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Use of Toxicity Indexes in Reference to Carbon Dioxide for a Vehicle Equipped with a Two-Stroke Engine without an Exhaust Aftertreatment System

Łukasz Rymaniak[1], Bartosz Ziętara[1], Natalia Szymlet[1*], Daniel Kołodziejek[2]

[1] Institute of Combustion Engines and Powertrain, Faculty of Civil and Transport Engineering, Poznan University of Technology, ul. Piotrowo 3, 60-965 Poznań, Poland

[2] Institute of Railway Transportation, ul. Mazowiecka 42, 60-623 Poznań, Poland

* Corresponding author e-mail: natalia.szymlet@put.poznan.pl

ABSTRACT

Research work on the new assessment of environmental indicators using equipment from the PEMS group (Portable Emission Measurement Systems) with motor vehicles is being developed. Due to the miniaturization of equipment, there are new measurement possibilities for more and more numerous groups of vehicles, including two-wheelers. The article presents the research and a summary of the results of a moped equipped with a two-stroke engine, approved in accordance with the Euro 3 standard. The research object is mainly used for driving in urban traffic. Therefore, the research route was created as the first communication frame in the Poznań agglomeration. In the analysis of the results, the author's M toxicity index was proposed, which is based on the assumption that CO_2 emission is a measure of the correctness of the combustion process. The equipment from the PEMS-AxionR/S+ group, characterized by small dimensions and low weight, was used to determine the actual motion parameters and the emission of toxic compounds. In the analysis of the measurement results, dimensionless indicators of toxicity M of gaseous compounds were determined and a comparative analysis was made with the values of other objects obtained in the course of previous research (motorcycle, passenger car, off-road vehicle, hybrid bus and agricultural tractor). Due to the engine design (two-stroke type), the worst environmental indicators were obtained for CO and HC compared to other tested vehicles.

Keywords: moped, PEMS, toxicity index, exhaust emission, real driving conditions.

INTRODUCTION

Single-track engine powered vehicles are a wide range of both mopeds and motorcycles with a large range of displacement and power. It also includes tricycles and light quadricycles up to 400 kg unladen weight. Despite the great variety, the share of these vehicles is small compared to other vehicle categories. Compared to other means of transport, they are characterized by low maintenance costs and high mobility, especially in urban areas. They are used in the transport of people and materials, their usage is wide-ranging.

In Poland, in 2019, the total number of registered motorcycles reached a value of almost 1.6 million, including over half a million motorcycles up to 125 cm^3 (Figure 1), while the number of mopeds at that time was almost 1.4 million.

Since the beginning of 2022, have been registered 26,674 single-track vehicles. Compared to the previous year (2021), it is more by 10.9%. About 70% of the total number of single-track vehicles are motorcycles: 17,203 units (+17.4% y/y). There were 7,471 new mopeds (-1.5% y/y). However, when analyzing the first registrations of new motorcycles in 2021 according to the engine displacement, it is noted that over 42% of them are vehicles equipped with engines with a displacement equal to or less than 125 cm^3 (Figure 2). A year earlier, the share of this category of motorcycles was as high as 52.4%.

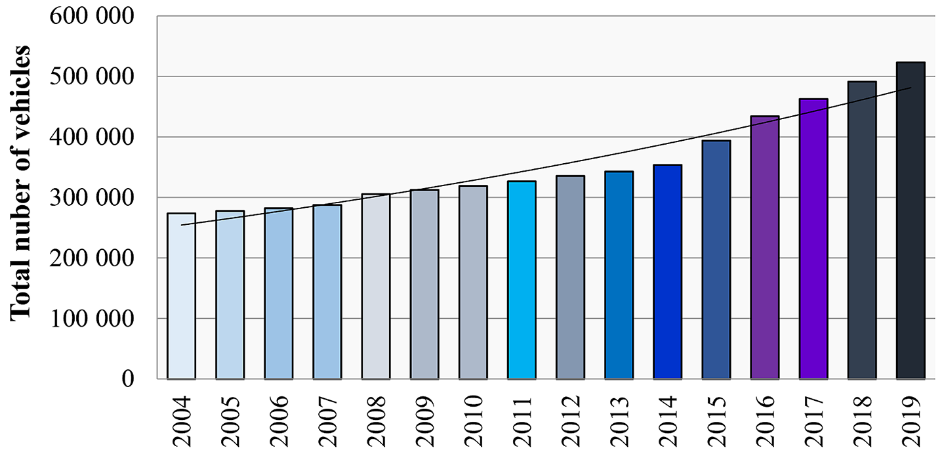

Figure 1. The total number of motorcycles <125 cm³ in Poland in 2019 [GUS, 2021]

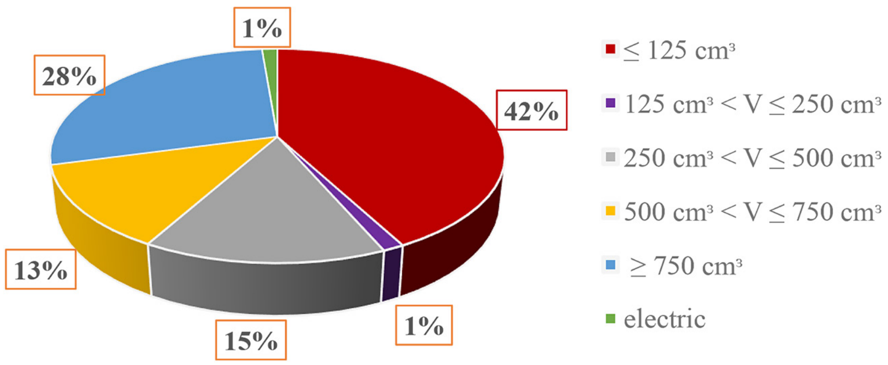

Figure 2. First registrations of new motorcycles in 2021 by engine displacement [PZPM, 2020]

TOXICITY INDEXES IN THE ECOLOGICAL EVALUATION OF THE VEHICLE

Comparing ecological indicators: road emissions [g/km] and unit emissions [g/kWh] for different types of vehicles is difficult and often not very obvious. This is due to the fact that, depending on the nature of the operation of a given vehicle, the indicators relate emissions to various parameters – road or work [Sarkan et al., 2019; Borut et al., 2021; Sarkan and Stopka, 2018]. Differences between different powertrains, operating conditions and driving style are also a problem. The main product of combustion in internal combustion engines is CO_2. The emission value of this compound is directly related to fuel consumption, but also to the quality of the combustion process. Toxic compounds such as CO, HC or NO_x are products of partial and incomplete combustion as well as the course of combustion at high temperature and pressure. Thus, by comparing CO_2 emissions to other emitted toxic compounds, it is possible to determine the toxicity index M [Merkisz and Rymaniak, 2017b]. The structure of the index M allows expressing values without dimension. The mentioned index was used in the evaluation of various groups of vehicles, but it was never used for an object equipped with a two-stroke engine without exhaust gas aftertreatment systems.

$$M_j = b * \frac{e_{real,j}}{e_{CO_2}} \quad (1)$$

where: M – dimensionless toxicity index [–];
j – the toxic compound to which the indicator relates;
b – universal constant (CO, HC, $NO_x = 10^3$; PM = 10^5);
$e_{real,j}$ – unit, road emissions lub or the compound mass determined during, tests [g/kWh; g/km; g];
e_{CO_2} – unit, road emissions lub or the CO_2 mass determined during, tests [g/kWh; g/km; g].

In the works [Szymlet et al., 2021; Merkisz and Rymaniak, 2017a; Rymaniak et al., 2021], the authors used the dimensionless toxicity index M. In the cited publications, the following objects were assessed:

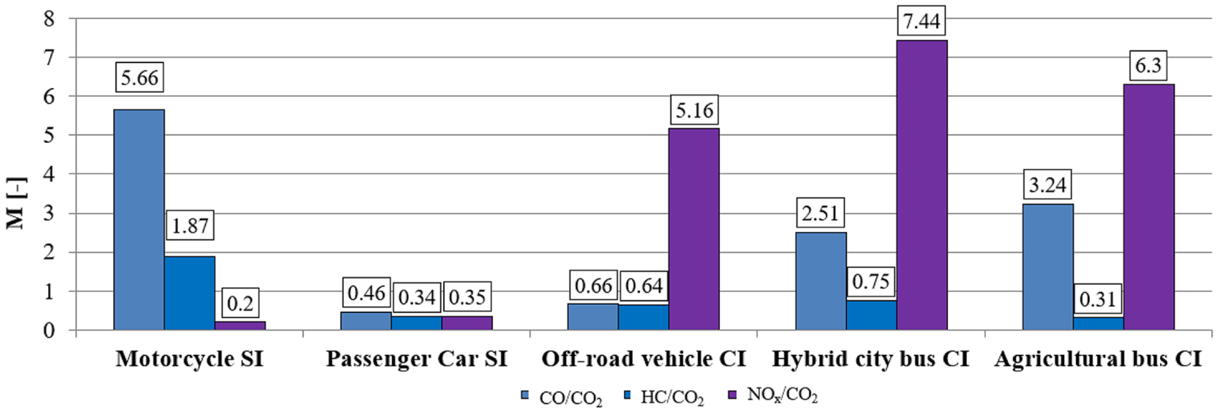

Figure 3. Comparison of the toxicity indicators determined for vehicles of different categories in the paper works [Szymlet et al., 2021; Merkisz and Rymaniak, 2017a; Rymaniak et al., 2021]

- motorcycle with SI engine (volume: 0.7 dm^3; power: 55 kW, Euro 4) [Szymlet et al., 2021];
- passenger car with SI engine (volume: 0.9 dm^3; power: 64 kW, Euro 5) [Merkisz and Rymaniak, 2017a];
- off-road vehicle with CI engine (volume: 2.5 dm^3; power: 140 kW, Euro 4) [Merkisz and Rymaniak, 2017a];
- hybrid city bus with CI engine (volume: 6.7 dm^3; power: 209 kW, Euro 5, series hybrid drive, electric motor with a power of 240 kW) [Merkisz and Rymaniak, 2017a];
- agricultural tractor with CI engine (volume: 6.7 dm^3; power: 116 kW, Stage IIIA / Tier 3) [Rymaniak et al., 2021].

The summary of the obtained results is shown in Figure 3. All objects were tested in real operating conditions, except for the motorcycle. For this vehicle, tests were carried out on a chassis dynamometer, where the parameters of the actual work were reflected. The analysis of the presented results shows that the highest values of the toxicity index occur for objects with CI engines in terms of NO_x emissions. It is particularly noticeable for the city bus, the specific nature of working in a hybrid drive was conducive to the formation of this compound. For the motorcycle, significant values were found for CO. Each of the tested vehicles was equipped with a four-stroke engine and exhaust gas aftertreatment systems.

RESEARCH METHODOLOGY

The tested object was a two-stroke moped matching the L1e vehicle class. It has a single-cylinder, crankcase-scavenged engine with a displacement of 0.049 dm^3. It is powered by a mixture of gasoline and oil in the proportion of 1:50 (1 part of oil for 50 of gasoline). The engine is air-cooled and has a power of 2.5 kW at 7000 rpm and a torque of 3.9 Nm at 7000 rpm. The vehicle was produced in 2008. Table 1 summarizes the data relating to the research object. Figure 4 shows the entire vehicle with the measuring equipment installed.

Measurement equipment from the PEMS (Portable Emission Measurement System) group - Axion RS by Global MRV was used to carry out

Figure 4. Test vehicle with the AxionR/S+ equipment

Table 1. Technical data of the test object

Parameter	Value
Engine type/fuel	2–stroke, SI
Displacement [dm^3]	0.049
Maximum power [kW/rpm]	2.5/7000
Maximum torque [Nm/rpm]	3.9/7000
Exhaust gas treatment system	Brak
Drive system	Conventional, CVT
Compliance with the norm	Euro 3

Table 2. Technical specifications of the Axion R/S+ measurement equipment [www.globalmrv.com, 2022]

Gas	Measurement range	Accuracy	Resolution	Type of measurement
HC	0–2000 ppm	± 3 %	1 ppm	NDIR
CO	0–10%	± 3 %	0.01 vol. %	NDIR
CO_2	0–16 %	± 4 %	0.01 vol. %	NDIR
NO	0–5000 ppm	± 3 %	1 ppm	E-chem
O_2	0–25%	± 3 %	0.01 vol. %	E-chem
PM	0–300 mg/m³	± 2 %	0.01 mg/m³	Laser Scatter

the tests [Rymaniak et al., 2021; Szymlet et al., 2020]. This device allows measuring the intensity of toxic compounds such as: CO_2, CO, HC, NO_x, PM. It is equipped with a GPS connection, thanks to which both the speed and the position of the vehicle are determined. The device has appropriate modules for the analysis of individual exhaust gas components. Details on the measurement characteristics can be found in Table 2. Thanks to the software based on the Windows 7 operating system and the program created in the LabVIEW environment, it allows to present the obtained results in a Microsoft Excel spreadsheet. The data recorded in the sheet are sampled at a frequency of 1 Hz, and in addition to the intensity, other parameters are also recorded, such as: vehicle speed, rotational speed of the crankshaft, absolute pressure and/or mass air flow, and inlet air temperature.

The apparatus and all required accessories have been calibrated with test gases. Aim of this procedure was to establish reference values, but also to check that all the measuring cells of the instrument give the correct indications. After the equipment and the entire object were prepared and checked, a test run was made. The route was based on the first transport frame of Poznań, where the conditions for urban use are the most important. Its length is 9.3 km, and the actual route and driving profile are shown in Figure 5.

RESULTS

The test of the object was carried out under actual operating conditions, which means that the vehicle was moving along a designated real route, which was the first communication frame of the city of Poznań. An important factor was the movement of the object in the stream of vehicles, which resulted in the introduction of many variables, such as: sudden stops, changes of the surface, possible dangerous situations on the road. These variables are characteristic for the actual operation and at the same time make it impossible to compare the tested vehicles on the basis of the distance covered only. Due to the vehicle's capabilities and restrictions related to city traffic, the vehicle used the full speed range. The greatest share in the vehicle speed is when stationary and near the speed of 50 km/h, which is the maximum speed of the vehicle.

Based on the data collected during the study, a summary of the share of work depending on the speed and acceleration of the vehicle was made (Figure 6).

This allowed to determine the conditions under which the object was moving. The predominant share of working time occurred for small accelerations and braking in the range (0; 1> m/s^2 and <-1; 0) m/s^2, amounting to almost 60%. This

Figure 5. a) test route location b) driving profile [www.gpsvisulaizer, 2022]

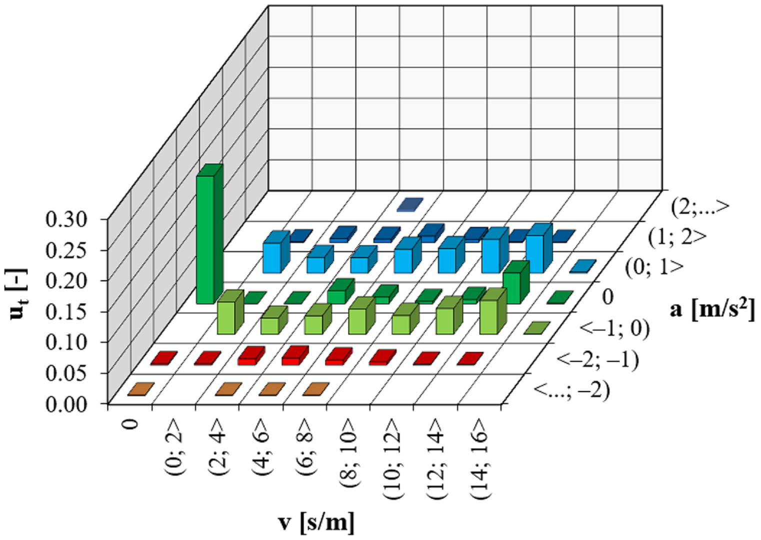

Figure 6. The area of variability of work parameters of the research object during measurement tests

share was achieved in the entire speed range from 0 to 16 m/s, i.e. the maximum speed that mopeds can achieve. Additionally, an important aspect is traveling in urban traffic together with other road users. One can also notice a small share of the maintained speeds, i.e. when the acceleration was 0 m/s^2, the largest shares for this value were obtained for standstill and driving at maximum speed. The reason for such a distribution of the share for zero acceleration is the CVT gearbox of the tested moped. It is difficult to maintain a constant speed in it, this is due to the fact that the combustion unit in the tested vehicle is characterized by a low maximum torque and a wide range of useful rotational speeds of the crankshaft.

Acquisition of measurement data was performed with a frequency of 1 Hz. On this basis, the pollutant emission and operating parameters of the test object (speed, acceleration, rotational speed of the crankshaft) were developed - Figure 7. Share of carbon dioxide in the harmful compounds of the tested exhaust gases is the highest, its course reflects the instantaneous fuel consumption, and so it is related to the load on the driveline. The maximum values reached 521 mg/s, and the average value for the measurement test was 200.7 mg/s. The waveforms of speed and emitted carbon dioxide are similar, which confirms the relationship between the load and the change in speed.

In the presented characteristics, there is a noticeable relationship between the products of partial and incomplete fuel combustion. The emission rates of carbon monoxide, hydrocarbons and carbon dioxide have the same course, only nitrogen oxides have a different course. Such dependencies result from the nature of the formation of these compounds and the nature of the power supply of the tested object. The engine of the tested object is supplied with gasoline by a carburetor, and the obtained results indicate that the fuel mixture regulation was rich in fuel (lambda > 1). The CO emission intensity is significant, which is half the result of the CO_2 value. Carbon monoxide is a product of incomplete combustion, which indicates an excess of fuel in relation to the oxygen contained in the combustion chamber. In addition, their formation was influenced by a lubricating oil, characterized by long hydrocarbon chains. Oxygen deficiency can be both local and global in the entire volume of the combustion chamber. For this compound a maximum value of 241 mg/s was recorded and the average was 74 mg/s.

Hydrocarbons appearing in exhaust gases are mainly products of incomplete combustion. The mechanism of the emission of this compound is also caused by the local oxygen deficiency and, in the case of this object, the use of a mixture of fuel and oil. The oil contained in the mixture does not burn completely, and in the scavenging process it gets to the exhaust system, increasing the emissions of hydrocarbons. Additionally, the oils used in the mixtures are protected against temperature so that they do not degrade on the friction pairs which they lubricate [Spezzano et al., 2008; Wajand J.A. and Wajand J.T, 2005]. The maximum hydrocarbon emission rate was 29 mg/s, and the test average was 9.8 mg/s.

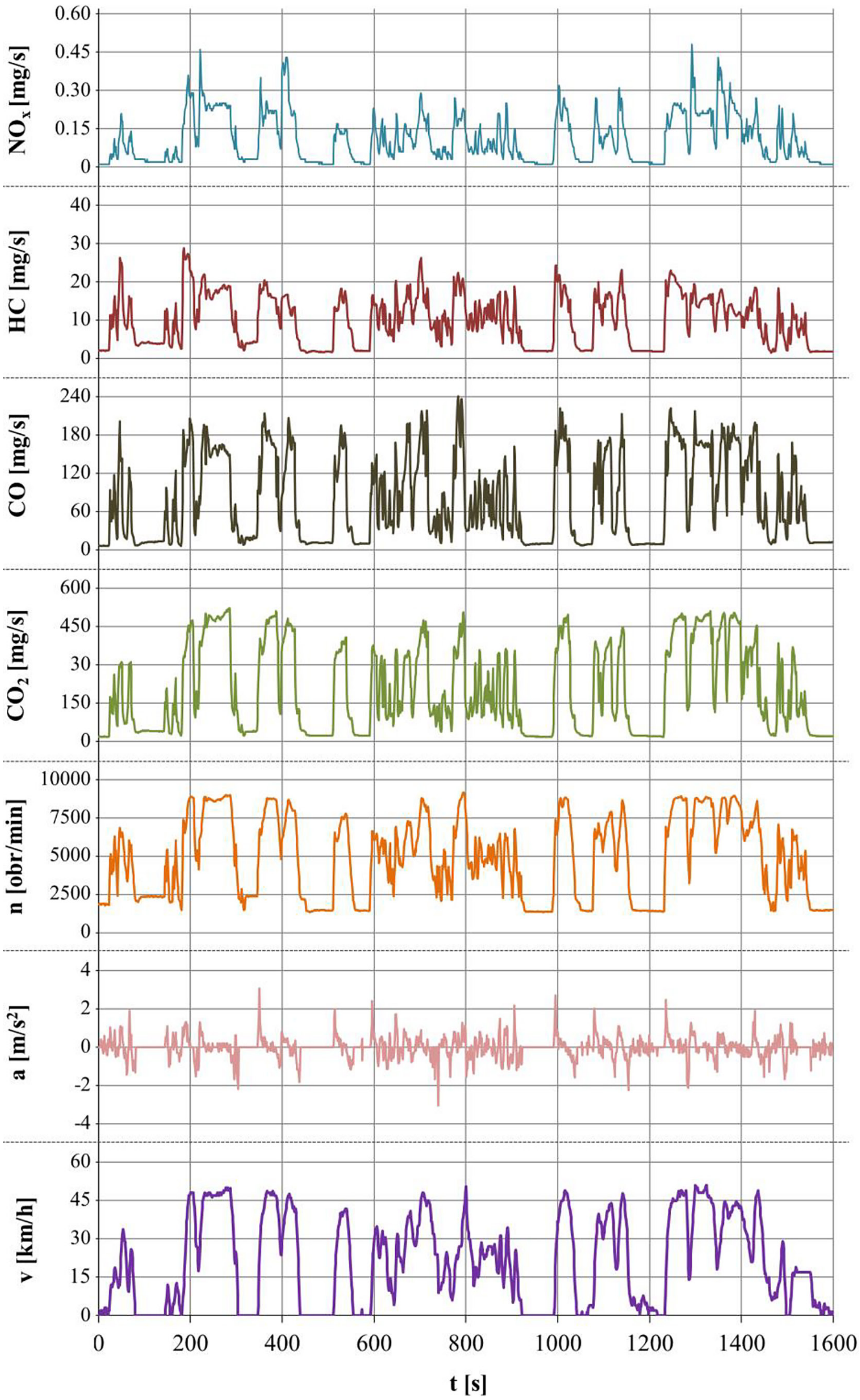

Figure 7. The operating vehicle parameters and emission characteristics presented in time

Among the considered harmful compounds, the lowest values of pollutant emissions were obtained for nitrogen oxides. According to Zeldovich's mechanism, the main factor contributing to the formation is high temperature. Rapid changes in vehicle speed mean high loads and hence high temperatures in the combustion chamber. For this reason, the highest values were obtained during intensive acceleration (up to 0.5 mg/s). While maintaining the speed, the load decreases, resulting in a lower temperature in the combustion chamber, and thus the formation of nitrogen oxides. On the basis of the obtained results, it can be concluded that the tested object was characterized by low thermal efficiency.

Based on the recorded data of the emission per second and the vehicle operation parameters, the road emission of the object during the tests was determined (Figure 8). The vehicle had a mileage of over 20,000 km, it was operational during the tests, after the technical service. The obtained data indicate that the emission of toxic compounds exceeded the limits applied for the Euro 3 standard. CO emission was exceeded more than 13 times, while for HC + NO_x it was exceeded by 41%. According to the Euro 3 standard for mopeds, only the sum of these components is considered. The conditions of the conducted research had an impact on exceeding the limits The object approval directives required tests on a chassis dynamometer in established tests for new propulsion units [Kamińska et al., 2021; Fuć et al., 2017; Merkisz et al., 2015]. The tests were carried out in actual operation, where there is a significant variability of the operating parameters of the drive system [Pielecha et al. 2019; Szałek et al., 2021; Kuranc et al., 2020]. This especially refers to transient operating conditions - sudden changes in load and rotational speed of the crankshaft. Similar trends for other objects were observed in the works of other authors [Merkisz et al., 2016; Kamińska et al., 2019; Warguła et al., 2022].

The determined values of the toxicity index M for individual toxic compounds are shown in Figure 9. Currently used exhaust gas aftertreatment systems in vehicles often have a conversion degree greater than 90% after obtaining appropriate operating temperatures.

No such systems were used in the tested object, and additionally the need to use lubricating oil with fuel contributes to obtaining significant ecological indicators. The highest value was recorded for the M_CO/CO_2 ratio and it was

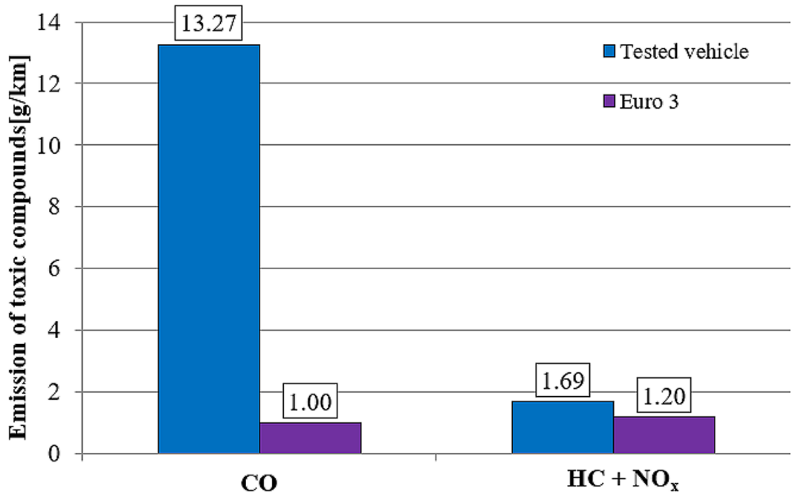

Figure 8. Comparison of the road emissions results of the tested vehicle with the limits of the Euro 3 standard

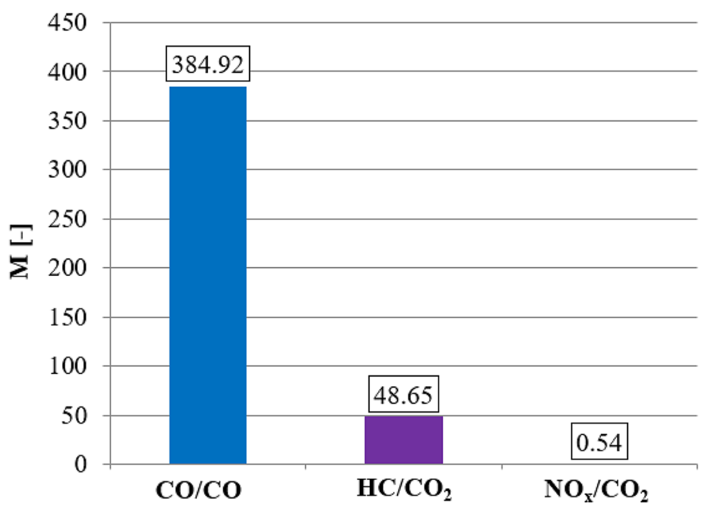

Figure 9. Comparison of M emission indicators for CO, HC and NO_x obtained during the test drive

384.92. The lowest value of 0.54 was obtained for M_CO/NO_x. In the absence of exhaust gas after-treatment systems, it proves the low efficiency of the drivetrain (low efficiency of the combustion process). Comparing the obtained results with the objects mentioned in Chapter 2, the presented trends are the closest to the motorcycle with the SI engine. However, the values for the tested object are many times higher: for CO 68 times and for HC 26 times.

CONCLUSIONS

Tests of road vehicles equipped with internal combustion engines are constantly developed and developed. Measurements in real operating conditions play a particularly important role in this work. The scope of activities is not only detailed in the context of the research itself, but also the analyzes of the obtained results. The article presents tests of a moped equipped with a two-stroke engine without an exhaust gas aftertreatment system. During the tests carried out at the object, the emission values of toxic exhaust gases were recorded, on the basis of which the intensity courses per unit of time were determined. Such a compilation of all harmful exhaust gas components together with the speed course, facilitated the assessment of the characteristics of the drive unit and the essence of the correlation between the emitted compounds.

In addition to the emission of pollutants, toxicity indicators related to CO_2 emissions were also determined for it. The use of this parameter makes it possible to assess the environmental performance of the object in a dimensionless manner, which is an advantage in the case of this type of vehicle. The obtained results for M_CO/CO_2 and M_HC/CO_2 reached significant values, compared to other tested objects mentioned in chapter 2. On this basis, a conclusion was made - for vehicles without exhaust gas aftertreatment systems, the formula for the toxicity index M may omit the universal constant for the assessment CO and HC. However, it should be clearly stated which of the compared objects have such systems and which do not.

In tests of single-track vehicles, it is necessary to develop pollutant emission tests in real operating conditions. It becomes possible due to the miniaturization of measuring apparatus, as well as the development of research methods. This action is necessary due to the increasing population of the group of vehicles undertaken, which, according to forecasts, will develop. In the presented study, the emission of gaseous toxic compounds was assessed, in the perspective of subsequent studies the emission of particulate matter and the qualitative assessment of the emitted hydrocarbons using gas chromatography are to be carried out.

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