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Assessment of the Environmental Costs of Rail Buses in Poland Based on Research in Real Operating Conditions

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ABSTRACT

The article analyzes the environmental costs of Diesel Multiple Unit and Diesel Railcars operated in Poland. It consisted in determining the annual cost of gases and particulate matter emitted into the ambient air by the analyzed rolling stock. For this purpose, tests were carried out on the emission of harmful exhaust gases from a railbus equipped with the most commonly used drive system. The vehicle had two identical compression ignition engines meeting the Stage IIIB standard with a displacement of 12.8 dm^3. Maximum power of the engine was 390 kW at a rotational speed of 1800 rpm and a maximum torque of 2200 Nm at 1300 rpm. In order to measure harmful exhaust compounds, tests were carried out in real operating conditions using Portable Emission Measurement System (PEMS) equipment. The tests carried out in track conditions showed that the rail vehicle did not meet the approval limits for nitrogen oxides (real value – 2.43 g/kWh, emission standard – 2.0 g/kWh). However, it should be remembered that the limit values are established in stationary tests and not in actual operating conditions. In the next stage, the annual emissions of rail buses operating in Poland were estimated. For this purpose, data from the Office of Rail Transport on the number of vehicles registered in the country and the average distance traveled by the vehicles were used. The data obtained indicate that the vast majority (over 98%) of environmental costs are costs related to carbon dioxide emitted into the atmosphere.

Keywords: exhaust emissions, rail buses, RDE, PEMS, environmental costs.

INTRODUCTION

Environmental protection standards in force in the European Union (EU) are among the strictest in the world. Therefore, the actions taken by the EU and national governments have been clearly defined to shape European environmental policy in accordance with them. Therefore, numerous research programs and appropriate legislation and financing are being introduced. The main objectives include, among others, protecting, preserving and improving the EU's natural capital, transforming the EU economy into a resource-efficient, green and competitive low-carbon economy, and protecting against environmental pressures and threats to the health and well-being of its population.

Due to the significant impact of transport on air pollution, newer regulations are being introduced to reduce emissions of harmful compounds. The main goal of the EU is to introduce CO_2 zero emission regulations for vehicles by 2035. Intermediate emission reduction targets by 2030. was set at 55% for passenger cars and 50% for delivery vehicles [1]. The final form of the regulations was approved by the EU Parliament in February 2023 [2]. The aim of all these actions is to achieve a 90% reduction in greenhouse gases (GHG) from transport by 2050 compared to 1990. This will support the achievement of climate neutrality as part of the European Green Deal. However, according to the European Environment Agency transport is the only sector where GHG emissions have increased over the past three decades, by 33.5% between

1990 and 2019. Significant reductions in CO_2 emissions will not be easy as the rate of reduction has slowed [3]. Currently, forecasts indicate that the decline in emissions from the transport sector by 2050 will be only 22% [3], which is significantly different from the assumptions [1].

One of the actions to protect the environment in Poland was the introduction of the Act on "Environmental Protection Law" [4], which defined the principles of environmental protection and the conditions for the use of its resources, taking into account the requirements of sustainable development. The document refers primarily to the principles of determining the conditions for the protection of environmental resources, the conditions for introducing substances or energy into the environment, as well as the costs of using the environment. One of the sections of [4] concerns air protection, which consists in ensuring its best possible quality, in particular by:

- maintaining the levels of substances in the air below or at least at the permitted levels,
- reducing the levels of substances in the air at least to the permitted levels where they are not met,
- reducing and maintaining the levels of substances in the air below target levels or long-term objective levels or at least at these levels.

The regulation established the following levels:

- permissible levels,
- target levels,
- long-term goals,
- alarm levels (exceeding which even for a short time may pose a threat to human health),
- information levels for certain substances in the air.

Additionally, the exposure concentration level and the conditions under which the level of the substance is determined, such as temperature and pressure, were also determined, the values of which are important in the combustion process, which is confirmed by the works [5, 6].

Research on exhaust emissions from means of transport, especially during real operation, is relatively advanced topic. Such studies have been carried out on many types of vehicles such as passenger cars [7], heavy-duty vehicles [8], agricultural vehicles [9], construction machinery [10], ships [11], both using PEMS [12] and remote sensing [13] devices. However, in the case of railways, this is still a relatively poorly explored topic. The reason is primarily the costs and railway regulations, which make it very difficult to carry out such studies. For this reason, the number of publications in the area of exhaust emissions from rail vehicles is significantly smaller than from other, more accessible means of transport.

However, there are studies on exhaust emissions from rail vehicles using PEMS. In the work [14], an analysis of exhaust emissions from passenger diesel locomotives and railcars running on regular lines in the Czech Republic was carried out. In the works [15, 16], emission hot-spots were identified based on real world emission studies and strategies were developed to reduce fuel use and emissions for passenger rail. In the work [17], GHG emission factors from diesel-electric locomotives were estimated depending on operating conditions.

In the case of estimating environmental costs resulting from real exhaust emissions from means of transport, based on the conducted literature analysis, the situation is even less explored. There are studies on similar topics to those in this paper, but they mainly concern road and aircraft vehicles [18,19]. In the case of railway, they concern mainly CO_2 emissions and environmental costs, i.e. life cycle cost of railway lines [20]. The most thematically similar article was [21] which discussed the environmental costs resulting from bus emissions during real operation. However, there is lack of studies that estimate the environmental costs of emissions from rail vehicles based on measurements of exhaust emissions during real operation.

CHARACTERISTICS OF PASSENGER TRACTION ROLLING STOCK IN POLAND

Rail passenger transport is carried out using three types of traction vehicles: Multiple Units (MU), locomotives and railcars. Depending on the type of drive, these vehicles can be divided in Poland into electric, diesel and, from 2020, dual-drive (diesel and electric drive). The largest group of traction passenger railway vehicles in Poland in the years 2008–2022 are definitely Electric Multiple Units (EMU) (Figure 1) [22]. In 2022, their number amounted to 1206, which accounted for 59.3% of all passenger traction vehicles. The largest number of this type of vehicles, 1341 units, was used in 2015. Among the EMUs, the most popular series of vehicles, used since 1961 in Poland, is EN57 or its modernizations and derivatives (726 units in 2019) [23]. A popular type of vehicles used to transport passengers are electric

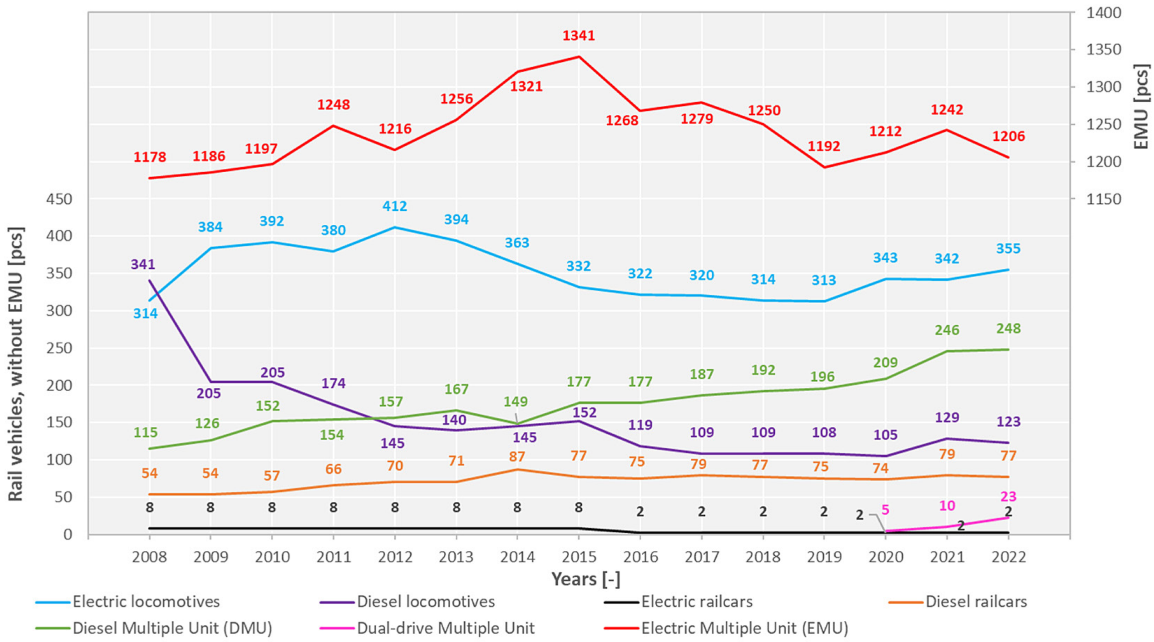


Figure. 1. Quantity of passenger railway rolling stock in Poland 2008–2022 (based on [22])

locomotives, which constitute 17.5% of passenger traction vehicles in Poland (355 vehicles). Their number has been gradually increasing since 2019.

Diesel passenger rolling stock in Poland in 2022 accounted for 22% (448 vehicles). The largest share of passenger vehicles propelled by internal combustion engines (ICE), i.e. 55%, were diesel multiple units (DMU) (248 vehicles). The number of this type of vehicles is two times bigger since 2008. In the case of diesel locomotives (123 vehicles and 27.5% of total number of diesel passenger vehicles in 2022), 18 additional vehicles have been added to the service over the last 3 years. However, this group of vehicles had very big reduction in quantity over 14 years, from 341 vehicles in 2008. The last group of traction rail passenger vehicles in Poland are railcars. In 2022 total number of this type of vehicles was 79, where 77 were diesel railcars (DR) and 2 electric railcars.

The newest type of vehicle in Poland is dual-drive multiple unit (DDMU), where 5 vehicles were introduced to the service in 2020. One year later, the number of these units were doubled to 10 vehicles. In 2022 there were 23 DDMUs in service. These vehicles have two independent types of drive – diesel (ICE) and electric (overhead electric traction). Thanks to such construction, the DDMU can commute on electrified and non-electrified routes. Such type of drive significantly increases versatility and reliability of the passenger vehicle on any type of railway line.

One of the important indicators of the modernity of the rolling stock is the age of the vehicle (Figure 2). Investments in modern rolling stock have stopped the increase in the average age of some groups of passenger railway vehicles operating on the Polish railway network. In the case of diesel and electric locomotives, as well as EMUs, a reduction of value of this indicator can be observed. Despite such actions, it should be borne in mind that it concerns the oldest groups of vehicles, where the age of the mentioned vehicles exceeds 20 years and more.

The oldest group of vehicles are locomotives, of which those powered by diesel traction are definitely in first place in terms of average age (in 2022 – 41.9 years). This means that statistically for this group of vehicles the year of production is 1981. The actions of the fleet owners allowed this group of vehicles to reduce the average age by almost 2 years compared to 2021 (from 43.8 years), but this value is still significant. Electric locomotives are, on average, almost a decade younger compared to diesel locomotives, and their average age over the last 5 years was the lowest in 2022 (32.2 years). This group includes the oldest actively used traction vehicle in passenger traffic, i.e. the EP05 locomotive manufactured in 1961 (61 years old). The average age of passenger locomotives has decreased while their number has increased in recent years. This means that younger or new vehicles were introduced into the service.

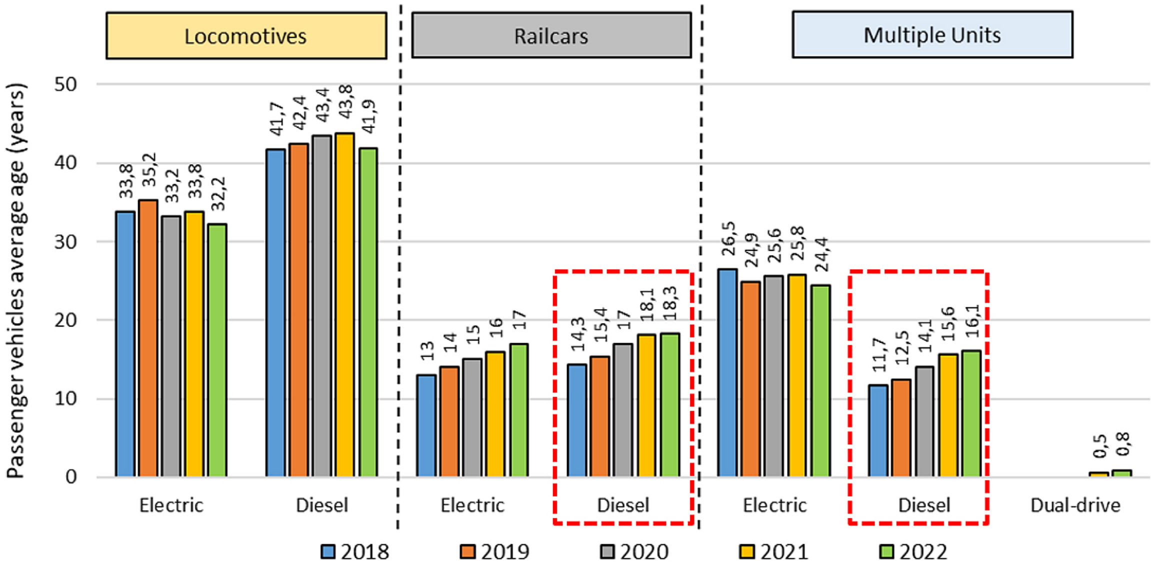


Figure. 2. Average age of passenger railway rolling stock in Poland in 2018–2022 (based on [22])

In the case of the largest group of vehicles in Poland (EMU), their average age decreased to 24.4 years in 2022 from 25.8 in 2021, and over the last 5 years this value has decreased by almost 2 years. This condition is mainly due to the liquidation of used EN57 vehicles, the number of which is gradually decreasing. Additionally, brand new vehicles are being introduced into service. In the case of DMU, the average age in 2022 was 16.1 years and is increasing every year. The MU group includes the youngest representative of passenger traction vehicles, i.e. DDMU, with an average age of 0.7 years. Vehicles with two drive sources that have been introduced to the Polish market for 3 years are modern and technically advanced brand new vehicles, which is why they are, on average, the youngest in the passenger fleet. In the case of DR and electric railcars, there is a visible trend of increasing average age. For both types of drive, the average age is similar and in 2022 it was 17 years for the electric drive and 18.3 for the DR.

LEGAL REGULATIONS IN THE CASE OF DIESEL MULTIPLE UNITS AND RAILCARS

Exhaust emission standards

DMU and DR are classified as non-road mobile machinery (NRMM) vehicles, therefore, in the case of exhaust emissions from ICE, exhaust toxicity limits are covered by the Stage standards. ICEs intended for DMU and DR are divided into categories that depend on the power and, in some cases, on the type of ignition (compression ignition (CI) or spark ignition (SI)), as well as the type of fuel used. The earliest introduced Stage standard is Stage I [24], which has been in force since 1999, then Stage II, Stage IIIA and Stage IIIB were introduced (Table 1). The current standard in force from 2021 for DMU and DR traction engines is Stage V (Table 2). Auxiliary engines used in vehicles of this type for the Stage V standard are classified into the NRE (Engines for mobile non-road machinery, suited to move or to be moved) or NRS (SI engines below 56 kW) categories and have been in force since 2019. The NRE category also includes the letter *v* or *c*, which means: *v* – variable speed engine, *c* – constant speed engine.

The limited emission values include such toxic compounds as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxide (NO_x) and particulate matter (PM), which are given as specific emissions expressed in g/kWh. For Stage V, an additional requirement is to measure the particle number (PN) related to the generated work (1/kWh). Legislative guidelines [26] specify that for rail vehicles, emissions of harmful exhaust gases are determined on the basis of the work generated by the drive system, i.e. in kWh. For ICEs intended for NRMM, emission measurement tests are performed on an engine dynamometer, which can be divided into the non-road transient cycle (NRTC) dynamic test and the ISO 8178 Test Cycle static test, also called non-road steady cycle (NRSC). NRTC is performed for cold start and hot start, and NRSC, depending on the engine, is performed

Table 1. Stage I – Stage IIIB emission standards for railcars (RC and DMU) [25]

Category	Net power (P)	Date	CO	HC	NO_x	PM
	kW		g/kWh			
Stage I						
A	130 ≤ P ≤ 560	1999.01	5.0	1.3	9.2	0.54
B	75 ≤ P ≤ 130	1999.01	5.0	1.3	9.2	0.70
C	37 ≤ P ≤ 75	1999.04	6.5	1.3	9.2	0.85
Stage II						
E	130 ≤ P ≤ 560	2002.01	3.5	1.0	6.0	0.2
F	75 ≤ P ≤ 130	2003.01	5.0	1.0	6.0	0.3
G	37 ≤ P ≤ 75	2004.01	5.0	1.3	7.0	0.4
D	18 ≤ P ≤ 37	2001.01	5.5	1.5	8.0	0.8
Stage III A						
RC A	P > 130	2006	3.5	4.0 [a]		0.2
Stage III B						
RC B	P > 130	2012	3.5	0.19	2.0	0.2
a – HC + NO_x.						

Table. 2. Stage V emission standards for railcars and auxiliary engines [25]

Category	Ignition	Net power (P)	Date	CO	HC	NO_x	PM	PN
		kW		g/kWh				1/kWh
Stage V – Railcars								
RLR-v/c-1 (railcars)	All	P > 0	2021	3.5	0.19	2.0	0.015	1 × 1012
Stage V – auxiliary engines								
NRE-v/c-1	CI	P < 8	2019	8.00	7.50 [a,c]		0.40 b	–
NRE-v/c-2	CI	8 ≤ P < 19	2019	6.60	7.50 [a,c]		0.40	–
NRE-v/c-3	CI	19 ≤ P < 37	2019	5.00	4.70 [a,c]		0.015	1 × 1012
NRE-v/c-4	CI	37 ≤ P < 56	2019	5.00	4.70 [a,c]		0.015	1 × 1012
NRE-v/c-5	All	56 ≤ P < 130	2020	5.00	0.19 [c]	0.40	0.015	1 × 1012
NRE-v/c-6	All	130 ≤ P ≤ 560	2019	3.50	0.19 [c]	0.40	0.015	1 × 1012
NRE-v/c-7	All	P > 560	2019	3.50	0.19 [d]	3.50	0.045	–
a – HC + NO_x, b – 0.60 for hand-startable, air-cooled direct injection engines, c – a = 1.10 for gas enfines, d – a = 6.00 for gas engines.								

for the required type of test with different engine operating points and "weighting factor".

Maintenance of rail vehicles

Due to applicable regulations, rail vehicles must be operated and maintained in the required and previously planned manner. For this reason, railway companies are obliged to have Documentation of the Rolling Stock Maintenance System (DRMS). The maintenance system is a complex and formalized process that specifies how a railway vehicle should be operated and maintained [27]. The railway undertaking, together with the rolling stock manufacturer, must develop a DRMS for a specific vehicle type that corresponds to the operating conditions of a given carrier. This means that the same type of vehicle may have different DRMS depending on the carrier or the nature of the vehicle's operation. Additionally, railway companies have considerable autonomy in determining the rules and method of operating and maintaining vehicles. At the same time, they are fully responsible for their safe operation.

The most common maintenance method is a five-level maintenance cycle, which is divided into the so-called light maintenance (P1, P2, P3) and heavy maintenance (P4, P5) (Table 3). This

Table 3. Description of the five-level rolling stock maintenance cycle

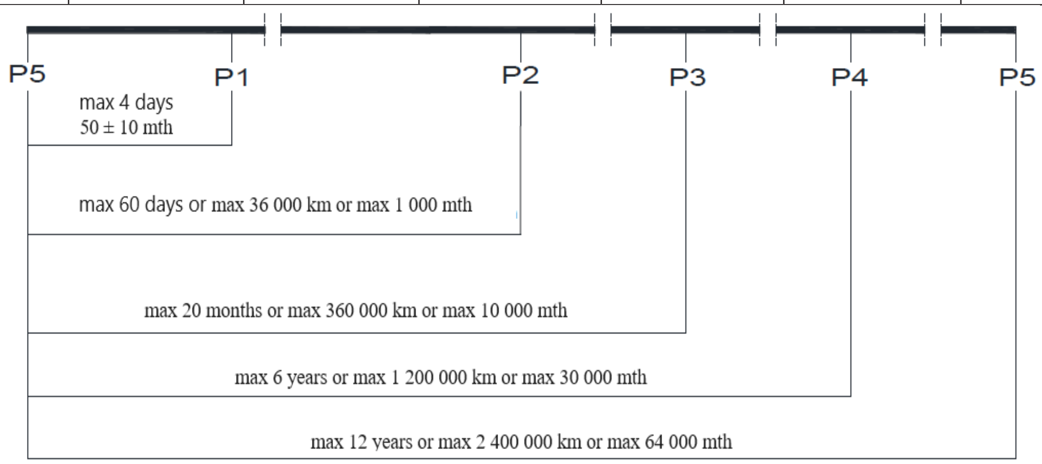
Level		Description
Light	P1	Control inspection. It includes checking or monitoring activities carried out before a railway vehicle go into the line, during ride or after the service. Some of these activities may be performed by the carrier's employees (driver, auditor) or using automatic on-board or trackside equipment.
	P2	Periodic inspection. It includes activities that prevent exceeding wear and tear limits, performed at specialized stations, in breaks between the next planned operation of the railway vehicle.
	P3	Extended inspection. It includes maintenance activities that prevent exceeding wear and tear limits, performed at specialized stations. During the inspection, the vehicle is out of planned service.
Heavy	P4	Revision repair. It includes activities related to corrective maintenance performed in repair plants with technical facilities and measurement stations.
	P5	Major repair or modernization. It includes activities aimed at improving the standard of a railway vehicle or its renovation, performed in specialized repair plants or at the manufacturer's plant.

system is based on intervals where, after reaching the limit points, the vehicle must undergo a given level of maintenance. The inspection should be performed according to the parameters of time, distance traveled or hours worked (mth), depending on which of these parameters is achieved earliest. These values are usually estimated based on the assumed operational data of the vehicles, e.g. daily mileage or average daily operating time of the vehicle. An example summary of maintenance cycles P1–P5 is presented in Table 4.

In the case of ICE drive units in rolling stock, they undergo light maintenance, where activities such as replacing injectors or turbochargers are planned. However, the most relevant maintenance levels are heavy maintenance (P4 and P5). During this process, the ICE must be removed from the vehicle and undergo a general inspection/reapair by the engine manufacturer or an authorized representative. The situation is similar with exhaust aftertreatment systems. The drive unit is replaced only when the technical condition is very poor or when the vehicle is modernized. This means that in most cases, when a vehicle undergoes heavy maintenance, the same ICE can continue to be used. This often means that despite major repairs, which take place approximately every 10–14 years depending on the vehicle, the same ICEs are still used, approved to the requirements that were in force many years ago.

Table. 4. An example of a five-level rolling stock maintenance cycle

Level	Time		Distance		Hours worked	
	Value	Unit	Value	Unit	Value	Unit
P1	max 4	days	-	km	50 ± 10	mth
P2	max 60	days	max 36 000	km	max 1 000	mth
P3	max 20	months	max 360 000	km	max 10 000	mth
P4	max 6	years	max 1 200 000	km	max 30 000	mth
P5	max 12	years	max 2 400 000	km	max 64 000	mth



Years of production and emission standards

Based on ORT data [28], the years of production of the DMUs (railcar or wagon) were compared with the exhaust emission standards for traction engines in force at that time (Figure 3). Out of the 449 vehicles, which included both traction vehicles and wagons, the vast majority were produced in the years when the Stage IIIA (2006–2011) and Stage IIIB (2012–2020) exhaust emission standards were in force. In the case of Stage I and Stage II, the marked area overlaps due to different dates of application of the standard due to the engine (power) category. For 57 vehicles, the production period was before the Stage emission standards came into force, i.e. before 1999, the oldest of which dates back to 1965. Knowing the maintenance cycle of rail vehicles, it can be assumed that the year of vehicle production is also the year of production, or rather assembly, of the engine. With this assumption, the rare ICE replacement and vehicle modernization are omitted.

RESEARCH METHODOLOGY

A DR equipped with two CI ICE with a displacement of 12.8 dm^3 was used for the research. The railcar was approved in accordance with the Stage IIIB standard, which means that it belonged to the group of vehicles produced in 2012–2020, which is the most widely used in Poland. The facility was fully operational and had an selective catalytic reduction (SCR) system. During tests of measurements of harmful exhaust compounds, it was noted that the vehicle met the assumed limit values for compounds such as CO (0.47 g/kWh), HC (0.13 g/kWh) and PM (0.01 g/kWh), but did not meet NO_x emission guidelines (actual value equal to 2.43 g/kWh). The tests were carried out during its real operation, so the journey took place with a normal load of passengers. The weight of the loaded vehicle with was estimated based on the average human weight, which is 82 kg (the average weight in Poland is 91 kg for a man and 73 kg for a woman) [29]. It was assumed that the vehicle's load capacity was 60% during the trip. The characteristics of the tested object are presented in Table 5. Measurements tests of harmful exhaust compounds were carried out during normal, everyday operation of the tested vehicle. It included a journey between Leszno and Zbąszynek, where the railcar generated a total work of over 158.7 kWh for both engines. The research object covered a distance of 75 km in 92 minutes at an average speed of 48.8 km/h, of which the total standstill time was less than 10 minutes, and the idling rate was 35% (Table 6 and Figure 4). The mobile Micro PEMS Axion R/S+ analyzer manufactured by Global MRV was used to measure harmful exhaust compounds (Table 7, Figure 5). It enables

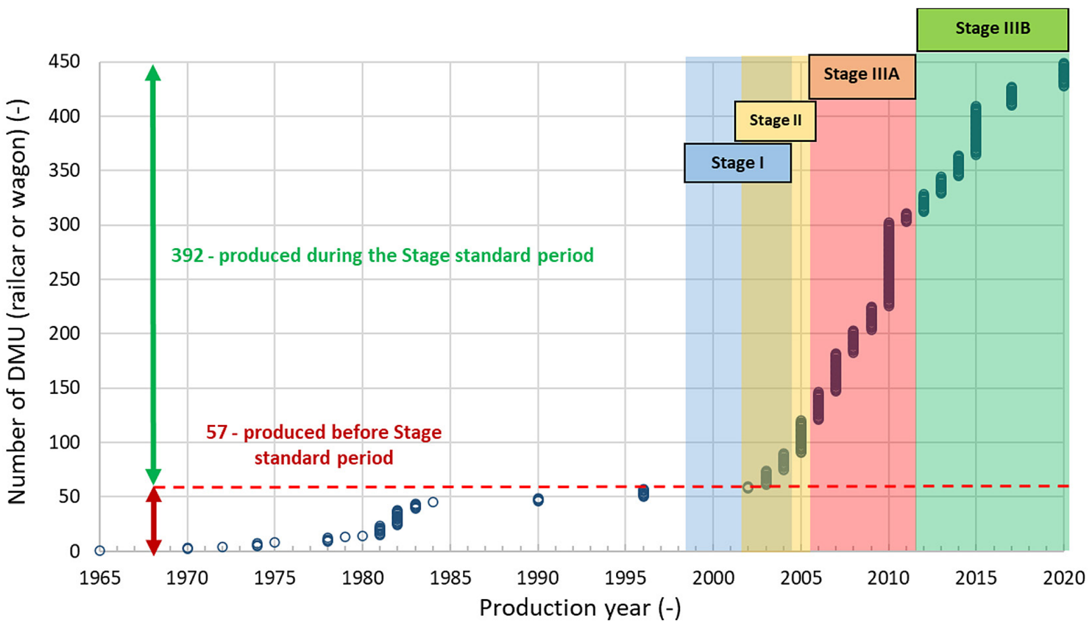


Figure 3. Years of production of 449 DMUs (railcar or wagon) used in Poland in 2020 in comparison with the applicable Stage emission standards [28]

Table 5. Characteristics of the research object

Parameter	Railcar
Engine type	2 x Diesel ICE
Number/arrangement of cylinders	6/in-line
Engine displacement [dm^3]	12.8
Maximum power [kW] / at engine speed [rpm]	390 / 1800
Maximum torque [Nm] / at engine speed [rpm]	2200 / 1300
Exhaust aftertreatment system	SCR
Emission standard	Stage IIIB
Total number of seats	250
Empty weight [t] Estimated weight with load [t]	86.5 98.8

Table. 6. Traffic indicators during the route of the research object

Distance	Work	Average speed	Max. speed	Acceleration			Total stops time	Total route time
				a = 0	a > 0	a < 0		
km	kWh	km/h	[km/h]	%			min	min
75	158.7	48.9	81	35	33	32	8.9	92

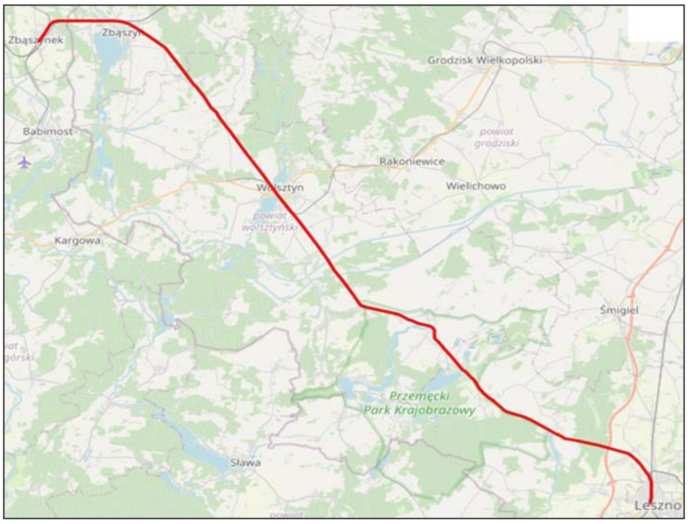


Figure 4. Research route [31]

measurement of the concentration of gaseous compounds and solid particles. The concentration of CO_2, CO and HC is performed using a non-dispersive infrared (NDIR) analyzer, while NO_x measurement is performed using an electrochemical analyzer. The PM concentration test is carried out using a method based on Laser Scatter, in which the speed of particle movement is

Table 7. Technical specifications of the PEMS Axion R/S+ equipment [30]

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 obj. %	NDIR
CO2	0–16%	±4%	0.01 obj. %	NDIR
NO	0–4000 ppm	±3%	1 ppm	E-chem
O2	0–25%	±3%	0.01 vol. %	E-chem
PM	0–300 mg/m^3	± 2%	0.01 mg/m^3	Laser Scatter

Figure 5. Measuring equipment [30]

measured. The exhaust flow is calculated based on data from the on-board diagnostic system or information from additional sensors (crankshaft rotational speed, pressure and temperature in the intake manifold) [30]. The measurements were performed at a frequency of 1 Hz.

ENVIRONMENTAL COSTS

The concept of environmental costs refers to various types of costs related to environmental protection activities. They are primarily related to environmental pollution and changes introduced therein. The principles of calculating and paying fees are specified in the "Environmental Protection Law" [4] and the resulting implementing acts [32, 33]. Emission standards are established for each source and place of gas and dust emissions into the air. The document specifies that their permissible value should be expressed in Mg/year for the entire system. The type and amount of gases and particles emitted into the air are given mainly in mg/m^3 of dry exhaust gases. The measurement takes place under strictly defined conditions. The temperature is 273 K and the pressure is 101.5 kPa. It is also allowed to express them in kg/h or in kg, for example per unit of fuel used [4].

Environmental fees are incurred for introducing pollutants into the air. These fees should be set based on the annual actual emissions specified in the report, taking into account information such as the types of substances released into the air and the emission volumes. If the terms of use of the environment are exceeded or violated, fees and an administrative fine will be incurred. The amount of these fees and administrative fines depends on the amount and type of gases and particulates emitted [4]. Detailed methods for calculating environmental costs along with unit rates of fees for gases or particulates are presented in Table 8 in Polish PLN, and are specified in the regulation [34].

Table 8. Unit fees for gases or particulates released into the air [34]

Types of gases or liquids	Unit fee [PLN/kg]
Carbon dioxide (in PLN/Mg)	0.29
Particulates from fuel combustion	0.35
Carbon monoxide	0.11
Nitrogen oxides (as NO_2)	0.53
Cylindrical, aromatic hydrocarbons and thier derivatives	1.44

ANALYSIS OF TOXICITY INDICATORS OF DIESEL MULTIPLE UNITS AND DIESEL RAILCARS

In the first stage of the study, the intensity of emission of harmful exhaust gases was analyzed. The analysis was performed during the entire work cycle lasting 92 minutes. The object covered a distance of 75 km at an average speed of 48.9 km/h. The total stop time was 8.9 minutes. During the entire journey, one of the vehicle's two identical engines performed work worth 79.3 kWh. The second emission of harmful compounds shows that throughout the entire route, harmful exhaust gases depended on the indicators of movement and work of the tested object. Figure 6 shows that in the case of all harmful exhaust gases, there is a directly proportional relationship between the value and the variability of the vehicle speed and the work performed by it. The highest values of harmful exhaust gases were, respectively: 19.39 g/s CO_2, 0.022 g/s CO, 0.007 g/s HC, 0.32 8 g/s NO_x and 0.0016 g/s PM. The average value of carbon dioxide was 2.6 g/s, and in the case of carbon monoxide this value reached 0.006 g/s. The average values of the other pollutants measured were 0.002 g/s for hydrocarbons, 0.033 g/s for nitrogen oxides and 1.4×10^{-4} particulate matter.

In order to analyze the values of pollutants measured during real operating conditions, an analysis of the road emissions of the tested object was carried out (Figure 7a). Legislative guidelines [26] specify that for rail vehicles the unit emission of harmful exhaust compounds should be defined on the basis of the work generated by the drive system. For the purposes of this work it was converted into road emissions as it was done in work [20] for urban buses. The railcar emitted a CO value of 0.95 g/km, and the CO_2 value was 387 g/km. Road emissions of HC, NO_x and PM were 0.26 g/km, 4.86 g/km and 0.02 g/km, respectively.

Taking into account the above, the authors estimated the annual emissions from DMUs and RCs operating in Poland (Figure 7b). The number of vehicles was determined on the basis of data included in the report of the ORT [22]. It was therefore assumed that 77 DR and 248 DMU vehicles are in use in the country. Additionally, based on the available Maintenance System Documentations, it was assumed that an average vehicle travels 219,000 km per year. Using this data, it was determined that the annual emission of CO_2 is 27.6 million kg, CO – 67.400 kg, HC – 18.300 kg, NO_x – 346.000 kg and PM – 1.440 kg (Figure 6b).

Comparing the results to those obtained in [21] in relation to road emissions, city buses performed much better in the case of carbon monoxide (0.36 g/km), hydrocarbons (0.01 g/km) and nitrogen oxides (0.19 g/km). In the case of NO_x, the greatest differences were obtained, and the results obtained were over twenty-five times greater. However, the railbus performed better in terms of carbon dioxide emissions (691 g/km), where the difference in results was almost two-fold. However, it should be taken into account that the analyzed city bus met the Euro VI standard (the latest standards for city buses), while the railbus was homologated in accordance with the Stage IIIB standard, introduced in 2012.

In relation to the annual emission of harmful exhaust gases, it is difficult to compare the obtained results because the article concerned vehicles of a different category, the number of which is much greater in Poland than in the case of the vehicles analyzed in the article. In addition, the analysis included only new vehicles homologated in accordance with the latest exhaust emission standard, while this article concerned the analysis of DMU and DR vehicles performed on the basis of sample tests conducted on a rail vehicle homologated in accordance with the Stage IIIB standard. According to the data included in the article [21], the number of city buses meeting the Euro VI standards registered in Poland was 3883, while in this work the estimated analysis included 325 vehicles, which means that the number of city buses was almost twelve times greater. However, the results are as follows: carbon dioxide is 201 million kg, carbon monoxide – 105 thous. kg, hydrocarbons 2.91 thous. kg, nitrogen oxides – 55 thous. kg, while particulate matter – 5.82 thous. kg. This means that the data obtained, compared to those obtained in this article, were more than seven times greater in the case of CO_2, one and a half times greater in the case of CO, and four times greater in the case of PM. Despite the much larger number of urban vehicles, they were characterized by much more favorable values for hydrocarbons and nitrogen oxides, where the results were more than six times lower.

The environmental cost analysis was prepared on the basis of the annual cost of gases and particles that are emitted into the ambient air by DMUs and RCs based on exemplary tests performed on

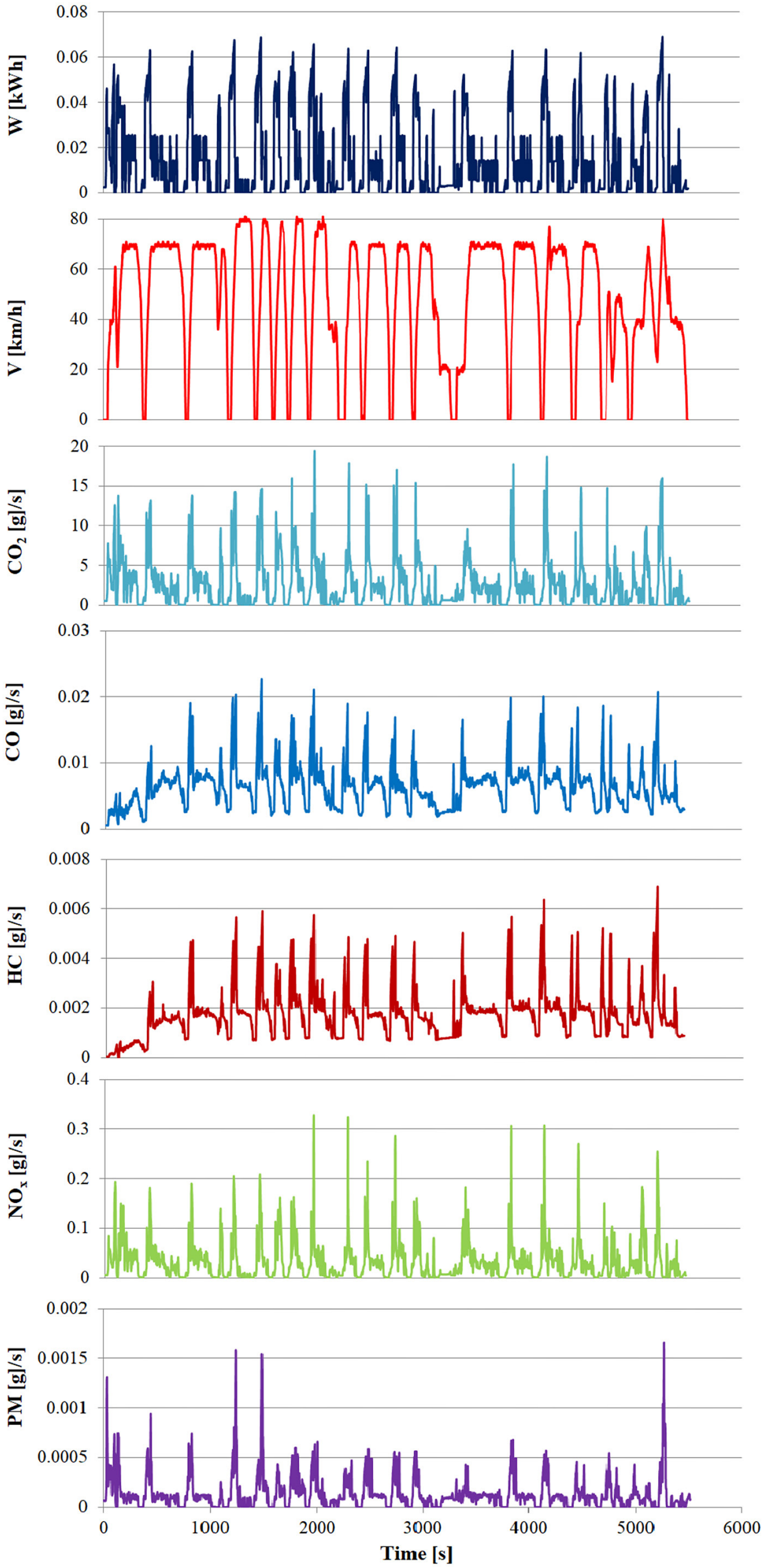


Figure 6. The parameters of the work and movement of the tested object and the intensity of the second emission during tests in real conditions

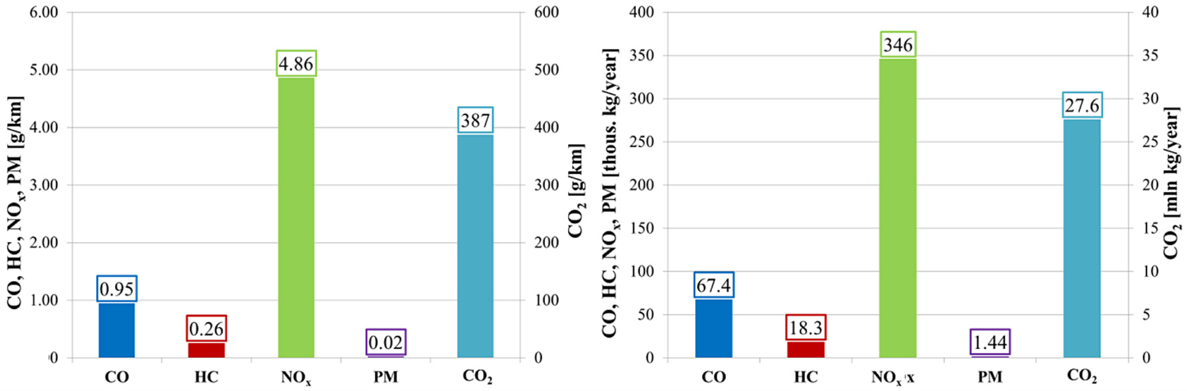


Figure 7. Emission of harmful exhaust compounds: a) road emissions, b) estimated annual emissions

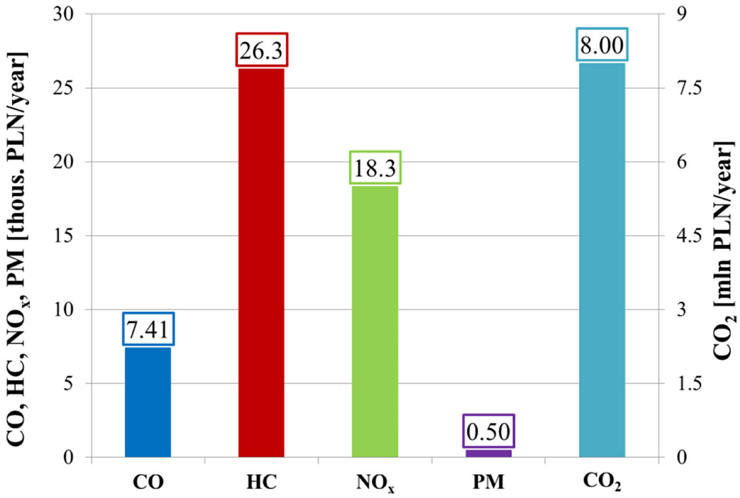


Figure 8. Annual cost of realizing of harmful gases and particles into the air from DMUs and RCs in Poland

the previously presented research object (Figure 8). The annual emission of pollutants was related to the unit fee rates included in the regulation [34] and presented in the Table 8. The analysis showed that the highest fee of 8 million PLN (24,600 PLN /vehicle) was for CO_2. The obtained value is over 150 times higher than the total fees for other toxic compounds. The cost of CO emissions amounted to 7410 PLN (22.8 PLN/vehicle). The smallest fees are incurred for introducing particles into the air, which are PM and they constitute 500 PLN (1.55 PLN/vehicle). The fees covering the emission of HC and NO_x amount to 26,300 PLN (80.9 PLN/vehicle) and 18,300 PLN (56.4 PLN/vehicle) respectively.

Based on the analysis of annual emission costs in [21], it was determined that the largest annual fee for all city buses meeting the Euro VI standard in Poland amounts to over 58 million PLN and concerns carbon dioxide emissions. The cost of carbon monoxide emissions amounted to 11,532 PLN. The smallest fees concern particulate matter emissions and constitute a cost of 2039 PLN. Fees covering hydrocarbon and nitrogen oxide emissions amounted respectively to 4194 PLN and 2933 PLN. A comparative analysis of the cost value for one vehicle indicates that in the case of all the values obtained, railbuses are less favorable. This is primarily due to the fact that older rail vehicles were analyzed than was the case for city buses, and also because the average mileage of railbuses is much greater than that of the analyzed road vehicles. The obtained values indicate that the largest difference was obtained in the case of HC and NO_x, where the environmental cost of a rail vehicle was almost 75 times greater. In the case of CO, the result obtained for railbuses was almost eight times less favourable, while for PM it was three times greater. The smallest difference was characteristic of CO_2 values, in the case of this compound the results obtained were 1.6 times greater than for urban road vehicles.

CONCLUSIONS

The article presents an assessment of the environmental costs of DMUs and RCs in Poland. For this purpose, tests were carried out in real operating conditions, during normal service with passengers. The vehicle was approved in the Stage IIIB standard, which is the most popular exhaust emission standard for this type vehicles operating in Poland. For the purposes of the article, instead of specific emissions, road emissions were calculated, in accordance with the calculation procedures contained in the regulations. Rates related to the use of the environment are established for gases and particles released into the air in the transport and industry sectors. The analysis of environmental costs for DMUs and RCs operating in Poland were carried out on the basis of: emission measurement tests, Regulation [34] and the adopted average mileage. The estimated annual emission of harmful exhaust gases amounted to over 28 million kg, of which the largest share was CO_2 (approximately 98.4%). The remaining toxic compounds emitted were 0.24% CO, 0.06% HC, 1.2% NO and 0.005% PM, respectively. The total cost for the entire population considered was 8.05 million PLN, which corresponds to almost 24.800 PLN per one exploited vehicle. The analyzes performed are only estimated because they were performed on the example of a specific vehicle, however, it should be noted that the analyzed vehicles are characterized by different drive units (condition and emission standard), variable passenger loads, travel on different routes in different track conditions, and the adopted average annual mileage is only assumed on the basis of available data from vehicles Maintenance System Documentations. However, it is not possible to determine in detail the real emissions of pollutants for all diesel passenger rail vehicles operating in Poland. It should therefore be assumed that the methodology adopted in this work allowed for obtaining results approximate to the actual situation.

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