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Analysis of pollutant emissions of a railbus based on Real Train Emissions measurements

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Pollutant emission measurements under real operating conditions using Portable Emission Measurement Systems (PEMS) have been conducted for various groups of vehicles and machinery for many years. Since 2014, Real Driving Emissions (RDE) procedures have been defined and implemented in homologation testing for Heavy Duty Vehicles (HDVs) and for Passenger Cars (PCs) and Light Duty Vehicles (LDVs) in 2017. In the case of Non-Road Mobile Machinery (NRMM), there is an ongoing effort to conduct real-world emission measurements; however, threshold values for harmful exhaust compounds have not yet been defined. This article presents an analysis of measurement results conducted for a rail bus equipped with two diesel engines. These six-cylinder engines have a displacement of 12.8 dm³ and an effective power output of 257 kW. Measurements were performed on a regular, non-electrified railway line between Krzyż Wielkopolski and Trzcianka, spanning a distance of 36 km. Additionally, the shunting operations of the rail bus at Krzyż Wielkopolski station were analyzed. During the study, emissions of gaseous compounds were measured using the Semtech DS analyzer by Sensors Inc.. In contrast, particulate mass was measured with an AVL Micro Soot Sensor, and the particle number and size distribution were assessed with the Engine Exhaust Particulate Sizer by TSI. Due to the use of a rail vehicle, the testing procedures were designated as Real Train Emissions (RTE).

Key words: *railbus, exhaust emission, Real Train Emission, real operating conditions, PEMS*

1. Introduction

The European Union continuously strives to increase the share of public transport due to its positive impact on reducing harmful exhaust emissions and noise into the atmosphere [8, 30, 31]. Rail transport, in particular, plays a key role in low-emission policies [33, 34, 36]. Rail multiple units are especially important in this context. They can be defined as at least two-car vehicles with a power source that functions as a single, cohesive unit during operation. Multiple units are primarily used for handling urban transit, transporting passengers from smaller towns to major metropolitan areas. Diesel-powered rolling stock is especially relevant here, as it can service regional routes on non-electrified lines, which in 2020 accounted for approximately 38% of all railway lines in Poland [40].

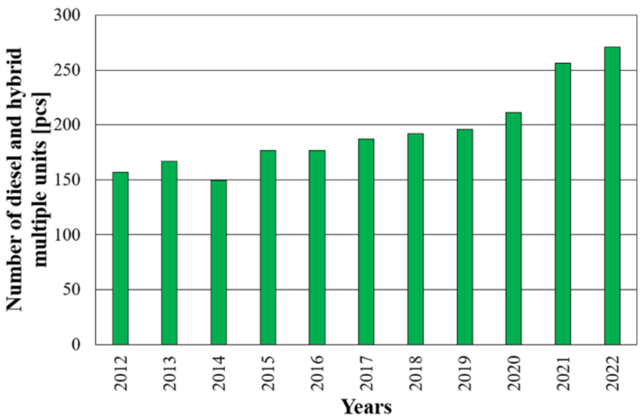


Fig. 1. Number of diesel and hybrid multiple units in Poland [38]

According to data from the Office of Rail Transport (UTK), in 2022, there were 248 diesel multiple units in operation across the country. Figure 1 shows changes in the number of rail vehicles in service over the past 10 years. The continuous increase in the number of multiple units powered by combustion engines is due to a growing interest in rail transport, especially on urban lines. Despite efforts to reduce their numbers, the costs and time required for constructing electrified infrastructure prevent a swift replacement of diesel units with electric ones. Since 2020, hybrid multiple units have become increasingly popular to prevent local emissions (especially in large cities). These vehicles operate on electric power within city limits, where electrified tracks are generally available until the end of the electric line. When leaving the electrified area, the vehicle's pantograph is lowered, allowing the multiple unit to continue its journey using the diesel engine. In 2022, there were 23 hybrid units in Poland, with operators continually working to expand the rail fleet nationwide. In December 2023, Poland's leading rail operator launched a tender for 35 dual-mode rail vehicles despite traditionally relying on classic locomotive and carriage configurations [35].

Data from the UTK on passenger numbers using rail transport from 2012 to 2023 (Fig. 2) indicates an increasing interest in rail transport. In 2023, Polish operators transported a total of 374.5 million passengers, an increase of approximately 32 million over the previous year. Since 2014, steady annual growth has been observed, except for 2020–2021, which saw a decline due to the COVID-19 pandemic and associated movement restrictions. Planned investments in infrastructure (both modernizing existing lines and building new ones), as well as investments in rolling stock, continue to contribute to the rising number of passengers. According to the Ministry of Infrastructure forecasts, the number of passengers is expected to exceed 500 million by 2030 [37].

Fig. 2. Number of passengers carried by rail in Poland [38]

On local railway lines, non-electrified lines and services where a small number of passengers travel, railbuses with conventional drives are most commonly used. They are a good alternative to larger locomotives, allowing lower emissions to be achieved. Their magnitude is closely dependent on the operational parameters of the object and its propulsion system, as well as factors related to actual operation, as in vehicles of other categories [10, 17, 39]. For this reason, standard type-approval measurements carried out under laboratory conditions do not reflect engine performance in real-world facilities during operation [9, 11, 16]. In order to determine the actual environmental impact of an object, measurements in actual operation are used. Their implementation makes it possible to objectively assess pollutant emissions and relate them to standards and limits. The development of measurement equipment of the PEMS (Portable Emissions Measurement Systems) type makes it possible to carry out such research tasks. Leading research centers worldwide are focusing on assessing emissions in real operating conditions from both on- and off-road vehicles [5, 6, 12, 32]. Due to the nature of the infrastructure and the characteristics of rail propulsion, such studies are only gaining popularity. The research presented in this paper was carried out to learn and understand the environmental impact of the test facility's operating conditions.

2. Homologation regulations for rail vehicles

The binding regulations in Europe on permissible emissions of harmful exhaust compounds from internal combustion engines used in NRMM (Non-Road Mobile Machinery) vehicles are laid out in Stage I–V standards [20–29]. These regulations were established in the European Parliament and Council Directive 97/68/EC [26] and in subsequent amendments, as follows:

- Stage I/II standard: Directive 97/68/EC [26], Directive 2002/88/EC [27]
- Stage III/IV standard: Directive 2010/26/EU [25], Directive 2010/26/EC [14]
- Stage V standard: Regulation (EU) 2016/1628 [29], Regulation (EU) 2017/654 [20], Regulation (EU) 2018/989 [22], Regulation (EU) 2017/655 [29], Regulation (EU) 2018/987 [21].

The first limits with legal power in the EU for non-road vehicles were introduced in the 1990s. Depending on engine power, they were gradually implemented in increasingly strict stages, from Stage I to V. Approval and certification of different engine categories are refused if an engine does not meet the requirements outlined in Directive [26], or if the emission of toxic compounds in exhaust gases exceeds the limits set by the relevant standard.

European emission standards for non-road vehicles were first announced in 1997 and implemented in two stages. In the initial stage, Stage I was introduced in 1999 with three engine categories based on power: Category A for engines with a rated power of 130 kW ≤ P ≤ 560 kW, Category C for engines with the smallest power ratings of 37 kW ≤ P < 75 kW, and Category B for all engines with power between those in Categories A and C, specifically 75 kW ≤ P < 130 kW. Stage II, implemented between 2001 and 2004, introduced a new category of engines with rated power of 18 kW ≤ P < 37 kW and changed the names of previous categories. This standard covered industrial equipment, construction vehicles (excavators, loaders), and special vehicles such as snowplows. Engines used in ships, railway locomotives, aircraft, and power generators were not covered by Stage I/II standards. Only with the introduction of Stage IIIA and IIIB standards between 2006 and 2013 were strict limits set for locomotive engines. These standards also introduced limits for engines exceeding 560 kW, marking the first restrictions specifically for powered rail cars. In this case, two categories of engines – RC (railcars) with power ratings above 130 kW – were taken into account.

The Stage IV emission standard was introduced in 2014, covering two categories of engines with power ratings from 56 kW to 560 kW. Compliance with this standard requires the use of exhaust gas treatment systems, such as SCR (Selective Catalytic Reduction) systems or DPF (Diesel Particulate Filter) technology. Stage V, the latest emission standard, includes RLL engines used in locomotives and RLR engines for rail cars. These standards have been in force since 2019 for engines below 56 kW and above 130 kW and since 2020 for engines with power ratings of 56–130 kW. The standard applies to locomotive drive engines, which are divided into two categories, though with the same emission values. Similarly, railcar engines are divided into two categories with identical values. It is also worth mentioning that with the Stage V standard, a particulate number (PN) limit was introduced for both RLR and RLL engine categories. The PN limit, which is 1×10^{12} 1/kWh, aims to significantly reduce emissions of fine particulate matter, which pose a significant risk to human health and the environment. In order to meet the imposed requirements, it was necessary for vehicle manufacturers to introduce advanced exhaust gas treatment systems, such as particulate filters (DPF).

Future initiatives are planned to study the emissions of harmful exhaust compounds under real-world operating conditions using specialized equipment from the PEMS (Portable Emission Measurement System) group. Table 1 presents the limit values for toxic compounds in the emission standards (Stage) related to non-road mobile machinery. Non-road vehicles are divided into different categories as part of the regulation of exhaust emissions in the European Union. They can be divided according to their use and technical characteristics. The designations presented in the article refer to specific groups of machines and vehicles, classified according to their power, use and type of propulsion. Here is what each category means:

Table 1. Limit values of toxic compounds from Stage I–V emission standards [23, 25, 26]

Stage	Category	P	CO	HC	NO_x	PM
		kW	g/kWh			
I	A	130 ≤ P ≤ 560	5.0	1.3	9.2	0.54
	B	75 ≤ P < 130	5.0	1.3	9.2	0.70
	C	37 ≤ P < 75	6.5	1.3	9.2	0.85
II	E	130 ≤ P ≤ 560	3.5	1.0	6.0	0.2
	F	75 ≤ P < 130	5.0	1.0	6.0	0.3
	G	37 ≤ P < 75	5.0	1.3	7.0	0.4
	D	18 ≤ P < 37	5.0	1.5	8.0	0.8
IIIA	RL A	130 ≤ P ≤ 560	3.5	4.0		0.2
	RH A	P > 560	3.5	0.5	6.0	0.2
	RH A	P > 2000	3.5	0.4	7.4	0.2
	RC A	130 < P	3.5	4.0		0.2
IIIB	R B	130 ≤ P	3.5	4.0		0.025
	RC B	130 < P	3.5	0.19	2.0	0.025
IV	Q	130 ≤ P ≤ 560	3.5	0.19	0.4	0.025
	R	56 ≤ P < 130	5.0	0.19	0.4	0.025
V	RLL-c-1	P > 0	3.5	≤ 4.0		0.025
	RLL-v-1	P > 0	3.5	≤ 4.0		0.025
	RLR-c-1	P > 0	3.5	0.19	2.00	0.015
	RLR-v-1	P > 0	3.5	0.19	2.00	0.015

- A: Engines of less than 8 kW. Applies mainly to small machines such as lawnmowers or small generators.
- B: Engines from 8 to 19 kW. Typical for small construction or gardening machinery.
- C: Engines from 19 to 37 kW. Includes medium-sized machines, such as smaller loaders or forklifts.
- D: Engines from 37 to 56 kW, used in medium-sized work machines and commercial vehicles.
- E: Engines from 56 to 130 kW, typical of larger construction machinery such as excavators and tractors.
- F: Engines from 130 to 560 kW, used in heavy machinery and vehicles such as large loaders and harvesters.
- G: Engines above 560 kW, used in machines with very high energy requirements, such as locomotives or the largest construction machines.
- RL A (Rail Locomotive A): refers to rail locomotives equipped with internal combustion engines with specific power and emission characteristics that comply with Stage V standards for the first group of locomotive engines.
- RH A (Rail High-speed A): a category covering engines for high-speed rail vehicles (e.g. high-speed passenger trains), where the emission requirements are adapted to the specific operation of this type of vehicle.
- RC A (Railcar A): applies to engines for use in railcars (railbuses) with specific power and emission characteristics, meeting the first group of standards for this category.
- R B (Rail Locomotive B): covers engines for heavier locomotives with higher horsepower, which must meet the more stringent emission requirements in the next regulatory group.
- RC B (Railcar B): refers to motor cars (railcars) with higher horsepower engines that meet more stringent emission requirements than RC A.
- RLR (Railcar Engines with rated power ≤ 560 kW): includes engines used in light rail vehicles such as railcars.
- RLL (Rail Locomotive Engines with rated power > 560 kW): covers engines used in heavy-duty diesel locomotives.

3. Research methodology

3.1. Description of the research object

The RTE measurements utilized a two-car diesel multiple unit intended for operation on non-electrified railway lines [7, 14, 15]. Given that this vehicle is referred to as a railbus by the leading Polish carrier, the same term has been adopted in this article. The research object features a lightweight, modular body structure with a lowered floor in the entry areas. Its length is 34,720 mm, width 2900 mm, and height 3800 mm (Table 2, Fig. 3). The vehicle is equipped with 94 seats and has enough space to accommodate 101 standing passengers. The railbus is powered by two diesel engines with compression ignition. Each engine has a displacement of 12.8 dm^3, generates a maximum power output of 257 kW, a maximum torque of 1500 Nm, and complies with the Stage II emission standard.

Table 2. Technical parameters of the research object

Parameter	Value
Vehicle	
Number of cars	2
Length	34,720 mm
Width	2900 mm
Height	3800 mm
Wheel diameter	840 mm
Service weight	56,000 kg
Number of seats	94
Number of standing places	101
Drive system	
Number of diesel engines	2 (compression-ignition)
Engine design	Inline, 6 cylinders in a horizontal layout
Displacement	12.8 dm^3
Maximum useful power	257 kW (350 HP) at 2000 rpm
Maximum torque	1500 Nm at 1000–1500 rpm
Emission standard	Stage II

The vehicle was manufactured in 2005, and the upgrade was carried out in 2013. The facility was technically sound during the research tests. A P3 inspection had been carried out prior to the tests, demonstrating the efficiency of the facility. The operation of the propulsion system was also checked using a diagnostic tester – no faults were detected. The railbus internal combustion engines were warmed up to an operating temperature of 88°C by the engine oil before the tests were carried out.

a) b)

Fig. 3. Railbus during RTE testing: a) vehicle prepared for measurements, b) view from the driver's cab

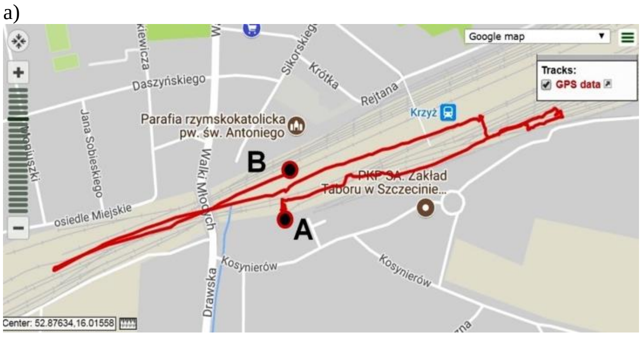
3.2. Test route

In the developed RTE method, selecting the test route was one of the key elements that reflected the operational conditions of railbuses. For this reason, it was decided that the measurements would be divided into two main stages (Fig. 4). The first stage involved manoeuvring the rail vehicle, which included travelling from the siding parking location (Point A in Fig. 4a) to the passenger platform at Krzyż Wielkopolski station (Point B). From this point, the railbus began its journey to Trzcianka (Point C in Fig. 4b), stopping at three intermediate stations. The measurement segment mentioned here is part of the railway line no. 203 connecting the Tczew station with the Kostrzyn station. This line is a very important part of the Polish railway infrastructure, in good technical condition, which is a crucial factor in rail vehicle testing [4, 14]. The total length of the test route was 39.12 km, of which 35.82 km covered the Krzyż Wielkopolski–Trzcianka route. The measurements performed took into account the permissible travel speed specified by the leading Polish carrier and stops at intermediate stations according to the timetable for this section. After completing the maneuvers and arriving at the platform, the vehicle waited approximately 14 minutes before departing the station. During this time, the vehicle's internal combustion engines were turned off. Measurements at point A (the beginning of the maneuvers) were conducted during a cold engine start. Table 3 presents the parameters of the test route.

Table 3. Technical parameters of research object

Parameter	Maneuvering	Main journey
Distance	3.30 km	35.82 km
Average speed	1.75 m/s	16.66 m/s
Maximum speed	6.97 m/s	28.44 m/s
Travel time	1879 s	2150 s
Total stop time	1073 s	319 s
Elevation gain	–0.8 m	39.2 m

a)



b)

Fig. 4. Test route diagram: a) maneuvering, b) main journey

3.3. Measurement equipment

The RTE tests used mobile PEMS (Portable Emission Measurement System) instruments designed for pollutant emission measurements under real operational conditions [12, 13, 18]. Determining the mass of a toxic compound requires measuring both the concentration and flow rate of exhaust gases. For this purpose, three devices were used – the Semtech DS by Sensors Inc., the Micro Soot Sensor by AVL, and the Engine Exhaust Particulate Sizer by TSI. The first device consists of a central unit that contains analyzers for measuring the gaseous components of exhaust:

a) FID (Flame Ionization Detector) – measures hydrocarbons in the range of 0–10,000 ppm

b) NDIR (Non-Dispersive Infrared) – measures carbon monoxide in the range of 0–10% and carbon dioxide 0–20%

c) NDUV (Non-Dispersive Ultraviolet) – measures nitrogen monoxide and nitrogen dioxide in the range of 0–3000 ppm

d) electrochemical oxygen sensor measuring in the range of 0–21%.

The device also includes a flow meter to measure the mass flow rate of exhaust gases using a Pitot tube. It is tightly mounted to the vehicle's exhaust system, and a heated hose, maintained at 192°C, delivers the sample to the main unit, where gaseous exhaust components are measured. The Semtech DS also has a GPS (Global Positioning System) vehicle positioning system, a weather station for measuring temperature, pressure, and atmospheric humidity, and allows data reading and recording from the diagnostic system. Particulate matter concentration measurements (conducted by determining carbon content in particles using the photoacoustic method) were performed with the second device – the Micro Soot Sensor. In the photoacoustic method, the exhaust sample is exposed to modulated light radiation, resulting in alternating heating and cooling of the sample, which periodically changes its size and generates medium vibrations. Sensitive microphones in the device register a sound wave with a specific amplitude and frequency. This only occurs when particulate matter is present in the sample – an impulse directly proportional to its concentration is then generated. In addition to mass concentration, a particle number concentration and particle size distribution were measured using the Engine Exhaust Particulate Sizer by TSI, which measures particles in the range of 5.6–560 nm. A detailed description of the devices used can be found in publications [1–3].

As shown in the diagram in Fig. 5, the mass and number concentrations of particulate matter were multiplied by the exhaust flow rate, thus obtaining the flow rate of these quantities. Summing them provided the total mass and particle count for the entire RTE test. Relating these values to the distance covered by the vehicle yielded the road emissions of particulate matter mass and number. The particle size distribution was presented as the total number of particles in the entire measurement range.

4. Analysis of test results in RTE conditions

4.1. Introduction to the analysis

The study of harmful emissions from exhaust gases under real operating conditions was divided into two stages. In the first stage, measurements were taken during shunting operations, covering a journey from a siding at the Krzyż Wielkopolski station to the passenger platform. In the second stage, the rail bus departed from Krzyż Wielkopolski to Trzcianka, stopping at three intermediate stations.

4.2. Shunting Operations

During shunting operations, the progression of second-by-second emission rates for gaseous compounds and particulate matter was examined. The analysis covered the entire work cycle, which lasted over 30 minutes. The vehicle covered a distance of 3.3 km at an average speed of 1.75 m/s, with a maximum speed of 6.97 m/s. In the first 10 minutes, the second-by-second emissions of harmful compounds remained very low, which can be attributed to a low speed of under 2.77 m/s and nearly constant acceleration. In the following phase, harmful exhaust compounds increased in measurement windows where the vehicle reached speeds above 5.55 m/s. For CO_2, the highest values occurred during the largest acceleration changes, exceeding ± 0.2 m/s^2. The maximum carbon dioxide emission rate was 57.9 g/s, with an average value of 6.2 g/s. Similar trends were observed for CO and HC, with maximum emission rates of 242.5 mg/s for carbon monoxide and 82.6 mg/s for hydrocarbons, while average rates were 43.2 mg/s and 19.3 mg/s, respectively. For NO_x emissions, the highest values were observed in the final phase of the cycle, indicating that the engine reached its highest temperature approximately 20 minutes into the test. The maximum nitrogen oxides emission rate was 1785.5 mg/s, with an average of 200.8 mg/s. The PM analysis showed that, after the first 10 minutes, values correlated with vehicle speed. Particulate matter emissions reached a maximum of 2.1 mg/s, with an average of 0.43 mg/s (Fig. 6).

To assess harmful exhaust emissions, the road emissions of a railbus were subsequently analyzed. The analyses revealed that the test object was characterized by CO_2 emissions of 3555 g/km, while fuel consumption amounted to 134.5 dm³/100 km. For the toxic compounds analyzed, the emission values were as follows: 24.6 g/km for CO, 1101 g/km for HC, 114.4 g/km for NO_x, and 0.073 g/km for PM (Fig. 7). In addition to the mass of particulate matter, its particle number (PN) and size distribution were also evaluated. The total PN during shunting operations amounted to 6.09×10^{13} (Fig. 8). The vehicle emitted the highest number of particles with diameters of 10.8 nm (9.96×10^{10}) and 9.31 nm (9.67×10^{10}).

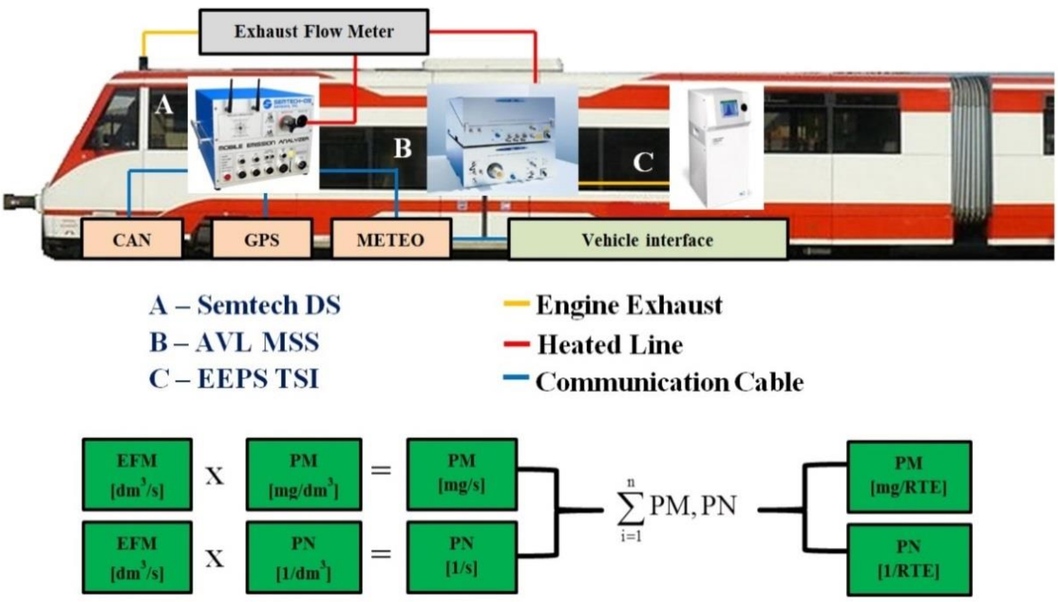


Fig. 5. Measurement equipment diagram used in RTE testing

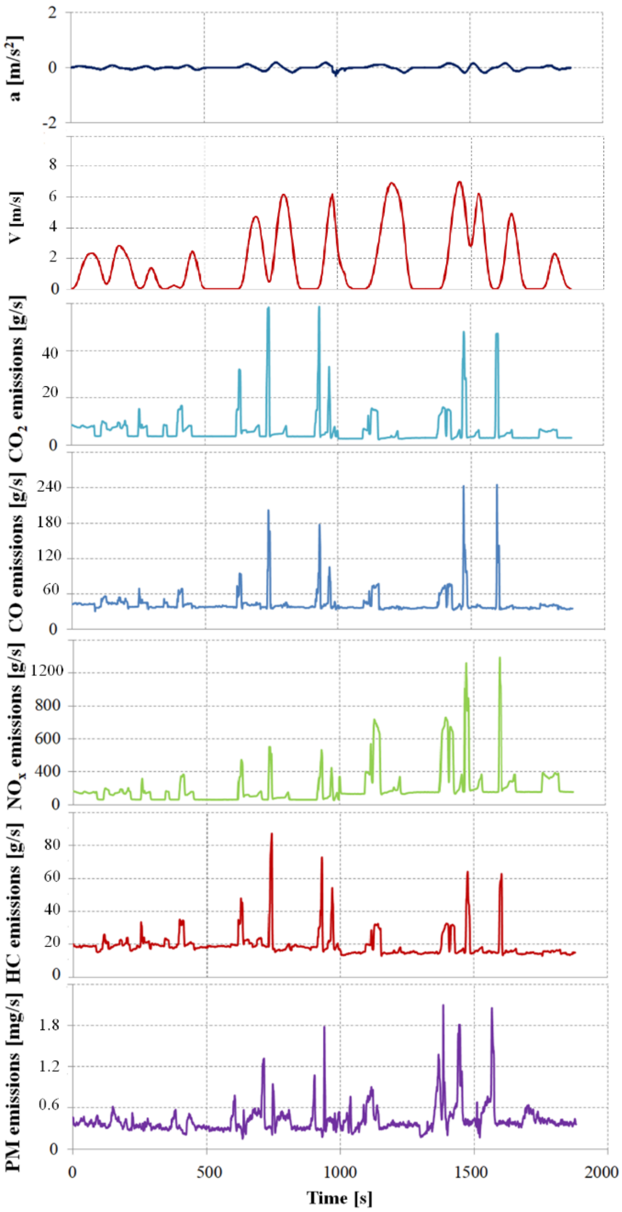


Fig. 6. The movement parameters of the tested object and the intensity of second-by-second emissions during shunting operations

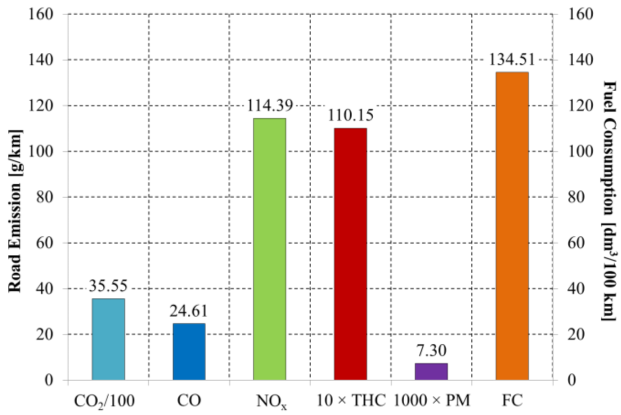


Fig. 7. Road emissions of harmful exhaust compounds and fuel consumption

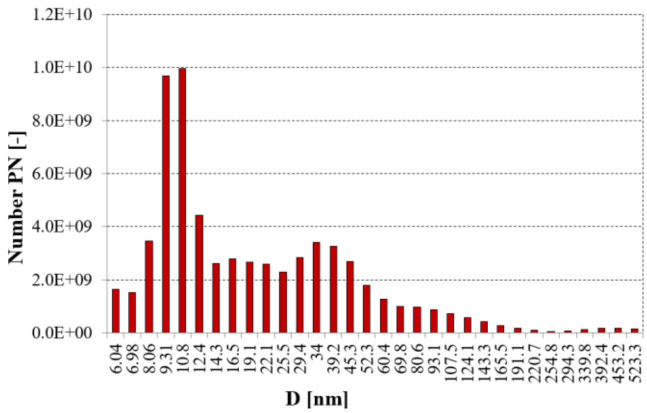


Fig. 8. Particle number and size distribution

In the next stage of the study, based on the recorded movement parameters of the tested object, time-density characteristics and pollutant emission intensities were determined as functions of speed and acceleration (v–a). The distribution of movement parameters was presented in one-sided closed intervals. Figure 9a illustrates the time shares within speed and acceleration intervals under real operating conditions of the tested rail vehicle. The highest value (31%) was recorded under conditions characterized by a vehicle speed and acceleration of 0, as well as in the speed range (0 m/s; 1.0 m/s> with minimal changes in vehicle acceleration. This is due to the nature of shunting operations, where the vehicle predominantly operates at idle. In the case of CO_2 emission intensity (Fig. 9b), the values are observed to be fairly evenly distributed across the entire range of movement parameters. Carbon dioxide emissions are directly related to fuel consumption, indicating that the vehicle consumed approximately the same amount of fuel regardless of speed and acceleration during shunting operations. A similar distribution of intensity was observed for all toxic gaseous exhaust compounds. The derived characteristics exhibit an even distribution of the recorded values for CO, HC, NO_x, and PM. This indicates that, during the conducted tests, the small variations in the vehicle's operating parameters did not lead to phenomena such as incomplete combustion or insufficient air-fuel mixture homogenization, which typically result in increased CO, HC, and PM emissions. Furthermore, due to the lack of significant load during the measurements, high temperatures and pressures in the combustion chamber were not observed, leading to low emissions of nitrogen oxides.

4.3. Test drive on the research route

During an actual drive on the Krzyż–Trzcianka route, the second-by-second emission intensities of gaseous pollutants and particulate matter were examined, similar to the procedure used during shunting operations. The route covered a distance of over 35 km, completed in approximately 35 minutes. During the test, the vehicle travelled at an average speed of 16.66 m/s, with a maximum speed of 24.44 m/s. The second-by-second emissions of all harmful exhaust compounds, except for CO, exhibited similar patterns throughout the trip. All values depended on the vehicle's speed and acceleration. The highest CO_2 emission reached 96.6 g/s, with an average of 31.7 g/s. For NO_x, HC, and PM, the average emissions were 388.7 mg/s, 52.3 mg/s, and 0.99 mg/s, respectively, while the maximum values were 1097.6 mg/s for NO_x, 136.7 mg/s for HC, and 6.67 mg/s for PM. For CO, the highest emissions were recorded during the initial phase of the trip, likely due to CO_2 dissociation in high-temperature zones or air deficiency and insufficient mixing of the air-fuel mixture. On average, the vehicle emitted 125.7 mg/s of CO, with a maximum value of 868.6 mg/s (Fig. 10).

To evaluate the emissions of harmful exhaust compounds, the next phase of the study focused on analyzing the road emissions of the tested vehicle. The analysis revealed that during real-world operation, the vehicle emitted CO_2 at a level of 19.1 g/km, with a fuel consumption rate of 71.25 dm³/100 km.

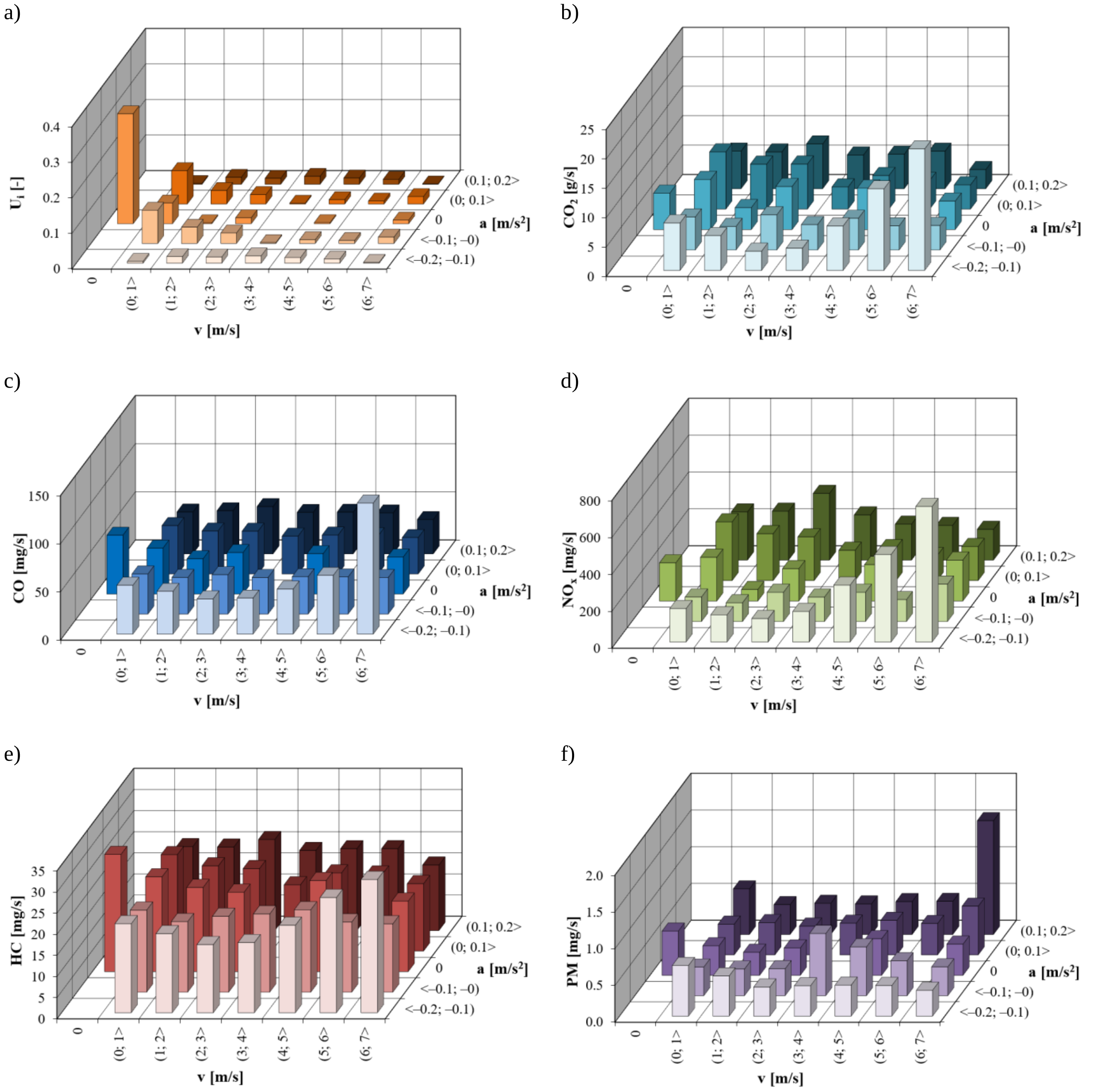


Fig. 9. Emission intensity of harmful exhaust compounds as a function of speed and acceleration: a) Operating time shares, b) CO_2, c) CO, d) NO_x, e) HC, f) PM

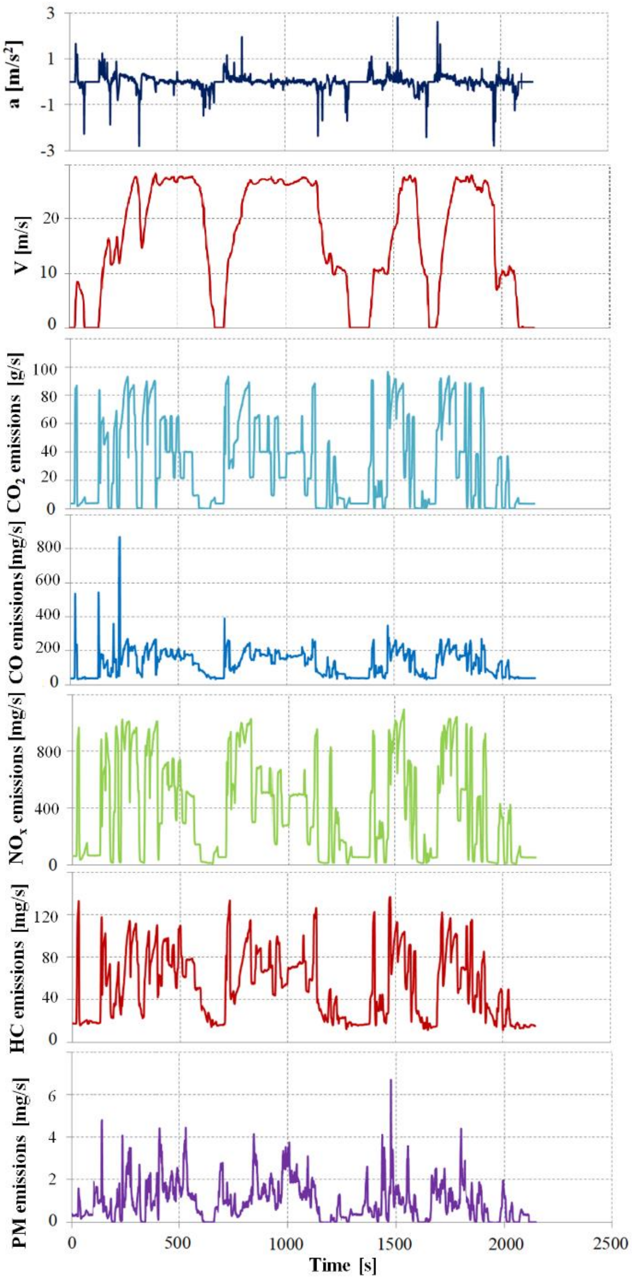


Fig. 10. The movement parameters of the tested object and the intensity of second-by-second emissions during test drive on the research route

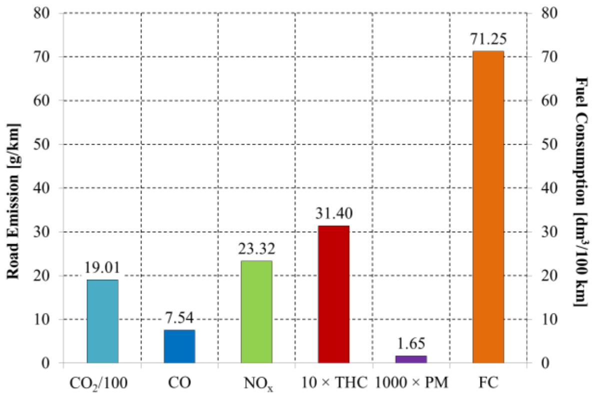


Fig. 11. Road emissions of harmful exhaust compounds and fuel consumption

For the analyzed toxic compounds, the emissions were as follows: 7.54 g/km of CO, 3.14 g/km of HC, 23.32 g/km of NO_x, and 0.0016 g/km of PM (Fig. 11). As with shunting operations, the analysis also included the particle number (PN) and size distribution of particulate matter. The total PN was 4.43×10^{14} (Fig. 12). The highest number of particles emitted had diameters of 9.31 nm (1.5×10^{10}) and 10.8 nm (1.49×10^{10}).

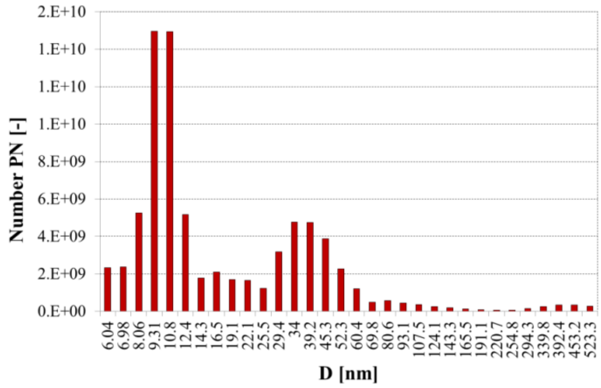


Fig. 12. Particle number and size distribution

Based on the registered movement parameters of the research vehicle during the tests, the characteristics of time density and emission intensity of pollutants as a function of speed and acceleration (v–a) were determined. The distribution of movement parameters was presented in one-sided closed intervals. Figure 13a shows the time shares in the speed and acceleration intervals during the real-world operation of the tested rail vehicle. The highest values –39.7% – were observed in the speed range of (25 m/s; 30 m/s>, both during steady-speed travel ($a = 0$ m/s²) and during minor accelerations and braking of the vehicle. This is due to the vehicle operating at its maximum allowed speed on certain sections of the route during the measurement trip. The analysis also accounted for the idle time at railway stations during operation, which accounted for a total share of 14.6%. The highest CO_2 emission intensity (Fig. 13b) was observed for acceleration values in the range (0 m/s²; 3.0 m/s²>, regardless of the vehicle speed. This emission is closely related to fuel consumption, indicating that during rapid accelerations, the vehicle consumed significantly more fuel compared to steady-speed travel or braking. The combustion process, and thus the fuel injection aspect, plays a critical role in the emission of harmful exhaust compounds, as highlighted in works [4, 19]. A similar emission intensity distribution was also observed for CO (Fig. 13c), with the highest values recorded in the acceleration range (0 m/s²; 3 m/s²> across the entire speed range. This is especially noticeable during rapid accelerations of the vehicle (1.5 m/s²; 3 m/s²> at low speeds (0 m/s; 10 m/s>, i.e., during the vehicle's acceleration from the railway station. During aggressive accelerations, a larger fuel dose is needed, and due to insufficient air intake and improper air-fuel mixture, incomplete combustion occurs, leading to increased carbon monoxide emissions. For nitrogen oxides (NO_x), the highest emission intensity was recorded in speed ranges corresponding to high vehicle speeds

(20 m/s; 25 m/s> and low speeds (0 m/s; 5 m/s> during vehicle acceleration (0 m/s^2; 1.5 m/s^2> (Fig. 13d). The distribution of NO_x is primarily associated with the temperature and pressure within the engine combustion chamber. In the case of emissions at medium speed ranges (5 m/s; 20 m/s>, the emission intensity distributions are similar, which is the result of using an exhaust gas recirculation (EGR) system in the tested vehicle. The highest intensity of hydrocarbon emissions was recorded in a single measurement window defined by the speed range (0 m/s; 5 m/s> and acceleration range (1.5 m/s^2; 3 m/s^2> (Fig. 13e). High emission intensities were noted across the entire acceleration range (0 m/s^2; 3 m/s^2> and throughout the speed range (0 m/s; 30 m/s>. The primary factor influencing hydrocarbon emissions is incomplete fuel combustion, which occurs during vehicle acceleration, similar to the case with carbon monoxide emissions.

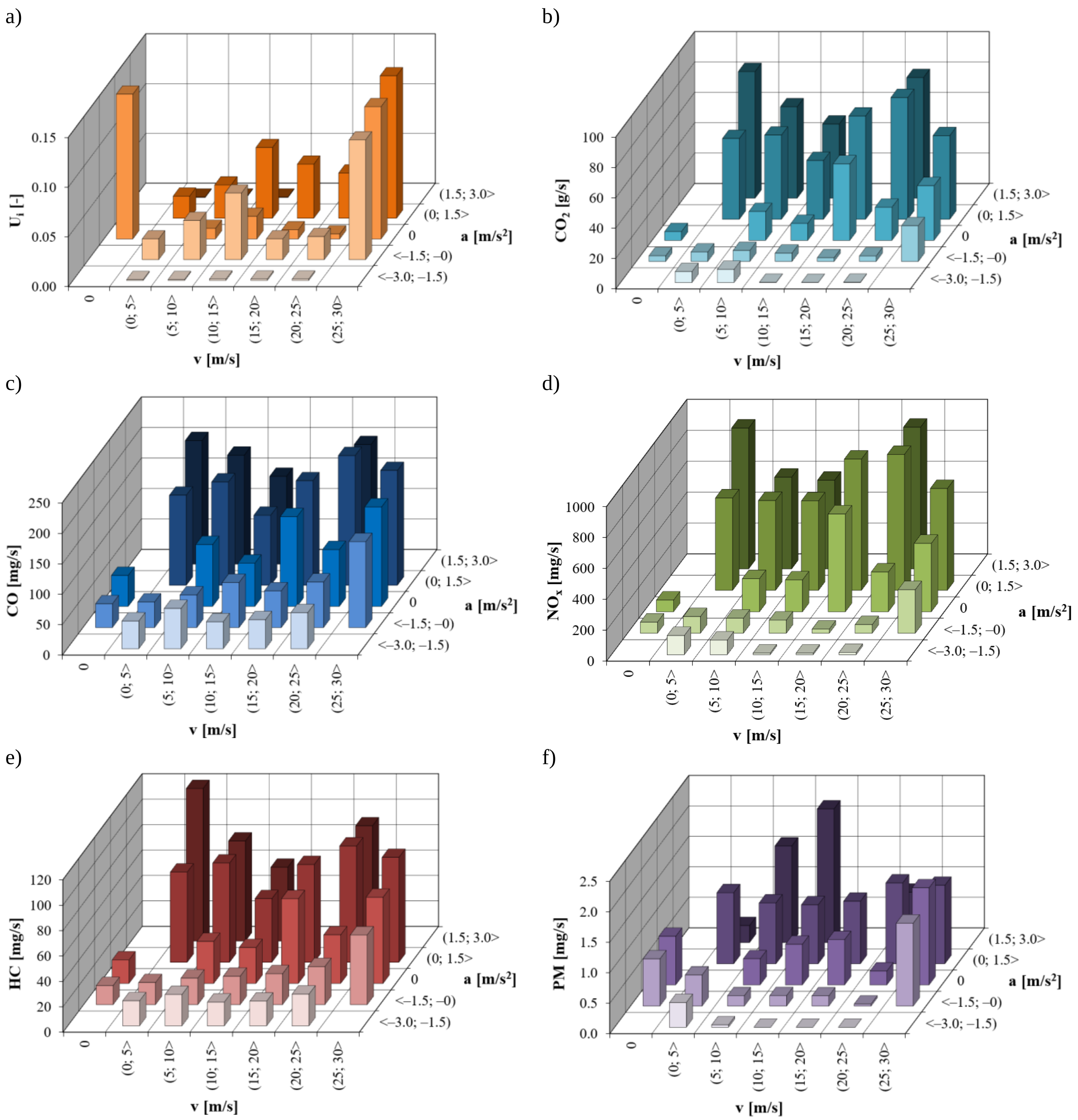


Fig. 13. Emission intensity of harmful exhaust compounds as a function of speed and acceleration: a) operating timeshares, b) CO_2, c) CO, d) NO_x, e) HC, f) PM

For particulate matter (PM), the highest emission intensity was recorded in high acceleration intervals (1.5 m/s²; 3 m/s²> and in the vehicle speed range (5 m/s; 15 m/s>) (Fig. 13f). A significant increase was also observed in the range corresponding to high vehicle speeds (25 m/s; 30 m/s> during braking, acceleration, and steady-speed travel. PM emissions are linked to incomplete combustion during heavy engine operation. During rapid acceleration or high-speed travel, fuel undergoes thermal breakdown during injection into hot flame zones, especially under heavy loads, where there is insufficient air for combustion.

5. Conclusions

This article presents pollution measurements of a rail bus under real operating conditions during shunting operations and regular railway route travel. Throughout the study, emissions of gaseous compounds and particulate matter were measured in terms of their mass, count, and size distribution using PEMS-type measuring equipment. The collected data was divided into stages that included an analysis of the intensity of second-by-second emission rates, road emissions, and the emission rates of harmful exhaust compounds as a function of speed and acceleration (v–a).

For tests conducted during shunting operations, the emissions of harmful exhaust compounds were relatively evenly distributed across the full range of vehicle motion parameters. This is due to the nature of shunting operations, which are characterized by minor changes in speed and acceleration. As a result, there were no significant fluctuations in the injected fuel dose, nor phenomena like incomplete combustion or insufficient mixing of the fuel-air mixture, which often lead to increased emissions. The high values of road emissions observed were primarily due to the relatively short distance travelled by the rail vehicle. This suggests that measurements of this type should be evaluated in terms of work performed, as recommended by standards (specific emissions).

Testing under real operating conditions provided knowledge of the actual operating parameters of the test object. This is valuable knowledge for adapting non-road vehicle test methodologies in terms of subsequent type-approval standards. Activities are being carried out all over the world on such issues. As many research centres have shown, qualitative and quantitative emission measurements in type-approval tests and actual operation differ – actual operation adversely affects PM and NO_x emissions in particular.

However, the studies conducted on the Krzyż–Trzcianka route indicated that the emissions of all harmful exhaust compounds were affected by the vehicle's acceleration. Acceleration of the vehicle is associated with transient operating conditions in drive engines – crankshaft speed and load change rapidly. Carbon monoxide increased during rapid accelerations as a product of incomplete combustion in the combustion chamber under limited air conditions. When the vehicle accelerates, a higher fuel dose is needed, and due to insufficient air and inadequate fuel-air mixing, incomplete combustion occurs, resulting in increased CO emissions. Nitrogen oxides (NO_x) are formed due to the oxidation of nitrogen present in the fuel-air mixture within the combustion chamber at high temperatures. During acceleration from a station, when the engine is under greater load and at high speeds, the combustion chamber experiences higher pressures, leading to increased NO_x emissions. In the case of hydrocarbons, the primary factor contributing to their emissions is incomplete fuel combustion, which, like CO emissions, occurs during vehicle acceleration. Insufficient mixing of the fuel-air mixture and flame quenching on cylinder walls lead to incomplete combustion under increased engine load during acceleration. Particulate matter (PM) emissions are similarly linked to incomplete combustion under increased engine load. During rapid acceleration and high-speed travel, fuel undergoes thermal decomposition during injection into hot flame-affected zones, particularly at high loads when there is insufficient air for combustion.

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Nomenclature

CO	carbon monoxide	NO_x	nitrogen oxides
CO_2	carbon dioxide	PEMS	portable emission measurement system
DPF	diesel particulate filter	PM	particulate matter
EGR	exhaust gas recirculation	PN	particulate number
HC	hydrocarbons	RTE	real train emissions
NNRM	non-road mobile machinery	SCR	selective catalytic reduction

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