Article citation info:
Bednarek M, Ziółkowski A, Siedlecki M, Duda W. Analysis of emissions from a heavy vehicle designed for transporting concrete. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-219241

Maciej BEDNAREK
Andrzej ZIÓŁKOWSKI
Maciej SIEDLECKI
Wiktor DUDA

Combustion Engines
Polish Scientific Society of Combustion Engines

Analysis of emissions from a heavy vehicle designed for transporting concrete

ARTICLE INFO

Received: 25 December 2025
Revised: 4 March 2026
Accepted: 12 March 2026
Available online: 21 April 2026

In the context of global efforts to reduce greenhouse gas emissions and air pollution, increasing importance is being attached to the accurate monitoring and analysis of emissions from transport, including commercial vehicles used in specialized applications. One of the key groups of vehicles whose emissions remain insufficiently studied is trucks equipped with pump-type superstructures (concrete mixers with concrete pumps), widely used in the construction sector. This article presents the results of research conducted on the emissions of harmful compounds from concrete mixers in real traffic conditions. The measurements were performed using the Axion R/S+PM portable emission measurement system from Global MRV, which enabled the mass measurement of pollutant emissions, including CO, CO_2, NO_x, and HC, under real truck driving conditions. Based on the collected data, the time-density characteristics of the tested compounds were determined as functions of crankshaft speed and engine load, and their emission intensity was determined as a function of vehicle speed. On this basis, the impact of changes in load weight on the emission intensities of the tested pollutants was demonstrated. The analysis of pollutant emissions from a heavy concrete transport vehicle enabled the determination of the impact of various road conditions and engine operation on the amount and type of compounds emitted. By monitoring operating parameters such as load and engine crankshaft speed, it is possible to gain a more accurate understanding of the mechanisms of exhaust emissions under actual vehicle operating conditions. In this way, it is possible to more effectively identify situations with particularly high pollutant emissions and determine the optimal operating conditions to reduce them.

Key words: *concrete transport, PEMS, exhaust emission, HDV, RDE*

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)

1. Introduction

Nowadays, transport is an integral part of the global economy and plays a significant role in the daily functioning of society. With the continuous increase in the number of means of transport intended for land traffic, it has become possible to transport various types of goods on a large scale, mainly thanks to the use of heavy vehicles. However, despite the benefits of this sector's development, growing public awareness has led to measures to protect the environment from its negative effects. An area of particular concern is road transport, especially heavy goods vehicles, whose activities generate significant amounts of pollutants such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) and particulate number (PN). Their emissions negatively impact air quality and pose a serious threat to the natural environment [8, 16, 23, 27].

Road transport has many aspects that make it a key factor in the functioning of the global economy. It ensures mobility, supports market integration and access to goods and services. Its development contributes to economic growth by facilitating the movement of people and goods, thereby promoting trade, production, and distribution, both nationally and internationally. The road network for road transport is one of the most extensive and coherent compared to other forms of transport. The dense infrastructure is perfectly suited to serving consumer, production and commercial areas, enabling efficient and effective logistics. In addition, road transport vehicles are adaptable to various types of transport, enabling them to handle even the most specific goods. Compared to other modes of transport, the costs of road transport are more favorable in terms of transport time to cost, making it more attractive economically. An important aspect of road transport is the possibility of direct access to the destination, which distinguishes it from other modes of transport and enables direct access to the destination [29]. The foundation of road transport is primarily heavy vehicles. Chart 1 shows the number of heavy goods vehicles registered in the European Union and in Poland in 2022 [7]. Their importance to the economy is particularly significant because they enable the transport of larger quantities of goods over long distances, delivering raw materials, products and materials necessary for the functioning of various industries. In addition, heavy goods vehicles are an integral part of global supply chains and enable connections between manufacturers, suppliers, and customers worldwide [9].

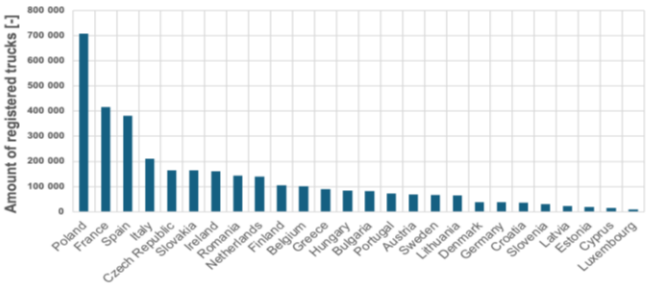

Fig. 1. Number of heavy goods vehicles intended for transport within the EU in 2022 [7]

The impact of road transport on the natural environment is significant and multifaceted. Vehicles not only generate noise during operation but also emit harmful and toxic compounds. Pollutant emissions from this sector are increasing mainly due to rising freight transport demand [22]. The distribution of pollutants emitted into the environment is subject to constant change, with traffic intensity and vehicle technical condition as the main determinants. Exceedances of the permissible emissions limit are often caused by insufficient road infrastructure. Particularly in large urban agglomerations, where traffic is heavy, traffic jams occur frequently. This process negatively impacts traffic flow, reducing vehicle speed and leading to frequent acceleration and braking, which in turn increases pollutant emissions [3]. Heavy-duty vehicles contribute significantly to pollutant emissions, shaping air quality and posing a major challenge for ecology. Their engines, especially those powered by diesel fuel, emit a variety of pollutants, including carbon oxides, nitrogen oxides, hydrocarbons, and particulate matter. The combustion of fuel (especially diesel fuel in CI engines) is the main source of these emissions. In recent years, the Polish transport sector has made significant efforts to reduce emissions, comparing favorably with its Western European competitors, thanks to investments in a new fleet. Furthermore, in 2011, it emitted 1.1 thousand tons of greenhouse gases per 1000 euros of added value generated, exceeding the average for all EU countries by 130%. However, by 2021, these emissions had fallen to 0.6 thousand tones, which was 80% of the European average [6]. Notably, in recent years, the number of electric trucks operating in the European Union has increased significantly. In 2021, it amounted to 1300 units, while in 2022 – 3800, a significant jump from 2019, when only 600 units were recorded. In Poland, although an upward trend is evident, the pace of electric vehicle adoption is much slower. Data from the European Alternative Fuels Observatory show that in 2022, only 12 electric trucks were in operation in Polish companies, which indicates the limited spread of this technology on the domestic transport market. This is mainly due to the long battery charging time and low load capacity, as well as limited range [6]. Currently, the transport sector in Poland emits approximately 8 million tons of greenhouse gases per year, but, according to plans, this figure will gradually decrease to zero within the next three decades. Reducing emissions by approximately 3 million tons per decade, while maintaining continuous economic growth, will require significant changes and innovations in the transport sector [5].

In an era of growing environmental awareness and stricter emission standards, increasing attention is being paid to analyzing the impact of transport on the environment – not only in passenger transport, but also in the freight sector. One of the less-researched but important areas is specialized vehicles, such as concrete pump trucks, commonly used in the construction industry to transport and pump concrete. The specific nature of their work – frequent stops, low speeds, loads resulting from concrete's weight – means that the emissions they generate can differ significantly from the declared values measured in laboratory or test conditions.

Therefore, researchers focus on obtaining as much information as possible about emissions in real traffic conditions. Such tests are carried out on passenger cars [1, 4, 14, 25, 33], heavy goods vehicles [11, 12, 17, 20] and other commercial vehicles [15, 26, 34]. Currently, there is a shortage of studies on the emissions of harmful compounds from heavy concrete transport vehicles. This topic is particularly important given the nature of these vehicles' work, as they often operate on construction sites and directly affect workers. Construction personnel are particularly exposed to suspended dust. According to the authors in [28], this exposure is particularly associated with dust containing free crystalline silica, which is generated, among other processes, during the processing of building materials. Importantly, in real construction conditions, workers are often surrounded by vehicles powered by combustion engines (e.g. excavators, loaders, concrete pumps), which emit much finer particulate matter (PM1 and PM2.5) [8]. These ultrafine fractions can penetrate deeply into the respiratory system, significantly increasing health risks, especially with prolonged exposure. This is confirmed by the studies presented in [30]. The authors [21, 24] also confirmed that particulate matter emitted by compression-ignition engines is carcinogenic and responsible for cardiovascular and respiratory diseases. An analysis conducted in Canada confirmed that particulate matter emitted from vehicles (including off-road machinery) is responsible for over 700 deaths [13].

An important aspect to consider in assessing emissions from heavy-duty vehicles is that they are operated under conditions that differ significantly from those assumed in type-approval procedures. The authors of this publication have identified a research gap concerning HDVs, whose operating model is based on their use also in off-road conditions [2]. The laboratory conditions in which standard emission tests are conducted do not reflect the actual operating profiles of heavy-duty vehicles, particularly those used in construction and forestry. As noted in the literature [14, 17, 27], vehicles in this category very often operate in environments with high topographical variability, unstable ground and variable loads, which affects the distribution of engine operating parameters and, consequently, the level of actual emissions. This group of vehicles also includes the object analysed in this study – a concrete pump truck – which is used not only on roads but also on construction sites and on unpaved, temporary access roads. The variability of operating conditions, combined with operating in load modes typical of transporting heavy materials, makes it reasonable to measure emissions in the vehicle's actual working environment.

2. Research methodology

2.1. Research objects

The research object was a Volvo truck designed for transporting concrete (concrete mixer), model VTR3R/VP, manufactured in 2022 (Fig. 2). The vehicle was equipped with a 323 kW combustion engine that complies with the Euro VI emission standard. The technical parameters of the vehicle are presented in Table 1.

Table 1. Specification of research objects

Parameter	Value
Purpose	Concrete mixer
Model	VTR3R/VP
Year of manufacture	2022
Nett weight	14430 kg
Permissible load capacity	19570 kg
Engine power	323 kW
Engine displacement	10837 cm^3
Emissions standard	Euro VI

Fig. 2. A truck designed for transporting concrete, serving as a research object

2.2. Measuring instruments

The research used a portable Axion R/S+PM IV generation emission measurement system from the American company Global MRV (Fig. 3a, 3b). It enabled mass measurement of emissions of pollutants such as CO, CO_2, NO_x, HC and PM in real driving conditions of a truck used as a research object. Table 2 presents the parameters of the Axion R/S+PM device corresponding to the types of pollutants tested. CO, CO_2 and HC were measured using an NDIR analyser, while NO_x was measured using an electrochemical analyser. In addition, PM particulate matter was measured using the laser light scattering method [10]. The Axion R/S+PM system offers high measurement accuracy and reliability, even in changing conditions. Its compact, lightweight design enables easy installation on various trucks without structural changes. The device provides real-time exhaust emission monitoring

Table 2. Emission measurement parameters by Axion R/S+PM [10]

	Measurement range	Measurement accuracy	Measurement repeatability
CO	0–10%	±3%	±2%
CO_2	0–16%	±3%	±2%
HC	0–2000 ppm	±4%	±2%
NO_x	0–5000 ppm	±1%	±1%
PM	0–250 g/m^3	±2%	±0,2%

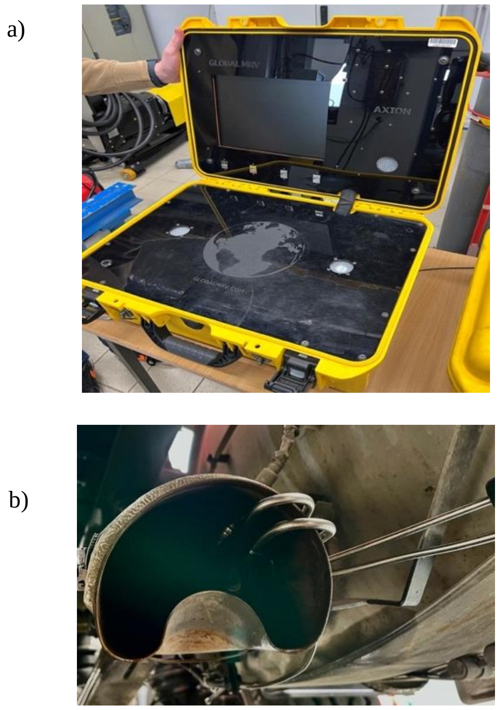

Fig. 3. a) Axion R/S+PM portable emission measurement system, b) PEMS probes installed on the truck's exhaust system.

2.3. Research cycle

The emission analysis was conducted on a 36 km measurement section. It began and ended at the cement plant located in Rogówko, Kujawsko-Pomorskie Province, Poland. The route's destination was a property in the same province, in Mirakowo. Due to restrictions on the vehicle's total permissible weight, the measurement route included national and provincial roads, as well as unpaved access roads. Its course is presented in Fig. 4. The first pollutant emission measurements were taken during loading. The vehicle then set off for the planned unloading location along the established test route. Pollutant emissions continued to be monitored during the subsequent stages of the route, i.e., during the journey to the unloading location, the unloading itself and the return to the starting point.

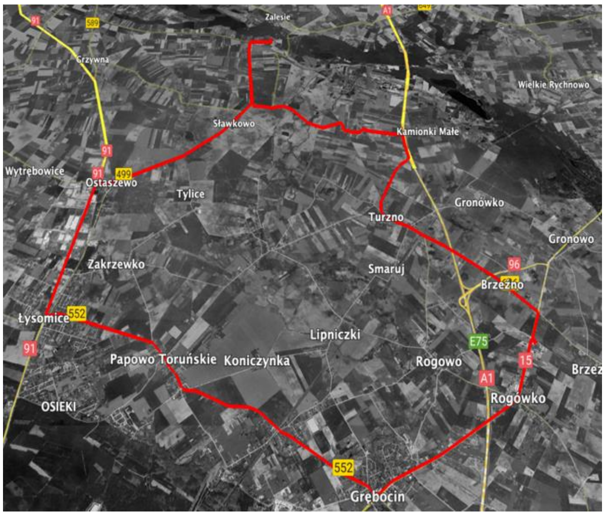

Fig. 4. Measurement route used to measure pollutant emissions

3. Results of the study

3.1. Analysis of the operating parameters of the engine

To accurately examine pollutant emissions from a heavy concrete transport vehicle, the test was conducted at different total weights. These differences resulted from variations in load quantity at different stages of the test route. At the starting point of the measurement route, the vehicle was loaded. Approximately 9 m^3 of concrete was used to reach its maximum possible load (1 m^3 of the mixture used weighs approximately 2,000 kg, so the vehicle was loaded with approximately 18 tons of concrete). Then, in accordance with the vehicle's operating model, the load was unloaded, and the vehicle returned to the starting point without additional load.

Both during loading (Fig. 5a) and unloading (Fig. 5b), the most frequently maintained crankshaft speed range was 600–800 rpm and, to a slightly lesser extent, 400–600 rpm. The load on the drive unit during unloading extends very slightly to the range of 400–800 Nm at a crankshaft speed of 400–800 rpm. This is a direct result of the pump delivering the load to a considerable height of approx. 30 metres for unloading at a specific construction site. The journey to the unloading site (Fig. 5c) took place with the vehicle at maximum load. As in the previous case, the engine crankshaft speed ranged mostly from 600–800 rpm, with occasional values up to 2200–2400 rpm. The engine load usually fluctuated between 0 and 400 Nm, sometimes reaching 1200–1600 Nm. During the journey to the base (Fig. 5d), the vehicle's weight was comparatively lower due to the lack of load. This stage was characterized by the widest range of engine crankshaft speeds, mostly maintained at 1200–1400 rpm and not exceeding 2200–2400 rpm. As in the case of the journey to the unloading site, the engine load usually fluctuated between 0 and 400 Nm and did not exceed 1600 Nm.

3.2. Analysis of the exhaust gas emission

The study also analysed the temporal density of pollutant emissions as a function of crankshaft speed and engine load. An indispensable part of the operation model of HDVs adapted for transporting concrete mix is their loading and unloading, during which the vehicle's combustion engine drives the pumps that pump the concrete mix during both filling and emptying of the system. It should be noted that standard concrete pump models can deliver concrete to heights of 20–30 m, corresponding to 6–10 floors of a building. Therefore, the authors subjected the unloading and loading processes to a similar analysis, which is presented in Fig. 6 and 7.

For CO, CO_2, THC and NO_x, the time density characteristics for the emissions of individual exhaust gas compounds as a function of crankshaft speed and engine load during loading and unloading are summarized in Fig. 6a–d. During loading, the areas of peak emissions occurred at speeds of 400–800 rpm and engine loads of 0–400 Nm. The situation was different during unloading (Fig. 7a–d), for which the emission areas of these compounds oscillated in the speed range of 0–1400 rpm, reaching the highest level at an engine load of 400–800 Nm for CO, CO_2 and THC, and 0–400 Nm for NO_x. Both during loading and unloading, the highest pollutant emissions therefore occurred at maximum engine load. The exception was NO_x emissions (Fig. 7d), which reached a maximum at the average engine load.

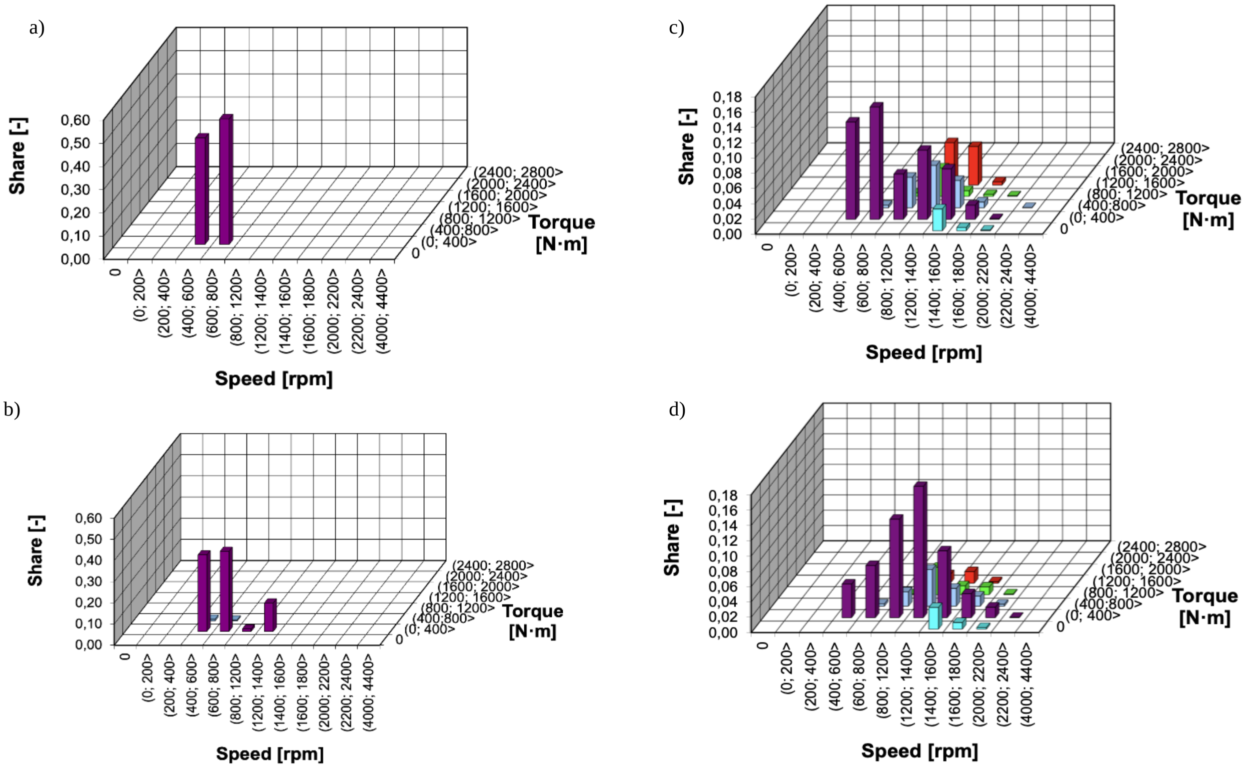

Fig. 5. Characteristics of working time as a function of engine speed and engine load a) during loading b) during unloading c) during travel to destination with load d) during return from destination without load

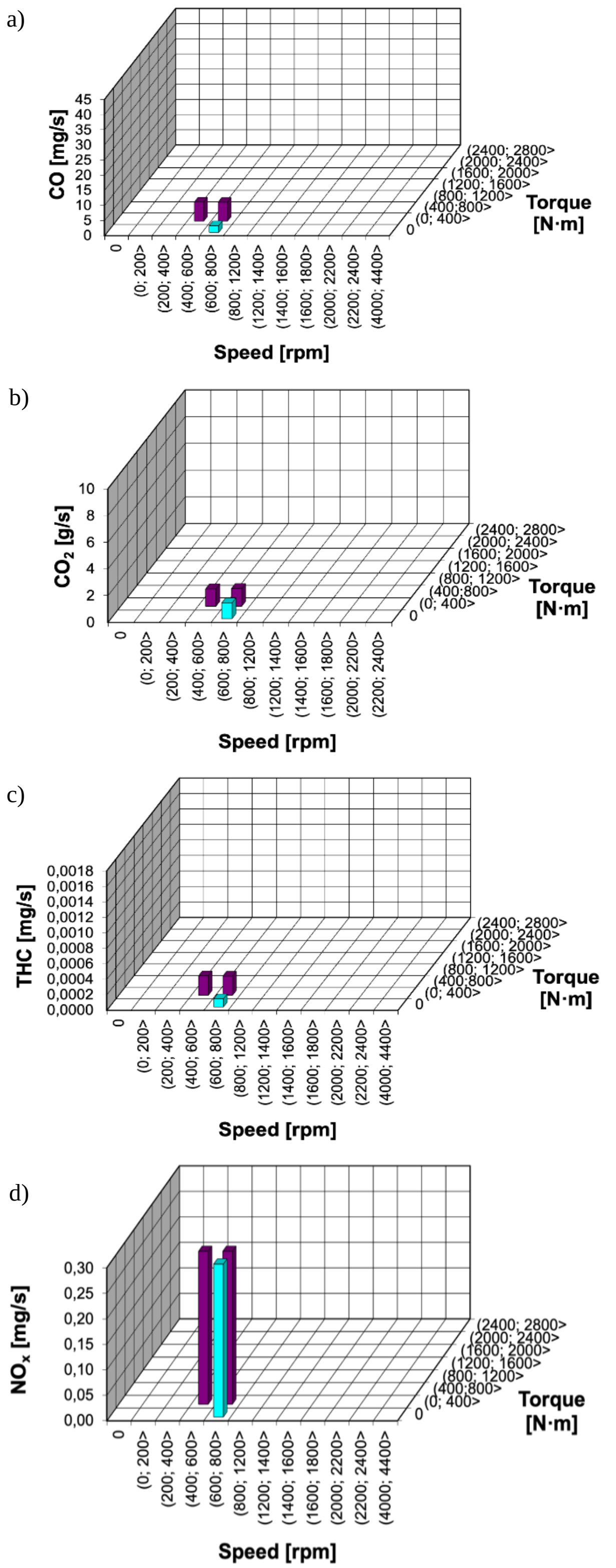

Fig. 6. Characteristics of time density of emissions as a function of crankshaft speed and engine load during loading: a) CO, b) CO_2, c) THC, d) NO_x

It should be noted that during loading, carbon monoxide emissions remain at lower levels of drive unit load (Fig. 6c). During concrete unloading (Fig. 7c), however, a significant increase in CO emissions can be observed at higher torque and rotational speed values. Due to the higher load, unloading generates higher emissions of the analysed compound, a direct result of the unit's more intensive operation (including the use of a pump). This relationship can be observed for carbon dioxide, which, as a product of complete combustion, increases in proportion to fuel consumption. During unloading, energy demand increases, leading to a clear increase in CO_2 emissions at higher unit operating parameters. Emissions of unburned hydrocarbons also increase during unloading (at higher crankshaft speeds). This may be due to irregular engine operating conditions during concrete emptying.

Nitrogen oxide emissions are closely related to combustion temperature, which increases with vehicle load. However, when analysing the graph, the opposite is observed. During the loading phase, significantly higher nitrogen oxide emissions were observed – in the operating range described by the crankshaft speed of 400–800 rpm and a load of 0–400 Nm. During the unloading phase, the operating range over which emissions of the compound were recorded is wider (400–1400 rpm; 0–800 Nm), but the number of emissions is marginal. During concrete unloading, the engine load is higher, but the higher exhaust gas temperature makes the SCR system more effective, significantly reducing NO_x emissions. During loading – the initial phase of the test – the exhaust gases do not reach a sufficient temperature for the SCR system to work effectively.

Therefore, emissions of the compound are significantly higher in the first stage of the test. When driving with a load (Fig. 8a–d), numerous sudden and short-term increases in the value of carbon monoxide CO emissions were observed, reaching up to 1900 mg/s. In contrast, when driving to the base (Fig. 9a–d), the density of peaks for this compound was slightly lower, as was the peak emission value, which was around 1400 mg/s. The results suggest that CO emissions increase with vehicle weight. Based on the characteristics of second emissions as a function of drive-unit load and crankshaft speed, very high carbon monoxide emission values were observed at medium and high torque (1200–2400 Nm) and at medium speeds during driving to the unloading site. When analyzing the graph, a clear area with very high emissions of the analyzed compound can be identified: the range of medium loads from 800 Nm to 1600 Nm at 1200–2200 rpm. This corresponds to typical driving conditions with a load on mixed roads (extra-urban and urban driving, varied speed profile). Returning to the loading site results in lower CO emissions, a direct consequence of the absence of concrete loading. The maximum values are up to 350 mg/s, but across almost every range, emissions are up to 40% lower than with a load. Higher values when driving without a load are due to dynamic route conditions that require sudden acceleration or hill climbing. Overall, the results obtained clearly show the complexity of truck emission behavior under real driving conditions. The differences observed between the loading and unloading phases confirm that emission levels depend not only on engine load, but also on the efficiency of the exhaust aftertreatment system and driving dynamics. Analysis of emission maps provides valuable insights into the impact of various operating parameters on the formation of harmful compounds.

For carbon dioxide emissions, both with and without a load, they are concentrated in the same engine operating ranges (1200–2000 rpm, 1200–2000 Nm). The CO_2 emission characteristics show that emissions of this compound increase almost linearly with increasing engine load (Fig. 8b and Fig. 9b), clearly reflecting the increase in fuel-air mixture combustion during concrete transport. Returning vehicles without a load results in significantly lower CO_2 emissions (approx. 10–20% difference). However, the distribution of characteristics is very similar to that obtained for concrete transport. The highest emissions occur at torques of 1200–2000 Nm and speeds of 1400–2000 rpm, which means that even without a load, the vehicle emits a lot when accelerating or driving uphill. The highest emissions occur during typical engine operation, i.e., at medium speeds and medium or high torques, which is the case when driving outside built-up areas.

THC (total hydrocarbons) emissions remained at a relatively low level (Fig. 8c, Fig. 9c). The characteristics show an increase in hydrocarbon emissions with increasing speed, but these values are not significant. Maximum emissions are 0.02 mg/s for driving with a load and 0.025 mg/s for measurements taken during the return to base. This confirms the effectiveness of the exhaust gas purification systems. It is characteristic that the spread of THC emissions is wider for driving without a load – the characteristics show significantly more emission peaks for different load values and crankshaft speeds.

When driving to the unloading site, the highest nitrogen oxide emissions occur in the speed range of 800–1600 rpm and in the load range of 800–2000 Nm (Fig. 8d). Significant emissions occur at the highest torque values and at around 800–1200 rpm. A significant load on the drive unit occurs at relatively low crankshaft speeds when starting or climbing hills while transporting a load. When driving without a load (Fig. 9d), the recorded NO_x emissions are significantly lower. Particularly high emissions of this compound also occurred at 800–1200 rpm and 1600–2000 Nm torque. Sudden peaks in NO_x emissions when driving without a load may have been caused by sudden and short-term operating conditions of the drive unit (including sudden dynamic acceleration) during which the SCR system was unable to effectively reduce the nitrogen oxides produced.

An analysis of emission characteristics shows that peak pollutant formation occurs during periods of increased torque demand, regardless of vehicle load. While advanced exhaust aftertreatment systems can significantly reduce total emissions, operating conditions such as acceleration, hill climbing and variable loads continue to pose a significant challenge for effective emission control. These results highlight the need to optimize both driving strategies and emission system calibration to effectively reduce environmental impact under varying load conditions. In addition, accounting for weather conditions and route specifics can further improve the effectiveness of measures to reduce harmful emissions, which is important for protecting air quality in urban and non-urban environments. It also enables better planning of transport operations and optimisation of vehicle performance in real driving conditions.

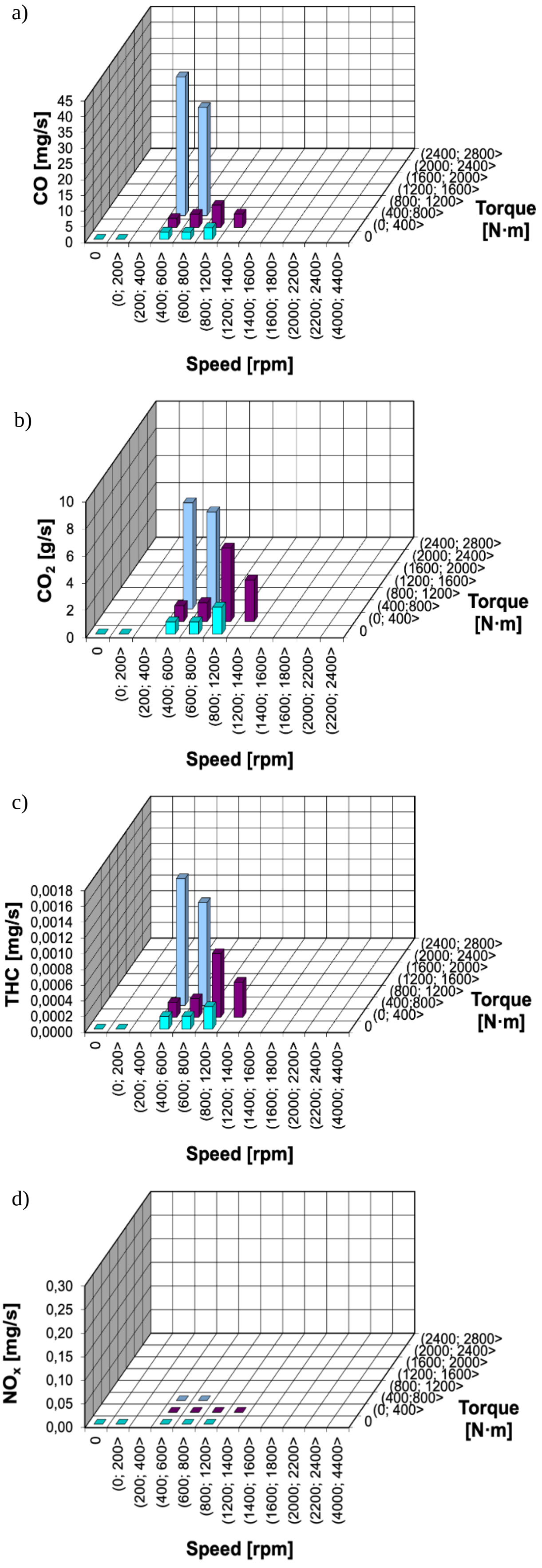

Fig. 7. Characteristics of time density of emissions as a function of engine speed and engine load during unloading: a) CO, b) CO_2, c) THC, d) NO_x

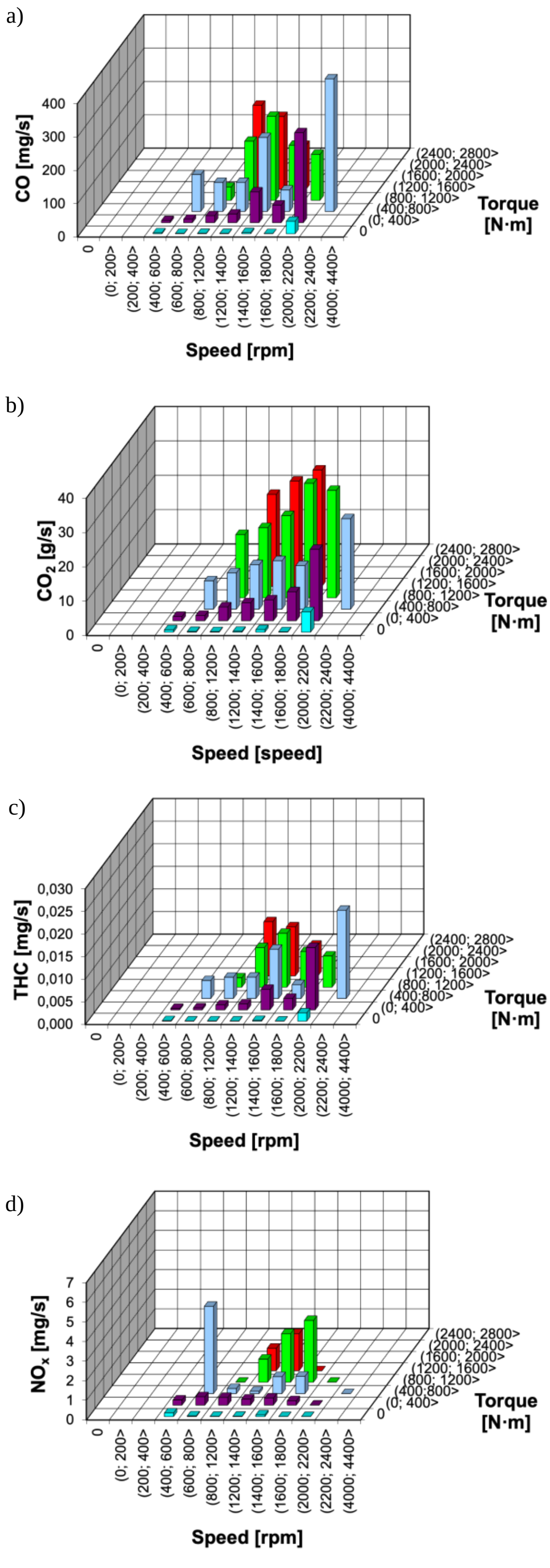

Fig. 8. Characteristics of time density of emissions as a function of crankshaft speed and engine load during travel to the destination (with load): a) CO, b) CO_2, c) THC, d) NO_x

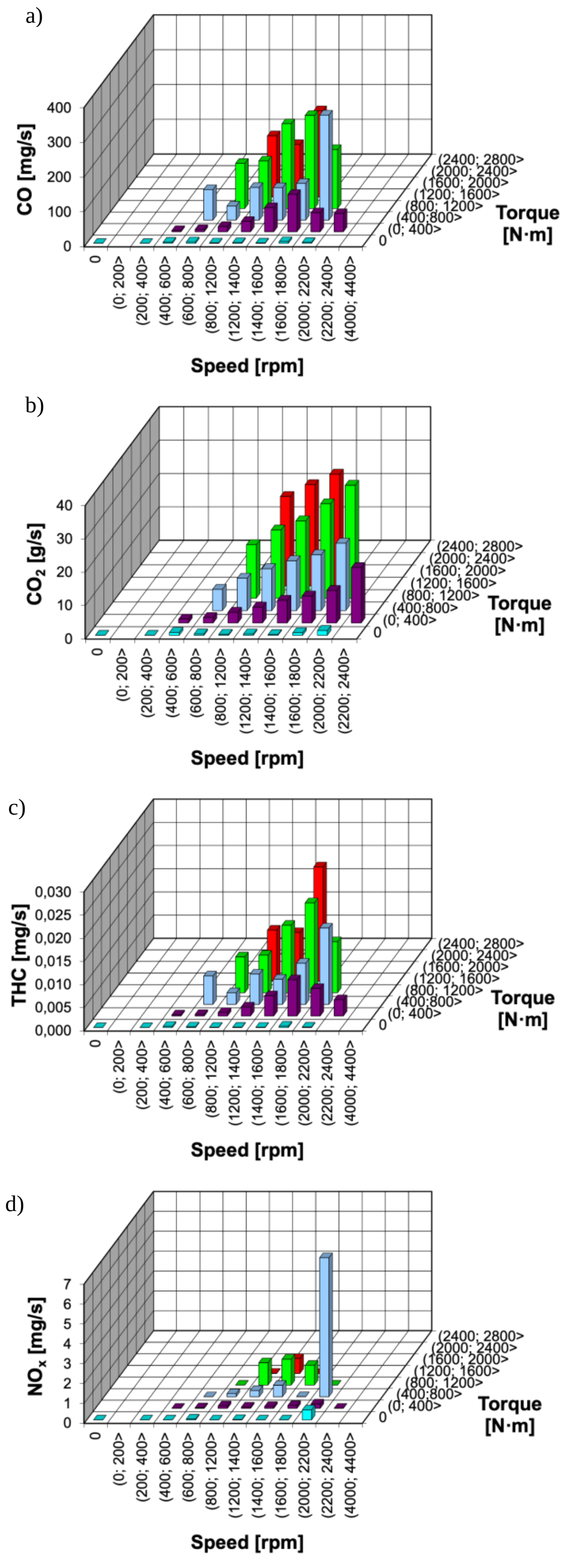

Fig. 9. Characteristics of time density of emissions as a function of crankshaft speed and engine load during travel to base (no load) a) CO b) CO_2 c) THC d) NO_x

Comparative graphs of road emissions of toxic exhaust gases for load transport and return without load were prepared. In both cases, the vehicle travelled just over 23 km (Fig. 10). The measured values are relatively low, with carbon monoxide as the dominant harmful emission. The percentage analysis showed that concrete transport increased road emissions by approximately 80% for CO, 35% for THC, and 150% for NO_x. Higher nitrogen oxide emissions during concrete transport result from higher unit loads and increased combustion temperatures. However, it is worth emphasizing that emissions depend primarily on the engine's thermal load and the SCR system's efficiency, which is designed to reduce nitrogen oxides. In fact, emissions are influenced not only by the weight of the load being transported, but also by the driver's driving style and transitional conditions (e.g., rapid acceleration). THC emissions are low in both cases, confirming the effectiveness of HC purification systems. A similar analysis was performed in [32], which presented studies of heavy vehicle emissions in real traffic conditions. Their studies showed increases of 18–41% in NO_x emissions, 6–67% in CO emissions, and 37–125% in THC emissions. It is important to note that the study was conducted in three variants – empty, half-loaded and fully loaded vehicles in relation to the permissible total mass. The test was based on driving on paved urban, extra-urban and motorway roads. In the tests presented in this paper, the vehicle performs work in accordance with its operating model, travelling on both unpaved and paved roads. In article [16], the authors analysed nitrogen oxide emissions from over 200 heavy goods vehicles. Their research also showed that NO_x emissions depend on the SCR system's efficiency and the driver's driving style, including the number of accelerations and sudden braking events. The results clearly indicate that the emission profile of a heavy-duty truck is closely correlated with operating conditions and the specific nature of the transport task. Despite relatively low total emissions, the noticeable differences between driving with and without a load emphasise the importance of optimising vehicle use to minimise environmental impact. The results show that even slight changes in driving dynamics or route characteristics can lead to significant fluctuations in emissions. Therefore, continuous monitoring and further calibration of emission control systems can contribute to a measurable reduction in exhaust emissions. The observations presented not only confirm the trends noted in earlier studies but also emphasize the importance of measuring actual driving conditions for a reliable assessment of the environmental performance of heavy goods vehicles in specific transport applications.

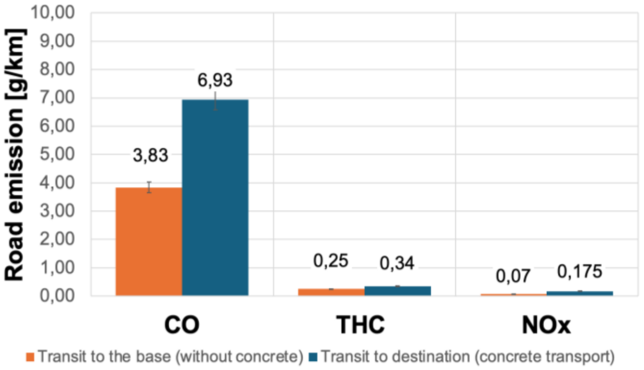

Fig. 10. Road emissions of CO, THC and NO_x

4. Summary

The conducted research on pollutant emissions from a heavy-duty concrete transport vehicle provided important conclusions on the impact of various factors on emission levels and the nature of engine operation under different operating conditions. The results indicate that despite meeting the Euro VI standard, emissions under RDE conditions remain significant under high transport loads. Driving with a full load of concrete is associated with increased fuel consumption and CO emissions, especially during acceleration and uphill driving. Returning without a load results in lower engine load and reduced emissions, though periodic increases are still observed during higher-power demand.

Furthermore, analysis of the engine's performance characteristics showed that changes in crankshaft speed and engine load significantly affect pollutant emissions. High emissions typically occurred at maximum engine load, highlighting the need to monitor and optimise engine operating conditions in order to reduce emissions. The journey to the base, when the vehicle was unloaded, was characterised by lower load values and a wider range of engine speeds. However, even in this case, pollutant emissions remained a significant issue, especially at higher engine speeds.

In addition, significant differences in pollutant emissions were observed across different stages of the route, suggesting that driving dynamics and specific vehicle operating conditions can significantly affect the number of compounds emitted, particularly for HDVs, whose operating models force them to operate in off-road conditions. In such cases, road conditions are often variable and difficult to model, which significantly affects emissions from these vehicles and makes their estimation difficult.

Acknowledgements

The study presented in this article was performed within funded as part of the PhDBoost Programme: 0415/SPHD/0366.

Nomenclature

CO	carbon monoxide
CO_2	carbon dioxide
CI	compression ignition
FID	flame ionzation detector
GPS	global positioning system
HDV	heavy duty vehicle
NDIR	non-dispersive infrared
NO_x	nitrogen oxides
NDUV	non-dispersive ultra violet spectroscopy
NRMM	non-road mobile machinery

PEMS	portable emissions measurement system
PM	particulate matter
PN	particulate number
THC	hydrocarbons
SCR	selective catalytic reduction

Bibliography

[1] Adamiak B, Szczotka A, Woodburn J, Merkisz J. Comparison of exhaust emission results obtained from Portable Emissions Measurement System (PEMS) and a laboratory system. Combustion Engines. 2023;195(4):128-135. https://doi.org/10.19206/CE-172818

[2] Bednarek, M., Ziółkowski, A., Jagielski, A., Siedlecki, M. The analysis of the operating conditions of a heavy-duty engine of a vehicle designated for timber transport in terms of compliance with the RDE procedures. Combustion Engines. 2024;199(4):140-150. https://doi.org/10.19206/CE-193859

[3] Chłopek Z. Ochrona środowiska. Wydawnictwo Komunikacji i Transportu. (in Polish) Warsaw 2002.

[4] Czerwiński J, Comte P, Zimmerli Y, Reutimann F. Testing emissions of passenger cars in laboratory and on-road (PEMS, RDE). Combustion Engines. 2016;166(3):17-23. https://doi.org/10.19206/CE-2016-326

[5] European Commission. Poland – EU Climate Action. Climate Action Progress Report. Brussels: European Commission 2023.

[6] Eurostat. Road freight transport by vehicle characteristics. Eurostat Statistics Explained. (accessed on 2023 Dec 1). https://ec.europa.eu/eurostat/statisticsexplained

[7] Eurostat. Road freight transport by vehicle characteristics. Luxembourg: Eurostat 2024.

[8] Ferree PL, Polat M, Nøjgaard JK, Jensen KA. Airborne particulate matter and diesel engine exhaust on infrastructure construction sites in the Copenhagen metropolitan area. Ann Work Expo Health. 2024;68(8):791-803. https://doi.org/10.1093/annweh/wxae062

[9] Gis M. Emisja dwutlenku węgla z transportu drogowego. Część 2, pojazdy ciężarowe (in Polish). Transport drogowy. Warsaw 2017.

[10] Global MRV. Technical specifications of Axion R/S+PM device. https://www.globalmrv.com (accesseod on 2024 Jan 23).

[11] Grigoratos T, Fontaras G, Giechaskiel B, Zacharof N. Real world emissions performance of heavy-duty Euro VI diesel vehicles. Atmos Environ. 2019;201:348-359. https://doi.org/10.1016/j.atmosenv.2018.12.042

[12] Hata H, Kokuryo K, Ogata T, Kugata M, et al. Real-world measurement and mechanical-analysis-based verification of NO_x and CO_2 emissions from an in-use heavy-duty vehicle. Atmos Meas Tech. 2021;14(3):2115-2126. https://doi.org/10.5194/amt-14-2115-2021

[13] Health Canada. Human Health Risk Assessment for Diesel Exhaust – summary. Ottawa: Health Canada; 2016 Mar 4. Report published by Health Canada; date modified Jan 24, 2023.

[14] Kim W, Baek S, Baek S et al. Evaluation of exhaust emissions of agricultural tractors using portable emissions measurement system in Korean paddy field. Sci Rep. 2024; 14(1):3491. https://doi.org/10.1038/s41598-024-53995-0

[15] Lee D, Park J, Shin M, Lee J, Park S. Characteristics of real-world gaseous emissions from construction machinery. Energies. 2022;15(24):9543. https://doi.org/10.3390/en15249543

[16] Leonard J, Couch P, Durbin TD, et al. In-use emissions testing and activity profiles for on-road heavy-duty vehicles: summary of 200 heavy-duty vehicle emissions testing program from the University of California, Riverside and West Virginia University. Sacramento (CA): California Energy Commission, Energy Research and Development Division; 2023. Report No.: CEC-500-2023-002.

[17] Li P, Lü L. Evaluating the real-world NO_x emission from a China VI heavy-duty diesel vehicle. Appl Sci. 2021;11(3): 1335. https://doi.org/10.3390/app11031335

[18] Lijewski P, Merkisz J, Fuć P. Research of exhaust emissions from a harvester diesel engine with the use of portable emission measurement system. Croat J For Eng. 2013;34(1):113-122.

[19] Merkisz J. Analysis of exhaust emission from heavy duty vehicles in real traffic conditions. Combustion Engines. 2015;162(3).

[20] Perdikopoulos M, Karageorgiou T, Ntziachristos L, Cavellin LD, Joly F, Vigneron J et al. Developing emission factors from real-world emissions of Euro VI urban diesel, diesel-hybrid, and compressed natural gas buses. Atmosphere. 2025;16(3):293. https://doi.org/10.3390/atmos16030293

[21] Ristovski ZD, Miljevic B, Surawski NC, Morawska L, Fong KM, Goh F et al. Respiratory health effects of diesel particulate matter. Respirology. 2012;17(2):201-212. https://doi.org/10.1111/j.1440-1843.2011.02109.x

[22] Solakivi T, Ojala L. Environmental and economic potential of high-capacity trucks. Case Stud Transp Policy. 2024;18: 101284. https://doi.org/10.1016/j.cstp.2024.101284

[23] Stryhunivska O, Zwolińska B, Giel R. The management of harmful emissions from heavy-duty transport towards sustainable development. Sustainability. 2024;16(24):10988. https://doi.org/10.3390/su162410988

[24] Sydbom A, Blomberg A, Parnia S, Stenfors N, Sandström T, Dahlén S-E. Health effects of diesel exhaust emissions. Eur Respir J. 2001;17(4):733-746. https://doi.org/10.1183/09031936.01.17407330

[25] Szymlet N, Lijewski P, Rymaniak Ł, Sokolnicka B, Siedlecki M. Comparative analysis of exhaust emissions from passenger and motorcycles. Combustion Engines. 2019; 177(2):19-22. https://doi.org/10.19206/CE-2019-204

[26] Tu R, Li T, Meng C, Chen J, Sheng Z, Xie Y et al. Real-world emissions of construction mobile machines and comparison to a non-road emission model. Sci Total Environ. 2021;774:145733. https://doi.org/10.1016/j.scitotenv.2021.145733

[27] Tan D, Tan J, Peng D, Fu M, Zhang H, Yin H et al. Study on real-world power-based emission factors from typical construction machinery. Sci Total Environ. 2021;799:149436. https://doi.org/10.1016/j.scitotenv.2021.149436

[28] Tavakol E, Azari M, Zendehdel R, Salehpour S, Khodakrim S, Nikoo S et al. Risk evaluation of construction workers' exposure to silica dust and the possible lung function impairments. Tanaffos. 2017;16(4):295-303.

[29] Transport and Logistics Poland. Road transport in Poland 2023. Warsaw: Transport and Logistics Poland 2023.

[30] Vallabani NVS, Gruzieva O, Elihn K, Huarez-Facio AT, Steimar SS, Kuhn J et al. Toxicity and health effects of ultrafine particles: Towards an understanding of the relative impacts of different transport modes. Environ Res. 2023; 231(2):116186. https://doi.org/10.1016/j.envres.2023.116186

[31] Valverde V, Mora BA, Clairotte M, Pavlovic J, Suarez-Bertoa R, Giechaskiel B et al. Emission factors derived from 13 Euro 6b light-duty vehicles based on laboratory and on-road measurements. Atmosphere. 2019;10(5):243. https://doi.org/10.3390/atmos10050243

[32] Wang X, Song G, Zhai Z, Wu Y, Yin H, Yu L. Effects of vehicle load on emissions of heavy-duty diesel trucks: a study based on real-world data. Int J Environ Res Public Health. 2021;18(8):3877. https://doi.org/10.3390/ijerph18083877

[33] Weiss M, Bonnel P, Hummel R, Provenza A, Manfredi U. On-road emissions of light-duty vehicles in Europe. Environ Sci Technol. 2011;45(19):8575-8581. https://doi.org/10.1021/es2008424.

[34] Zhang M, Liu X, Li K, Huang H, Hu H. Real-world emission for in-use non-road construction machinery in Wuhan, China. Environ Sci Pollut Res Int. 2023;30(16):46414-46425. https://doi.org/10.1021/es200842410.1007/s11356-023-25453-3)

Prof. Andrzej Ziółkowski, DSc., DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.

e-mail: *andrzej.j.ziolkowski@put.poznan.pl*

Maciej Bednarek, MEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology.

e-mail: *maciej.bednarek@doctorate.put.poznan.pl*

Maciej Siedlecki, DEng. – Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland.

e-mail: *maciej.siedlecki@put.poznan.pl*

Wiktor Duda, Eng. – Faculty of Civil and Transport Engineering, Poznan University of Technology.

e-mail: *wiktor.duda@student.put.poznan.pl*