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EXHAUST EMISSION TEST PERFORMANCE WITH THE USE OF THE SIGNAL FROM AIR FLOW METER

EKSPLOATACYJNE BADANIA EMISJI SPALIN Z WYKORZYSTANIEM SYGNAŁU Z PRZEPŁYWOMIERZA POWIETRZA*

The paper presents selected technical solutions in the area of exhaust emissions research conducted in real operational conditions of a vehicle. The author describes his own road emissions research methodology with the use of information about the air flow supplying an engine (OBD II) and the measured volumetric shares of particular fumes components (exhaust gas analyser). Test results confirm the possibility of applying this measurement method, and their analysis shows the inadequacy of the type-approval tests compared to the real operation of the vehicle.

Keywords: *exhaust emission test, mobile systems, emissions of CO_2, driving tests.*

W pracy omawiane są wybrane rozwiązania techniczne w zakresie badań emisji spalin w warunkach rzeczywistej eksploatacji pojazdu. Autor opisuje własną metodykę drogowych badań emisji spalin z wykorzystaniem informacji o wydatku powietrza zasilającego silnik (OBD II) i zmierzonych udziałów objętościowych poszczególnych składników (analizator spalin). Wyniki badań potwierdzają możliwość stosowania opisanej metody pomiarowej, a ich analiza wskazuje ponadto na nieadekwatność testów homologacyjnych w odniesieniu do realnej eksploatacji pojazdu.

Słowa kluczowe: *badania emisji spalin, mobilne systemy pomiarowe, emisja CO_2, testy jezdne.*

1. Introduction

The high pace of the development of motorization, apart from its many advantages, creates ecological organic threats. The literature reports emphasize the significance of the negative impact of motorization on the environment, especially with regard to noise emission, the risk of heavy metals, as well as the ambient air quality which is treated as a priority [5, 22, 23]. In the general European profile ca. 20% of the anthropogenic emission of CO_2 come from transport sources. The adverse effect of internal combustion engines on the environment is determined, among others, by the estimation of harmful pollutants emission levels in relation to the limits set in the applicable legal acts [21]. For example, by 2012 the JRC (Joint Research Centre) had carried out tests in real road traffic conditions for 16 new vehicles from group of LDV (Light Duty Vehicle). The test results confirmed the fulfilment of the Euro 5 and Euro 6 requirements in almost all cases. The exception was the emission of NO_X from vehicles equipped with CI engines, which significantly exceeded the limits [21, 26]. Among others, it is due to the problem of controlling the engine in a vehicle. Indeed, it is difficult to achieve low fuel consumption and high power output with low emissions of NO_X and PM (Particle Matter).

New engines are initially tested at laboratory engine's dynamometer test-stands for exhaust emissions. Then the results are being analysed and then corrective control algorithm changes are introduced. After that further trials and adjustments are conducted, and then the following ones. So far such a procedure was satisfactory but the complexity of modern combustion engines controlling systems makes the optimization of engines more complicated [7, 12]. The examples of such systems with a high reduction potential in the area of NO_X and PM emissions and fuel consumption are engines based on compression ignition of homogeneous mixtures – HCCI (Homogeneous Charge Compression Ignition). They require precise controlling of the variable valve timing, variable compression ratio, and especially, exhaust gas recirculation and direct fuel injection [7]. The interrelationship between the variable parameters makes it difficult to develop a coherent strategy.

The next step after the tests at an engine dynamometer is testing of the vehicle mounted engine at a chassis dynamometer, and finally testing it in real road traffic conditions. The latter tests provide a lot of information about the true impact of the vehicle on the environment the real emissions and fuel consumption. They, in fact, reflect the real conditions of the vehicles use [15–17, 24–26].

Vehicle manufacturers, ensuring compliance with emission standards, base mainly on the official driving cycles. Necessarily, they apply conditions for the measurements which inherently were to provide the base for vehicles evaluation. Unfortunately they differ from the conditions of the vehicles later real operation. That can lead to a distortion of the market image of the product, particularly from the point of view of its user.

An example of a very problematic research are tests of hybrid propulsion systems, whose parameters can be objectively verified only in traffic conditions [15].

The review of the literature on the subject of emissions testing in natural operation of vehicles [1, 12, 15–17] indicates that there are highly specialized measuring instruments, generally referred to PEMS (Portable Emission Measurement System), although they are very expensive. Road tests with the use of PEMS have shown that in the case of certain fumes ingredients their emissions are about a couple of hundred percent greater than the values encountered in the type-approval tests [13, 17].

The presented thesis led the author to conduct exhaust emissions tests under the conditions of vehicle real operation, but with the use of a simplified measuring method and commonly available equipment instead of the type-approval tests. The methodology of the research

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** and the preparation of a set of results is quite laborious but it allows to obtain information on emissions or fuel consumption. Additionally, it points out the possibility of constructing simplified systems or separate measuring devices that can be used in comparative studies.

2. Exploitation exhaust emission tests

Exhaust fumes tests with the use of a diagnostic gas analyser have been for years the basic type of emission tests which are done during the periodic technical inspection of a vehicle at a vehicle inspection station or at a workshop installing gas supplying systems (LPG or CNG). The so called four-compounds gas analysers are used for the measurements. They enable the user to determine the content of the exhaust gases: carbon monoxide (CO), carbon dioxide CO_2, oxygen O_2, hydrocarbons HC (sometimes an additional option is the measurement of nitric oxides NO_X) [10]. The devices of this type are also used in scientific research, examples of which are described in the literature [8, 9, 18, 19].

The homologation approval tests are much more complicated. They are conducted in laboratory chassis dynamometers and are based on special driving cycles, forming the basis for vehicles comparisons, as well as their assessment in relation to the adopted emission limits [1, 3, 13, 20]. In this case, the measuring apparatus is more complicated. Dilution tunnels are used for the exhaust gas sampling system maintaining a constant volume of samples – CVS (Constant Volume Sample), and heated measuring lines are applied to prevent the formation of condensate, while the detectors of gaseous components are adapted to their physical-chemical properties [1, 20].

The tests carried out in conditions of road traffic are the most desirable when we analyse the research for the information about the real fumes emission to the environment.

The author's own studies carried out during road trips, as well as presented in the literature [4, 11, 28] have shown that the registration of selected engine operating parameters via interface DLC (Data Link Connector) can be very useful for the evaluation of an engine operating conditions, and, in the case described by the author, also to calculate the quantity of emitted fumes and their harmful ingredients.

3. Research methodology

Due to the fact that the gas analyser measures the volumetric shares of selected exhaust components without the possibility of determining their rates of flow, there is a need to complete the system under construction with an element enabling the definition of the flow. Accordingly, DLC can be used to register the airflow passing through the intake manifold.

To determine the mass flow of a particular exhaust component, one must specify the volumetric shares of the major exhaust components, designate the relationship between volumetric and mass shares of the components, and make an assumption that the mass of the fumes is the sum of the mass of air and the mass of combusted fuel. In fact, the mass of the fumes is reduced by the mass of the (possible) condensate.

The information on volumetric shares of some components has been obtained as a result of the gas analyser measurement. However, the shares of N_2, H_2O and Ar were needed, too. To obtain that purpose the combustion reaction was examined (1).

$$C_\beta H_\alpha O_\varepsilon + \lambda\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot O_2 + \lambda\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot\frac{78}{21}N_2 + \lambda\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot\frac{1}{21}Ar \rightarrow$$
$$\rightarrow \beta\cdot CO_2 + \frac{\alpha}{2}H_2O + \lambda\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot\frac{78}{21}N_2 + \lambda\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot\frac{1}{21}Ar + (\lambda-1)\cdot\left[\left(\beta+\frac{\alpha}{4}\right)-\frac{\varepsilon}{2}\right]\cdot O_2 \quad (1)$$

where:

$C_\beta H_\alpha O_\varepsilon$ – fuel,

$\beta, \alpha, \varepsilon$ – molar ratio of carbon, hydrogen, oxygen to carbon in the hypothetical fuel molecule $C_\beta H_\alpha O_\varepsilon$,

λ – air excess coefficient,

O_2, N_2, Ar – selected air components,

CO_2, H_2O, O_2, N_2, Ar – selected exhaust components.

Literature data differ in indicating molecular composition of gasoline [7, 10, 20]. The substitute formula $C_1H_{1,89}O_{0,016}$ has been finally accepted for the calculations [20]. It has been initially assumed that the spark-ignition engine combustion is stoichiometric ($\lambda = 1$), overall and total. Basing on the calculated coefficients at the combustion process products (2) their volumetric shares were determined.

$$C_1H_{1,89}O_{0,016} + 1,4645\cdot O_2 + 5,4396\cdot N_2 + 0,0697\cdot Ar \rightarrow$$
$$\rightarrow 1\cdot CO_2 + 0,945\cdot H_2O + 5,4396\cdot N_2 + 0,0697\cdot Ar \quad (2)$$

This way we obtained: 12,68% – H_2O, 13,42% – CO_2, 72,97% – N_2 and 0,94% – Ar. These are the major components of the fumes of the gasoline engine working on the stoichiometric mixture. Unfortunately, there is no information about the emissions of other gases arising from the defects of the real combustion process. Simplifying, it can be assumed that their shares are relatively small and do not affect the next calculations significantly.

For further analysis calculated values of the volumetric shares of N_2 and Ar (2) were used, (a) and in the case of the other ingredients the measured values were utilized. The share of H_2O was treated as consequential.

It should be noticed that for the stoichiometric mixture the mass of emitted fumes is greater than the mass of utilized air by the mass of the fuel which is 1/14.28 of the mass of air. Finally, also minor changes of the air excess coefficient λ were included with the use of Brettschneider's formula (3) [10,20] and the measured volumetric shares of CO, CO_2, HC, O_2 and NO_X.

$$\lambda = \frac{c_{CO_2} + \frac{c_{CO}}{2} + c_{O_2} + \frac{c_{NO}}{2} + \left[\frac{\alpha}{4}\cdot\frac{3,5}{3,5+\frac{c_{CO}}{c_{CO_2}}} - \frac{\varepsilon}{2}\right]\cdot\left(c_{CO_2}+c_{CO}\right)}{\left[1+\frac{\alpha}{4}-\frac{\varepsilon}{2}\right]\cdot\left(c_{CO_2}+c_{CO}+K1\cdot c_{HC}\right)} \quad (3)$$

where:

λ – air excess coefficient,

C_{CO}, C_{CO2}, C_{HC}, C_{O2}, C_{NOx} – volumetric exhaust components shares [%],

For the calculation it has been assumed:

$\alpha = 1,89$ – molar ratio of hydrogen/carbon for the fuel,

$\varepsilon = 0,016$ – molar ratio of oxygen/carbon for the fuel

$K1 = 6$ – a conversion factor for the HC calculations from FID method (Flame Ionisation Detector) to NDIR (Non-Dispersive Infrared) [20].

Next, the formula determining the relationship between the fumes outlay and the outlays of given components has been set (4).

$$q_i = q_{air}\cdot\left(1+\frac{1}{\lambda\cdot AFR}\right)\cdot x_{mi} \quad (4)$$

q_i – mass outlay of the i-th component [$g\cdot s^{-1}$],

q_{air} – mass outlay of the air [$g\cdot s^{-1}$],

x_{mi} – mass share of the i-th component [-].

To complement the formula (5), the relationship between the volumetric and mass shares of particular components was specified with the use of their molar masses:

$$x_{mi} = \frac{c_i \cdot \mu_i}{\sum_{j=n}^{j=1} c_j \cdot \mu_j} \qquad (5)$$

where:

c_i – volumetric share of the i-th component [-]

μ_i – molar mass of the i-th component [g·mol^{-1}]

$$\sum_{j=n}^{j=1} c_j \cdot \mu_j = \mu_{CO} \cdot c_{CO} + \mu_{HC} \cdot c_{HC} + \mu_{CO_2} \cdot c_{CO_2} + \mu_{O_2} \cdot c_{O_2} + \mu_{NO_X} \cdot c_{NO_X} + \mu_{N_2} \cdot c_{N_2} + \mu_{Ar} \cdot c_{Ar} +$$
$$+ \mu_{H_2O} \cdot \left(1 - (c_{CO} + c_{HC} + c_{CO_2} + c_{O_2} + c_{NO_X} + c_{N_2} + c_{Ar})\right) \qquad (6)$$

Table 1. Molar mass of selected fumes components expressed in [g·mol^{-1}]

μ_{CO}= 28,01	μ_{CO2}= 44,009	μ_{O2}= 31,999	μ_{H2O}= 18,015
μ_{HC}= 86,202 (1)	μ_{NOx}= 38,006 (2)	μ_{N2}= 28,013	μ_{Ar}= 39,948

1 – data for hexane C_6H_{14}, 2 – data for NO_X in composition (NO –50% NO_2 –50%)

The presented dependences were used for further calculations and, thanks to that, the emissions of selected fumes components were obtained for urban driving conditions.

Table 2. Toyota Verso MPV Facelift 1.8 Valvematic 147 HP [29]

Fuel consumption	EU Directive 80/1268 to 1999/100 EC
- average - combined	6,8 l/100km
- on the road (highway)	5,7 l/100km
- town	8,7 l/100km
CO2 emission	158 g/km
emission standard	Euro 5
fuel	petrol fuel 95
curb weight	1430-1525kg (1500kg)
engine	2ZR-FAE
number and cylinders arrangement	4, rzedowy
valves	16 v, DOHC, Valvematic
fuel injection system	MPI
displacement	1798 cm^3
maximum engine power	108 kW (147 HP) by 6400 rpm
maximum torque	180 Nm, by 4000 rpm
year model	2013
drive type, transmission axle	front axle drive, 6 gear, manual
maximum speed	190 km/h
acceleration (0 do 100km/h)	10,4 s

Table 3. Toxic exhaust gas components emission limits for the tested vehicle [21]

Curb weight kg	Engine type	Fuel	Emission limits mg/km				Validity
			CO	NMHC	HC	NO_x	
below 2620	PI, MPI	petrol, natural gas, liquefied petroleum gas	1000	68	100	60	type approval from 01.09.2009.

3.1. Object of research

The object used in tests was the new vehicle of Toyota make, model Corolla Verso 2013 with a mileage of 16500 km, equipped with a multipoint fuel injected gasoline engine 2ZR-FAE with a variable valve timing system Valvematic [29] and a system EOBD (European On Board Diagnosis) and DLC enabling the connection of an engine's performance data recorder.

Before the vehicle was introduced to the market it had been subjected to the type-approval tests, as a result of which, the conformity with the requirements of the emission standard Euro 5 had been proven. The limits for this vehicle are presented in table 3.

Tab. 3. Toxic exhaust gas components emission limits for the tested vehicle [21]

3.2. Measurement instruments

The main devices used in the research were: MGT5 exhaust gas analyser of MAHA make classified in class 0 according to OIML (Organisation Internationale de Métrologie Légale), an engine data recorder and a phone with a GPS receiver to record the data of the route travelled.

Fig. 1. View of MGT5 analyser prepared for tests

Table 4. Selected technical data of MGT5 analyser [10]

Measured parameter	Measurement method	Range	Resolution indications
carbon monoxide CO	NDIR	0-15% vol.	0,001%
carbon dioxide CO_2	NDIR	0-20 % vol.	0,01%
hydrocarbons HC	NDIR	1). 0 - 4000 ppm	0,1 ppm
hydrocarbons HC	NDIR	2). 0 - 20000 ppm	1 ppm
oxygen O2	electrochemical	0-15 % vol.	0,01%
	electrochemical	4-25 % vol.	0,01%
nitric oxides NO_x	electrochemical	0-5000 ppm	1 ppm
λ	computing	0,5-9,99	0,01

Table 5. Selected technical parameters of the recorder OBD Log [28]

Vehicle interface	EOBD, 16 pin socket
Supported protocols EOBD	J1850-41.6, J1850-10.4, ISO9141-2 K/L, ISO 11898
Power	DLC connector OBD, USB from PC
Sampling frequency	1 second
Working time	up to 90 hours
Operating temperature	-40°/+85°C

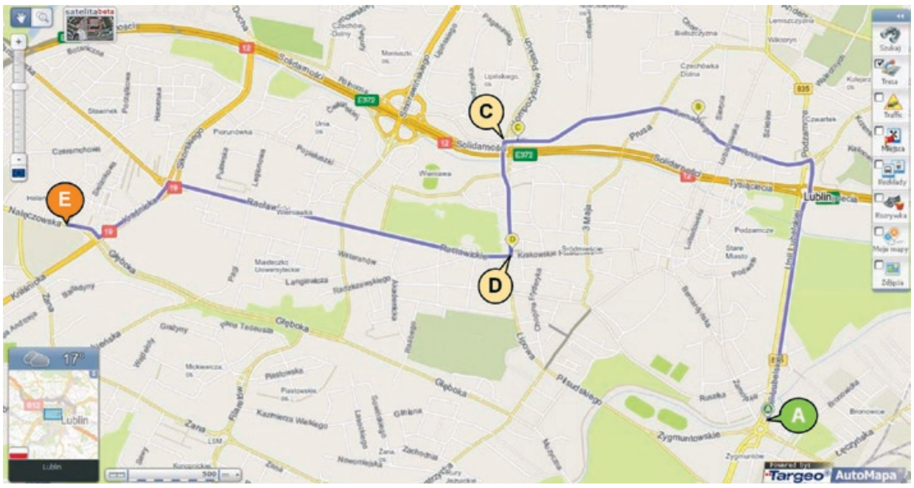

Fig. 2. The route plan for the urban driving measurement [27]

To read and record the selected parameters of the engine the device called OBD Log of Texa make was used whose basic data are listed in Table 5.

3.3. Measurements in road conditions

Driving was carried out in a manner adapted to other road users while driving in Lublin on a route of 6.95 km length with the average speed of $v = 25.8$ km/h. The starting route point (A) (Fig. 2) is located at an altitude of about 168 meters above sea level, and its end point (E) is about 50 meters higher. The greatest gradient of altitude changes is located in the middle part of the route, between points C and D (approx. 30 m). Temperature, atmospheric pressure and relative humidity average levels were 18°C, 981 hPa and 67% respectively. The vehicle was loaded with its own mass, the mass of the measurement equipment, a driver and a passenger. Before the drive, the test object had been weighed on a car scales and the total mass of 1726 kg had been noted. At the beginning of the drive the engine of the vehicle was warmed up.

Similar tests have been also carried out for suburban driving. However, due to their more stable nature only the urban test bas been presented.

4. Results of research

Knowing the changes of the mass expenditure of the individual components of exhaust fumes as functions of time, as well as the route length and the travel time, emissions can be expressed in g/km, just like for the type-approval tests (Table 3). However, to make it possible, it is necessary to measure and record the air flow and volumetric shares of the fumes components.

Due to the length of the gas analyser measuring pipe, its current indications concern the previous status of the engine from a few seconds before. For the accuracy of the emission calculations it is therefore significant to properly adjust the results recorded by the analyser and the air flow data. After the synchronization of the data it can be assumed, due to the accuracy of the measurement equipment and sensors, that the error of this method will not exceed a few percent and its value will be decreasing as the speed of driving will stabilize.

Figure 3 illustrates the values of fumes shares against the running speed and the mass air flow. The relationship of the air flow and the running speed is connected with the engine load and its rotational speed. Changes in volumetric shares also correlate with engine load. However, they are not so strong as air flow changes which have a significant impact on the emissions scale.

The effects of calculations based on the methodology described in chapter 3 are presented in Figure 4. In this case, the increase of exhausted gaseous amounts accompanying the increase of engine load, for example during acceleration, it is clearly visible. It is especially clear in the case of CO emission analysis, which is observed just during acceleration. It is near zero while driving without acceleration, which is represented by the flat nature of the CO emission curve (Fig. 4) observed in those periods.

The mass of the exhaust gases emitted in the test is presented in another bar chart (Fig. 5). The results of the calculations show that during the test, the car's engine emitted nearly 7,5 kg exhausts, in which 1,48 kg was carbon dio-

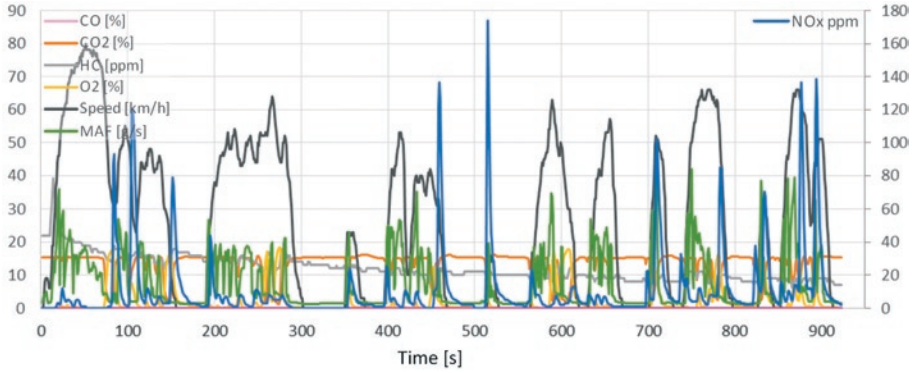

Fig. 3. The volumetric shares of selected fumes components registered during the urban drive against the running speed

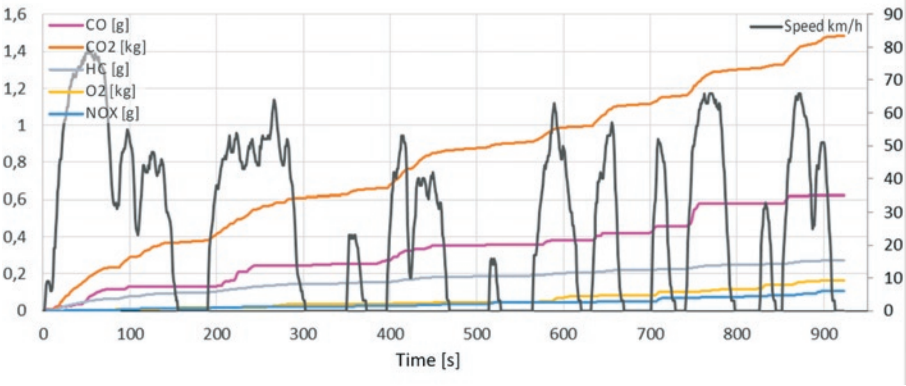

Fig. 4. The chart of cumulative emissions of selected fumes components obtained on the basis of the registered fumes composition

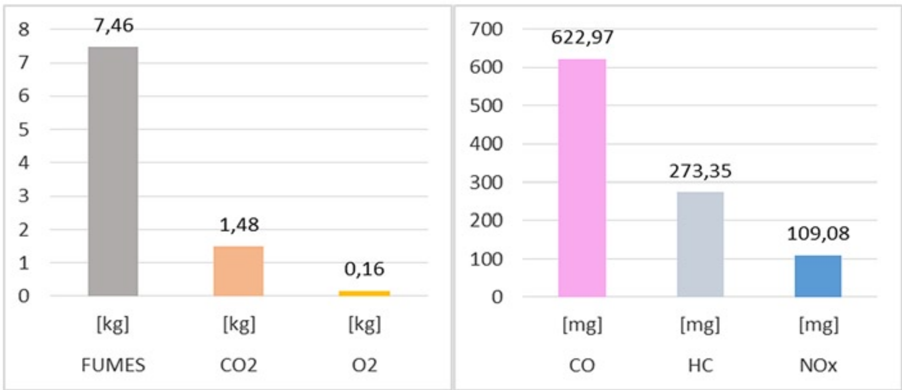

Fig. 5. Mass emissions of selected components of exhaust gases during the test

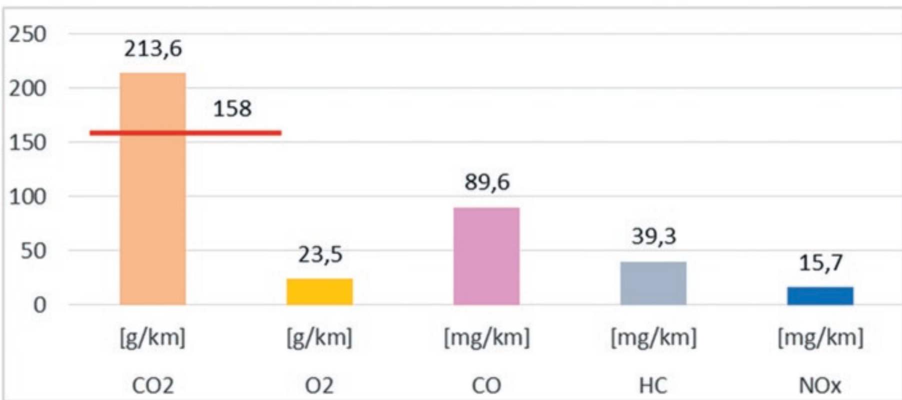

Fig. 6. The emissions of the selected components of exhausts during the test per kilometre

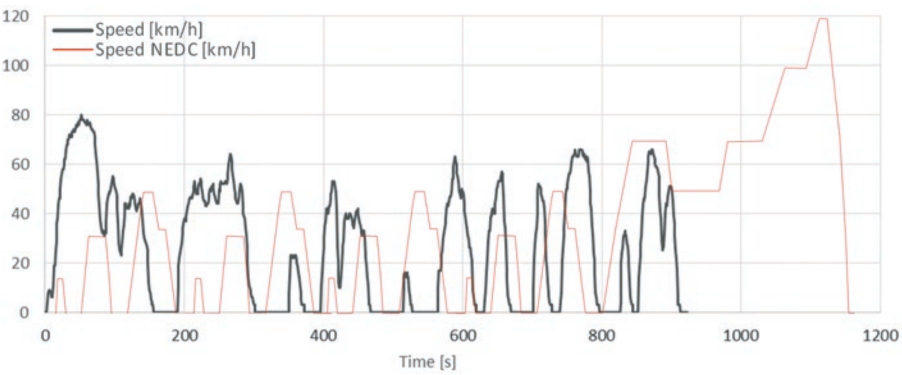

Fig. 7. The speed runs in the performed test and in NEDC

xide. Carbon monoxide emission was 623 mg, hydrocarbons ca 273 mg and nitric oxides ca 109 mg. This information is not clear without the reference to the distance travelled. Figure 6 is the supplement which allows the reader further evaluation. Therefore, it can be concluded that 213.6 g/km of carbon dioxide were issued in the test and the value (Fig. 6) is 35% bigger than the one obtained in the approval-test (Table. 2), while the emissions of toxic exhaust substances do not exceed the allowable standard values [21].

CO_2 emission, higher by more than 35%, is the result of a different than NEDC driving test. The test has been executed in conditions differing from the NEDC conditions due to the character of driving in a given agglomeration.

In the described case there are different vehicle properties and different moving resistances associated with them. Larger values of speed and its local fluctuations (Fig. 7) as well as higher vehicle weight (1726 kg) and hill route (average w = 0.7%) contribute to an increase of the engine's load and CO_2 emission. On the other hand, it should be noted that the test was implemented at the hot engine without the cold phase which would certainly additionally increase the emissions of CO_2 and CO and HC.

5. Summary and conclusions

The research and its results described in the paper confirm the possibility of the use of simplified method to exam the emission in a normal exploitation of a vehicle. However, the obtained data show that the real operation of the vehicle in an urban environment differs significantly from the specific nature of the NEDC test. (Fig. 7).

Comparing vehicles on the basis of such a test also seems to be an imperfect approach because it does not include full loads of an engine. The driver who controls a dynamic engine will surely try to use its power when fighting for a better position at the lights.

Hence there is a need for tests which also include situations where there occurs an acceleration with a maximum intensity, accompanied by random disturbances and operating states of an engine difficult to represent in a laboratory. Therefore, it should be emphasized that the road tests show the most accurately the real nature of the work of an engine work and its impact on the environment. The literature data confirm the need for changes in that area and indicate their tendencies [2, 6, 24].

Based on the analysis of the subject and the presented results of the research, the following conclusions can be made:

– the study described in the paper confirm that the emission measurements are possible with the use of a diagnostic gas analyser and signals available from EOBD via DLC,
– exhaust emissions measured in actual road conditions can significantly vary from the limits specified for the type-approval test performed in a laboratory (213 g/km vs 158 g/km),

– the presented research methodology and the results preparation are quite laborious but they show the possibility of constructing similar measurement systems that enable the user an automatic calculation and results registration for the quantitative exhaust emissions,
– the approval-tests such as NEDC can contribute misunderstandings, because vehicle users will nearly never reach the fuel consumption (CO_2 emission) at such a low level that is stated for the approval-test.

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