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THE ASSESSMENT OF VEHICLE EXHAUST EMISSIONS REFERRED TO CO_2 BASED ON THE INVESTIGATIONS OF CITY BUSES UNDER ACTUAL CONDITIONS OF OPERATION

OCENA EMISJI ZANIECZYSZCZEŃ Z POJAZDÓW W ODNIESIENIU DO CO_2 NA PODSTAWIE BADAŃ AUTOBUSÓW MIEJSKICH W RZECZYWISTYCH WARUNKACH EKSPLOATACJI*

The paper discusses the assessment of the exhaust emissions from heavy-duty vehicles following investigations under actual traffic conditions. The environmental characteristics presented thus far were mainly based on unit or road emissions. The paper presents an analysis of exhaust emissions referred to the harmful CO_2, which was assumed as measure of correctness of the combustion process. The parameters determining this way are referred to as emission indexes. The research objects were 18-meter city buses fitted with three types of powertrains: conventional engine, hybrid (electric motor combined with a diesel engine) and a spark ignition engine fuelled with compressed natural gas (CNG). All buses were Euro V–EEV compliant. The measurements were performed according to the SORT 2 driving test procedure on the test route within the Poznan agglomeration. Investigations performed under actual traffic conditions allow a true assessment of environmental performance of a given research object because they cover a much greater engine operating parameter variability range compared to laboratory and homologation tests. The performed road tests and their analysis led to conclusions related to the applicability of the developed method of emission assessment based on emission indexes for vehicles fitted with different powertrains.

Keywords: *city bus, emission of CO_2 and other exhaust components, laboratory and actual test conditions, powertrain, emission index.*

W artykule przedstawiono rozważania dotyczące oceny emisji zanieczyszczeń z pojazdów ciężkich na podstawie badań realizowanych w rzeczywistych warunkach eksploatacji. Przedstawiane do tej pory charakterystyki ekologiczne silnikowych środków transportu opierały się przede wszystkim na emisji jednostkowej lub drogowej. W pracy przedstawiono analizę emisji związków toksycznych odniesioną do związku szkodliwego CO_2, dla którego założono, że jest miarą poprawności realizacji procesu spalania. Wyznaczone w ten sposób parametry nazwano wskaźnikami toksyczności. Obiekty badawcze stanowiły osiemnastometrowe autobusy miejskie wyposażone w trzy rodzaje układów napędowych: konwencjonalny i hybrydowy z silnikami ZS, a także pojazd zasilany sprężonym gazem ziemnym z silnikiem ZI. Wszystkie autobusy spełniały normę Euro V–EEV. Pomiary wykonano zgodnie z procedurą testu jezdnego SORT 2 oraz na trasie badawczej w aglomeracji poznańskiej. Badania w warunkach rzeczywistej eksploatacji pozwalają dokonać rzetelnej oceny ekologiczności danego obiektu badawczego, ponieważ obejmują znacznie większy obszar zmienności parametrów pracy silników spalinowych w porównaniu z laboratoryjnymi testami homologacyjnymi. Wykonane badania drogowe i ich analiza pozwoliły na sformułowanie wniosków dotyczących słuszności stosowania opracowanej metody oceny emisji zanieczyszczeń, bazującej na wskaźnikach toksyczności, dla pojazdów wyposażonych w różne rodzaje układów napędowych.

Słowa kluczowe: *autobus miejski, emisja CO_2 i związków toksycznych w spalinach, eksploatacyjne i testowe warunki badań, układ napędowy, wskaźnik toksyczności.*

1. Introduction

The conditions of operation of a combustion engine under actual traffic conditions are characterized with a wide range of engine speeds and torques. This has a direct impact on the vehicle fuel consumption and exhaust emissions that may be expressed with a variety of characteristics. For the PC (passenger car) vehicle category, it is the road emissions that are most frequently used i.e. the mass of a given exhaust component is referred to a given distance covered (e.g. g/km). In the case of HDV (heavy-duty vehicles) vehicles and non-road vehicles, the most efficient way to asses their environmental impact is to use unit exhaust emissions, i.e. the mass of a given exhaust component is referred to performed work (e.g. g/(kW·h)). Heavy-duty vehicles use engines of high torques; therefore, the homologation tests are performed exclusively on engine test beds (measurement cost optimization). To some extent, these tests simulate the actual operating conditions of a vehicle, yet they do not fully reproduce the actual vehicle driving cycle, particularly if city buses are the case [11].

Based on the works carried out in recent years, we know that the qualitative and quantitative measurements of exhaust emissions performed under laboratory conditions may significantly diverge from the actual emissions of a vehicle from a given category. This is also the case for HDV [7, 13]. Therefore, actions are being taken to devel-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** op detailed and universal methods of assessment of exhaust emissions under actual conditions of operation (RDE – real driving emissions) [2, 6, 8–10]. The rapidly advancing PEMS (portable emissions measurement system) equipment and its miniaturization allows carrying out increasingly more accurate tests of vehicle environmental performance under actual operating conditions. Currently, pilot projects are underway worldwide addressing this issue [1, 3, 8, 12].

The homologation standards applied thus far, related to the environmental performance of vehicles of different categories were based on laboratory tests performed only on chassis or engine dynamometers. Legislation introduced in the European Union (Euro VI/6) force the performance of measurements under actual operation [4]. This aims, inter alia, at the assessment of the environmental performance of a given solution at individual points of work of an engine or a vehicle other than that predefined in laboratory tests. It also aims at determining the emission indexes for compliance in operation. Research and development works very often rely on time density characteristics (TD – time density) and 3D emission characteristics created on their basis that present second-by-second emission of a given exhaust component as a function of: engine speed – torque (n–T) or vehicle speed – acceleration (V–a). Given the time of operation, it is possible to characterize motion with a discrete function of coordinates T and n.

To determine the emission characteristics, parameters related to motion or work of a vehicle are utilized. In terms of road emission, it is quite simple to determine the covered distance, which is recorded in both the OBD system (calculated based on instantaneous vehicle speed) and the GPS system (global positioning system) – an inseparable component of the PEMS equipment. The determination of actual work performed by an engine or the entire powertrain (if hybrid vehicles are the case) is more difficult when calculating the unit emission of a given exhaust component. Instantaneous power output is calculated based on the engine speed and load, the values of which can be pulled from the OBD system. The first of the said parameters is obtained directly by induction sensors or Hall effect sensors and the data obtained with this method are sufficient. The torque is obtained from the pressure values in the fuel system and the opening time of the injector, which is critical for the accuracy of the measurement [5]. In homologation tests, the 'net' parameters of power output and load must be considered, i.e. parameters obtained on a test stand at the end of the crankshaft with additional aggregates [14], which is why certain divergence appears compared to the values obtained under actual operating conditions. The reason for this is that the data pulled from the OBD system allow for engine internal resistance. In the calculations, one can allow for this by including the percentage share of friction, but it is some sort of simplification, because the actual resistance is dependent on a variety of factors. These factors are rarely linear and they change with the parameters of the engine operation.

2. The assessment of the exhaust emissions referred to CO_2

As a result of combustion of hydrocarbon fuels in the engine, thermal energy is released along with a variety of components harmful for the environment. Carbon dioxide CO_2 forms as a result of complete oxidation, while CO, THC (total hydrocarbons), NO_x and particulate matter (mass and number) are a result of non-full and incomplete combustion at high temperatures. They are unwanted by-products having great impact on the natural environment. Therefore, in different regions/countries of the world various kinds of emission related restrictions are imposed on motor vehicles. Carbon dioxide is not a toxic component but harmful – it contributes to the greenhouse effect and in higher concentrations is poisonous for the living organisms.

Given the physicochemical course of oxidation inside the combustion chamber, we may assume that CO_2 is a measure of correctness of this process, which is why it is considered useful in the assessment of the exhaust emissions from many types of combustion engines. Besides, when defining a powertrain as a combustion engine together with aftertreatment systems, we may also consider aspects related to the environmental impact of vehicles of different categories, particularly in terms of road tests. To this end, it is necessary to apply a quantitative emission index M defined with the quotient:

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

where: M – dimensionless emission index [–]; j – exhaust component, for which the emission index was determined; b – universal constant (for CO, THC and $NO_x = 10^3$, for PM = 10^5); $e_{real,\,j}$ – unit or road emission or mass of the exhaust component j determined in the test [g/(kW·h); g/(km); g]; e_{CO2} – unit or road emission or mass of CO_2 (tantamount to $e_{real,\,j}$) [g/(kW·h); g/(km); g].

3. Research methodology under actual vehicle operation

Three 18-meter city buses of similar performance were used for the research. Such vehicles are most often used on heavily loaded bus routes, where many passengers are carried. The first research object was fitted with a conventional diesel powertrain, the second research object was a serial hybrid and the third research object was fitted with a CNG-fuelled spark ignition engine (Fig. 1). In the paper, they have been marked: DIESEL, HYBRID and CNG respectively. All buses were homologated, complete and fully operative. Each of the objects was compliant with the Euro V – EEV (Enhanced Environmentally Friendly Vehicle). In order to prepare the vehicles for the tests a dummy load was installed to simulate the passenger load during daily operation – the weight of bus including the load was 24 000 kg.

The exhaust emissions tests performed under actual traffic conditions allow an obtainment of actual environmental and economic indexes. A careful selection of the test routes is extremely important in the process of development of the measurement methodology (Fig. 2). In city traffic, the operating conditions are influenced by many factors (road congestion, traffic organization, traffic lights), which is why it is characterized by a great variability and randomness. During the development of the research methodology, it was assumed that the measurement would be performed on city buses in actual traffic in SORT 2 complex trapezoidal normalized tests (Standardized On-Road Tests 2 – Easy Urban) defined by UITP (Union Internationale des Transports Publics - International Organization for Public Transport) [13]. The characteristics of the test have been presented in Fig. 2a. The tests were carried out on a city route of a local bus operator, classified as one of the most heavily occupied routes (length and number of carried passengers) (Fig. 2b). The total length of the test route was 11.2 km and covered 27 bus stops including bus terminals. The test run started in the northern part of the city and continued through streets of various congestion to the exact downtown area of Poznan.

A portable emissions measurement system (PEMS) was used for the tests under actual traffic conditions: SEMTECH DS and AVL MSS (Fig. 3). The equipment allows carrying out tests on spark ignition and diesel engines compliant with the standard of Euro III and higher. The exhaust gas of the tested vehicle is passed to the mass flow probe, where a sample is taken. The tested volume of the gas is transported through a heated line to a set of SEMTECH DS analyzers. At this point the concentrations of individual gaseous components are measured: THC (FID – flame ionization detector), NO_x (NDUV – non-dispersive detector, ultra violet), CO_x (NDIR – non-dispersive detector infra red), and O_2 (electrochemical sensor). At the same time, a sample of exhaust gas is taken to the portable MSS analyzer, where a)

Parameter	DIESEL
Type/fuel	4-stroke, CI/ diesel fuel
Displacement [dm^3]	9.2
Compression ratio	17.5
Maximum power output [kW]/[rpm]	265/1900
Maximum torque [N·m]/[rpm]	1450/1100–1700
Aftertreatment	SCR/DPF

b)

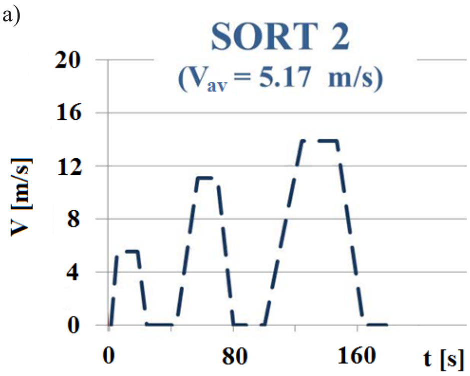
Parameter	HYBRID
Type/fuel	4-stroke, CI/ diesel fuel
Displacement [dm3]	6.7
Compression ratio	17.2
Maximum power output [kW]/[rpm]	209/2300
Maximum torque [N·m]/[rpm]	1008/1200–1800
Aftertreatment	SCR/DPF

c)

Parameter	CNG
Type/fuel	4-stroke, SI/ compressed natural gas
Displacement [dm3]	8.9
Compression ratio	12
Maximum power output [kW]/[rpm]	239/2000
Maximum torque [N·m]/[rpm]	1356/1300–1400
Aftertreatment	TWC

Fig. 1. Technical specifications of the research objects

a)



Parameter	SORT 2
Average speed [m/s]/[km/h]	5.17/18.6
Share of stationary vehicle in the test [%]	33.4
Constant speed in profile 1 [m/s]/[km/h]/[m]	5.6/20/100
Constant speed in profile 2 [m/s]/[km/h]/[m]	11.1/40/220
Constant speed in profile 3 [m/s]/[km/h]/[m]	13.9/50/600
Time of stationary vehicle after profile [s]	20/20/20
Distance in the test [m]	20

b)

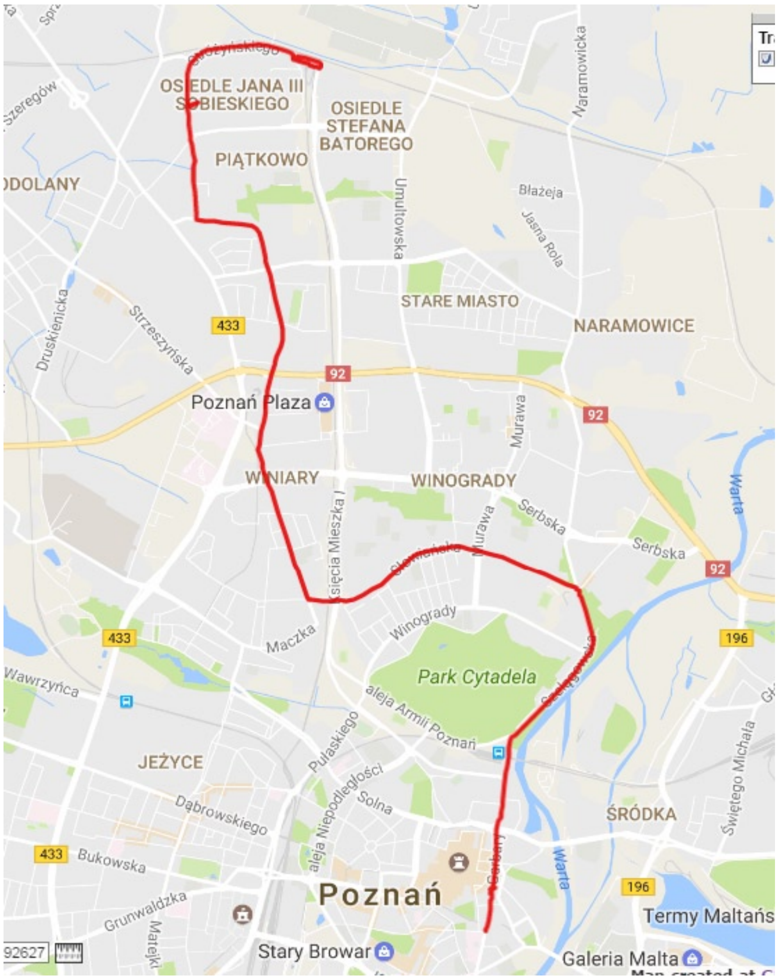


Fig. 2. RDE research methodology: a) SORT 2 driving cycle, b) city bus route [15]

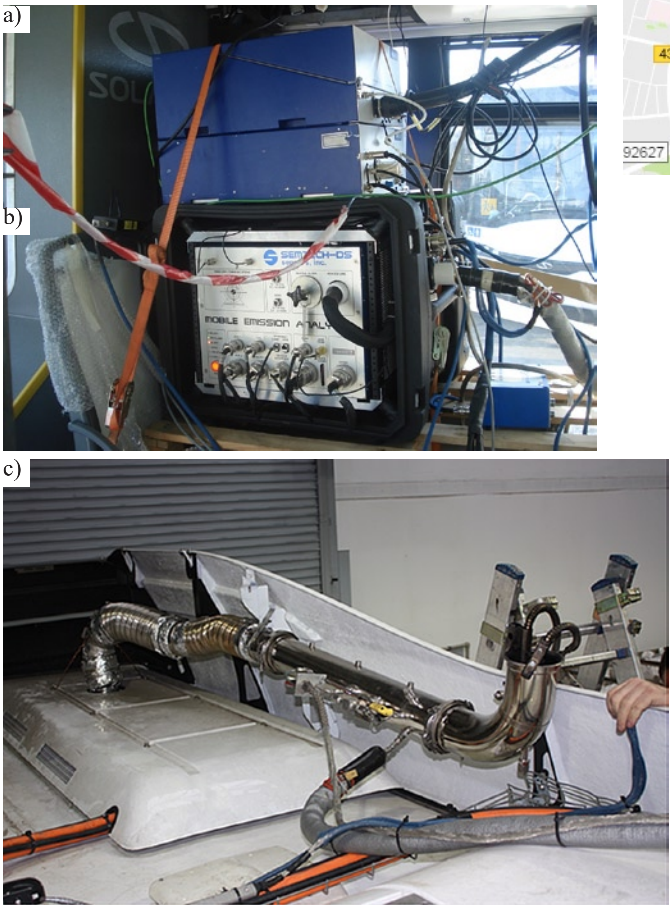


Fig. 3. View of the PEMS equipment during operation on a bus: a) AVL MSS 483, b) SEMTECH DS, c) mass flow meter of the exhaust gas

the concentration of PM is measured based on the photoacoustic method.

4. Results

4.1. Exhaust emissions referred to CO_2 in the SORT test

Based on the performed tests, a second-by-second emission of individual exhaust components (CO, THC, NO_x and PM) was determined that was referred to the second-by-second emission of CO_2. Individual relations along with the operating parameters of the engines and the speed curves of the diesel vehicle selected for the presentation of results have been shown in Fig. 4. The presentation indicates that always during engine braking, when the engine is propelled by the vehicle wheels and the second-by-second emission of CO_2 is close to zero, a significant increase of the dimensionless index M occurs. This confirms unwanted phenomena inside the engine cylinders – choking the flame, non-full and incomplete combustion as well as very poor performance of the aftertreatment systems. Such a situation always occurs when the gear is reduced, which is confirmed by the engine torque and speed curves. Based on the values obtained for the index M_NO_x/CO_2 (85 during braking in the second profile of the test) it is possible to infer that the efficiency of the SCR, whose operation mainly depends on the temperature and exhaust gas mass flow is reduced. The maximum values of individual indexes were obtained for: $M\_CO/CO_2 = 191$ and $M\_PM/CO_2 = 31$ in the third profile of the SORT 3 test and $M\_THC/CO_2 = 4.6$ that occurred in the first stage of the analyzed cycle.

Consider of the recorded emissions of individual exhaust components, a bar graph of the calculated M indexes for the SORT 2 was drawn (Fig. 5). For CO and THC referred to CO_2 the highest values were obtained by the vehicle fueled with CNG. The vehicle fitted with a spark ignition engine reached a value 8 times higher for

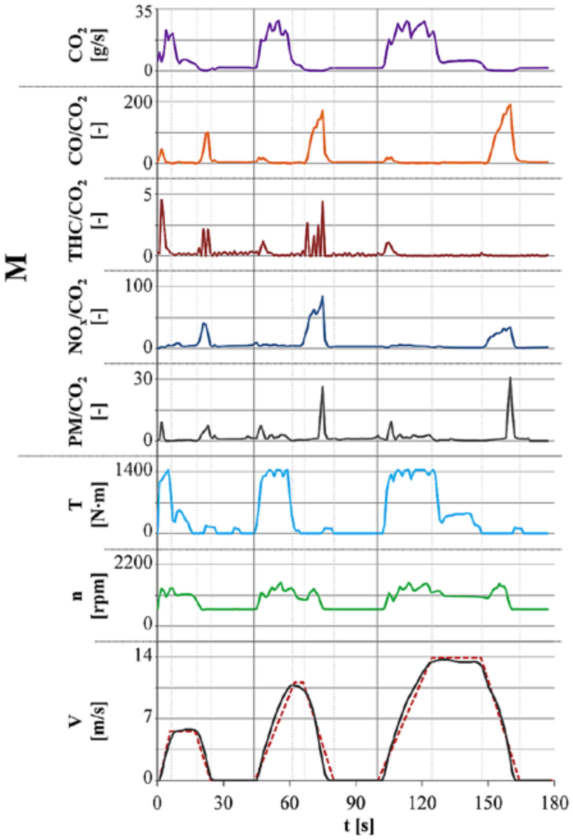


Fig. 4. The curves of vehicle speed, engine speed, engine torque, emission rate of CO_2 and index M for CO, THC, NO_x and PM recorded during the SORT 2 road test

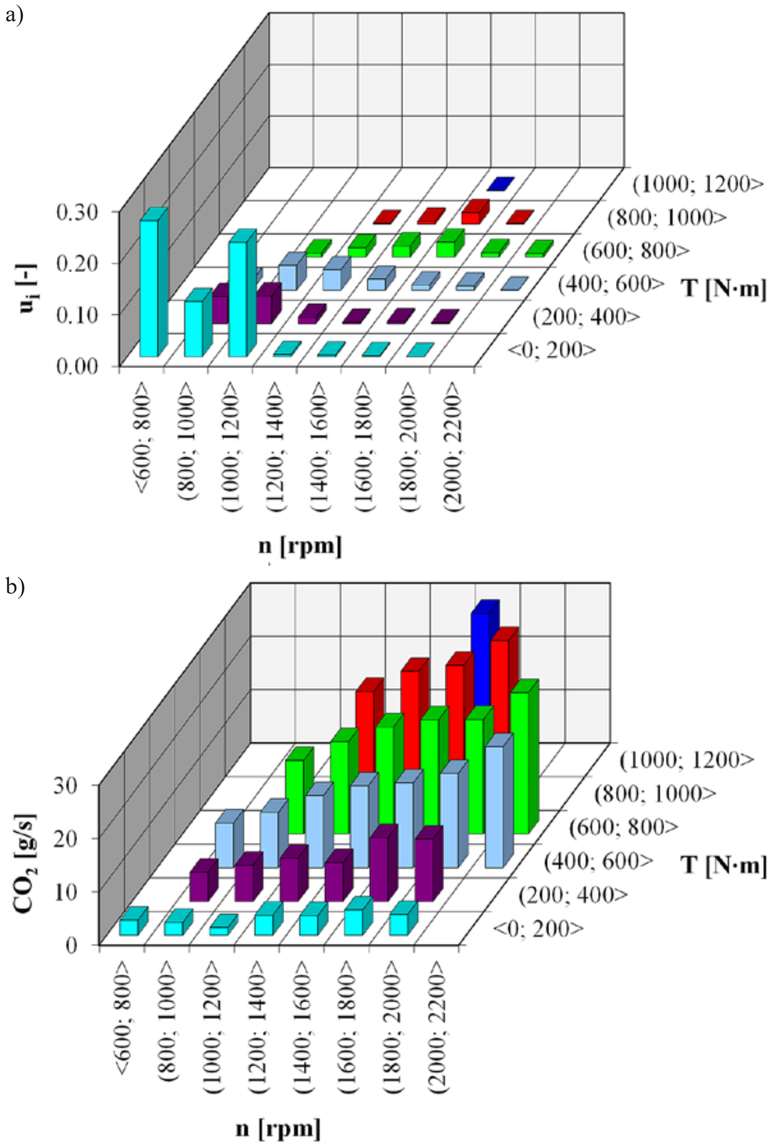


Fig. 6. Characteristics of the hybrid vehicle during the measurements: a) engine operating time share, b) CO_2 emission rate in the speed and torque intervals

M_THC/CO_2 compared to the other vehicles. It resulted from the characteristics of the applied fuel. It is noteworthy that non-methane hydrocarbons (NMHC) have a significant share of above 98% in these results. NMHC are deemed harmful but not toxic. The highest index of M_NO_x/CO_2 of 6.97 was observed for the hybrid powertrain, where an engine of the lowest maximum torque was applied. The vehicle frequently operated under increased load (higher efficiencies, higher temperature inside the cylinders during combustion), which was impactful on the obtained results. The application of an alternative fuel or a hybrid powertrain, where the electric motor successfully assisted the combustion engine when driving off and accelerating, yielded lower values M_PM/CO_2 values compared to the conventional diesel solution. For this bus the calculated emission index was M_PM/CO_2 = 1.77. Besides, in the third tested vehicle, no PM dedicated aftertreatment system was applied and such low values obtained resulted from the application of a gaseous fuel that very well mixes with air inside the combustion chamber as well as the thermodynamic cycle, in which the engine operated.

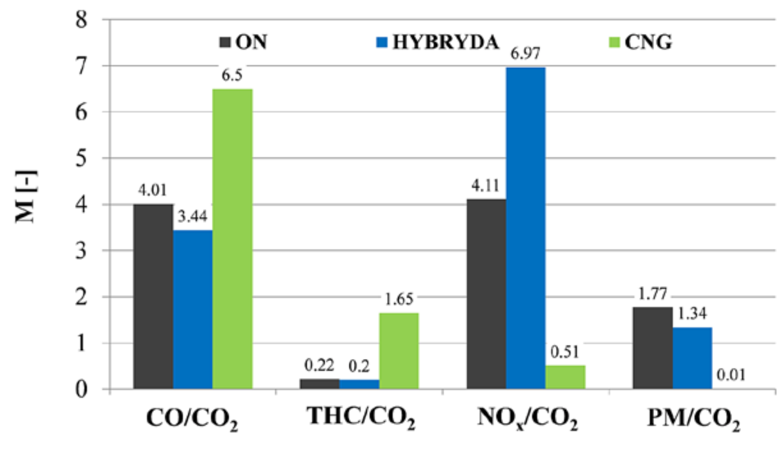


Fig. 5. M emission indexes for CO, THC, NO_x and PM obtained during the normalized SORT 2 test

4.2. Exhaust emissions referred to CO_2 on a city route

Following the analysis of the operating time share of a combustion engine, one may observe that the hybrid bus obtained the highest values of 26.4% for idle speed for the torque in the range ⟨0 N·m; 200 N·m⟩ (Fig. 6a). In the test under analysis, a significant part of the operating time was observed for the parameters (1000 rpm; 1200 rpm⟩ and ⟨0 N·m; 200 N·m⟩ that constituted 22% of the entire test run on the city route. For the test

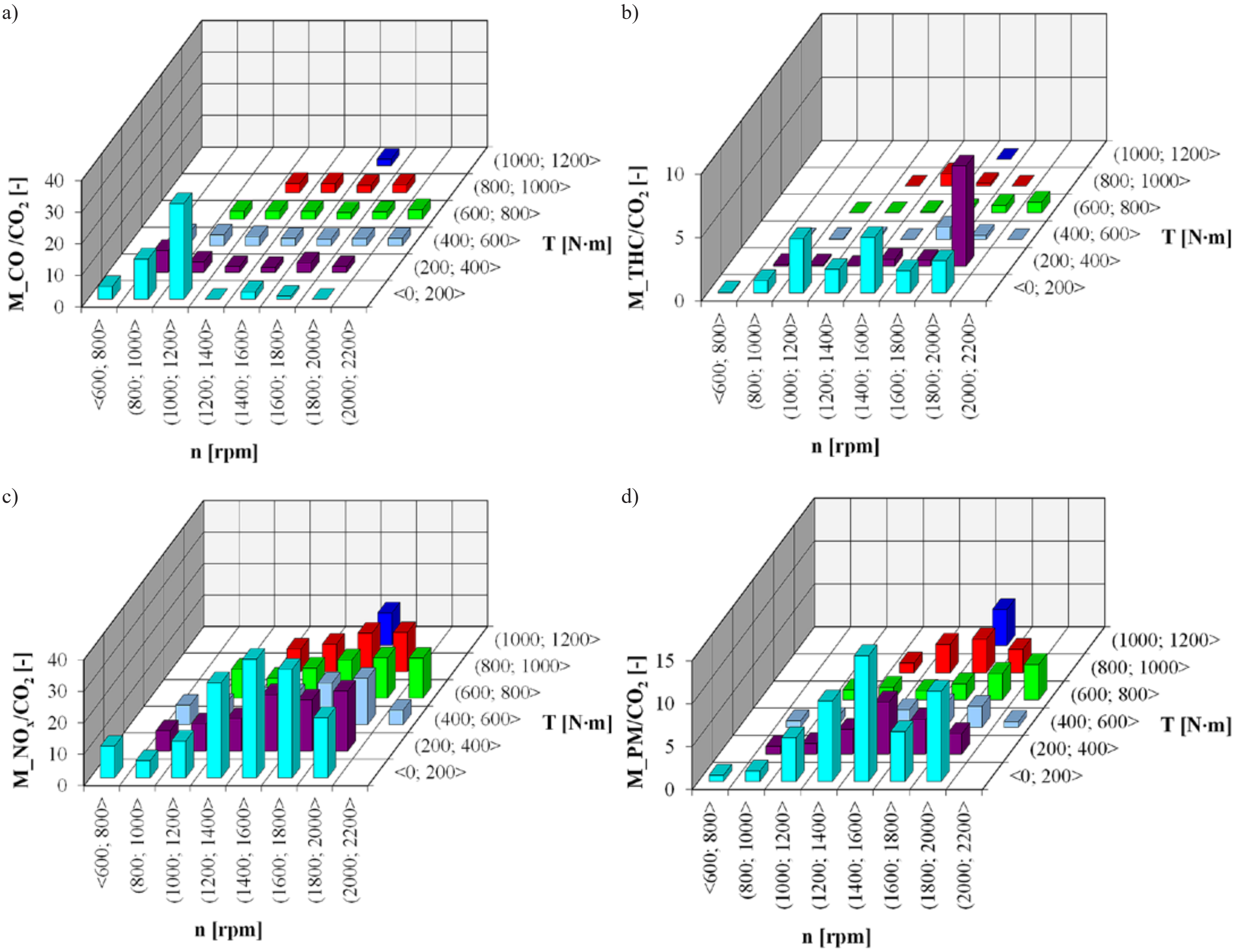


Fig. 7. Characteristics of the dimensionless index M of the hybrid vehicle during measurements of individual exhaust components: a) CO, b) THC, c) NO_x and d) PM

run between the said intervals, an operating time share of 10.7% was determined. The collective operating time share of the engine in the range (800 rpm; 1200 rpm⟩ and (200 N·m; 600 N·m⟩ was 17.2%. For the individual intervals not mentioned in the analysis, the values did not exceed 4%.

For diesel engines, the CO_2 emission rate mainly depends on the load. For the hybrid bus, due to the cooperation of the powertrain components, the values were influenced not only by torques but also engine speeds (Fig. 6b). This was caused by the use of electric energy to assist the vehicle propulsion, particularly during acceleration. The maximum value for the research object under analysis was 28.7 g/s in the range (1600 rpm; 1800 rpm⟩ for the greatest loads. The average for the entire test run was 13.8 g/s and the lowest CO_2 emission rate was obtained in the load range of up to 200 N·m in the entire range of engine speeds.

The emission rate of individual exhaust components recorded during the hybrid bus tests on the city route was referred to the emission of CO_2. For the emission index M_CO/CO_2 the most important values were obtained in the engine speed range (800 rpm; 1200 rpm⟩ at lowest loads, where, in the subsequent individual intervals, the following were obtained respectively: 12.7 and 30.2 (Fig. 7a). In the outstanding intervals, the average was 2.5 and the characteristic distribution was even. Index M_THC/CO_2 reached significant values (3 on average) in the area of the smallest loads up to 200 N·m at the speeds in the range (1000 rpm; 2000 rpm⟩ (Fig. 7b). For the intervals described with parameters (200 N·m; 400 N·m⟩ and (1800 rpm; 2000 rpm⟩ an index of 7.9 was recorded, which may indicate a significant flame choke (fading combustion) inside the engine cylinders. The outstanding intervals were characterized by an index not exceeding 0.97.

The highest values of the emission index M_NO_x/CO_2 (up to 37.7) were determined for the engine speed range (1200 rpm; 2000 rpm⟩ at loads up to 200 N·m (Fig. 7c). This confirms a limited efficiency of the selective catalytic reduction system dosing the reducing agent based on the exhaust temperature and mass flow. In the said area, conditions disadvantageous for high catalytic efficiency occured. In the outstanding engine operating range an even distribution of the index was observed as the engine speed increased – for the outstanding intervals of the characteristics, 10.5 was obtained on average. In the range of engine speeds above 1000 rpm covering the smallest loads, the highest M_PM/CO_2 indexes were obtained in individual intervals from 5.2–14.7 (Fig. 7d). the smallest values of the discussed emission index were recorded in the area of medium torques, in the entire range of engine speeds, which indicates best combustion (complete and full) in this interval of the operating parameters of the tested engine.

Similarly to the measurements performed in the SORT 2 test, the emission indexes of all tested objects indicate that the smallest values of M_CO/CO_2 and M_THC/CO_2 were obtained for the hybrid bus (Fig. 8). The combination of an electric motor with a combustion en-

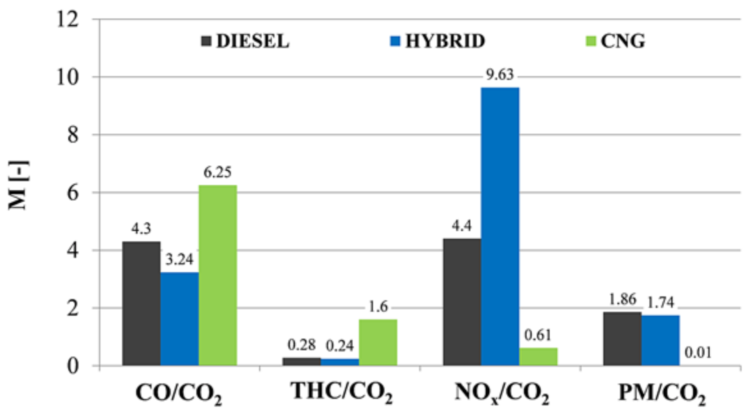


Fig. 8. Emission indexes M for CO, THC, NO_x and PM during road tests on a city route

gine resulted in an increased powertrain efficiency, which positively influenced the analyzed indexes reaching 3.24 and 0.24 respectively. Again, the highest values were obtained for the CNG-fueled vehicle fitted with a three-way catalytic converter characterized by a high conversion rate (NO_x reduction). This contributed to such a low level of M_NO_x/CO_2 reaching 0.61. As for PM, the highest indexes were recorded for the conventional vehicle – 1.86. The hybridization of the powertrain positively influenced the M_PM/CO_2, index, but the application of CNG allows an obtainment of values that are 100 times lower in the analyzed area.

5. Conclusions

The presented assessment of the exhaust emissions from city buses based on tests performed under actual traffic conditions leads to conclusions related to the engine alone as well as the entire powertrain (including aftertreatment systems). The presented and discussed results confirm that applying an emission index, being the ratio of the emission of a given exhaust component to the emission of CO_2, allows considering it in the assessment of exhaust emissions from conventional solutions, hybrid solutions and such based on alternative fuels. The interpretation can be made for all types of characteristics (including discrete ones), which is particularly useful in the research on environmental performance in transport, particularly under actual conditions of operation. The presented coefficient is somewhat a measure of correctness of the fuel combustion inside the engine cylinders and a measure of efficiency of the aftertreatment systems. The emission index M should definitely be used in road tests because, given its dimensionless quality, it provides new explorative opportunities – it is designed to render the final test results independent of the covered distance or performed work during the test. It is possible to limit the number of boundary conditions for the conditions that must be met under actual operation. This is very beneficial in the assessment of environmental performance and completion of measurements because the homologation road tests are difficult to carry out due to a variety of limitations regarding time, speed and acceleration shares, covered distance and work performed by the engine. For the above reasons, the application of the emission index may turn out very useful in the assessment of hybrid powertrains. The analyses presented in the paper are some of the first of this type and their results and conclusions motivate to continue the research on exhaust emissions referred to the emission of CO_2.

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