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Determining the environmental indicators for vehicles of different categories in relation to CO_2 emission based on road tests

The article discusses the possibility of determining the environmental indicators for vehicles of different categories in relation to CO_2 emissions. These are called toxicity indicators because they concern the compounds: CO, THC and NO_x. Three Euro V compliant vehicles with different propulsion systems types were used for the study: a 0.9 dm^3 urban passenger car with a SI engine and a start-stop system, a 2.5 dm^3 off-road vehicle with a CI engine, and a city bus with a hybrid drive system in series configuration and a CI engine with a displacement of 6.7 dm^3. Measurements were made in actual operating conditions in the Poznan agglomeration using a portable emissions measurement system (PEMS). The paper presents the characteristics of the operating time shares of vehicles and propulsion systems as well as CO_2 emissions depending on the engine load and crankshaft rotational speed for individual vehicles. The determined toxicity indicators allowed to indicate their usefulness, to make comparisons between tested vehicles, and to identify directions for further work on the application and interpretation of these indicators.

Key words: *CO_2 emission, combustion engines, PEMS, RDE, toxicity indicators*

1. Introduction

Combustion engine pollutant emission tests are no longer conducted exclusively on engine dynamometer stations. Research conducted on emissions in real operating conditions, referred to as RDE – real driving emissions, is essential. For heavy-duty vehicles (HDVs) these tests have been a part of their type approval for several years [3]. They are required for service conformity assessment. For passenger cars (PC) the road measurements will become required from 1 September 2017 in accordance with the Euro 6c [2]. Testing in real driving conditions allows a thorough assessment of the ecological indicators in the full range of the internal combustion engine's operating parameters, which has not been previously tested in laboratory measurements [4, 7, 8]. In addition, these tests allow for the performance assessment of not only the internal combustion engine but also the entire drive system (e.g. hybrid). The drive system ecology depends on two main factors: the type and effectiveness of the exhaust aftertreatment system and the combustion process in the cylinder.

The emissivity and efficiency of the combustion engine depends to a large extent on the exothermic oxidation reaction quality. Its course is complex because it deals with issues described in organic chemistry (fuel), inorganic chemistry (combustion products) and physical chemistry (equilibrium and speed) [6]. Piston engines are most often powered with liquid fuels (diesel, petrol). For this reason, in the combustion process it is important not only to mix the fuel with the oxidizer, but also to ensure quick fuel evaporation. In this aspect gaseous fuels, such as natural gas (NG), are preferred because they are already in the form of a volatile gas [5]. However, gaseous fuels are generally characterized by lower caloric content.

According to the theory of absolute rate of combustion [1], each chemical reaction proceeds according to a scheme which will be described by the simplest elementary reaction between the two reactants A and BC. If reactants A and BC are involved in the reaction and AB and C are produced as a result of the reaction, the A-B-C complex, referred to in the literature as the transitional complex, is always present on the path. This scheme is written as:

$$A + BC \rightarrow \text{active complex A-B-C} \rightarrow AB + C \qquad (1)$$

The basic condition for the process (1) is the contact during particle collisions. In addition, the appropriate spatial orientation and also for the particles to possess the energy of activation E. During combustion the rate of reaction depends exponentially on the temperature. This relation is expressed by the Arrhenius equation in the form:

$$k = A \cdot \exp\left(-\frac{E}{RT}\right) \qquad (2)$$

where there are two constants: the pre-exponent A and the activation energy E. The physical meaning of both constants is due to existing theories of matter construction [2]. Nevertheless, because of the complexity of these theories the values of these constants are usually determined experimentally.

Affecting the combustion process in a combustion engine can have a positive impact on its environmental indicators and performance parameters. Therefore, modern engineered constructions use many advanced technical solutions to improve the combustion process. These are primarily: high pressure direct injection systems with staggered dose, variable valve timing systems, turbocharging, as well as inlet manifold solutions that ensure adequate swirling when filling cylinders with the fuel dose [9]. Frequently mentioned systems have a smooth adjustment of their operating settings and operate interdependently.

2. Use of CO_2 emissions in the assessment of toxic emissions

The ecological indicators of the vehicle are based primarily on specific emissions – the mass of the harmful substance that is released relative to the work performed (also used in the assessment of machines with internal combustion engines) and the road emission – the mass of the harmful compound that is released relative to the distance traveled. Special indicators of the emitted flue gas component mass in relation to the work performed are more commonly being adopted for operated machinery (e.g. plowed area, truncated tree volume, etc.). The emission indicators determined in such a way sometimes make it difficult to compare between vehicles, as it depends on the type of drive system used (e.g. hybrid), the operating conditions (e.g. urban or highway drive), driving style, etc.

The primary combustion product in an internal combustion engine is CO_2, which is classified as a harmful compound. Its content in the flue gas depends on the amount of fuel burned and the quality of the oxidation process. Other harmful compounds in exhaust gases, also characterized as toxic, are formed during incomplete or imperfect combustion, and in the presence of high temperatures and pressures. The emission limits included in the type approval standards refer to the CO, THC (NMHC + CH_4), NO_x, PM, PN, and also NH_3 in vehicles equipped with SCR (selective catalytic reduction). The only product that does not affect air pollution is water vapor.

By analyzing the characteristics of the piston engine operation, the fuel oxidation mechanism and the formation of toxic compounds, it can be assumed that the CO_2 emission rate is a measure of the combustion process efficiency. Comparing the emissions of toxic compounds with CO_2 emissions, it is possible to determine the toxicity indicators M_j that characterize a particular engine or drive system (if non-exhaust gas purification systems are also used in the system). Such ecologically defined indicators enable an efficient comparison between different combustion engines. The quantitative toxicity indicator is defined as:

$$M_j = b \cdot \frac{e_{RDE,\,j}}{e_{CO_2}} \tag{3}$$

where: M – dimensionless toxicity indicator [–], j – the toxic compound, for which the emission indicator has been determined, b – a constant (for CO, THC and NO_x = 10^3, for PM = 10^5), $e_{RDE,\,j}$ – specific or road emission or emitted mass of the toxic compound j determined as a result of emission testing [g/(kW·h); g/(km); g], e_{CO_2} – specific or road emission, or CO_2 mass determined as a result of emission testing (same as $e_{rzecz,\,j}$) [g/(kW·h); g/(km); g].

3. Research methodology

Research in the actual vehicle operating conditions is becoming more and more common. This type of research is useful in assessing both the ecological indicators and the operating parameters of the drive systems, e.g. in construction or optimization. Road tests have been carried out to assess the validity of the discussed considerations for the determination of toxicity indicators from motor vehicles. Three Euro V compliant vehicles were used for the measurements, with different types of drive systems (Table 1, Fig. 1). A passenger car with a 0.9 dm^3 two-cylinder SI engine and an active start-stop system was designated as vehicle A. The second test vehicle (vehicle B) was an off-road 2.5 dm^3 CI engine pick-up. Vehicle C was a city bus with a CI engine and a hybrid drive in series configuration. The engine's displacement was 6.7 dm^3, and the power of the electric traction motor used was 240 kW.

Testing of vehicles A and B in real traffic conditions was performed on the same test route No. 1 (Fig. 2a). New European Driving Cycle (NEDC) guidelines were included in its selection. In some parts of the route there were a number of intersections, which made it possible to map the highly urban driving conditions. In addition, sections on which the vehicle could accelerate to higher speeds were selected, which allowed to simulate suburban travel and to the main communication arteries. The total length of the test route was 11.6 km. The third vehicle was tested on Route 2 selected according to its purpose (Fig. 2b). The route covered

Table 1. Vehicle technical parameters

Parameter	Tested vehicle		
	Vehicle A	Vehicle B	Vehicle C
Engine type/fuel	4-stroke, SI/Gasoline	4- stroke, CI /Diesel	4- stroke, CI/Diesel
Displacement [dm^3]	0.9	2.5	6.7
Compression ratio	10	15	17
Max. power [kW]/[rpm]	64/5500	140/4000	209/2300
Max. torque [N·m]/[rpm]	145/1800	400/2000	1008/1200
Aftertreatment system	TWC	DOC/DPF	DOC/SCR/DPF
Drive system	Start–stop system	Conventional	Series hybrid drive, electric motor with a power of 240 kW
Vehicle curb weight [kg]	1 300	2 500	24 000


a)
b)
c)

Fig. 1. Tested vehicles: a) vehicle A, b) vehicle B, c) vehicle C

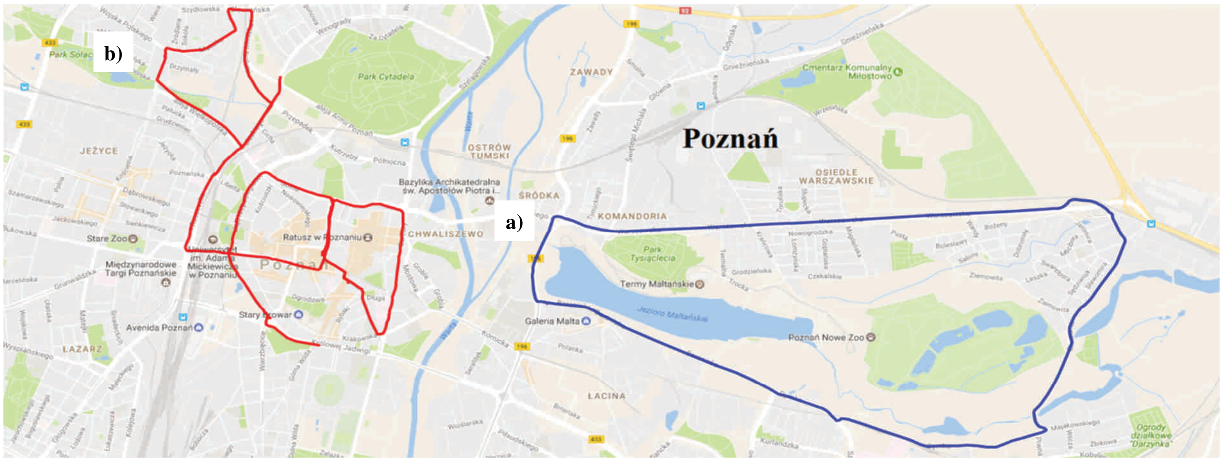

Fig. 2. Routes used in RDE tests: a) route No. 1 for vehicle A and B, b) route No. 2 for vehicle C [11]

the urban operating conditions, including bus stops. The total route distance was 12.2 km. All measurements were made on weekdays, in the morning. This was to achieve similar and comparable traffic and congestion conditions.

SEMTECH DS mobile device was used in the evaluation of the toxicity indicators. It is used in real operating conditions and is classified as a portable emissions measurement system (PEMS). The analyzer kit allows measuring emissions from both SI and CI engines that meet the norms Euro 3 and above. Its principle of operation is shown in Fig. 3. The exhaust gases are sampled out of the exhaust gasses main mass flow, the sample's temperature is kept at 191°C. Then they are directed to the set of analyzers: flame ionization detector (FID) – for THC measurement, non-dispersive detector ultra violet (NDUV) – NO_x measurement, non-dispersive detector infra red (NDIR) – CO_x measurement. In the last stage, the measurement of the oxygen content of the exhaust gas by electrochemical method is carried out. The instrument enables synchronization with the GPS positioning system, LAN connection and meteorological data system, as well as communication with the vehicle's OBD [10].

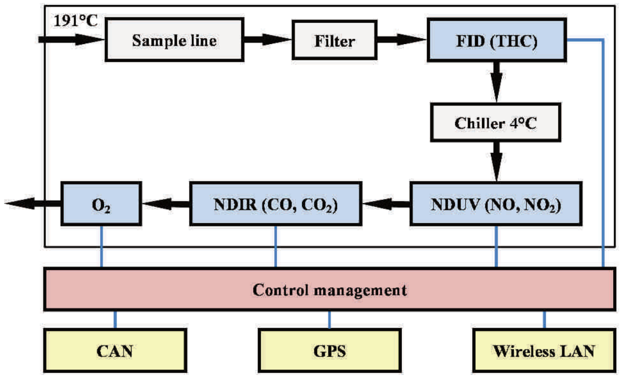

Fig. 3. SEMTECH DS operating schematic [10]

4. Real driving emissions results

4.1. Analysis of the vehicles and combustion engines operating conditions

Based on the recorded speed profiles of the individual vehicles, their operating time share characteristics in the speed-acceleration (V–a) parameters were determined. Vehicles A and B were tested on the same route at a similar time of day, resulting in similar characteristics. The registered average speeds of these cars were 44.3 km/h and 37.4 km/h respectively. Therefore, Figure 4 shows the distribution of the vehicle A's operating time share only. The total time spent stationary for passenger cars in the test reached the same value of 13.7%. Maximum speed reached during test did not exceed 22 m/s (79.2 km/h). The greatest share of operating time occurred in the speed intervals (8 m/s; 20 m/s⟩ for acceleration ⟨–0.8 m/s^2; 0 m/s^2) and (0 m/s^2; 0.8 m/s^2⟩, where the recorded share of operating time for vehicle A was – 19.1% and 29%; and vehicle B – 16.3% and 28.7%. For driving at a constant speed in the interval (16 m/s; 20 m/s⟩ the time share was 11% and 5.9% respectively.

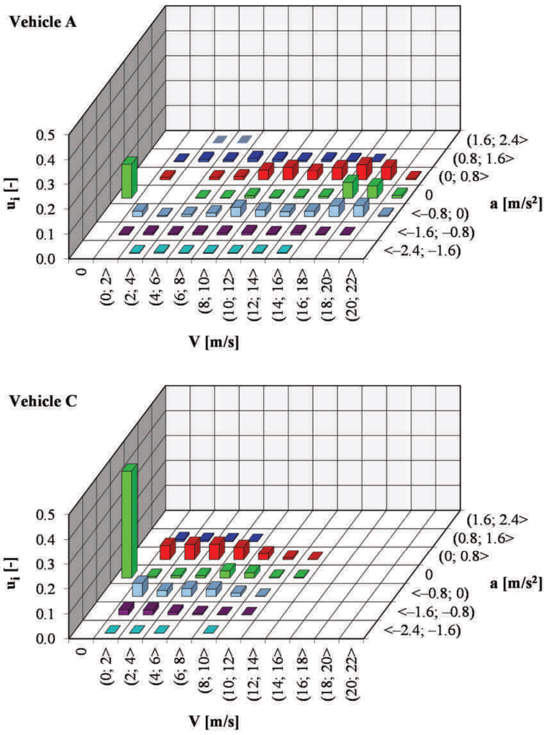

Fig. 4. Shares of vehicles operating time in speed and acceleration compartments during road tests

In the study of the city bus, the maximum share of operating time of 43% was recorded for vehicle being stationary, which was due to the vehicle's operation characteristics (servicing bus stops) and the traffic conditions in the city center. The maximum speed recorded on the measurement route was 12.2 m/s (43.9 km/h). The highest share of operating time occurred in the speed ranges of (0 m/s, 8 m/s⟩ for acceleration ⟨-0.8 m/s^2, 0 m/s^2) and for (0 m/s^2, 0.8 m/s^2⟩. In the remaining speed and acceleration ranges, the determined time share values did not exceed 2.8%.

When analyzing the emission of the tested vehicles, it is important to know the internal combustion engines operating parameters, as shown in Fig. 5. The time share characteristics are shown in coordinates of the crankshaft rotation speed to engine load. The petrol vehicle had the highest share of 50% operating time for rotational speeds in the range of (1800 rpm, 2600 rpm⟩ with the engine load not exceeding 20%. In the load range of more than 80%, the assigned value of operating time share was 12%. The engine characteristic had an effect on the resulting distribution of the work area of the engine, especially the torque curve, which is characterized by small values in the engine speed range of less than 1600 rpm.

The compression ignition engine used in vehicle B had the largest variation of operating parameters. The highest share of operating time was recorded for engine speeds not exceeding 1000 rpm at engine loads of up to 20%, which constituted 29.1% of the total operating time. For the same load in the speed range (1000 rpm, 2600 rpm⟩ the operating time share of 44.7% was determined. The large value of this time share was derived from the characteristics of the internal combustion engine – high torque is reached from the idle speed already. In the remaining single compartments, the shares of operating time did not exceed 3%.

The hybrid drive used in vehicle C had a significant influence on the obtained distribution of the engine operating time share characteristics for that vehicle. Moreover, the engine was loaded with additional torque associated with the operation of functional systems (e.g. pneumatic system and the air conditioning). The highest value of 40.6% was found for the lowest engine speed range of (20%; 40%⟩. In the performed test conditions, the speed range of (1000 rpm, 1400 rpm⟩ for load range ⟨0%; 80%⟩, in which the total time share value of 31% was registered, had the most significant impact on the overall results. This was mainly due to the interaction with the electric motor in the hybrid drive, which converted the engine torque into electric power. For the same reasons the lowest rotational speed and load range the time share was only 2%.

4.2. Ecological results analysis

In order to determine the tested engines toxicity indicators, it is useful to determine their CO_2 emissions depending on the operating conditions of the internal combustion engines (Fig. 6). Based on the characteristics, it can be stated that the analyzed harmful compound emission intensity of vehicle A depends primarily on the load. For speeds above 1400 rpm with loads in the range (80%, 100%⟩ as well as speed (1800 rpm, 3400 rpm⟩ and loads ⟨60%, 80%⟩ CO_2 emissions are greater than 7.4 g/s (maximum 14.2 g/s). For vehicles labelled B and C, equipped with CI engines, the emission characteristics are clearly dependent on engine speed and load. In both cases, the maximum CO_2 emission occurred at engine load above 80%: for vehicle B it was 29.7 g/s at speed (3000 rpm, 3400 rpm⟩ and for vehicle C it was 32.4 g/s for maximum crankshaft rotational speed. However, it should be noted that the engine operating time shares in these compartments were below 3%. In single compartments where the registered maximum engine operating time share was recorded, the emissions were respectively: A (u_i = 35%) – 2.9 g/s; B (u_i = 29.1%) – 1.1 g/s and C (u_i = 40.6%) – 3.2 g/s.

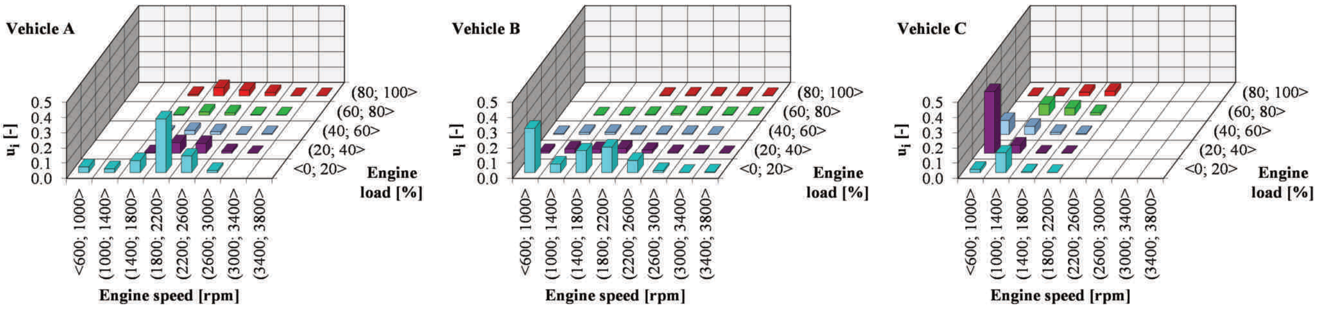

Fig. 5. Operating time shares of internal combustion engines in crankshaft speed and load ranges obtained in road tests

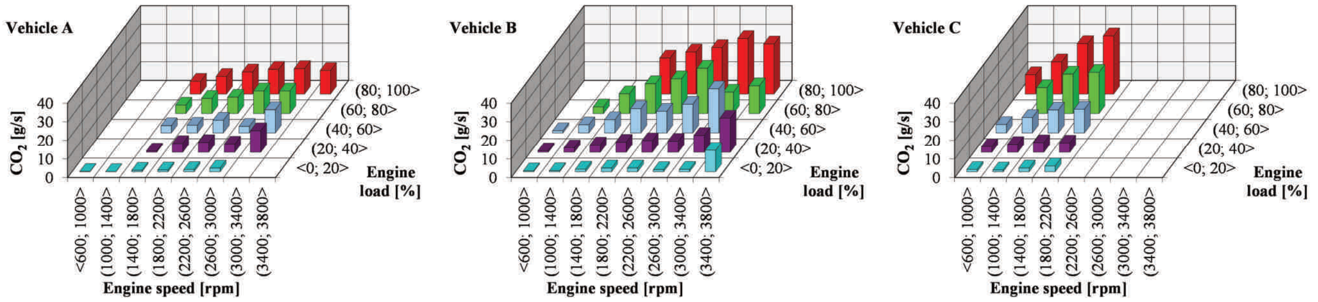

Fig. 6. CO_2 emissions concentration in the speed and torque compartments during road tests

In order to assess the dependence of NO_x emissions on CO_2, the recorded values of emission intensity of these compounds were compared, taking into account time compliance (Fig. 7). Based on the obtained characteristics it can be stated that their distribution is strongly dependent on the exhaust gas aftertreatment system used. In vehicle A, the three-way catalytic reactor was characterized by a high degree of conversion, and NO_x reduction. For CO_2 emissions of up to 6 g/s, the value of the toxic compound compared did not exceed 0.01 g/s. During the entire study cycle the maximum value reached was 0.06 g/s that occurred during dynamic acceleration. For vehicle B, where no notible NO_x reduction systems have been used, a dependence has been obtained – with the increase in CO_2 emission intensity, the NO_x emission values also increased. The resulting distribution was undoubtedly influenced by the exhaust gas recirculation system (its effect was to reduce NO_x emissions in exchange for higher CO_2 emission values). The maximum NO_x emission of 0.22 g/s was recorded for corresponding CO_2 emissions of 23 g/s.

The least regular dependence of NO_x on CO_2 emissions occurred for the city bus. This was due to both the exhaust gas recirculation system and the selective catalytic reduction system. In this system, the conversion rate depends primarily on the temperature and mass flow rate of the exhaust gas – with a higher flow rate, the conversion rate is lower. Urea is added in doses, depending on the thermodynamic parameters present in the catalytic reactor. The absence of linear NO_x reduction resulted in a CO_2 emission intensity of about 32 g/s when the NO_x emission intensity was in the range of 0.05–0.43 g/s. It should be noted that the combustion engine of this vehicle, due to the interaction with the electrical components, has been operating in the range of high efficiency (high temperature in the combustion chambers), which has a very high impact on NO_x emissions compared to other toxic compounds.

As illustrated by the previous example the engine exhaust aftertreatment systems have a very significant impact on the values of the analyzed toxicity indicators. For a vehicle with an SI engine, the excess air ratio λ, which directly affects the performance of a three-way catalytic converter, is undoubtedly also significant. Figure 8 shows the recorded speeds of the tested vehicles as a function of the distance travelled, along with the values of the M_CO/CO_2 toxicity indicators. Recorded mileage for vehicle A clearly indicates that the vehicle acceleration dynamic has a significant impact on the toxicity indicator. Dynamic speed increase results in a M_CO/CO_2 value of above 15. During constant speed motion and braking, this indicator does not exceed the value of 3. This was caused by the high engine load – a small heat unit was heavily loaded during intense acceleration, which could have led to an enrichment of the fuel mixture and thus change the value of the excess air ratio, which guarantees the effective operation of TWC.

For the other researched vehicle the relation between the toxicity indicator curve and the velocity curve were noted. The increase in M_CO/CO_2 was recorded during braking, especially during slight decelerations using engine braking. In this process, the CO_2 emission (being the denominator of the coefficient) tends towards 0. Therefore, even a small CO emission results in high values from the calculations. In addition, the resulting curves indicate incomplete combustion in the cylinders. The indicator reached a maximum value of 40. Whereas during acceleration, the indicator did not exceed the value of 4. Similar tendencies were observed for the vehicle C. The M_CO/CO_2 ratio depends primarily on braking. Despite the hybrid system, vehicle movement had a significant impact on the characteristics. It should also be noted that the maximum toxicity indicator values were even five times greater than in the vehicle B tested. This is due to the difference in the combustion engines used (power and displacement) and the type of vehicle (mass and purpose) and operating conditions. In the acceleration process, the factor obtained only a small value – in this vehicle, the propulsion system was boosted by a supercapacitor system storing the energy recovered in vehicle braking.

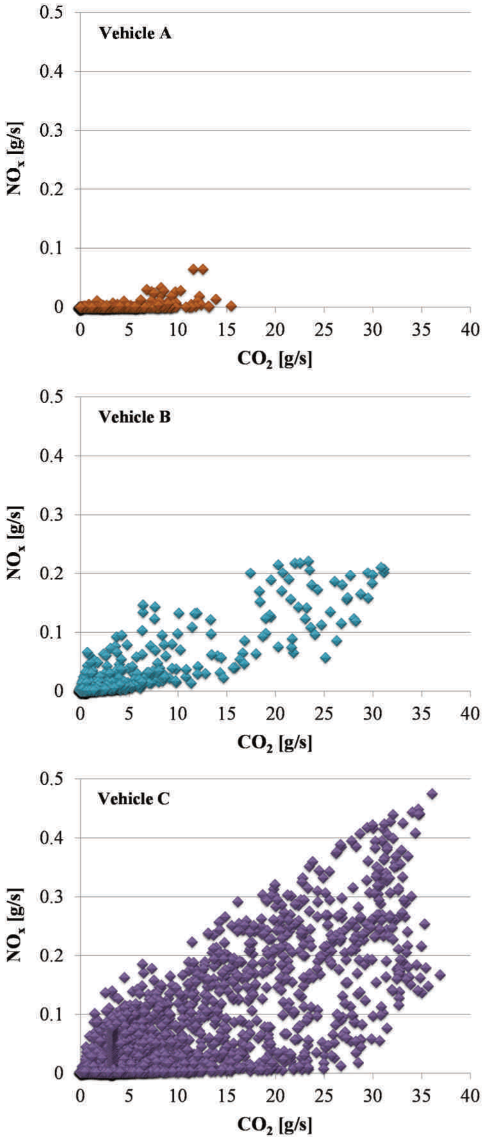

Fig. 7. Comparison of NO_x and CO_2 emissions during road tests with respect to time compliance

Based on the analysis of the results obtained for the M_THC/CO_2 indicators, very close correlations were obtained as were found with the M_CO/CO_2. For the first test vehicle its values depended primarily on acceleration,

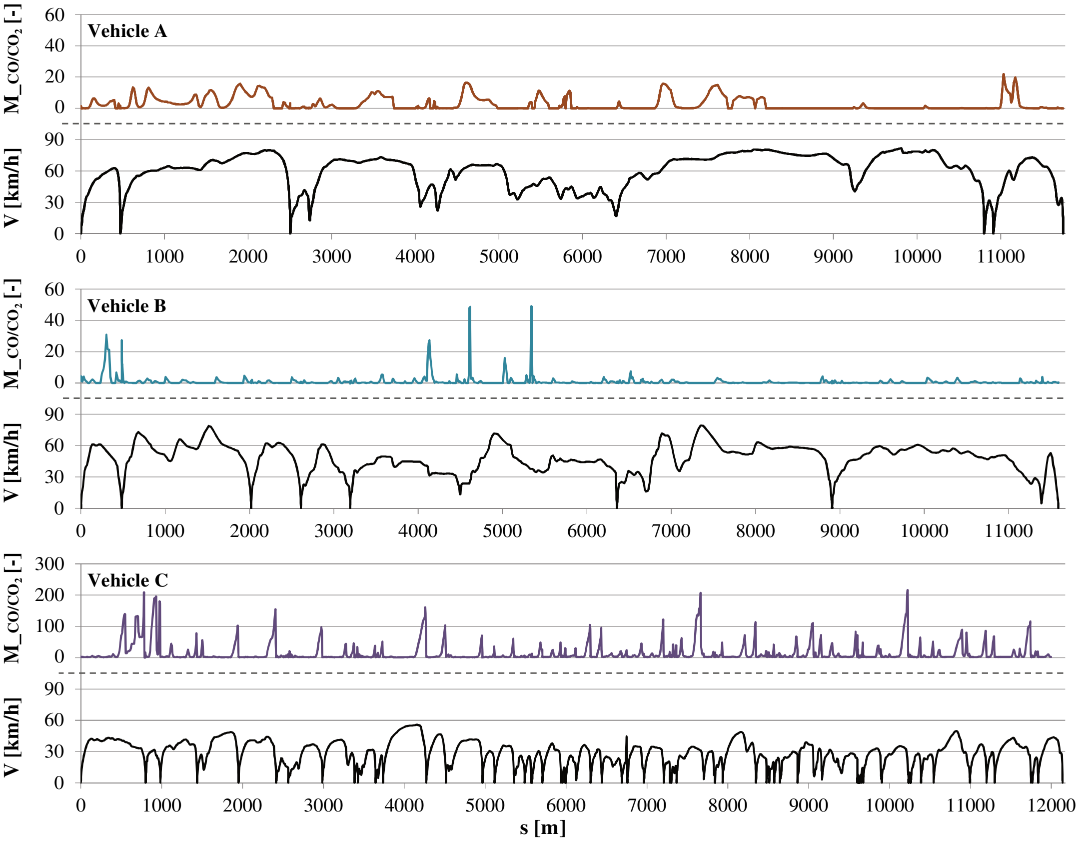

Fig. 8. Vehicle speed curves and the M index for the CO emission values recorded during road tests

while for vehicles with CI engines the maximum values was obtained during braking. This is due to the fact that THC emissions are somewhat similar in origin to CO emissions and oxidation of these compounds uses a single exhaust aftertreatment system with one or more catalysts.

Taking into account the entire emission of pollutants recorded in the road tests, total toxicity indicators for CO, THC, and NO_x were determined (Fig. 9). The largest value was achieved for the pick-up, while the smallest for the urban passenger car with an SI engine. The most significant differences occurred with the M_CO/CO_2, where the value for vehicle C – 2.51, was 5.5 times that of vehicle A and 3.8 times that of vehicle B. With respect to M_NO_x/CO_2, vehicle A reached 0.35 – while the indicator for vehicle B was t 14.7 times greater and for vehicle C more than 21 times greater. The low M_NO_x/CO_2 ratio for the first vehicle was primarily due to the highly efficient exhaust gas aftertreatment system that significantly reduced the amount of the analyzed toxic compound. A relatively small internal combustion engine was used in the test bus due to the development and capabilities of the hybrid system. However, this solution caused the engine to work more frequently in the areas of higher load (higher efficiency, high cylinder temperatures during combustion), which had a significant effect on the results obtained in the road measurements. Taking into account the considerations made, it must be stated that, during the analysis and assessment of ecological toxicity indicators, it is also necessary to take into account the purpose and design of the vehicles together with the exhaust gas aftertreatment systems used.

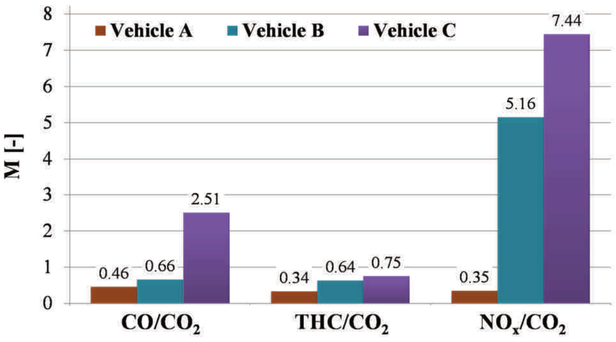

Fig. 9. Summary of toxicity index M for CO, THC, and NO_x

5. Conclusion

The research presented in the study was of an urban passenger vehicle, an off-road vehicle and a city bus. The only difference in the measurement procedures was the other test route used for the third vehicle – this resulted in the need for reliable operating conditions complemented by the servicing of the bus stops. In order to compare the results obtained from the two routes, the performance characteristics of the vehicles and their internal combustion engines were calculated. This allowed to indicate the differences between the trips, which were influenced mainly by the types of drive systems used and the traffic conditions. For vehicles A and B, the highest share of operating time occurred in the load range of up to 20%, while for the bus they were in the range of ⟨20%, 40%⟩. The CO_2 emission distribution for each vehicle in terms of engine load and the crankshaft speed was then presented and discussed for given combustion engines.

The presentation of the NO_x emissions as a function of CO_2 has allowed to determine the environmental performance of the tested vehicles for those exhaust components, and to assess the impact of the exhaust gas aftertreatment systems applied. The most effective in this respect was a gasoline-powered vehicle equipped with a three-way catalytic reactor. The calculated M_CO/CO_2 toxicity indicators made it possible to conclude that in gasoline vehicles their values depend primarily on acceleration parameters, whereas in vehicles with CI engines their value depends mainly on engine braking. Based on the analysis of toxicity indicators, it can be concluded that they are useful in ecological assessment of vehicles of different categories and their comparison. The presented and discussed research results show that the use of a toxicity indicator, which is the emission ratio of a particular toxic component relative to the corresponding CO_2 emission, makes it possible to consider conventional and hybrid solutions together. The indicator shown is in a way a measure of the fuel's combustion efficiency and a tool for evaluating the performance of exhaust gas aftertreatment systems. When determining the environmental indicators based on the assumed model, the results are independent of the distance traveled and the work performed by the drive system in the test. However, when analyzing and evaluating ecological toxicity indicators, it is also necessary to take into account the purpose and design of vehicles together with the exhaust gas aftertreatment systems used. For these reasons, its use can be particularly useful when evaluating drives in the design and construction phase and in future type approval operations.

Acknowledgements

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Nomenclature

a	acceleration
b	a constant of the toxicity indicator
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
e	emission of harmful exhaust components
FID	flame ionization detector
GPS	global positioning system
k	rate constant
LPG	liquefied petroleum gas
M	toxicity indicator (dimensionless)
NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
NEDC	New European Driving Cycle
NG	natural gas
OBD	on-board diagnostic
PEMS	portable emission measurement system
R	universal gas constant
RDE	real driving emissions
s	distance
SCR	selective catalytic reduction
T	temperature
TWC	three way catalyst
u	share coefficient
V	velocity

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