

Article

Investigations of Exhaust Emissions from Rail Machinery during Track Maintenance Operations

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Abstract: The paper presents the investigations of exhaust emissions under actual operation of two rail vehicles: a track geometry vehicle and a clearance vehicle. The environmental assessment of this type of objects is difficult due to the necessity of adapting the measurement equipment and meeting the safety requirements during the tests (particularly regarding the distance from the overhead electrical lines). The authors have proposed and developed a unique research methodology, based on which a detailed exhaust emissions analysis (CO, HC, NO_x, and PM) was carried out. The complex assessment included the unit and on-track exhaust emissions. In the analyses, the authors also included the operating conditions of the powertrains of the tested machinery. The obtained environmental indexes were referred to the homologation standards, according to which the vehicles were approved for operation. Due to the nature of operation of the tested vehicles, the authors carried out a comprehensive environmental assessment in the daily and annual approach as well as in the aspect of their operation as combined vehicles, which is a novel approach to the assessment of the environmental performance of this type of objects.

Keywords: exhaust emissions; rail machinery; combustion engines; real driving emission; PEMS



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1. Introduction

Transport is one of the main sources of environment pollution on a global scale, the effect of which is the climate change caused by the greenhouse gases (GHG). It also has a local impact exhibited by the occurrence of smog in city agglomerations. Most of the scientists now agree that climate change is caused by greenhouse effect (GHE) that is largely influenced by the emission of CO₂ [1–3]. According to the numerous WHO reports, the pollution level in city agglomerations is high in both developed and developing countries. According to WHO, 90% of the city population worldwide breathes air that exceeds the emission limits and the number of fatalities caused by air pollution is also high [4]. Today, transport is one of the main consumers of energy with its share amounting to almost 30% [5]. The research by European Environmental Agency indicates that transport generates 20% of the entire world emission of CO₂, almost 10% PM₁₀ and 39% NO_x [6,7]. It is forecasted that by 2050 the number of vehicles worldwide will double [8]. The exhaust gas from diesel engines that is generated by, inter alia, locomotives and other rail vehicles has been classified by WHO as carcinogenic [4]. All these factors substantiate the need to continue research and development of low emission transport in terms of new systems and vehicles. Today, public transport (as opposed to individual) is perceived as one of the more promising solutions. Numerous investigations indicate that public rail transport is more advantageous environmentally and economically [9–12]. However, one should mind the negative impact of railroad transport on the environment. Majority of these works pertains

to the exhaust emissions referred to the carriage of people and goods without including the cost related to the maintenance of the railroad infrastructure. The reduction of the exhaust emissions from transport is realized through a variety of methods, not only through the organization of transport but also the advancement of technologies such as hybridization, aftertreatment systems [13], or alternative fuels [14–16].

An important aspect in the reduction of the exhaust emissions is the measurement methodology. The engines of locomotives and other rail vehicles are tested in laboratories during the process of homologation. The tests are performed under conditions simulating actual operation. In recent years RDE (Real Driving Emissions) tests on the fuel consumption and exhaust emissions have become increasingly significant. On 1 September 2017 the European Commission included these tests to the homologation procedure for light duty vehicles (LDV). RDE tests create new exploratory and development possibilities regarding vehicle powertrains. Investigations performed during actual operation allow a full exploration of the relations among the driving parameters and the exhaust emissions that laboratory conditions cannot assure. In laboratory conditions it is impossible to reproduce all the operating parameters. Literature widely describes the problem of non-representativeness of laboratory tests carried out on specially prepared test stands [17–23]. The Stage V regulation includes a requirement for engine Original Equipment Manufacturers to test engines installed in machines over their normal operating duty cycles. This will be done by the use of a PEMS. So far, however, no limit values have been introduced for harmful exhaust gas compounds.

Numerous publications describe the exhaust emission and fuel consumption tests performed on LDV [24–27], HDV [19] and non-road [28–30] vehicles while there is a significant deficit of publications discussing investigations performed on rail vehicles under actual conditions of operation. This mainly results from the homologation legislation. These regulations do not prescribe measurements under actual operation. Still, attempts to perform tests on rail vehicles (mainly locomotives) under actual operation have been made and described but only in a limited number of papers. Attempts to measure the exhaust emissions were already made several years ago. The methods of obtaining the emissions were based on the calculations made from the data received from the railroad operators and emission standards [31]. Another method was the use of measurement data of the concentrations of the emission components obtained from mobile laboratories used on passing rail vehicles [32–35]. However, research conducted in this way provided only estimate values of the exhaust emissions. Full exploratory potential appeared with the introduction of the PEMS equipment (Portable Emissions Measurement System). One can still see a deficit in literature describing the direct measurements performed on rail vehicles, especially track maintenance vehicles, in their actual operation, hence the observation that this type of research is still in its initial phase of development. There are a few publications discussing the measurements with the use of PEMS equipment for locomotives and passenger trains, as presented in the article. However, it should be emphasized that there are no publications describing the use of PEMS equipment for emission measurements for machines performing track works. This is also evidenced by the lack of developed measurement procedures. There are no developed, generally accepted, and used procedures for measuring emissions of harmful exhaust gas compounds with the use of PEMS equipment for railway vehicles. Currently, such procedures only exist for road vehicles. The application of the PEMS equipment and the development of the research methodology have been described in [36–38]. Initially, the PEMS equipment was used in dynamometer measurements and stationary rail yard measurements for different settings (notch) [38–40]. The cited publications are to be treated as an introduction and preparation to the PEMS investigations under actual operation of track maintenance vehicles. When analyzing the publications describing the investigations of exhaust emissions one can observe a significant diversity in terms of the test routes, applied equipment, and obviously, results. This is most likely the effect of lack of standardization of the research procedures for the discussed group of vehicles. It is, therefore, fully justified to publish the results

of such investigations that are a contribution to the development of the said research procedures. The most popular research objects in testing under actual operating conditions are locomotive engines—Prime Mover Engine [40–43]. Kim et al. [43] investigated the exhaust emissions from a locomotive and compared the obtained results with the applicable limits. The analysis also covered the relations between the engine operating parameters and the exhaust emissions. The per-passenger-km emissions were analyzed in [42]. They attempted similar investigations with road vehicles and the obtained results once more confirmed the positive environmental impact of the rail transport compared to individual one. Graver et al. [41] investigated the benefits of the application of biofuels in locomotives in actual operating conditions. Graver and Frey [41] described the exhaust emission results from six locomotives of different emission standards (Tier 0+ and Tier 1+). The results were also compared with the emissions from road vehicles.

The above-mentioned research examples related to the vehicles are practically all the existing ones when it comes to the emission testing of rail vehicles with the PEMS equipment. These few examples do not cover all the problems related to the exhaust emissions and measurement methods when it comes to rail vehicles. As mentioned above, majority of the measurements pertains to locomotives used in the carriage of passengers and cargo. There are no publications describing the measurements performed on other rail vehicles under actual conditions of operation, which is why any new experience and observations are invaluable in this matter. We should aim at introducing the RDE tests in the homologation procedures of rail vehicles in the future, similarly to LDV and HDV ones. Such attempts should also be naturally assumed. In this paper, the authors describe the investigations of exhaust emissions from special rail vehicles (track maintenance machinery) performed under actual operating conditions. The paper focuses on this group of vehicles because of their regular periodic use in track maintenance in order to assure its good technical condition and safe operation. Recently, in Poland rail infrastructure modernization works have been underway. The track works, whose total length amounts to 19,000 km are serviced by machines and rail vehicles. In Poland the population of this type of machinery amounts to over 1600 special vehicles. According to the data of the Polish Rail Transport Office, the structure of traction vehicles in relation to locomotives in the country is as follows: electric passenger locomotives—313, diesel passenger locomotives—108, electric freight locomotives—1509, diesel freight locomotives—2146 [44]. The dates of manufacture of these machines reach 1961, i.e., decades before emission limits were introduced [45]. It should be stressed that the promotion of mass transport in Europe and worldwide owing to its ecological benefits is tightly related with the intensification of the track use, which automatically forces an increasing use of maintenance machinery and equipment.

2. Materials and Methods

The authors performed the emission tests of: CO₂, CO, HC, NO_x, and PM [46–50] for two rail vehicles. The first one is a machine used to monitor the tracks, inspect the rails, test their geometry, and measure their profiles. The other vehicle is a clearance vehicle used to check the clearances around the track with a laser profilometer or a photogrammetric system. The maintenance of the rail track in the state of full operativeness requires performing ongoing maintenance, planning and carrying out repairs. The basic technical specifications of the tested vehicles and their engines have been presented in Table 1 and their view in Figure 1.

Table 1. Technical specifications of the tested objects.

Parameter	Track Geometry Vehicle	Clearance Vehicle
Type of engine	diesel	diesel
Number of cylinders and valves per cylinder	12 4	6 2
Cylinder capacity	32.1 dm ³	7.15 dm ³
Diameter per stroke	144 mm × 162 mm	108 mm × 130 mm
Maximum power at engine speed	950 kW 1800 rpm	141 kW 2300 rpm
Maximum torque at engine speed	5345 Nm 1350 rpm	702 Nm 1400 rpm
Emission standard	Stage IIIB	Stage II
Vehicle weight	40 t	36.1 t
Maximum speed	140 km/h	90 km/h
Aspiration	turbocharger	turbocharger
Injection system	direct	direct
Injector type	Electronic Unit Injector (EUI)	Unit Injector (UI)

**Figure 1.** Tested objects: I—track geometry vehicle, II—clearance vehicle.

For the measurements, the authors used the PEMS equipment [51–56] designed to perform measurements under actual conditions of operations (AxionR/S+). The equipment can measure the gaseous exhaust components: CO₂, CO, NO_x, HC and the mass emission of particulate matter (PM). In order to determine the emission of CO₂, CO, and HC a non-dispersive infrared sensor (NDIR) is used and to determine the emission of NO_x an electrochemical analyzer is applied. For the measurement of PM, the Laser Scatter method is applied. Table 2 presents the basic technical specifications of the AxionR/S+ measurement equipment.

Table 2. Technical specifications of the PEMS Axion R/S+ equipment.

Exhaust Component	Measurement Range	Relative Measurement Accuracy	Distribution	Method of Measurement
HC	0–4000 ppm	±3%	1 ppm	NDIR
CO	0–10%	±3%	0.01 vol.%	NDIR
CO ₂	0–16%	±4%	0.01 vol.%	NDIR
NO	0–4000 ppm	±3%	1 ppm	E-chem
O ₂	0–25%	±3%	0.01 vol.%	E-chem
PM	0–300 mg/m ³	± 2%	0.01 mg/m ³	Laser Scatter

The measurements of the exhaust emissions were carried out when the machines were in operation. The works were carried out on two portions of the track of different lengths (Figure 2). Table 3 presents the parameters during the tests on the rail tracks. The tests were carried out on various routes due to the possibility of conducting research works and

making the facilities available by owners/operators. Obtaining permits for this type of research is difficult and depends on many factors. Both of the presented rail vehicles are used on selected test routes.

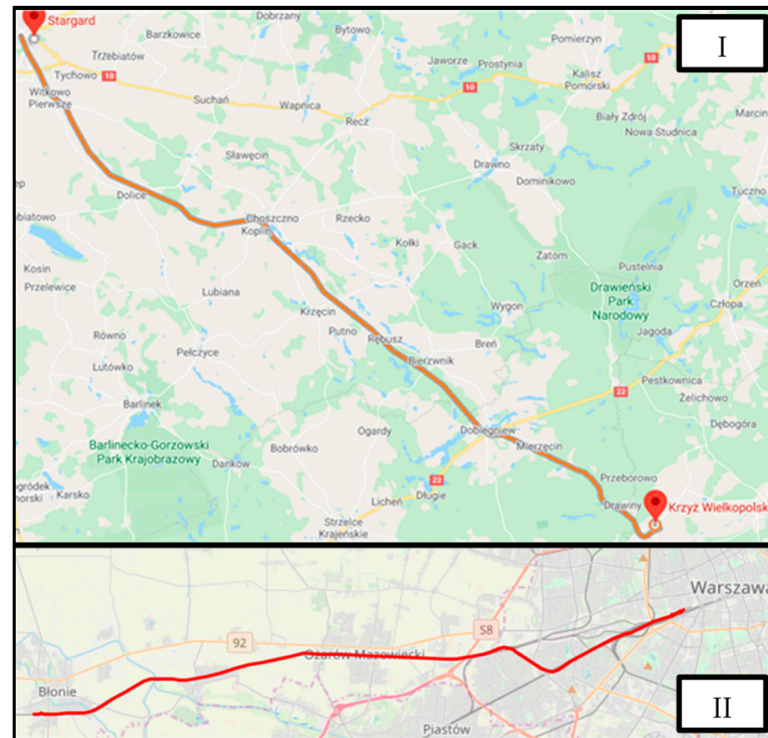


Figure 2. Test routes, I—track geometry vehicle, II—clearance vehicle.

Table 3. Operating parameters during the tests.

Parameter	Diagnostic Vehicle	Track Geometry Vehicle
Distance [km]	74.2	37
Maximum speed [km/h]	126.8	68.4
Average speed [km/h]	65.9	45.7

3. Analysis of the Results

The aim of the performed tests is to present the total emission and environmental load during the actual operation of the research facilities. The instantaneous emission rate is correlated with the vehicle speed that, in turn, is correlated with the engine load. All the instantaneous emission rate curves of all individual exhaust components were characterized by the highest values during the initial stages of the test and at the moments of deceleration (Figure 3).

The distributions of the emission rate are tightly related and inversely proportional to the curves of the vehicle speed. Vehicle I had higher fuel consumption (38,954 g) and generated higher emissions—CO₂ (123,219 g), CO (130 g), HC (19.4 g), NO_x (734 g) and had a lower value of PM (4.25 g). In relation to the covered distance, this vehicle had a better environmental performance. Vehicle II, on average had 25% lower values of the accumulated fuel consumption (28,140 g) and accumulated exhaust emissions (CO₂—89,000 g, CO—122.4 g, HC—15.5 g, NO_x—524 g), which resulted from the 50% shorter test distance. The vehicle also had a 65% higher emission of PM (7.34 g). The vehicle had worse environmental performance. The analysis of the results did not include information about the condition of the engine during the measurements, because it was hot. This means that the temperature of the coolant was stabilized—variable start was not taken into account.

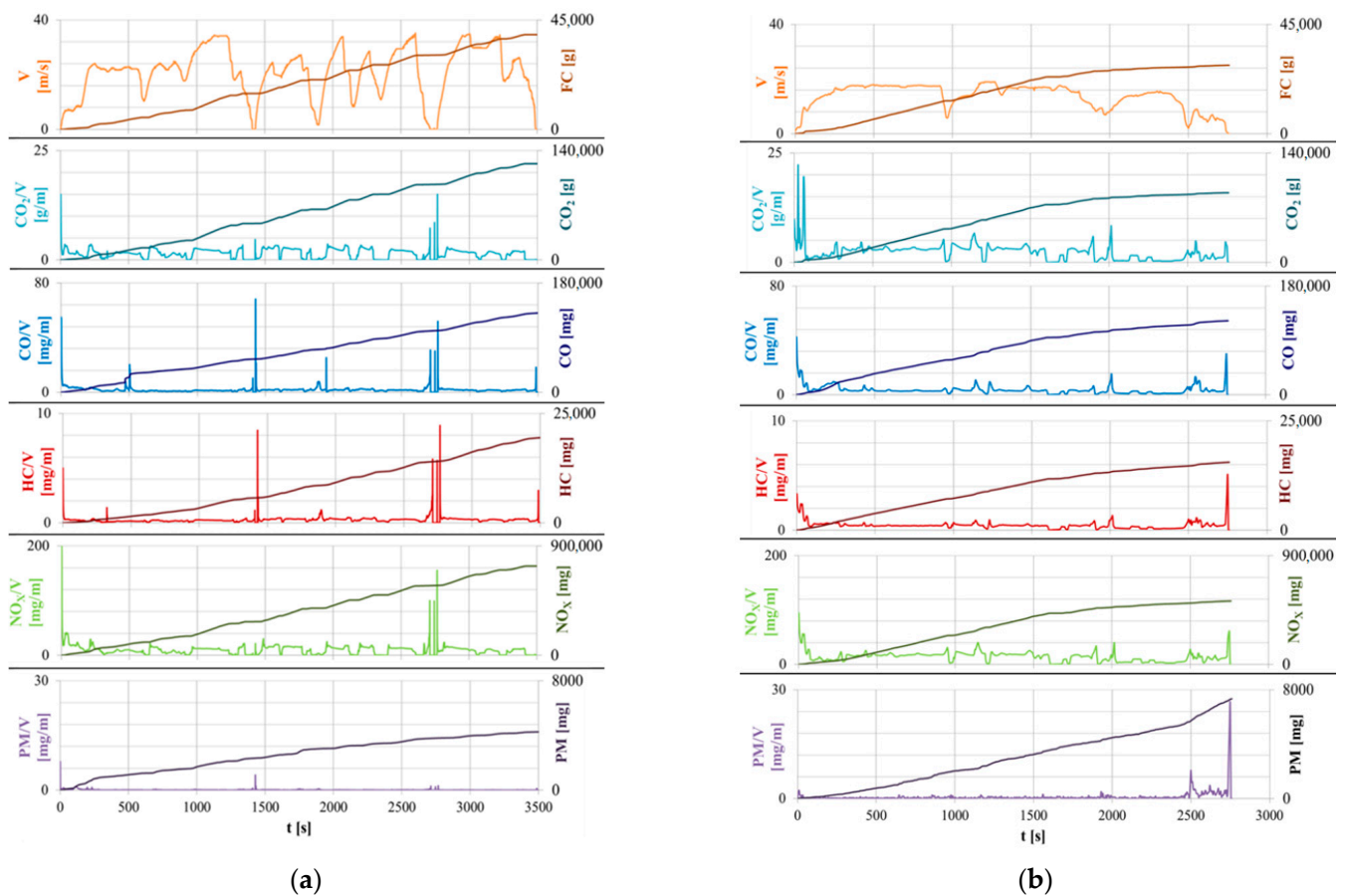


Figure 3. Tracing of the vehicle speed and the instantaneous on-track emission rate under actual conditions of operation: (a) track geometry vehicle, (b) clearance vehicle.

The analysis of the test results was supplemented with the analysis of the unit exhaust emissions (Figure 4a). The engines work was calculated on the basis of parameters such as rotational speed and load. In the clearance vehicle, they were recorded using Axion R/S + measuring equipment with a number of appropriate sensors, while in the case of the second research object—track geometry vehicle, on-board diagnostics (OBD) system was used, from which the desired engine operating parameters were read.

The unit emission of CO during the test of the clearance vehicle was higher than that of the track geometry vehicle and amounted to 1.59 g/kWh (twice as high). It is noteworthy that, for both vehicles, the emission of CO was lower than the admissible one (Stage II and Stage IIIB). Moreover, the emission of hydrocarbons was higher for the clearance vehicle. It amounted to 0.20 g/kWh and for the track geometry vehicle: 0.12 g/kWh. Similarly to the above-described on-track emission, the difference is also smaller compared to the emission of CO. The emission of NO_x for the tested vehicles was 6.82 g/kWh and 4.49 g/kWh and in both cases these values are higher than the maximum admissible ones. Besides, one should note that for the diagnostic machine, the emission of NO_x exceeded over two times in relation to the Stage IIIB limit. For the diagnostic machine, also the emission of PM under actual condition of operation is higher than the Stage IIIB limit. It was three times lower than the PM emission of the second vehicle, but for this engine the Stage II limit applies. Based on the obtained results, it was confirmed that the engine of the diagnostic machine (newer generation Stage IIIB engine) under actual operating conditions has a higher emission of both NO_x and PM. This observation is somewhat disturbing. The emission of NO_x and PM are the two key exhaust components when it comes to diesel engines and reducing their emission is the most difficult task. Obviously, formulating

unambiguous conclusions based on two tested objects is clearly unfounded but spurs on to continue research in this matter.

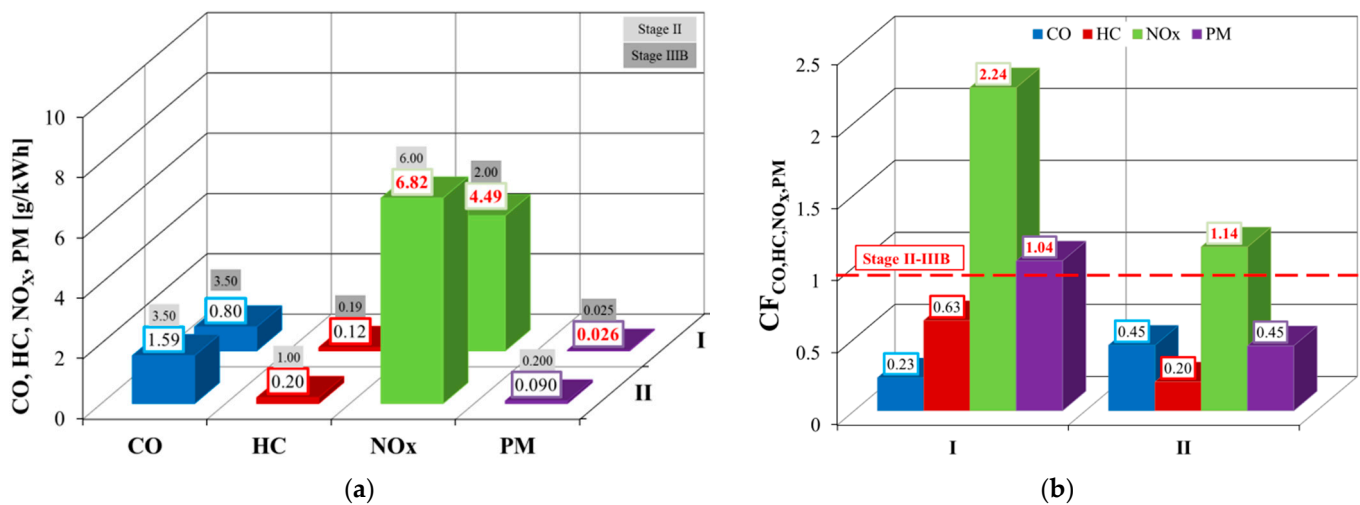


Figure 4. (a) Unit emissions of the investigated vehicles, (b) coefficients conformity factor for regulated emissions, I—track geometry vehicle, II—clearance vehicle.

The differences between the actual operating results and the limits of the exhaust emission standards are most likely results from the different engine-operating parameters (actual operation and in laboratory tests), which confirms the non-representativeness of these tests. This conclusion is in line with the conclusions of other researchers for other categories of vehicles and engine. Besides, this conclusion should be treated as a supplement to the current state-of-knowledge as, to date, track maintenance machines have not been investigated under their actual operating conditions. Scientific literature does not indicate such cases.

In order to complete the emission analysis (Figure 4b), the obtained unit emission factors of pollutants were compared to the type-approval standards in which the tested vehicles were allowed to operate. For this they used the CF (conformity factor) [56–60] from the entire test, according to the formula:

$$CF_j = \frac{E_{RDE,j}}{E_{norm,j}} \quad (1)$$

where:

j—the harmful compound for which the conformity factor was specified,
 $E_{RDE,j}$ —road emission obtained under real driving conditions ([g/kWh])
 $E_{norm,j}$ —value of emission limit in the applicable emission standard ([g/kWh])

The developed CF coefficients were calculated for individual research objects in terms of their approval standards, respectively: object I—Stage IIIB; object II—Stage II. For the older type approval standard, the emission limits for individual toxic compounds were much higher. As demonstrated on the basis of the analysis carried out using CF, the emission of pollutants exceeded for the first research object in the scope of NO_x and PM (by 24% and 4%, respectively). For the second research object, the NO_x emission was exceeded only by 14%. However, it should be noted that the conditions of approval tests (engine tests) were different from the conditions of actual operation.

Further investigations covered the analysis of the on-track emissions in relation to the annual distance covered by the vehicle (Figure 5). Assuming that a diagnostic vehicle can inspect 400 km of tracks per day, it translates into 40,000 km per annum [61].

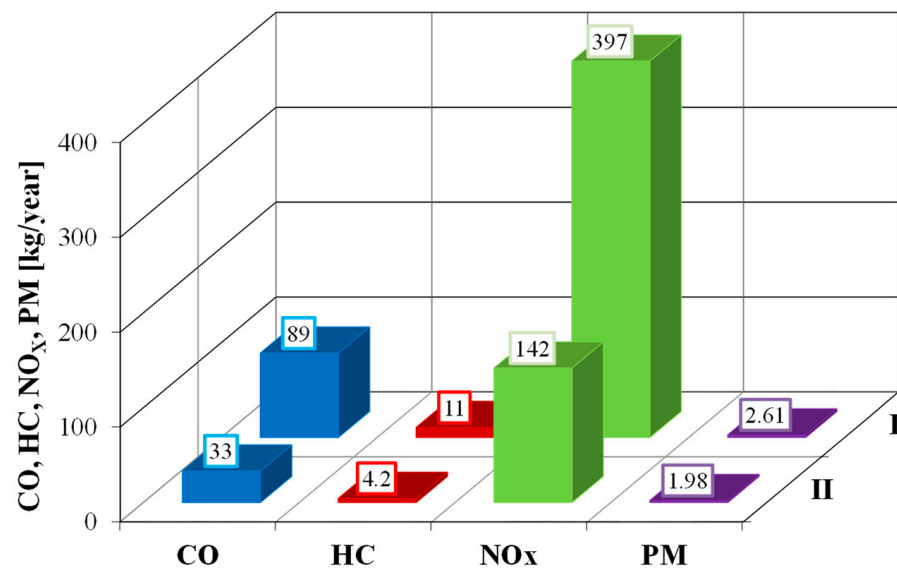


Figure 5. Annual on-track exhaust emissions, I—Track geometry vehicle, II—Clearance vehicle.

The clearance vehicle, given its lower maximum speed and operating characteristics, covers its annual distance that is four times shorter (10,000 km), which is why its annual emissions are lower. Based on the performed investigations, it was observed that the highest emission is the emission of NO_x and amounts to 397 kg per annum for the diagnostic vehicle. The second vehicle has an almost three times lower emission of this component. The annual emission of CO is 89 kg per annum for the diagnostic vehicle and 33 kg per annum for the clearance vehicle. The emission of HC is 11 kg per annum and 4.2 kg per annum for the two vehicles respectively and the emission of PM is 1.98 kg per annum and 2.61 kg per annum for the two vehicles respectively.

Based on the measurements and recorded test drive parameters of the investigated vehicles, the on-track exhaust emissions were determined (Figure 6a). For the on-track emissions, the greatest differences (order of magnitude) were observed for PM.

The lower emission of this component had the clearance vehicle, which is most likely owing to the higher emission category of this vehicle (Euro IV). This engine was fitted with a diesel particulate filter. A significant difference (almost four times) was recorded for the emission of CO, but in this case it was lower for the diagnostic vehicle meeting the Euro III emission standard. Analogically, also the emission of HC was higher for this engine but the difference was not as high and amounted to approx. 20%. Both engines were fitted with oxidation catalysts and the higher emission of CO and HC for the clearance vehicle probably results from the operating conditions of the engines and the operation of the catalytic converters. The on-track emissions obtained in combined operation were referred to predefined work cycles of 100 km for each of the vehicles (Figure 6b). This reference value was adopted because it corresponds on average to one day operation of the described research objects on railway lines. The obtained values were—554 g/cycle carbon monoxide, 68 g/cycle hydrocarbons, 2408 g/cycle nitrogen oxides, and 26.4 g/cycle particulate matter. The clearance vehicle, on average, generated 64% of the relative emission of individual exhaust components. The greatest difference was obtained for particulate matter, for which vehicle II generated 75.2% (19.8 g/cycle) of the accumulated PM value for the entire measurement cycle. For the outstanding exhaust components these values were—CO—60% (331 g/cycle), HC—62% (42 g/cycle), and NO_x—58.8% (1417 g/cycle).

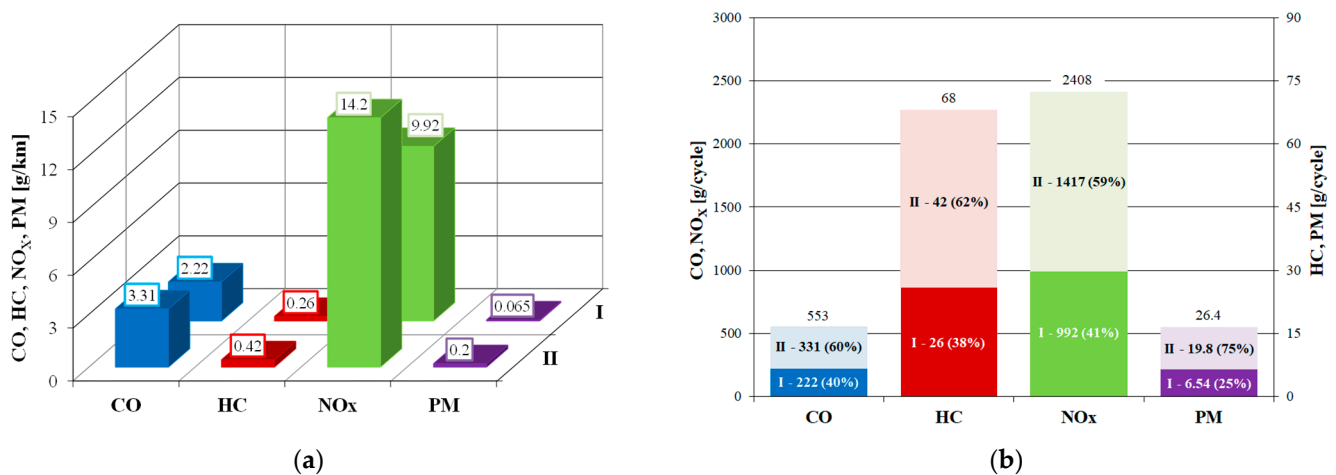


Figure 6. Exhaust emissions: (a) on-track emissions (b) emissions per work cycle, I—track geometry vehicle, II—clearance vehicle.

4. Conclusions

The conclusion that arises from the results of the investigations are the significant divergences in the emissions of individual exhaust components compared to the admissible values prescribed in Stage II and IIB of the investigated engines [17,19–23,43]. These results were confirmed by the determined CF coefficient, which showed the relative differences through its structure. It is noteworthy that the newer generation engine under actual operating conditions significantly exceeded the emission values of NO_x and PM compared to the homologation limits. Such a clear trend was not observed for the older generation engine meeting the Stage II standard. The engine of this vehicle was in a good technical condition, and its emission results were compared to the standard, which has significantly lower limits than were required for object I, which takes into account the conformity factor. However, as regards the above, for the conclusions to become unambiguous, one needs to reinforce them with further research of engines of different emission categories, including the latest ones.

The described investigations and results substantiate the necessity of further advancement of the methods of testing rail vehicles and machinery under actual conditions of operation using the PEMS equipment. The current conviction that this type of investigations is the best method of determination of the exhaust emissions is commonplace and appears to be indisputable. Scientists should aim at making this method a generally accepted one for the discussed group of vehicles, similarly to the road vehicles. In the future, such tests should be included in the homologation procedures of rail vehicles. When analyzing the current achievements in this matter, one can state that the said methods are still in their initial phase of development, which is confirmed by the limited number of relevant publications.

When referring to the obtained results, one can state that all the distributions of the emission rate curves are tightly related and inversely proportional to the curves of the vehicle speed. The presented characteristics of unit emissions indicate that a lower emission of all exhaust components was obtained for the diagnostic vehicle. Vehicle I was fitted with a DOC catalytic converter (Diesel Oxidation Catalyst) that influenced the obtained emission of CO and HC. When testing vehicle II, a higher unit emission of NO_x was obtained on the level of 6.82 g/kWh. The vehicles operated at a higher average load, which resulted in an increased temperature and pressure inside the cylinder and directly influenced the emission of nitrogen oxides. In relation to the unit emission of particulate matter, vehicle I was fitted with a diesel particulate filter (DPF) and had the emission value of 0.03 g/kWh. For vehicle II, the PM value was 0.09 g/kWh. The deterioration of the PM emission values

is influenced by the engine variable operating conditions, which leads to an increase in the local share of incomplete and non-full combustion inside the engine cylinders.

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