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Comparative test of an internal combustion engine ecological indicators in real operating conditions and on a dynamic engine dynamometer

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Abstract. The paper presents internal combustion engine emission tests results, carried out in real operating conditions and in a laboratory stand equipped with a dynamic brake. The measuring stand simulates the vehicle's operating conditions registered in real traffic, which influenced the variability of the internal combustion engine operating parameters. The research route included urban roads with different traffic levels. The article discusses the method of creating the preparationprocedure of the route simulation, modeling of the vehicle properties and the driver's actions. The AXION R/S mobile device was used in the research. It belongs to the group of portable emissions measurement systems. It enabled carrying out analyzes for both the exhaust gases emission (CO, CO_2, NO_x and THC) as well as for the assessment of particulate emissions. In addition, a comparison of fuel consumption as well as speed runs recorded during tests have been presented. The test objects were two identical compression ignition engines with a displacement of 1.3 dm^3 and a maximum rated power of 66 kW. The exhaust gas aftertreatment systems included an oxidation catalyst and a particulate filter. The performed research allowed to assess the effectiveness of simulating the actual operating conditions on the engine dynamometer using the obtained emission characteristics. The need to further develop the mathematical models used in simulations was discussed. The performed analyzes lead to considerations being made regarding the idea of substituting road emission tests with measurements in laboratory conditions at dynamometer stations.

1. Modern methods of testing internal combustion engines

Manufacturers of internal combustion engines used in all vehicle groups are obliged to create solutions characterized by the best performance indicators (considering power and torque characteristics), ecological and economic indicators, low weight, durability etc. Often in a given engine it is necessary to reach a compromise between the mentioned parameters, while making sure to meet all the limits defined by the legislators [1]. To achieve this, it is necessary to conduct multi-range research and development. Thus it is necessary to develop and improve measuring techniques that allow obtaining the largest amount of information in a fast and cheap manner. The continuous development of information systems, control systems and measurement tools allows developing research techniques for internal combustion engines as well as entire drive systems. A particular development in this field occurred in recent years, thanks to the creation of stands with dynamometers for dynamic tests and the development of portable emission measurement systems (PEMS).

Dynamic test benches allow changing the combustion engine operating parameters in a defined way, i.e. it is possible to define transient states. Dynamic engine dynamometer benches can also be used to power the tested object – it is therefore possible to simulate engine braking, for example. In this type of modern test benches, the software used enables defining the vehicle construction parameters, designing a virtual route and the driver's driving characteristics. The use of these tools allows creating simulations that reflect the actual operation of the engine in the vehicle while driving. The development of equipment from the PEMS group allows the assessment of operating parameters and ecological indicators of a given vehicle in its real operating conditions[2,3,4,5]. It is a modern measurement concept that requires the use of specialized equipment that meets stringent requirements in terms of accuracy, mobility (related to mass, dimensions and power consumption), sampling frequency, etc. [6,7,8]. Such tests are becoming more and more popular, they have also been required in the type approval process of various vehicle groups.

2. Research methodology

The aim of this research was to compare the ecological indicators determined in real operating conditions with the results obtained on a laboratory stand with a dynamic brake. The test objects were two identical combustion engines equipped with complete exhaust gas aftertreatment systems. Their use ensures compliance with Euro 4 standards.

The entire research has been divided into two parts. The first measurement series was made in real operating conditions. The test object was a light commercial vehicle equipped with a 66 kW compression-ignition engine (Table 1). The measurements were made on an urban route in the Poznań

Table 1. Test engine technical data

Engine type	Diesel
Number and arrangement of cylinders, number of valves	4 cylinders, in-line, 16 valves per cylinder
Displacement	1,3 dm^3
Maximum power	66 kW/4000 rpm
Maximum torque	200 Nm/1500 rpm
Compression ratio	17:1
Fuel injection	common rail
Type of charger	VGT, intercooler
Emission reduction and aftertreatment systems	DOC, DPF

Figure 1. The test route used for performing road emission measurements [9]

agglomeration (Figure 1). It was selected in order to obtain conditions typical for a city centre as well as sections where higher speeds were permitted (reaching the agglomeration borders and a drive through the main bypass roads). The total test drive distance was 12.5 km.

The AxionR/S+ PEMS type mobile equipment was used for tests in real operating conditions [10,11]. This device is used to measure the exhaust emission of: hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and particulate matter (PM). The device measurement parameters are presented in Table 2. The concentration of the first three of these compounds is measured using an NDIR analyser (nondispersive infrared sensor). Electrochemical analysers are used to determine NO and O_2. In the measurement of PM, a method based on Laser Scattering is used. The test apparatus is equipped with a meteorological station, a GPS and a module allowing to record data from the on-board vehicle diagnostic system. Measurement and data acquisition is carried out at a frequency of 1 Hz. Corrections are made to the obtained results are being made based on the acquired data and the road/unit emission of measured pollutants is calculated[12].

Table 2. Technical specifications of the mobile emission measurement device used

Gas	Measurement Range	Accuracy	Resolution	Type of Measurement
HC	0–4000 ppm	± 8 ppm abs. or ±3% rel.	1 ppm	NDIR
CO	0–10%	± 0.02% abs. or ±3% rel.	0.001 vol. %	NDIR
CO_2	0–16%	± 0.3% abs. or ±4% rel.	0.01 vol. %	NDIR
NO_x	0–4000 ppm	± 25 ppm abs. or ±3% rel.	1 ppm	E-chem
O_2	0–25%	± 0.1% ppm abs. or ±3% rel.	0.01 vol. %	E-chem
PM	0 mg/m^3 to 300 mg/m^3	± 2%	0.01 mg/m^3	Laser Scatter

The second part of the research included the preparation of tests on a laboratory bench equipped with a dynamic brake – AVL DynoRoad. First, the vehicle was simulated. Its design features, that affect the operation of the internal combustion engine, have been specified. These parameters included, among others: vehicle mass, type of driving, wheel size, type and characteristics of the gearbox, air resistance coefficients, mechanical gears efficiency, etc. Then the operation of the clutch and accelerator pedal when shifting gears was simulated. The simulation procedure is presented in Figure 2. The next steps taken concerned the programming of the route. Its characteristics were defined on the basis of other research results discussed in more detail, among others in [13,14]. It should be noted that the simulated route was identical to that in the real operating conditions. In order to simulate the driving, the functions of the vehicle speed change in time f = V(t) and changes in the road angle in time f = α(t) were used. The ISAC 400 software installed at the test bench allowed to calculate all simulated values using appropriate algorithms and control maps. In this way, current information was defined for the internal combustion engine. As a result, the defined range of operating parameters variability included both steady and transient states.

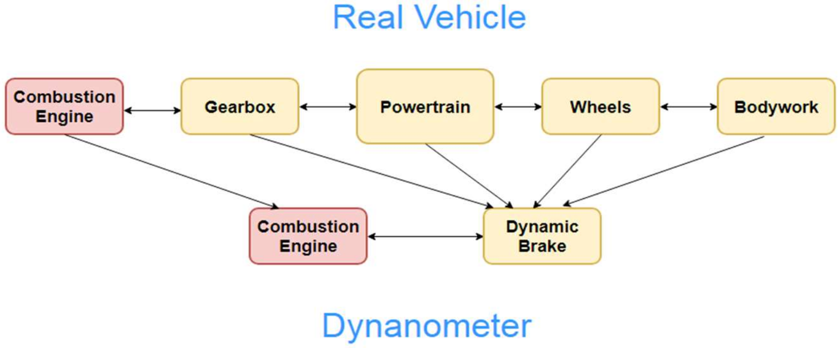

Figure 2. Schematic of a vehicle simulating process on a test bench

The data necessary for performing the simulation were recorded during measurements in real operating conditions (e.g. vehicle speed, road gradient). The data provided by the vehicle manufacturer as well as measurements and own calculations were used. The test bench at which the research work was carried out has full infrastructure allowing the implementation of automated tests. In the construction of the station itself, a three-phase, asynchronous electric machine with a cage construction was used. The maximum received power is 120 kW, and the torque is 510 Nm. The efficiency of the bench exceeds 90%. During operation, the combustion engine generates mechanical work which is converted into electricity in the brake, which after voltage and frequency transformation is transferred to the external network.

Before starting the measurement, the test engines were warmed up to obtain their constant thermal conditions. This guaranteed the proper operation of exhaust gas aftertreatment systems. In both research cycles, the same mobile exhaust gas analyser was used. Each time the test equipment was calibrated and zeroed before measurements, in order to make the results independent of background contamination.

3. Comparison of actual and simulated operating conditions

Based on the data recorded from the on-board diagnostic system and the GPS (in the first measurement cycle) as well as information from the engine dynamometer, the speed profiles of the test vehicles were determined (Figure 3). In real operating conditions, the maximum vehicle speed was 78 km/h, while the average speed was 30.6 km/h. In the simulation on the test bench, the maximum speed was 79.3 km/h, and the average speed reached 30.5 km/h. These values are similar to each other, but the speed profile itself was different in both research cycles. This is also confirmed by the distribution of the test vehicles operating ranges time density shown in Figure 4. The operating conditions obtained in the real drive were different than in the programmed test at the dynamometer station. It was influenced by, among others the traffic congestion and road infrastructure conditions. Figure 3b compares the obtained speeds taking into account their compatibility over time. The determination coefficient of $R^2 = 0.9885$ was determined using the data from the performed drive cycles. In addition, the formula of the obtained linear relationship is presented.

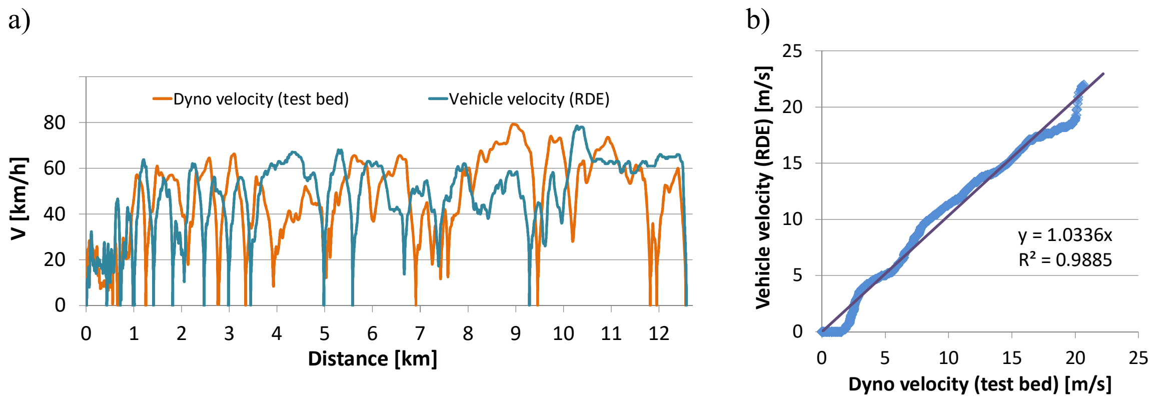

Figure 3. The test vehicles operating parameters: a) speed characteristic in real operating conditions and on the dynamometer test bench; b) speed comparison in subsequent research cycles, including its compliance over time

The range of vehicle performance parameters change as a function of speed and acceleration in subsequent test cycles was not the same (Fig. 4). In both cases, the largest operating time share occurred for the vehicle being stationary and constituted respectively: 12.2% in real traffic conditions and 14.2% in the drive simulation on the dynamometer. Larger operating time share with constant speed was found for the first test cycle, reaching the value of 11.7% (excluding vehicle stops). In the second cycle this value was found to be 4.1%. For the speed range (0 m/s; 21 m/s⟩ with accelerations in the range ⟨–0,8 m/s^2; 0 m/s^2) and (0 m/s^2; 0,8 m/s^2⟩ operating time shares obtained equalled 26.9% and 34% for the first cycle respectively, in the second part of the research, this was 41.2% and 33%, respectively. The range of variation in operating parameters (taking into account individual ranges) in real operating conditions was higher by 12.8% in relation to the test cycle performed on the dynamometer station.

a) b)

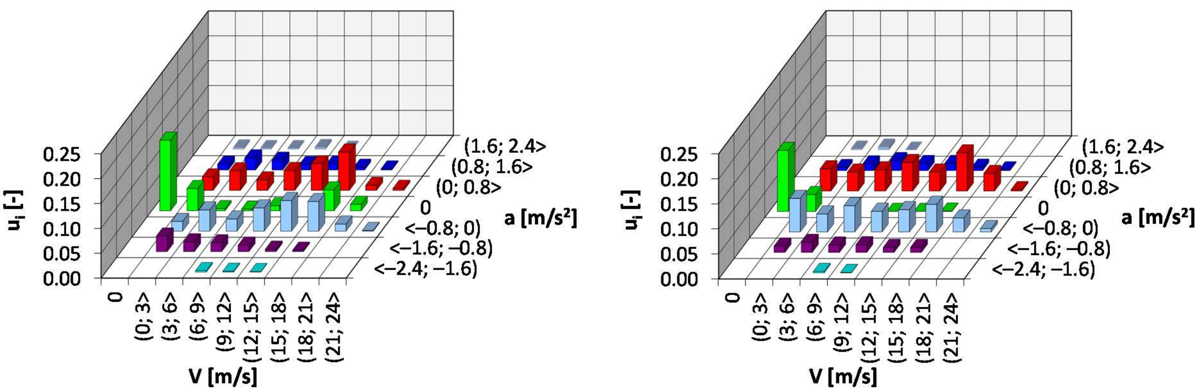

Figure 4. Engine operating time shares in the speed and acceleration ranges: a) drive cycle in real operating conditions; b) the drive cycle simulated on a dynamometer

4. Analysis of ecological indicators

The recorded CO_2 emission values have been referred to the vehicle operating conditions. As a result, it was possible to determine the impact of the real and simulated vehicle performance parameters on the resulting ecological indicators (Figure 5). From the relation between these parameters, the exhaust emission values of CO_2 can be concluded to have depended strictly on the speed and acceleration values. In the vehicle standstill operating range, the values obtained in subsequent drive cycles were 4 g/s and 3.1 g/s respectively. This difference was the result of a slightly higher load of the actual vehicle when idling, which is caused by aspects such as the radiator fan starting and the additional load coming from the compressor – where these parameters have been omitted in the simulation. For the real route, the highest exhaust emission value of 8.5 g/s was recorded in the speed range of (12 m/s; 15 m/s⟩ and acceleration range (1.6 m/s^2; 2.4 m/s^2⟩. For the simulated drive, the highest CO_2 emission values of 7.4 g/s were obtained in the range of these parameters described as (18 m/s; 21 m/s⟩ and (0.8 m/s^2; 1.6 m/s^2⟩. The average CO_2 emission in the test drives was recorded at 2.2 g/s

a) b)

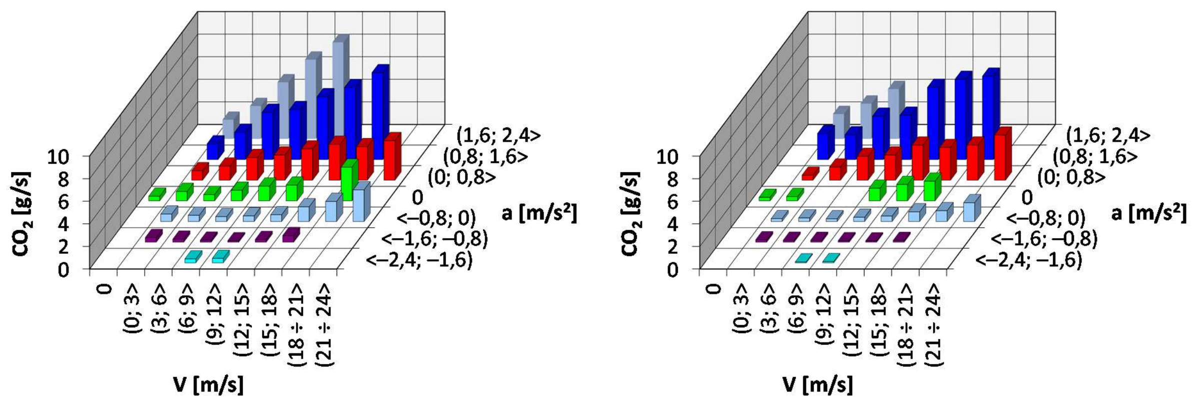

Figure 5. CO_2 exhaust emissions in the tested vehicle speed and acceleration ranges: a) drive cycle in real operating conditions; b) the drive cycle simulated on a dynamometer

and 1.9 g/s respectively. Some non-zero emission values of the analysed compound occurred in the negative acceleration range, presumably due to various reasons, including the test route characteristics

– e.g. changes in relative heights caused the vehicle to slow down when the internal combustion engine was experiencing load. Engine braking was also used in some cases.

The time-dependent emission of CO_2 is directly proportional to the fuel consumed by the internal combustion engine. At the same time, these parameters are strongly related to the instantaneous engine load. Hence, the ecological indicators characteristics of the tested vehicles were determined and presented as a function of the engine speed and the CO_2 emission value.

The NO emission intensity depends on both the crankshaft speed and the engine load associated with CO_2 emissions (Figure 6). A larger range of operating parameters in defined ranges was obtained in real driving conditions. For this test vehicle, the highest NO emission of 47.2 mg/s was determined in the engine speed range of (2600 rpm; 2900 rpm⟩ and CO_2 emission in the range (6 g/s; 8 g/s⟩. During the tests on the engine dynamometer the maximum NO emission value obtained was 44 mg/s in the data range defined as (2300 rpm; 2300 rpm⟩ and (8 g/s; 10 g/s⟩. The minimum values of the analysed toxic compound were obtained in the idle operation range (in the range of the lowest rotational speed and CO_2 emission), where in the subsequent cycles the obtained emission values were 1.6 mg/s and 1.1 mg/s. The average time-dependent NO emission for subsequent test cycles was: 18.4 mg/s and 14.7 mg/s.

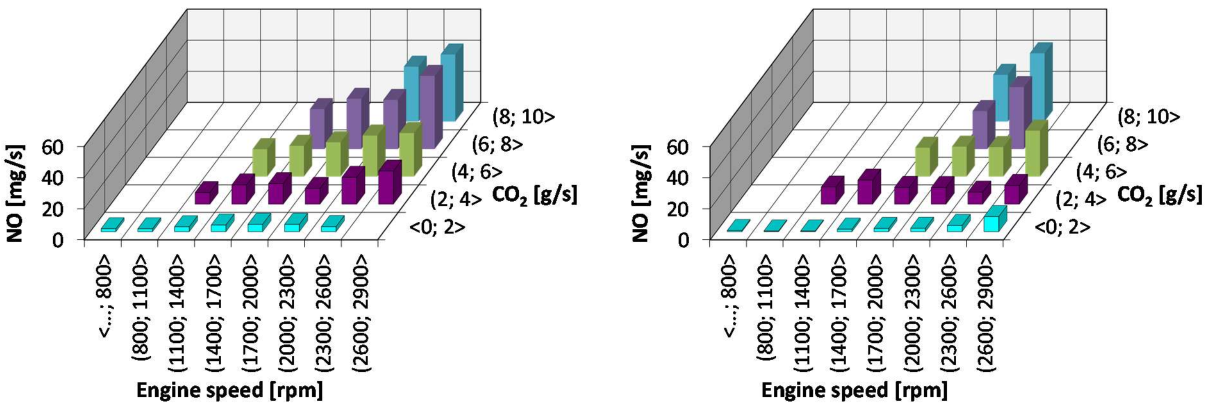

Figure 6. The NO emission values in the engine speed and the CO_2 emission ranges associated with the engine load: a) drive cycle in real operating conditions; b) the drive cycle simulated on a dynamometer

Due to the dual-function oxidation reactor used in the test vehicles, the distribution of THC and CO exhaust emission was very similar. For this reason, the article presents only the time-dependent THC emission characteristics (Fig.7). As in the previous case, the obtained values depended mainly on the engine speed and load. Taking obtained values into account it can be concluded that at high load the injected fuel dose did not mix thoroughly and incomplete combustion has occurred. The highest THC emission values (1.9 mg/s and 2.2 mg/s, respectively) occurred at the rotational speed over 2300 rpm and CO_2 emission exceeding 6 g/s. Considering the entire variability range of the defined parameter ranges, the average THC emission in the first measurement cycle was 1 mg/s, while in the second cycle 1.1 mg/s.

The distributions of PM emissions in the conducted test cycles were varied (Fig.8). For tests in real operating conditions it can be concluded that the obtained distribution of emission values depends both on the engine speed and load. However, in the second test cycle, the engine speed did not impact the obtained emission values at all. This was due to the particulate filters being filled to various degrees. For the second test vehicle full filter regeneration occurred before the measurements began, which resulted in a very high operation effectiveness.

a) b)

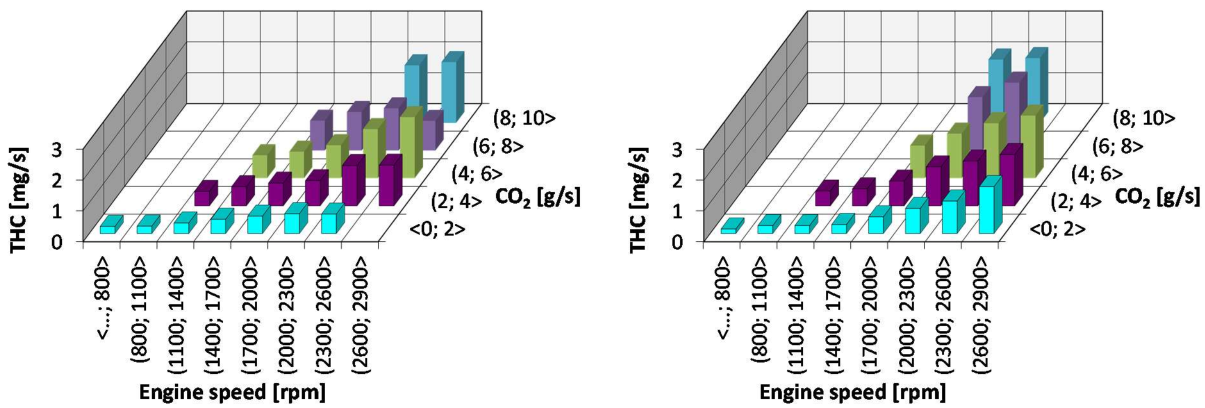

Figure 7. The THC exhaust emissions in the engine speed and the CO_2 emission ranges related to the engine load: a) drive cycle in real operating conditions; b) the drive cycle simulated on a dynamometer

The highest emission values of the considered compound in both test cases occurred for the engine speed higher than 2000 rpm and CO_2 emissions over 8 g/s. In this range mean PM emission values of 0.2 mg/s and 0.12 mg/s were obtained in subsequent cycles. The average PM emission of 0.052 mg/s and 0.02 mg/s was obtained for the whole test cycles.

a) b)

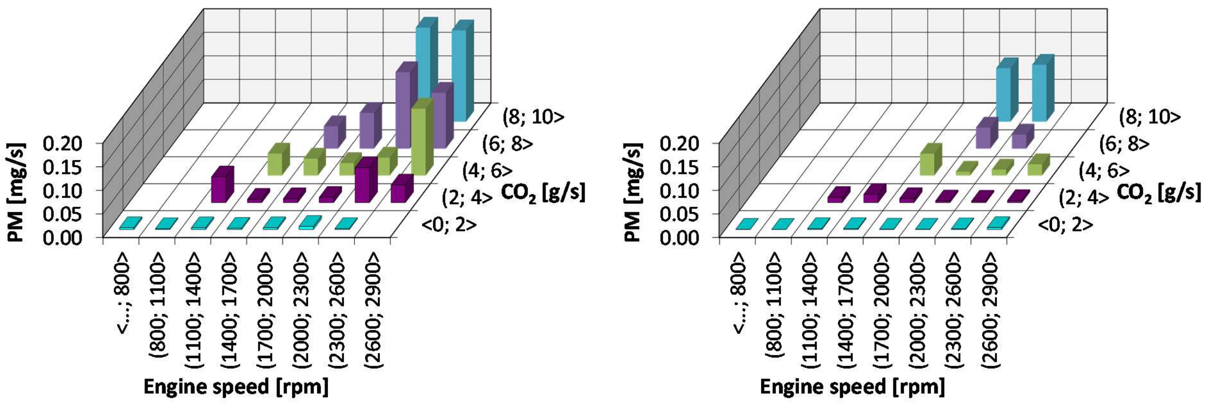

Figure 8. The PM exhaust emissions in the engine speed and the CO_2 emission ranges related to the engine load: a) drive cycle in real operating conditions; b) the drive cycle simulated on a dynamometer

Based on the recorded data, road exhaust emissions were determined in subsequent measurement cycles (Table 3). Higher CO_2 and NO_x emissions (by 11% and 77% respectively) were obtained during tests in real operating conditions with respect to measurements on the dynamometer. This was related to the greater engine operating parameters variability range and a more dynamic driving style. The higher NO_x emission value indicates that higher temperatures were obtained in the combustion chamber, which relates to a higher efficiency of the tested engine. Similarly, the more dynamic driving style has contributed to higher CO_2 emissions, which is proportional to fuel consumption. Higher values of THC and CO road emissions were obtained at the engine dynamometer during the real driving simulation measurements. This indicates a greater share of partial and incomplete combustion. Cases of too large load values in the range of low engine rotational speeds were observed during the whole test.

The biggest differences in the test results occurred for the PM road emissions. This contributed to its very high operating efficiency when performing the test cycle. The supplement to the presented data is the fuel consumption calculated using the carbon balance method. This method uses CO_2, CO and THC road emissions. The fuel consumption values were 10% higher for the performed road tests than for measurements made in the laboratory. Several factors influenced this result. Primarily, in the first measurement cycle a more dynamic driving profile was obtained. In addition, the vehicle engine was loaded with additional power receivers: light supply, air conditioning system, air vents, etc., which were not simulated at the dynamometer station. In addition, during the test drive simulation, the influence of side and front winds was not taken into account, but only the aerodynamic resistance of the vehicle itself.

Table 3. Comparison of road emission and fuel consumption results determined using the carbon balance method

Emisson of:	Real drive	Dynamometer
CO_2 [g/km]	172.2	155.9
THC [g/km]	0.06	0.083
CO [g/km]	0.599	0.872
NO_x [g/km]	0.663	0.375
PM [g/km]	0.018	0.001
Fuel Consumption [dm^3/100 km]	6.58	5.98

Using the exhaust emissions results, it is possible to relate their value to the emission standards met by the tested vehicles (Figure 9). For this purpose, the Conformity Factor (CF) was determined, as was done in [15] and [16]. The marked red dashed line on the chart shows the Euro 4 limit values. The obtained results indicate that both test vehicles exceeded the permitted CO, THC and NO_x road emission limits. However, it should be noted that the reduced Euro 4 emission limits include measurements in the NEDC test cycle. It was only with the introduction of the Euro 6c that the RDE measurements method and the possible deterioration factors in the exhaust emissions were defined.

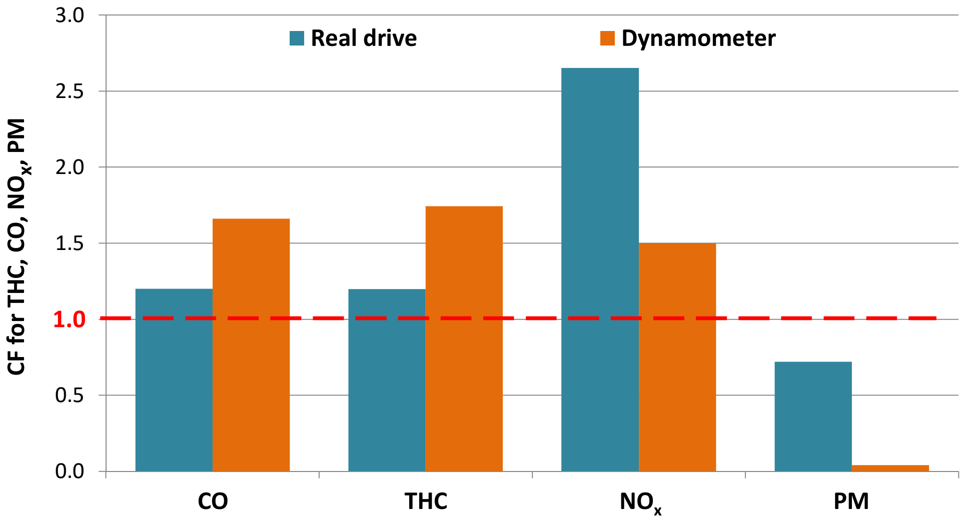

Figure 9. Comparison of obtained road emission with Euro 4 limit

5. Conclusions

The article presents a comparison of exhaust emission tests carried out in real operating conditions with tests carried out on a test bench equipped with a dynamic brake. From the obtained emission values and registered operating parameters variability ranges, it can be concluded that the road tests simulated on the engine dynamometer have been largely representable. The same equipment was used in both measurements, and the research cycles were started by establishing the thermal states of the tested engines. This has had a positive effect on the comparative analysis of the obtained results, as any errors related to the measuring devices used were excluded, and the same initial conditions were obtained in subsequent test cycles.

The obtained results justify the statement that the test bench correctly modeled the road emission test, in which the vehicle speed, road profile, driving style, gear changes and physical features of the vehicle and drive system components were defined. There were several factors that contributed to differences in the obtained road emission values. One of the basic ones is omitting the additional engine load associated with powering the lights, air conditioning and ventilation system in the simulation tests. The influence of wind was not taken into account, only the aerodynamic resistance associated with the vehicle profile. In addition, the obtained results could also have been affected by possible simplifications used in mathematical models implemented in the research station software. The comparison of the obtained road emission values with the Euro 4 limits, indicates that the tested engines exceeded the limit emission values for CO, THC, as well as NO_x. The biggest differences in the obtained results were registered for the PM emission. This was due to the regeneration of the particle filter before the second measurement cycle. The emission of PM during tests at the engine dynamometer was significantly lower due to the high efficiency of the regenerated filter.

From the conducted tests, the conclusion was made that it is possible to simulate the real operation of the vehicle on a test bench equipped with a dynamic brake. This makes it easier to test not only the internal combustion engines, but also the drive system components and the physical characteristics of the vehicle, which can be modelled in any way using simulation. In addition, the use of engine dynamometers can significantly reduce test costs, as well as shorten the time they require to perform.

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