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Analysis of emissions and fuel consumption from forklifts by location of operation

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The share of road transport accounts for more than 85% of the total structure of freight transportation. In this process, mainly motor vehicles are used to carry out the freight work. In addition to them, forklifts are also used, whose task is to load and unload goods. These vehicles are categorized as NRMM (Non-Road Mobile Machinery). Forklift trucks have internal combustion or electric drive. The paper presents an analysis of the emission of pollutants and fuel consumption from forklift trucks equipped with diesel and LPG power. The study uses the author's test taking into account the raising/lowering of a pallet, a loaded and unloaded run. The measurements were made in the warehouse and outside the warehouse using the Portable Emission Measurement System (PEMS) equipment. The aim was to show the influence of loading conditions on the emission of pollutants and fuel consumption.

Key words: *forklifts, PEMS, exhaust emission, fuel consumption*

1. Introduction

Transport is one of the most important branches of the national economy, which directly affects its development, but at the same time it is one of the main sources of air pollution. According to the European Environment Agency, in 2016, road transport was responsible for emissions of about 39% of NO_x, 20% of CO and CO, and 10% of PM10 [4]. Although the SARS-CoV-2 pandemic caused the number of passengers transported to decrease in 2020, an increase in the amount of freight transported and the transport work performed was observed in the case of freight transported by road. According to the report "Cargo and Passenger Transport in 2020" published by the Central Statistical Office, the amount of passengers transported decreased against 2019 by more than 49%, while a 21% increase was observed in the case of freight transported by motor transport [7]. It is worth noting that the demand for freight transportation will increase in the coming years [2]. With greater vehicle transport capacity, this will result in increased emissions of pollutants into the atmosphere. As it has been shown [6], the amount of fuel consumption and CO_2 and NO_x emissions in cargo transport directly results from the amount of mass of the transported goods. Analyzing the literature, one may notice that there are many studies devoted to the issue of emission of pollutants in the process of cargo transportation by heavy vehicles [6, 13, 16]. However, there is a deficit of research works on the emission of pollutants during the performance of loading tasks, which are an indispensable element of the process of cargo transportation. These works are performed with the use of various manipulation means, including forklifts equipped with combustion engine units, the emission of which is a threat to human health, as well as negatively affect the environment causing its degradation [5, 14].

One of the most frequently used tools for loading or unloading freight are forklift trucks, discussed in this paper, which belong to the NRMM (Non-Road Mobile Machinery) vehicle category. During the approval process of non-road vehicles the emission of pollutants is measured on the basis of the stationary NRSC (Non-Road Steady-State Cycle) and dynamic NRTC (Non-Road Transient Cycle) tests. Since the operating conditions of the engines during actual operation differ significantly from the test conditions, more reliable data on engine unit emissions is provided by RDE (Real Driving Emission) tests. The possibility of obtaining reliable measurements has led to the fact that tests under real operating conditions are increasingly used to determine the emission performance of NRMM vehicles and can be complementary to tests performed under laboratory conditions [3, 9, 10, 17]. For forklift trucks, however, the method of conducting the RDE test has not yet been established. One procedure is the VDI 2198 test. However, this standardized cycle used to determine the fuel consumption of forklifts only represents the operation of the device in the warehouse, omitting, among other things, the driving of the forklift without a load. Thus, this method does not represent the emissions and energy intensity of a forklift performing loading tasks [5]. It should also be noted that the variety of ways of organizing loading processes should be taken into account when determining the test procedure of forklifts. Nowadays, forklifts have found their application in large logistics centers, closed warehouse halls and open yards. These sites vary in size, floor, weather conditions, etc. These conditions directly affect the way the forklift trucks are used, which results in a different structure of emissions and fuel consumption by devices operating in different conditions.

Currently, there are few publications on emissions from internal combustion forklifts. The topic has been covered in only a few publications [1, 8]. Determining the emission performance of forklift trucks used during loading operations is even more important as they are used in the direct vicinity of humans, contributing to the deterioration of their health. This is of particular importance when working in closed spaces.

2. Research methodology

2.1. Research objects

In order to determine the relationship in fuel consumption and emissions between forklift trucks operating in different conditions, two machines were tested. One forklift truck was equipped with a diesel engine and the other with a LPG (liquefied petroleum gas) engine. Both units had similar empty weights and were loaded with the same payload.

The self-ignition engine vehicle had a four-cylinder unit with a capacity of 2486 cm^3 and maximum power of 36 kW at 2500 rpm. The driving unit of the second test object was a spark-ignition engine with a capacity of 2237 cm^3 and a maximum power of 38 kW. This vehicle was equipped with a TWC (Three-way catalytic converter) system. The data of each object are listed in Table 1.

Table 1. Specification of research objects

Parameter	Vehicle 1	Vehicle 2
Type of engine	CI	SI
Engine capacity	2486 cm^3	2237 cm^3
Maximum power output	36 kW at 2500 rpm	38 kW at 2100 rpm
Maximum torque	175 Nm at 2300 rpm	160 Nm at 2100 rpm
Number of cylinders	4	4
Emission standard	Stage IIIA	Stage IIIA
Aftertreatment	–	TWC
Cargo weight	1000 kg	1000 kg
Cart empty weight	3560 kg	3600 kg

Fig. 1. Research object with installed measurement equipment

2.1. Measuring instruments

The research has been carried out using the SEMTECH DS analyzer made by Sensor Inc. The instrumentation, belonging to the PEMS (Portable Emissions Measurement System) group of devices, makes it possible to measure CO, CO_2, NO_x, HC and O_2 concentrations in exhaust gases during real operating conditions. The instrumentation also enables the realization of fuel consumption and exhaust mass flow rate measurements.

The exhaust gases are taken directly from the vehicle's exhaust system. The pipe that delivers exhaust gases to the apparatus is heated up to 191ºC. This procedure is done to eliminate condensation of hydrocarbons. The mass flow rate of the test gases is measured using a flow meter, which works according to the Pitot tube principle. After the gases have been purged of solids, the sample is passed to the individual analyzers where the concentration of the compound is measured. The FID (Flame Ionization Detector) analyzer measures the concentration of unburned hydrocarbons, the NDUV (Nondispersive Ultra Violet Detector) analyzer measures the sum concentration of NO and NO_2. The NDIR (Nondispersive Infrared Detector) analyzer measures the concentration of carbon monoxide and carbon dioxide.

SEMTECH DS is also equipped with electrochemical sensor enabling examination of oxygen content in the analysed exhaust gases. The data on engine operating parameters are obtained from the OBD system. Additionally, the device, thanks to the cooperation with GPS, enables to determine the location of the tested object [9, 11]. The table below summarizes the measurement characteristics of each exhaust gas compound by the analyzer (Table 2).

Table 2. Specification for measurement of exhaust gas compounds by Semtech DS [11]

Tested compound	Measuring range	Accuracy of measurement
THC	0–10000 ppm	±2.5%
NO_x	0–3000 ppm	±3%
CO	0–10%	±3%
CO_2	0–20%	±3%
O_2	0–20%	±1%

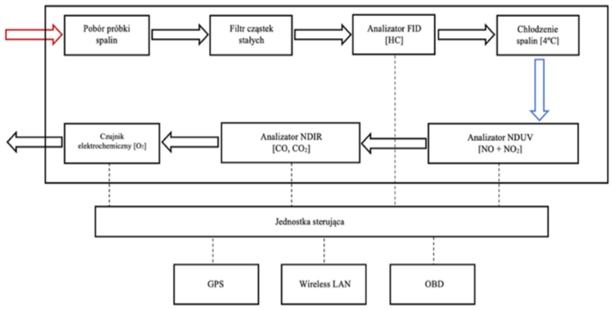

Fig. 2. Scheme of the operation of the SEMTECH DS analyzer [12]

Fig. 3. SEMTECH DS analyzer [11]

2.2. Research cycle

Forklift trucks are widely used in many industries – they are used in production halls, warehouses and distribution and logistics centers. In the case of transport processes, one of their main tasks is to carry out loading and unloading of goods from vehicles. The study of fuel consumption and emissions of forklift trucks was carried out on the basis of a modified VDI2198 (Fig. 4) test proposed by one of theauthors of the publication. The test includes the "empty run" i.e. driving the forklift truck without any load.

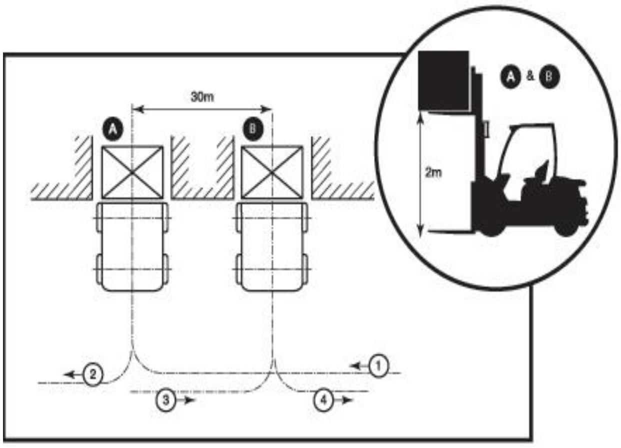

Fig. 4. The VDI2198 test [15]

The proposed test cycle (Fig. 5) consisted of the following stages:

1. loading and lifting to a height of one meter and lowering in bay A,
2. drive the cart out of bay A,
3. drive the cart to bay B (30 m),
4. lowering and unloading of the goods in bay B,
5. drive out of bay B,
6. Unloaded driving to bay A.

In order to show the influence of operating conditions on the emission structure and fuel consumption, the above cycle was carried out in two variants – at an external storage yard and inside a closed warehouse.

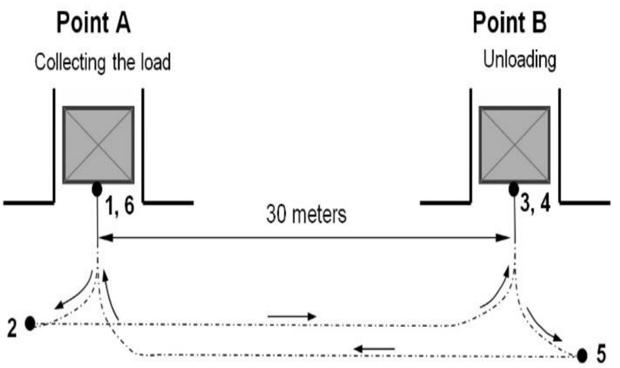

Fig. 5. Scheme of the research cycle

3. Results of the study

Tests of forklift trucks powered by diesel and LPG were performed in a developed research cycle realizing 10 repetitions for each condition – travel outside and inside the warehouse. The objects were loaded with the same mass of cargo and the runs were performed by the same operator. Outside the warehouse, the runs were made on a paved surface. In the storage hall, on the other hand, the floor was made of concrete. It was characterized by a smooth surface and the absence of possible irregularities, in contrast to the cobblestone surface. During the measurements, the exhaust gas compounds were measured: NO_x, CO, THC and CO_2. In this paper, the on-road emission values of NO_x, CO, and THC are presented for 10 measurement cycles to demonstrate the repeatability of the runs performed. Turning to the analysis of the NO_x road emission for a forklift powered by diesel, it was noticed that its values during the passage with and without the load are higher for the measurements made in the warehouse (Fig. 6). This is due to the higher dynamics of the trip, which was made possible by the quality of the substrate on which the forklift truck moved. Analyzing also the influence of the mass of the transported load on the NO_x emission values, it was shown that the average difference between the travel with and without the load was 5.2 g/km outside the hall, and 4.4 g/km in the warehouse hall. In both cases, loading the forklift with cargo resulted in a 40% increase in on-road NO_x emissions.

Carbon monoxide emissions showed a similar relationship. Driving with a load resulted in an increase in on-road emissions of over 45% for both test variants. In contrast to nitrogen oxides, higher emissions were observed for carbon dioxide during off-storage trips. This relationship was a result of the forklift driving more steadily and quietly in the outdoor storage yard (Fig. 7). The driving style was due to the fact that the operator had to adapt the driving dynamics to the unevenness of the ground when driving over paving stones, in order to ensure the safe transport of the load. The average on-road CO emissions during the work in the outdoor storage yard were almost twice as high during the load carriage and amounted to 4.2 g/km.

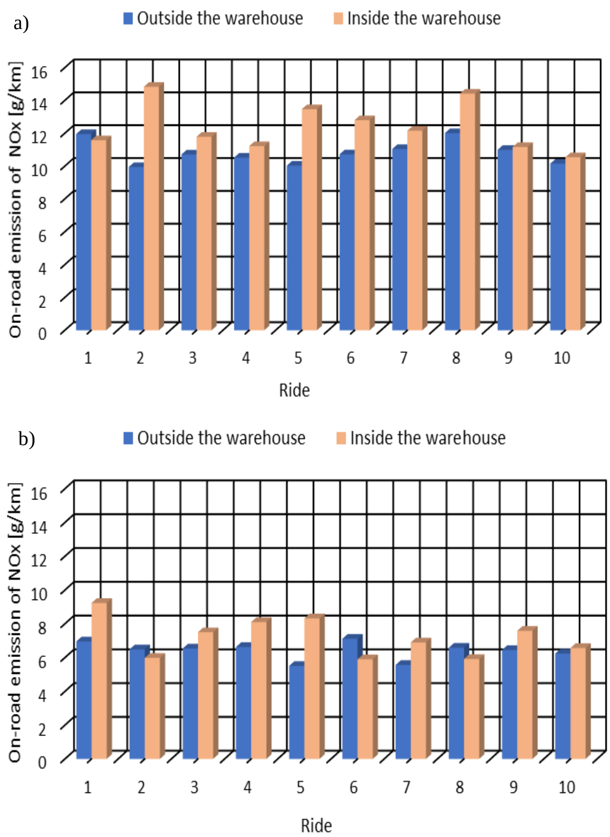

Fig. 6. On-road emissions of NO_x of a forklift truck equipped with a CI engine: a) when carrying a load, b) when driving unloaded

Tests under actual operating conditions showed significantly higher THC emissions for runs inside the warehouse (Fig. 8). On average, the value was 1.4 times higher for both loaded and unloaded runs. This trend may be due to the direct injection of the fuel dose into the flame. When analyzing the average emission of unburned hydrocarbons, it is worth noting that loading the truck with one ton of load, resulted in an increase in emissions by 60% relative to the so-called "empty run".

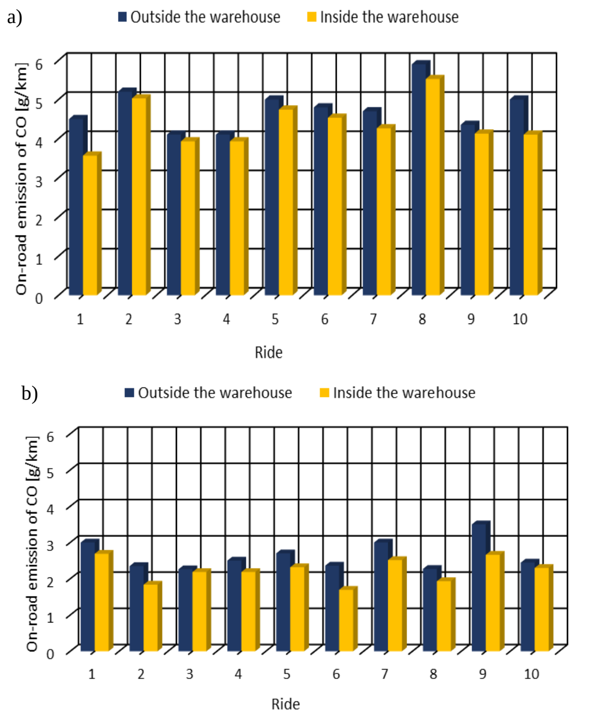

Fig. 7. On-road emissions of CO of a forklift truck equipped with a CI engine: a) when carrying a load, b) when driving unloaded

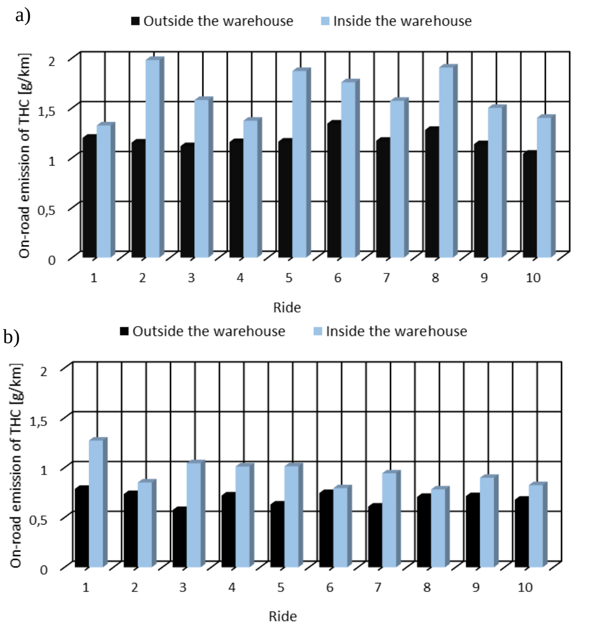

Fig. 8. On-road emissions of THC of a forklift truck equipped with a CI engine: a) when carrying a load, b) when driving unloaded

The analysis of the on-road emissions of nitrogen oxides for the LPG truck shows exactly the same trend as for the diesel truck (Fig. 9). For each trip, both for driving with and without load, the emissions were higher when the forklift was operating inside the warehouse. This is also due to the way the forklift is operated. While transporting the load, the average NO_x emission was 30.06 g/km when operating inside the warehouse and 33.76 g/km when driving outside. The difference in emissions of the previously mentioned compound is 11%.

Testing of the LPG powered forklift showed higher on-road carbon monoxide emissions during trips outside the warehouse. This trend is consistent with the diesel-powered forklift and is also due to the driving dynamics of the unit (Fig. 10).

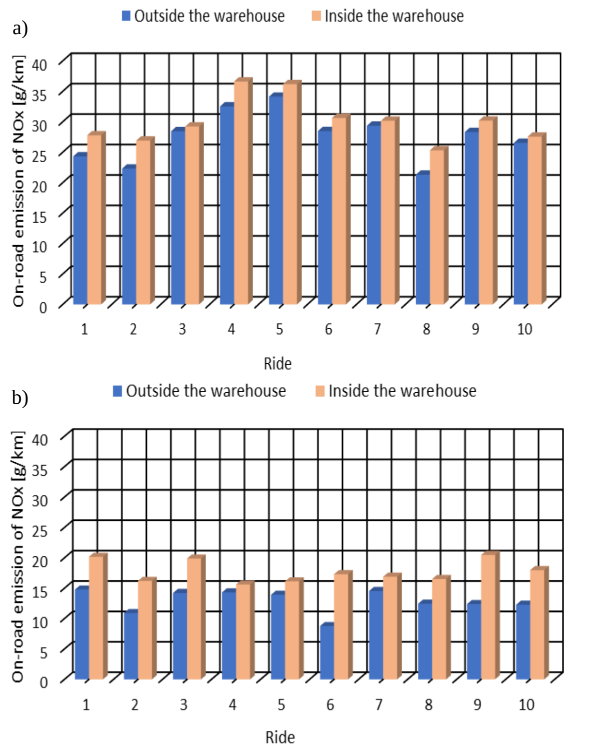

Fig. 9. On-road emission of NO_x of a forklift truck fitted with a SI LPG engine: a) when carrying a load b) when driving unloaded

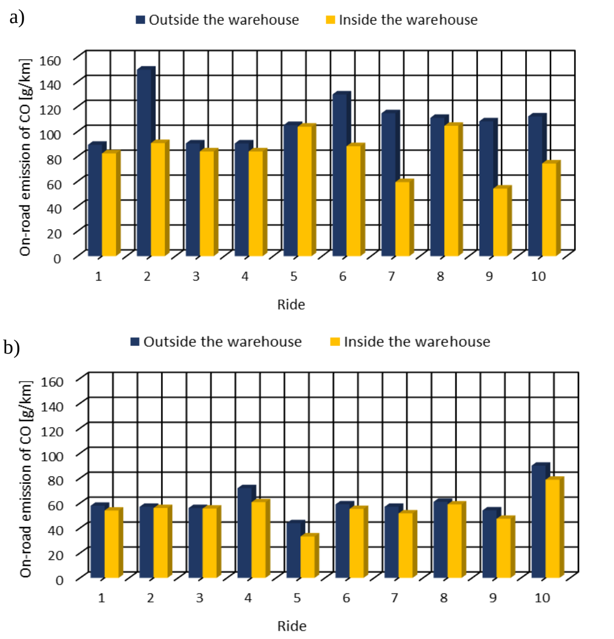

Fig. 10. On-road emission of CO of a forklift truck fitted with a SI LPG engine a) when carrying a load b) when driving unloaded

The average CO emissions for loaded trips are 88.6 g/km for the indoor test and 109 g/km for the outdoor yard trip, respectively. For the unloaded forklift test, the on-road emissions reached an average of 55.2 g/km in the indoor yard and 47.5 g/km in the outdoor yard. Such large increases relative to the compression-ignition truck are due to low-temperature mixture combustion and local and global air shortage. In addition, the reason may be due to the fact that LPG vehicles face the problem of variable composition of the fuel-air mixture, which also increases emissions. The difference in CO emissions for trips with a load inside and outside the warehouse is about 19%. Comparing this to and unloaded trip inside and outside the warehouse the difference is 5 percentage point lower at around 14%.

Turning to the analysis of THC emissions of LPG-powered trucks, increased emissions can be observed during indoor operations. This trend was maintained for each stage of the unit operation (Fig. 11). Much higher emission of the compound is a result of low efficiency of the TWC system, which did not fully oxidize propane and butane. Additionally, it is worth noting that loading the unit with cargo resulted in a more than 3-fold increase in hydrocarbon emissions relative to unloaded runs.

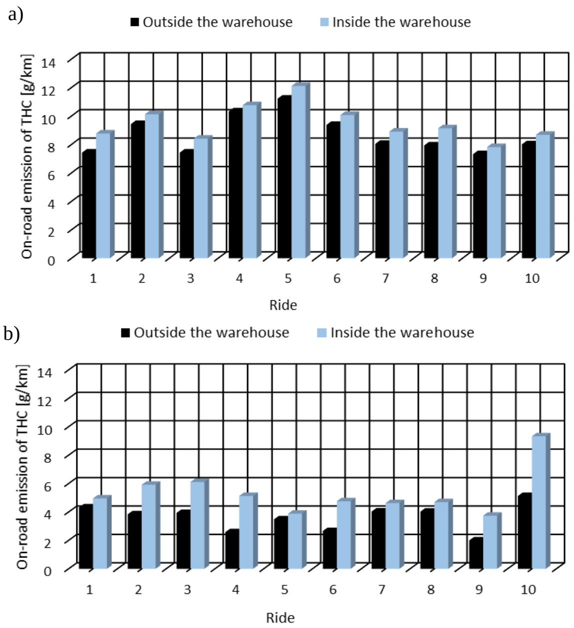

Fig. 11. On-road emission of THC of a forklift truck fitted with a SI LPG engine: a) when carrying a load b) when driving unloaded

Analyzing the recorded data of the study (Fig. 12), the average fuel consumption of the self-ignition engine from forklift was 83 dm^3/100 km when carrying a load outside the hall, while without a load it is 51 dm^3/100 km, in the case of trips inside the hall the average specific fuel consumption for carrying a load is 96 dm^3/100 km and 55 dm^3/100 km without a load. An inverse relationship was recorded in the specific fuel consumption for the LPG vehicle. For the trip with cargo outside the hall, the average specific fuel consumption is 203 dm^3/100 km, and 73 dm^3/100 km without cargo. On the other hand, in the case of recording the drive inside the hall, the measured values were 168 dm^3/100 km with load and 84 dm^3/100 km without load, respectively. Such a correlation is influenced, similar as in the case of the emission of harmful toxic compounds, by the quality of the ground on which the test objects moved and the driving technique of the driver who was responsible for driving them.

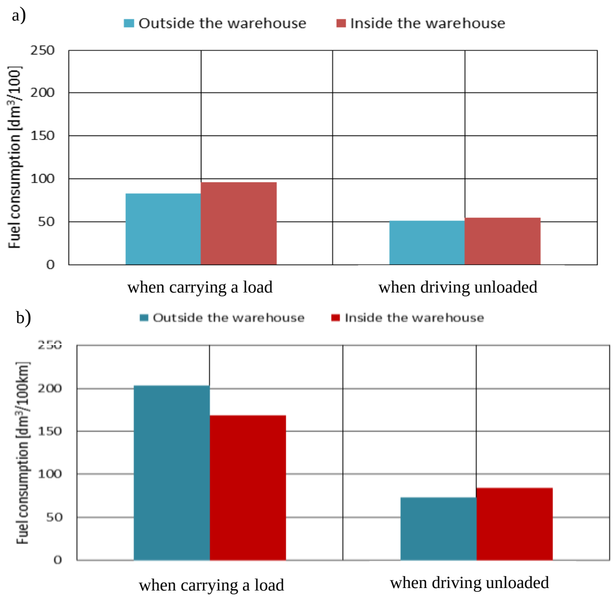

Fig. 12. Average specific fuel consumption, a) compression ignition engine vehicle, b) LPG vehicle

4. Summary

Road transport in the total structure accounts for the majority of the share compared to the other transport modes. Two forklift trucks were tested, which differed in the type of fuel used to power the internal combustion engines installed in them. In addition, the author's research test related to the testing of vehicles from the NRMM category using the PEMS apparatus for measuring harmful toxic compounds of exhaust gases was implemented. Emissions of nitrogen oxides and hydrocarbons both in the vehicle equipped with a compression-ignition engine and powered by LPG were higher during the drive inside the hall. This is due to the type of substrate, the driver's dynamics and driving style. This poses a particular threat to employees of closed warehouses who are directly exposed to these compounds. In the case of carbon monoxides, emissions were higher during off-hall trips. The authors also decided to compare the results related to the emission of harmful toxic compounds for both unloaded and loaded trips. The results were several times higher when carrying a load of 1000 kg. The average specific fuel consumption also increased when the cargo was carried. Increasing the load on the power unit through the cargo was one of the components of the increase in the previously mentioned parameter. In conclusion, both the place where the transport took place and whether the test object transported a cargo of a given mass influence the increase in emission of harmful toxic compounds of exhaust gases. The method proposed by the authors makes it possible to assess the processes of cargo loading. Conclusions from the analysis can be used to optimize logistic processes and help in designing warehouse infrastructure.

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Nomenclature

CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
FID	flame ionization detector
GPS	global positioning system
LPG	liquefied petroleum gas
NDIR	non-dispersive infrared
NDUV	non-dispersive ultra violet spectroscopy
NO_x	nitrogen oxides
NRMM	non-road mobile machinery
NRTC	non-road transient cycle
NRSC	non-road steady-state cycle
PEMS	portable emissions measurement system
SI	spark ignition
THC	hydrocarbons
TWC	three way catalyst

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