh for nitrogen oxides. However, the report did not specify any particulate limits. The favorable results result from the fact that the engine of the tested object was modernized in 1995 in order to improve its ecological indicators.

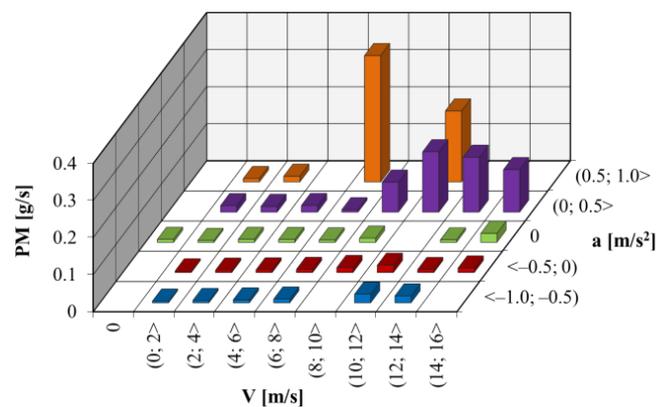


Fig. 14. PM exhaust emission intensity of the tested vehicle in speed and acceleration intervals

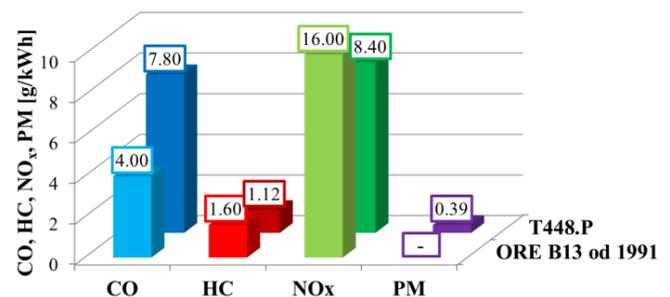


Fig. 15. Summary of test results with the limit values of harmful exhaust compounds according to ORE B13 Rp 22 in force since 1991

## 6. Summary

The number of diesel rail vehicles operated in Poland, their share in the rolling stock and planned investments indicate that non-electrified rolling stock will still constitute a significant part of rail vehicles in Poland. Successive exhaust emission standards for rail vehicles reduce the maximum specific emissions of toxic compounds. Tests on the emission of toxic compounds from rail vehicle engines should evolve towards combining stationary tests and measurements in real operating conditions.

The presented example of testing a rail vehicle during real operation proves that it is possible to learn more about the operating conditions of locomotives and their influence on ecological indicators. The test object had an engine in good technical condition (after renovation), thanks to which the obtained specific emission results indicate that it meets the limit according to which it was approved in addition to CO. In addition, it is not possible to emit PM as the ORE

B13 standard did not define a value for this toxic compound.

The use of PEMS equipment makes it possible to measure emissions during the normal operation of rolling stock – taking into account the limitations related to the gauge and safety. However, the introduction of the conformity factor CF may allow effective use of tests under real engine operating conditions and comparison of their results with the maximum values specified by EU standards. It should also be expected that remote sensing solutions for measuring rail vehicles will allow to identify the most environmentally harmful vehicles for further research.

## Nomenclature

CAN	controller area network
CF	conformity factor
CI	compression ignition
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
DPF	diesel particulate filter
FID	flame ionization detector
GPS	global positioning system
HC	hydrocarbons
ISO	international organization for standardization
LAN	local area network
NDIR	non-dispersive infrared

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NDUV	non-dispersive ultra violet
NO <sub>x</sub>	nitrogen oxides
NTA	new type approval
OBD	on-board diagnostics
ORE	centre for education development
PEMS	portable emissions measurement systems
PM	particulate matter
RDE	real driving emissions
SCR	selective catalytic reduction
SI	spark ignition
WLTP	world harmonized light-duty vehicles

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