Chapter 6

Measurement of Exhaust Emissions under Actual Operating Conditions with the Use of PEMS: Review of Selected Vehicles

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Abstract

This paper is a synthetic approach to real driving (RDE) from selected vehicles: light-duty vehicle (LDV), heavy-duty vehicle (HDV). The tests were performed with the portable emission measurement system (PEMS) equipment under actual traffic conditions. The paper discusses problems of measurement methodology and emission of CO, HC, NO_x, and PM. The performed investigation confirms that the main problem is the emission of NO_x and PM, which usually is higher than the emission level. The obtained results show that the RDE method is very complex, but is the only way to provide invaluable information on the actual on-road exhaust emissions, not obtainable under laboratory conditions. In recent years, methods of exhaust emission testing under actual operating conditions have been developing rapidly. New technologies for extra low engine emissions pose a new question: does emission testing in a standard laboratory reflects real life emissions of a vehicle in use? In order to answer this question, it is necessary to measure the vehicle in-use emissions. Today, we know that the engine operating conditions (engine load and speed) in laboratory tests are not compliant with the conditions of actual operation. That is why the results of such tests are so desirable.

Keywords: exhaust emission, HDV, PC, PEMS, RDE

1. Introduction

Exhaust emissions have long been the leading factor determining the improvement of powertrains and combustion engines. The technological advancement causes an increased emission of the greenhouse gases, CO_2 in particular, while one of the most important sources of its emission is the combustion of fuel in engines. Another aspect tightly related to the operation of combustion engines is engine exhaust emissions. Today, we know that the exhaust components generated by engines such as CO, HC, NO_x, and PM are hazardous to humans. The report published in 2012, International Agency for Research of Cancer (IARC), one of the branches of World Health Organization (WHO), informed that diesel exhaust gas causes cancer (IARC) [1]. Earlier, this exhaust gas was classified in a group containing factors referred to as probably carcinogenic. Upon analysis of the results of the most recent environmental research, the WHO scientists unanimously concluded that diesel exhaust gas causes cancer [2–4]. In the report of the US Environmental Protection Agency (EPA), following decades of research and laboratory tests on animals, it was confirmed that the particles are carcinogenic, and significantly contribute to the development of cancer, lung cancer in particular [5]. Therefore, carmakers treat the problem of exhaust emissions with priority.

Toxic exhaust emissions studies conducted in real operating conditions clearly show that the level of actual emissions from vehicles is greater than the test limit values [6]. Real driving emission (RDE) tests are very often used to optimize engine performance in terms of emissions and fuel economy. May et al. [7] point out that the emission of nitrogen oxides is greater in the RDE studies than that obtained in laboratory tests. Consequently, they recommend using the RDE test results for the optimization of engine control systems. Similar conclusions were reached in [8]. In this paper, the authors compared RDE emissions to simulation results using the COPERT simulating tool. Nitrogen oxides emissions in simulation tests were about 30% of the values obtained in the RDE tests. The authors of papers [9–11] point out that the important factors influencing the results of RDE tests are the conditions in which the research is conducted: traffic intensity, driver predisposition, or weather. Hence, the need to regulate the RDE testing procedures. It can therefore be concluded that due to the serious risk posed to human health and the need to develop techniques and methods for measuring toxic emissions, the RDE emissions tests are highly desirable.

The issue tightly related to the problem of exhaust emissions is the legislation controlling the exhaust emissions from engines and vehicles. Throughout the years, this legislation has evolved mainly toward reduction of the admissible levels of individual exhaust components and advancement of research methodology. Today, the procedures of exhaust emissions measurement include driving under actual operating conditions (RDE) using portable emission measurement system (PEMS). This type of research is becoming commonplace for all vehicle categories.

2. PEMS equipment

Currently applicable homologation legislation for heavy-duty vehicles (Euro VI) and the heralded proposal of future test procedures for this as well as other vehicle groups

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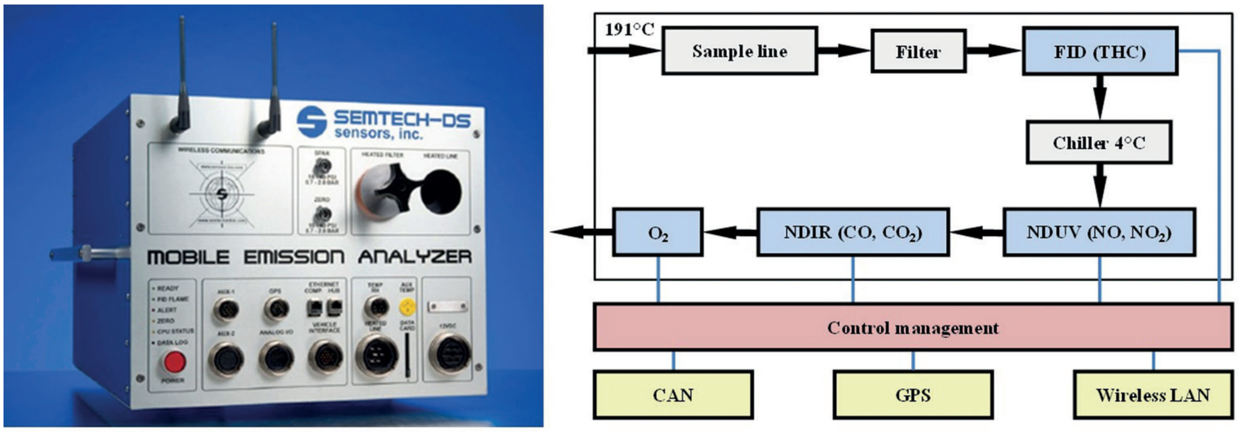
included the application of tests performed under actual driving conditions. This type of research, however, requires technologically advanced equipment (PEMS) that is increasingly often proposed by automotive measurement equipment manufacturers in their portfolio (AVL List GmbH, Horiba Ltd. and Sensors Inc.). This type of equipment can be used for testing machines and vehicles fueled with different fuels such as gasoline, diesel fuel, CNG, LPG, or oxygenated fuels. This also requires the application of special filters or exhaust gas diluters. Besides, the discussed equipment is characterized by high sampling frequency—a minimum of 1 Hz and reaching 500 Hz [e.g., high speed exhaust flow meter (EFM-HS)].

Due to the fast varying parameters of engines under actual conditions of operation and the advancement of aftertreatment systems, the equipment must be characterized by high measurement accuracy. The recording of ambient conditions is also necessary (pressure, temperature, humidity) as they have great impact on the measured values, hence additional corrective calculations are necessary. Therefore, the said measurement equipment often includes solutions (sensors, algorithms) that perform such procedures. What is more, the equipment must be characterized by low energy consumption, low weight and size, let alone high reliability. In order to perform a full analysis of the impact of a given type of powertrains and motion parameters of city buses on the environmental indexes, the following were utilized: SEMTECH DS (exhaust component concentration, oxygen content exhaust gas mass flow) as well as AVL MSS (used to determine the concentration of PM).

The presented measurement equipment is a unique set of analyzers allowing the determination of energy consumption and environmental performance of vehicles under actual conditions of operation:

- SEMTECH DS (**Figure 1**)—designed for the testing of gaseous exhaust components: NDIR: CO [%], CO_2 [%]; FID: THC [ppm]; NDUV: NO [ppm], NO_2 [ppm], and electrochemical O_2 [%];
- AVL MSS (Micro Soot Sensor—**Figure 2a**)—used to calculate the concentration of PM [mg/m^3] with the photo-acoustic method;
- TSI 3090 EEPS™ (Engine Exhaust Particle Sizer™ Spectrometer—**Figure 2b**)—allows determination of the size distribution of PM [nm];
- SEMTECH ECOSTAR (**Figure 3**)—allows measurement of both gaseous components and particulates (mass and number);
- AVL OTR (On The Road) OPACIMETER—used to test the exhaust gas opacity [%]; and
- SEMTECH LASAR—allows determination of the content of the exhaust gas including NH_3, N_2O, CH_4 [ppm].

The complementary analyzers are as follows: SEMTECH PPMD, SEMTECH LAM, AVL M.O.V.E., SEMTECH NMHC, AVL PARTICULATE COUNTER, TEXA NAVIGATOR TXT, and AVL INDIMICRO.



Parameter	Measurement method	Accuracy
Exhaust component concentration:		
CO	NDIR analyzer, measurement range 0–10%	±3%
HC	FID analyzer, measurement range 0–10 000 ppm	±2,5%
$NO_x = (NO + NO_2)$	NDUV analyzer, measurement range 0–3 000 ppm	±3%
CO_2	NDIR analyzer, measurement range 0–20%	±3%
O_2	Electrochemical analyzer, measurement range 0–21%	±1%
Exhaust gas flow	Mass flow rate T_{max} to 700°C	±2,5% range ±1% range

Figure 1. SEMTECH DS analyzer used for the measurement of exhaust gaseous components under actual conditions of operation [12].

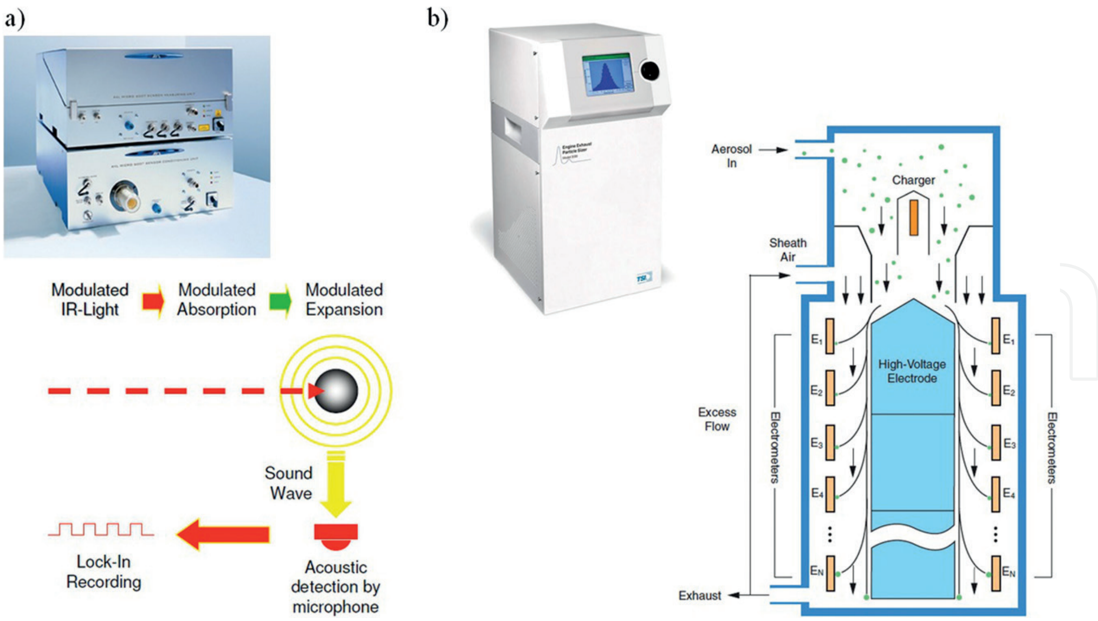


Figure 2. Equipment: (a) AVL MSS analyzers for the measurement of PM [13] and (b) TSI 3090 EEPS™ equipment for PM size distribution under actual conditions of operation [14].

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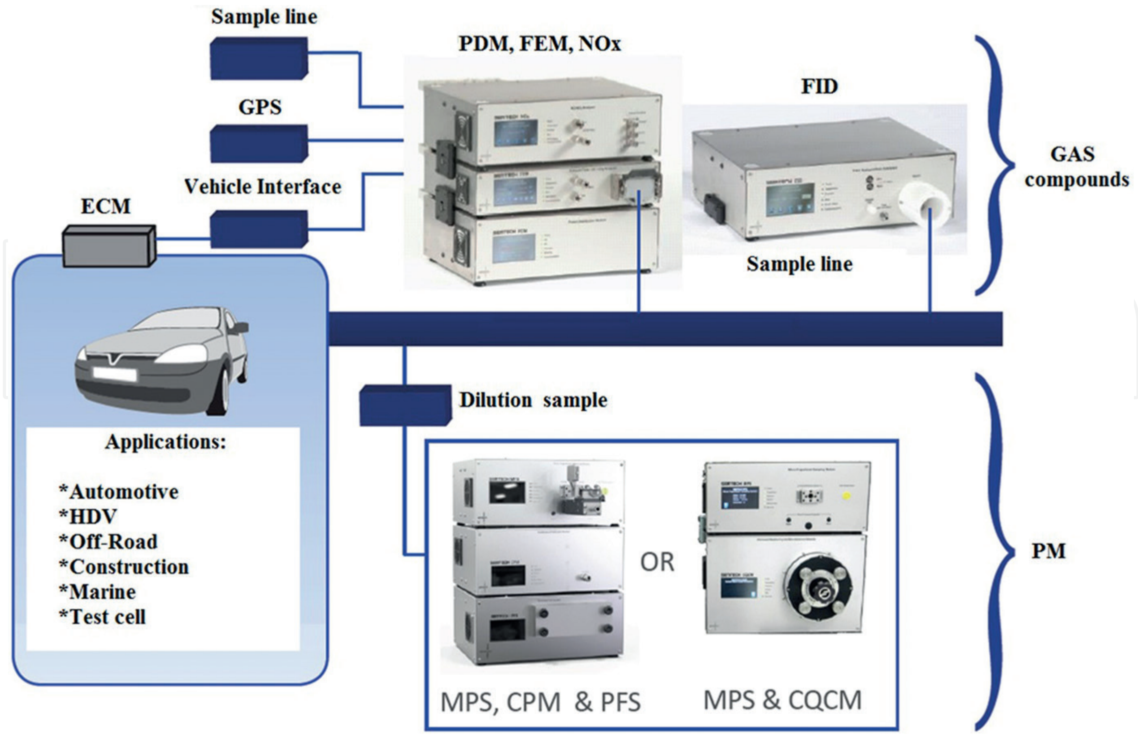

Figure 3. SEMTECH ECOSTAR analyzer for the measurement of gaseous exhaust components and particulate mass under actual conditions of operation [15].

3. Exhaust emissions legislation for light-duty vehicles

From the analysis of global exhaust emission standards for passenger cars (PC) and light-duty vehicles (LDV), we know that within the present decade, these standards will undergo modifications in all regions of the world (**Figure 4**). Due to the global reach of production and sales of motor vehicles by a variety of carmakers, a trend of unification of the test procedures is conspicuous. The exhaust emission limits are to remain varied and the introduction by a given legislator of additional tests will be allowed.

Currently homologation according to the ECE R83/06 directive describing the requirements for the obtainment of the Euro 5 and 6 standards. The details of the homologation legislation have been included in the EU (WE) 692/2008 regulation that is the amendment of regulation (WE) 715/2007. Item 1 article 3 of the (WE) 692/2008 regulation stipulates that in order to obtain a WE homologation in terms of exhaust emissions and the information related to vehicle repair and maintenance, the manufacturer confirms that the vehicles conform to the testing methods described in III–VIII, X–XII, XIV, and XVI of the said regulation. Aside from the said tests, the manufacturers are obliged to perform a procedure for conformity in operation, to check the operation of the on-board diagnostic system (OBD) and perform a measurement of the emission of CO_2 and fuel consumption. The regulation also includes the limits of individual exhaust components. For spark ignition engines of the Euro 6 standard, a limit of

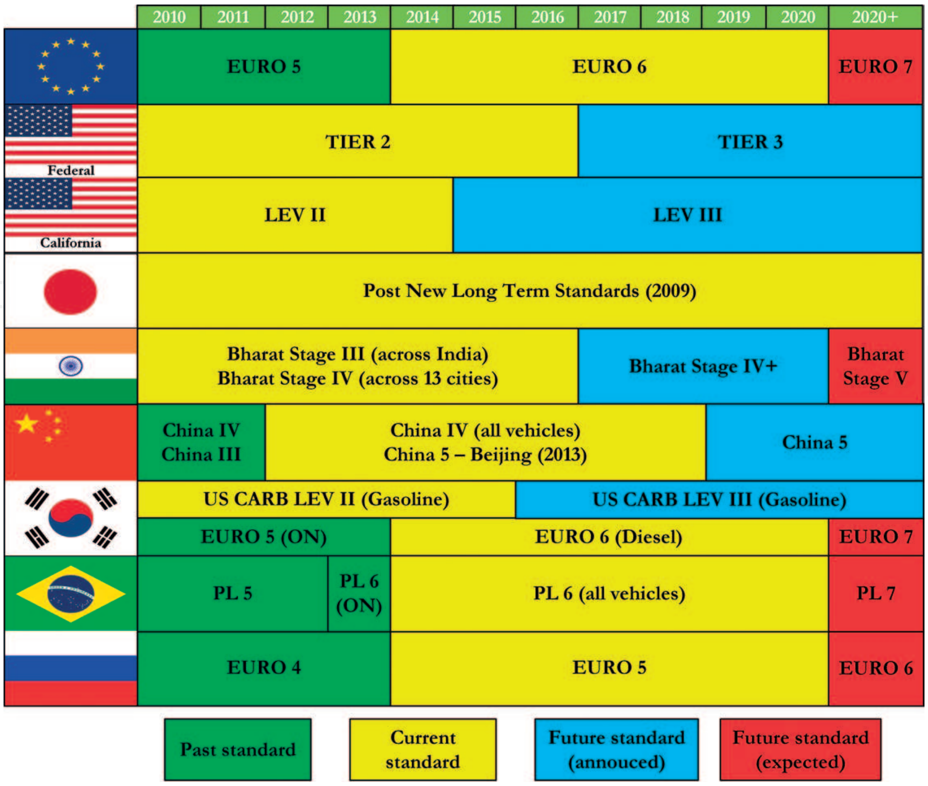

Figure 4. World emission standards 2010–2020 [16].

the particulate number (PN) was introduced for vehicles fitted with direct injected engines. Such regulations were not applicable in earlier standards.

Beside the exhaust emission limits, a very important aspect is the reduction of the emission of CO_2 from a fleet of vehicles. This emission is tantamount to fuel consumption. In 2007, European Commission (EC) proposed a 30% reduction of the emission of greenhouse gases in developed countries by 2020 and that the EU itself should undertake to reach at least a 20% reduction of these gases. Aside from the environmental aspects, the introduction of these regulations aims at accelerating and facilitating of the introduction of ultra low emission vehicles manufactured by the EU members. Regulation WE 443/2009 is applicable for the M1 vehicle category while WE 510/2011 is dedicated for the N1 category. Both legislations set the admissible limits of the road emission of CO_2, potential transition periods and deviations from these limits. The measurement of the CO_2 emission from both groups of vehicles is performed according to the methodology set forth in WE 715/2007 [17–19].

Prior to introducing the Euro 6 standard, an amendment of a series of regulations was planned. At the end of 2014, The European Commission passed to the European Parliament a motion (COM(2014) 28 final version) to amend the WE 715/2007 and WE 595/2009 regulation related to vehicle homologation procedures. The most important changes were as follows [16]:

1. increasing the gross vehicle weight from regulation WE 715/2007 (Euro 5 and 6) for the M_1, M_2, N_1, and N_2 vehicle categories from 2610 to 5000 kg;

2. changing the mass of CO_2 in the CoC mass of greenhouse gases as an equivalent of CO_2 and increasing or canceling the limit of the sum of hydrocarbons. Methane would then be construed as CO_2 equivalent;
3. introducing a limit of NO_2 emission into the supplement to the total NO_x limit. The maximum value of the emission must be determined based on the assessment of consequences;
4. supplementing of the tests (Type 6) with emission measurement of NO_x and NO_2, under low temperatures; and
5. authorizing the European Commission to update the limits of mass and number of particulates and the procedures of their measurement.

The most important amendment of the homologation procedures of PC and LDV vehicles is the replacement of the New European Driving Cycle (NEDC) with worldwide harmonized light vehicles test procedures (WLTP). They assume a global harmonization of driving cycles used for the testing of motor vehicles performed on chassis dynamometers. In ECE/TRANS/WP.29/2014/27 [20], a proposal has been presented for new test cycles that will be implemented in 2017. Three types of test cycles have been determined in this document, classified according to unit index of power (the ratio of effective power to the curb weight of the vehicle—PWr coefficient):

1. Class 1—low power output vehicles, PWr ≤ 22;
2. Class 2—vehicles in the range 22 < PWr ≤ 34; and
3. Class 3—high power output vehicles, PWr ≥ 34.

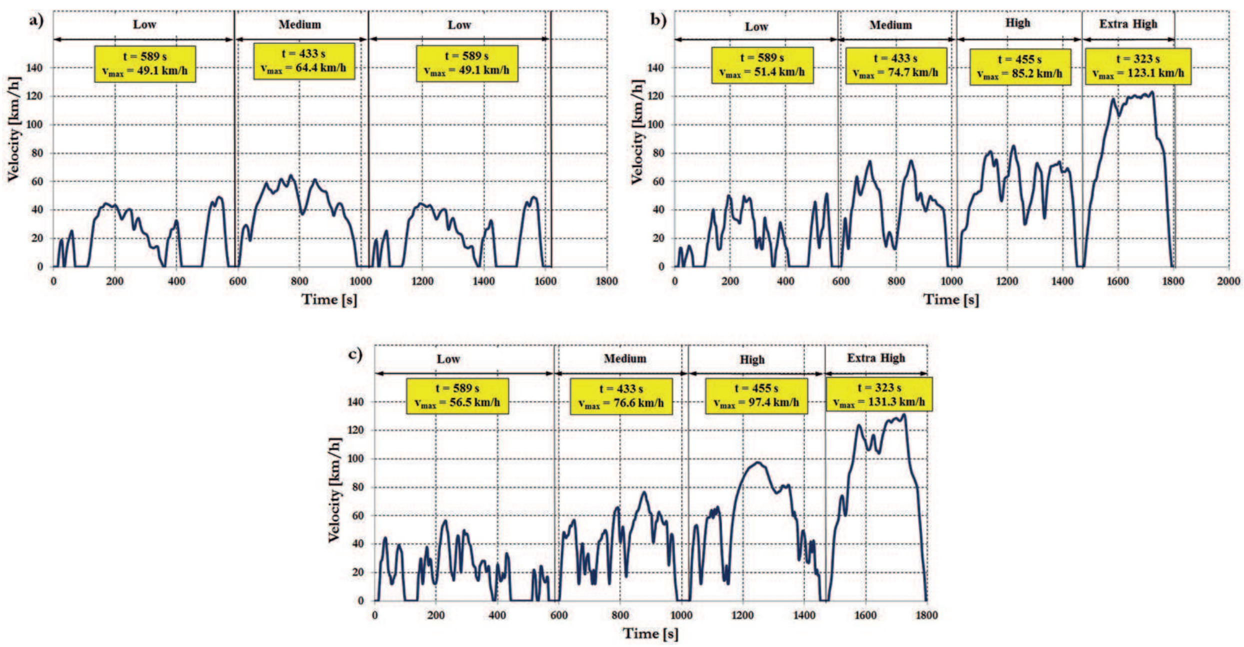

Figure 5. Curves of the WLTC driving cycle for vehicles: (a) Class 1, (b) Class 2, and (c) Class 3 [21].

For the Class 1 vehicles, the worldwide harmonized light-duty test cycle (WLTC) test is composed of three parts representing the driving conditions with two low and medium speed (**Figure 5a**). Its maximum value is 49.1 and 64.4 km/h, respectively. The average speed in the entire cycle is 33.3 km/h (counted without vehicle stationary) or 26.8 km/h including the vehicle stops that total 21.1% of the entire test duration. The test designed for Class 2 vehicles has an additional phase representing high speeds (**Figure 5b**). Its total time amounts to 1800 s and the vehicle covers a distance of 22.649 km. The values of the maximum and average speeds are different than those of the Class 1 vehicles. The most complex is the WLTC test for Class 3 vehicles (**Figure 5c**). It is composed of four phases. In the final part of the test, the vehicle develops a speed of 131.3 km/h [22]. In relation to the NEDC test, it is a 10% increase. The total WLTC test time for this class of vehicles is 1800 s. Comparing the WLTC test with the NEDC one, we can see a fundamental difference related to the velocity curve—the NEDC test is composed of repeated segments, while the WLTC tests have different velocity profiles that are a representation of the actual driving cycle. High variability of acceleration is a characteristic of these tests compared to the NEDC test of constant accelerations (**Table 1**).

	NEDC	WLTC Class 1	WLTC Class 2	WLTC Class 3
Time [s]	1180	1611	1800	1800
Distance [m]	11,023	11,428	22,649	23,262
Share of vehicle stationary [%]	33	21.1	15.8	13.4
Maximum speed [km/h]	120	64.4	123.1	131.4
Average speed [km/h]	33.6	26.8	50.4	51.8
Maximum acceleration [m/s^2]	1	0.76	0.96	1.58

Table 1. Characteristics of the NEDC and WLTC emission tests [20, 21].

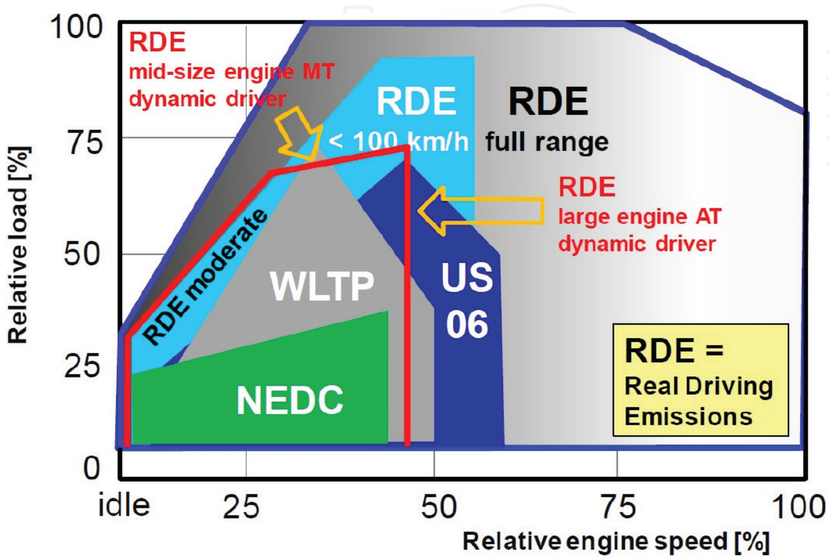

Figure 6. Engine parameters in different emission tests [22].

The work area of a combustion engine in the emission homologation tests is much smaller than the area occurring under actual operation (**Figure 6**). For this reason, an introduction of new methods of exhaust emissions measurements to the existing test procedures was proposed (real driving emissions). Portable emission measurement equipment will be used for this purpose (PEMS). On 10 March 2016, an EU Regulation—(UE) 2016/427 [23] was published containing a detailed description of the performance of these measurements for PC and LDV vehicles.

4. Tests of PC and LDV vehicles

4.1. Characteristics of the research objects and testing methods

Two vehicles were selected for the evaluation of the start-stop system. Vehicle A was fitted with a turbocharged gasoline engine of the displacement of 0.9 dm^3, fitted with a three-way catalytic converter (**Table 2** and **Figure 7**). The engine was characterized with a volumetric power output index of 70.8 kW/dm^3. Vehicle B was fitted with a diesel engine of the displacement of 3.0 dm^3. In this case, the volumetric power output index amounted to 58.7 kW/dm^3 and was lower by 17% than the index of vehicle A. The engine of this vehicle was fitted with a diesel oxidation catalyst (DOC) and a diesel particulate filter.

4.2. Testing methods

Exhaust emission tests (CO_2, NO_x, CO, and THC) were performed under real operating conditions of the vehicle in traffic in the Poznań city. The vehicle route during the tests has been shown in **Figure 8**.

The length of the route was 12.71 km. It was diversified and included a typical urban portion and an extra-urban portion where it was possible to drive at highway speeds (with a maximum speed of 120 km/h). The extra-urban portion was 5.5 km long. As shown in **Figure 8**, the length of the vehicle route during the road test was similar to that of the NEDC test [3]. The driving time in the road tests of approximately 1200 s was similar to that of the NEDC test.

Parameter	Vehicle A	Vehicle B
Type of ignition	Spark ignition	Compress ignition
Engine displacement	0.9 dm^3	3.0 dm^3
Cylinder number and arrangement	Straight—2	V—6
Maximum torque	145 N m @ 1800 rpm	550 N m @ 2000–2250 rpm
Volumetric power output index	70.8 kW/dm^3	58.7 kW/dm^3
Injection system	MPI	Common rail
Aspiration	Turbocharger	Turbocharger
Aftertreatment system	TWC	EGR, DPF, DOC
Type of transmission	Automatic	Automatic

Table 2. Characteristics of the tested objects.

Figure 7. The tested objects ready for the on-road exhaust emissions tests.

4.3. Analysis of the exhaust emissions from LDV vehicles

In order to determine the efficiency of the start-stop system, the exhaust emission measurements were performed for the system in the enabled and disabled mode. Average speed was selected as a criterion decisive of the possibility of comparison of both vehicle drives. Its maximum relative difference was assumed on the level of 5%. For vehicle A, the relative speed difference was 3.5% and for vehicle B—5%.

Figure 8. The road used for the exhaust emission testing (marked with red line) [created by GPSVisualizer.com].

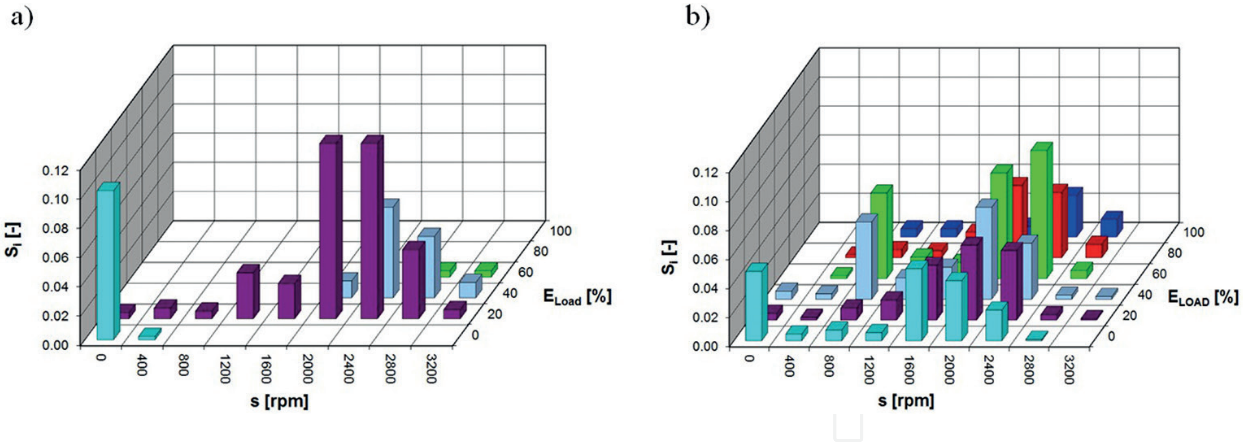

Figure 9. Characteristics of the operating time share referred to the engine (a) of vehicle A and (b) of vehicle B.

Based on the data recorded from the OBD system of the vehicles, the operating time share characteristics of the vehicle engines were made depending on the engine speed and torque (**Figure 9**). In the case of vehicle A, due to the start-stop system, as much as 11% of the driving time, the engine was off and for vehicle B it was 6%.

Figure 10 presents the changes in the exhaust emissions measured with the second-by-second resolution (CO_2, NO_x, CO, THC) and the engine speed on the example of vehicle B during a drive with the start-stop system enabled. Having analyzed the obtained courses, we have observed that the system switched off the engine seven times. The effect of this was obviously zero emission of CO_2 at that time. It has also been observed that in the first

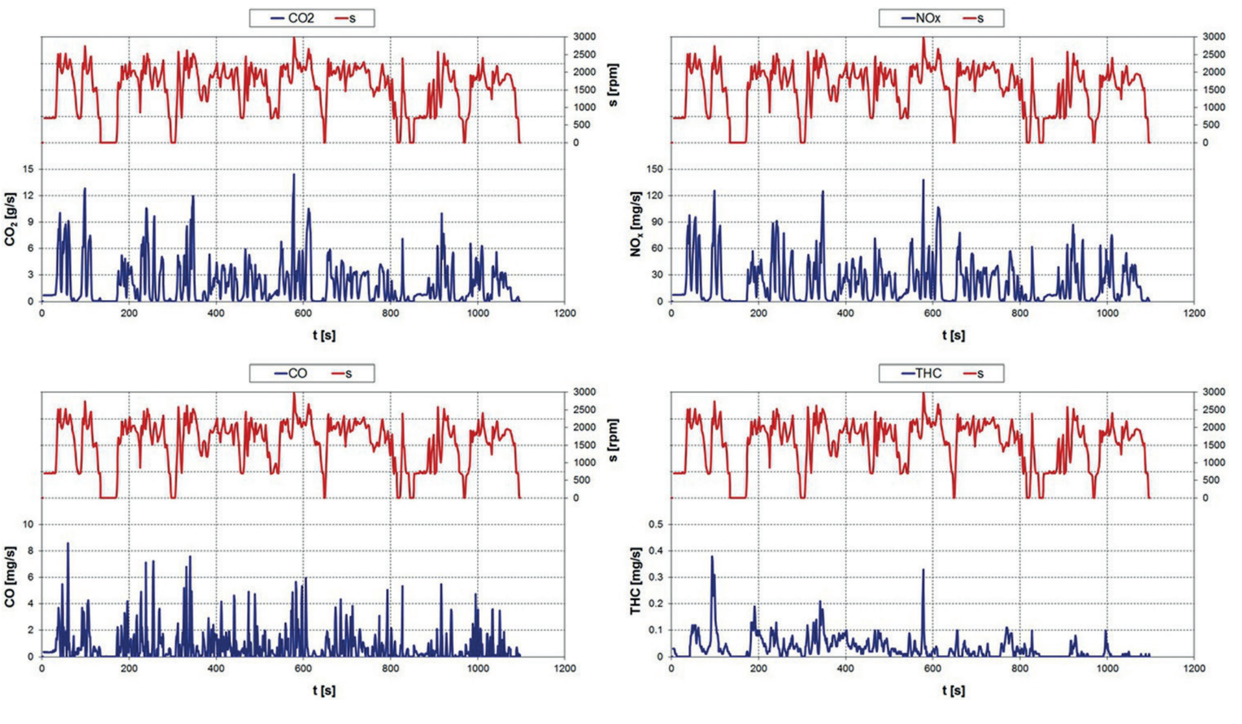

Figure 10. The courses of the emissions of CO_2, NO_x, CO, and THC measured with the second-by-second resolution and engine speed of vehicle B during a drive with the start-stop system enabled.

half of the test (0–600 s), the maximum values of the emission of CO_2 were lower than in the second part of the test. This depended on the characteristics of the test route—the second part of the test was a drive close to the extra-urban traffic conditions (a road portion of the entrance to the city). On this road portion, higher speeds were developed, which resulted in an increased energy demand of the engine, hence a growth in the emission of CO_2. In the case of the emission of NO_x and CO, a similar situation has been observed. The highest level of the emission of THC occurred in the first phase of the test. This most likely resulted from a cold engine start—lower temperature of the catalytic converter. We can deduct that the DOC catalyst in the beginning of the test did not reach the light-off temperature.

Based on the performed measurements, the on-road emissions of CO_2, NO_x, CO, THC, HC + NO_x as well as gas mileage were determined. The obtained values were compared to the limits set forth in the Euro 5 standard (**Figure 11**). The authors also determined the efficiency of the applied start-stop system. For vehicle A, the enabling of the system resulted in a reduction of:

- the emission of CO_2 by 7%;
- the emission of NO_x by 13%;
- the emission of CO by 12%;
- the emission of THC by 15%; and
- gas mileage by 9%.

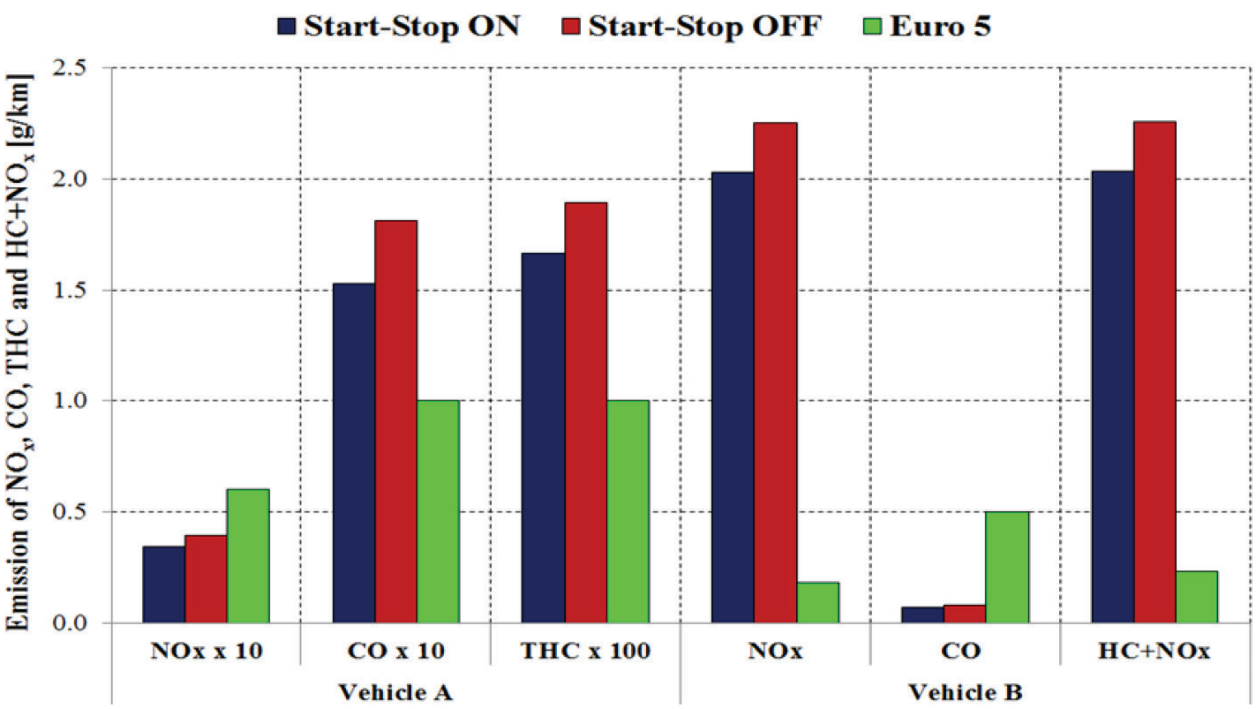

Figure 11. The obtained on-road emissions of NO_x, CO, THC, and HC + NO_x referred to the limits determined in the Euro 5 standard.

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For vehicle B, a reduction has been recorded of:

- the emission of CO_2 by 11%;
- the emission of NO_x by 10%;
- the emission of CO by 13%;
- the emission of HC + NO_x by 10%; and
- gas mileage by 12%.

The obtained results confirm the efficiency of the application of the start-stop system. It is worth emphasizing that the presented results reflect the actual benefits from the application of this system as the tests were performed in actual traffic; hence, certain operating factors having impact on the exhaust emissions and fuel consumption were taken into account—factors that are not always considered during laboratory tests.

5. Exhaust emissions legislation for engines of HDV vehicles

For the HDV group of vehicles, due to their specific design characterized by significant size and power outputs, homologation in terms of unit emissions is performed for the engine alone on engine test beds. For all Euro standards, performing tests at preset points of work in stationary tests is necessary. Since 2000, the Euro III standard is applicable for the homologated vehicles. It is based on: European transient cycle (ETC), European stationary cycle (ESC), and European load response (ELR). The same procedures are applicable for the Euro IV, V, and EEV standards, but the exhaust opacity test for heavy-duty vehicles is performed in the ELR test. The boundary values of the exhaust emissions for diesel engines have been reduced with the introduction of further directives and regulations (**Figure 12**). A relative reduction of the unit emissions of individual exhaust components was: CO—67%, HC—88%, NO_x—95%, and particulate mass—98%, respectively. For exhaust opacity, limits were applicable throughout the Euro III–V standards. Following the technological advancement of combustion engines and aftertreatment systems, an introduction of boundary values [particle number (PN)] in the Euro VI became necessary. Along with the introduction of the Euro III standard, an European transient cycle (ETC) became applicable in which the combustion engine was tested for dynamic operating parameters (**Figure 13**).

In the Euro VI standard, in relation to the previous regulations, requirements related to the diesel engine have been more extensively defined. The latest regulations do not allow for the additional division into regular standards and EEV.

During the development of the transient *World harmonized transient cycle* (WHTC) and stationary *World harmonized stationary cycle* (WHSC), road test results performed in selected EU member states, Japan and USA were taken into account. This aimed at approximating the test bed measurement cycles to the actual conditions of operation worldwide. The

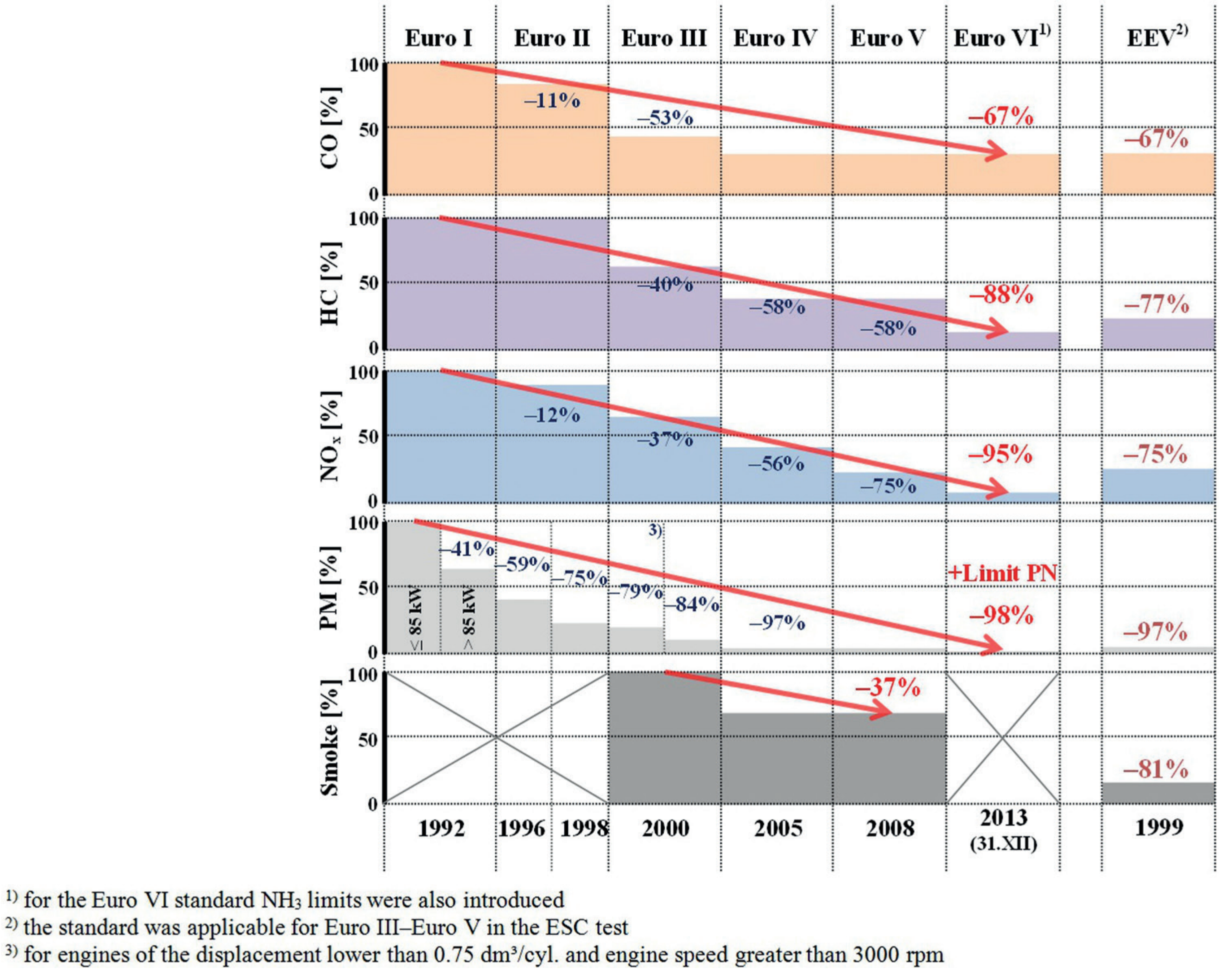

Figure 12. Relative reduction of the admissible unit emission values related to the subsequent Euro standards for stationary tests [24, 25].

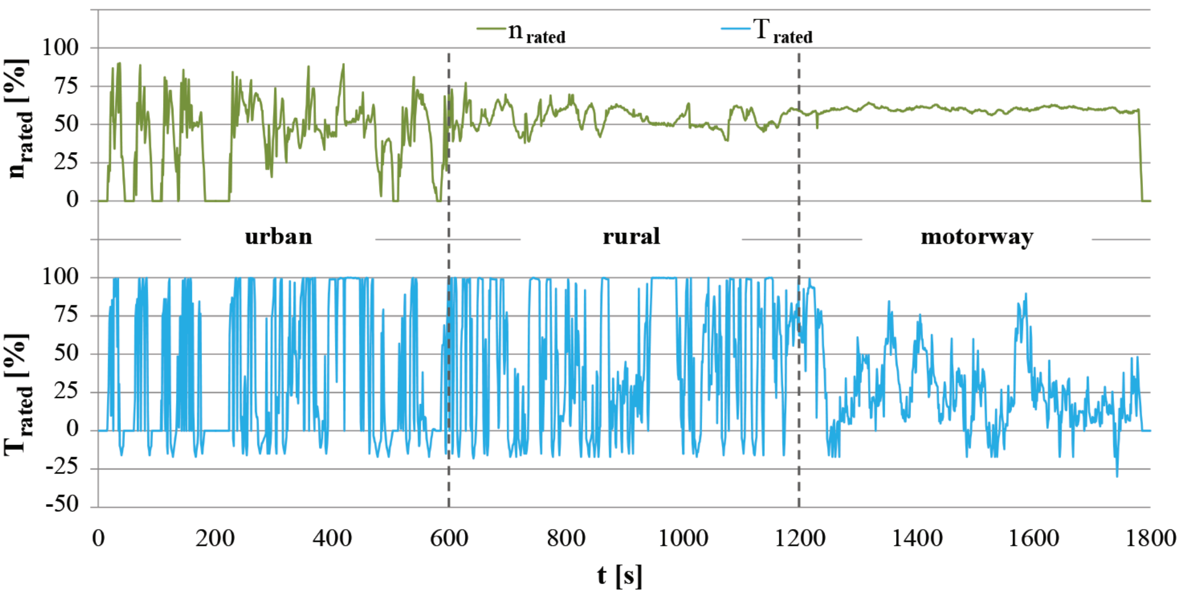

Figure 13. The engine torque and speed curves during the ETC test [26].

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previously applied tests were developed based on the European conditions exclusively. Detailed data on the realization of the tests are included in the *Global technical regulations* (GTR) no. 4 developed by UNECE [27]. Similarly to the transient cycle applicable for the Euro V standard, the WHTC trials can be realized on both chassis dynamometers and engine dynamometers, yet for the homologation, the latter option applies (**Figure 14**). There are three parts to the tests—urban driving, extra-urban driving, and expressway driving. The length of the trial is 1800 s. The length of the subsequent phases of the tests is 900 s, 481 s, and 419 s, respectively.

The WHSC test was designed to measure the exhaust emissions under steady state conditions and is composed of 13 phases, similarly to the ESC test (**Figure 15**). The main difference between the said cycles is different engine speeds (the latter standard provides for six main engine speeds) and the application of different weight coefficients, resulting from the durations for each point of work. Besides, the measurement at idle occurs twice. It is noteworthy that the average values of n and T are lower than in the ESC test, which indicates that the engine is under smaller load.

In the Euro V and Euro VI standards, mileages and periods of operation are given corresponding to a regular life cycle of a heavy-duty vehicle. Minimum mileages are also provided for the durability trials depending on the category and gross vehicle weight of the tested object. The legislation is supplemented with data related to the determination of coefficients of deterioration (more precise and unambiguous definitions have been included in the Euro VI standard) [18]. Important changes in the regulations were introduced in terms of the scope of supervision of the conformity in operation—it is now necessary to perform exhaust emission measurements under actual traffic conditions using PEMS. Earlier, only engines (removed from the vehicle) were tested.

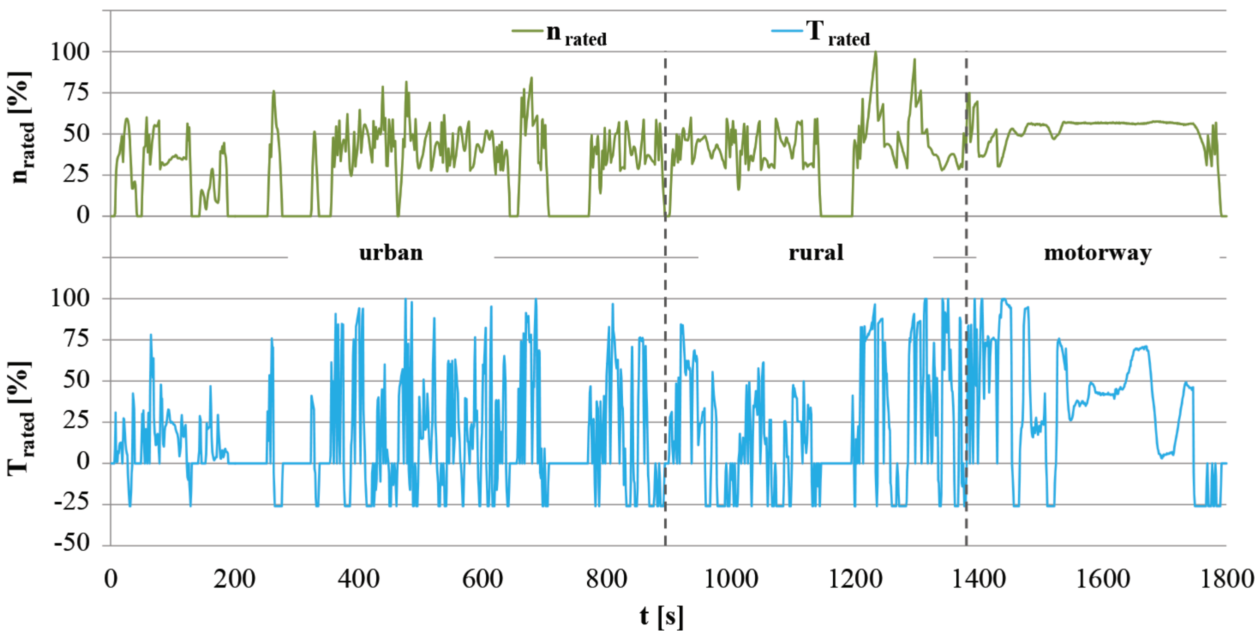
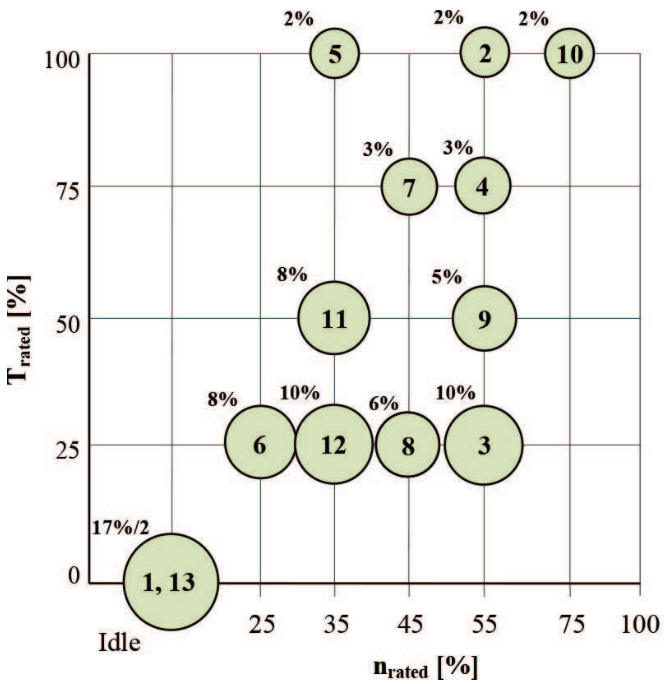


Figure 14. The engine torque and speed curves during the WHTC test [27].



Phase	Time covering the interval [s]
0	–
1	210
2	50
3	250
4	75
5	50
6	200
7	75
8	150
9	125
10	50
11	200
12	250
13	210

Figure 15. The course of the harmonized WHSC test (numbers 1 through 13 represent the order of phase completion; percentage values at subsequent phases indicate their weights) [27].

Regulation UE 582/2011 (schedule II) includes detailed requirements related to the determination of conformity in operation of the engines or vehicles. Out of the most vital information, it should be mentioned that the measurements must be performed on public roads of the UE member states, using typical driving styles and loads. This means that the tests are performed for standard (most frequently occurring) conditions of operation. During the test procedure, it is also important that the driver has sufficient skills and is properly trained to use the vehicle, preferably a person who uses this particular vehicle on a daily basis. If the tests cannot be performed under standard operating conditions, it is possible to use alternative routes. In light of the shortage of information on representative vehicle load, a replacement load is applied ensuring 50–60% of the maximum load.

Upon first registration of a complete vehicle fitted with a combustion engine from the homologated group of engines, the manufacturer must perform tests in operation within 18 months reaching a mileage of at least 25,000 km [28]. According to [29], the measurements must be repeated periodically, at least every 24 months throughout typical vehicle life cycle. The test route must include urban roads (speed range: 0–13.89 m/s), extra-urban roads (13.89–20.83 m/s), and expressways (in excess of 20.83 m/s). In justified cases, the order of the test routes may be changed. The shares of the drives under individual conditions depend on the category of the tested vehicle (**Table 3**). They are determined with the accuracy of ±5%, due to the actual traffic conditions that are hard to predict. It is very important that in the realized test route, five times the work performed during the WHTC test is obtained or five times the reference mass of CO_2 from the same test is reached.

The coefficients of conformity are determined for measurement windows identified with two methods: based on the mass of CO_2 or total work performed by the engine. In the legislation

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Category	Share of operating conditions [%]		
	Urban	Rural	Motorway
M_1, N_1	45	25	30
M_2, M_3 Class I, II & A	70	30	0
M_2, M_3 other	45	25	30
N_2	45	25	30
N_3	20	25	55

Table 3. Share of the operating conditions during the conformity in operation tests (HDV) [28].

process, in order to issue a decision, only the second variant should be performed. The tests include the unit emission of gaseous exhaust components: CO and THC (for diesel engines), NMHC and CH_4 (for spark ignition engines) as well as NO_x (for diesel and spark ignition engines). Currently, the mass and number of particulates is not taken into account. Besides, it is necessary to measure the exhaust gas mass flow, engine parameters, vehicle speed, ambient conditions, etc.

The assessment of the unit exhaust emissions is made using variable averaging windows (**Figure 16**). Their determination consists in obtaining the mass rate of the exhaust emissions for subsets of a complete data set, whose length is determined so that they correspond to the mass of CO_2 generated by the engine or work measured under transient conditions on a test bed (WHTC).

The condition for accepting the measurement window as valid is fulfilling the requirement of reaching an average power output exceeding 20% $N_{e\,max}$ in that window. In the entire test, the percentage of measurement windows must be 50% or more. If this is not obtained, the data

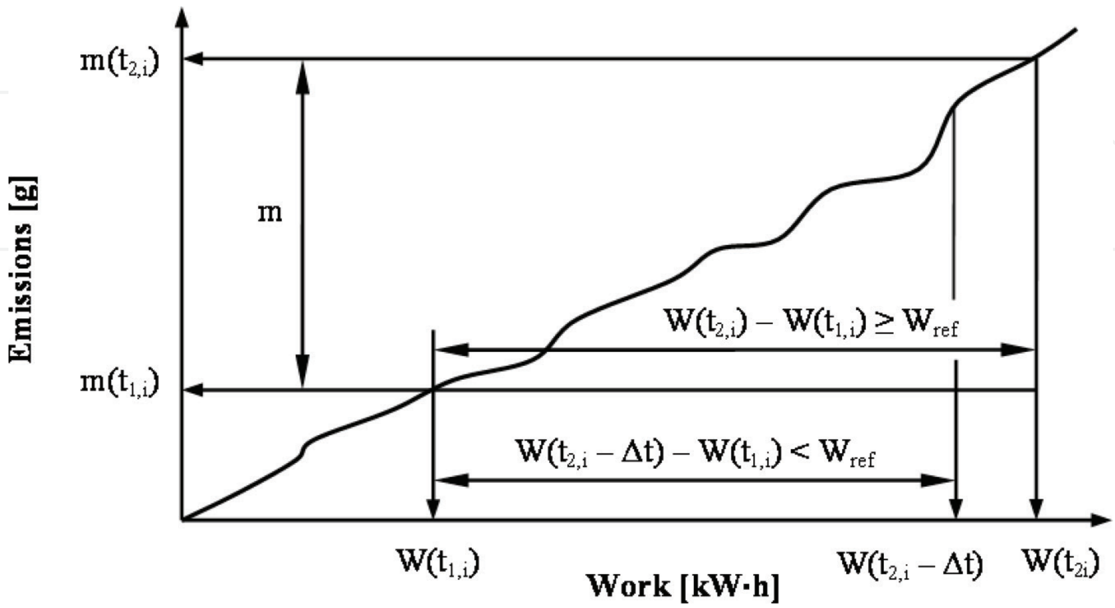

Figure 16. Determination of the measurement windows in the method based on reference work [28].

evaluation is repeated applying lower power output thresholds. The reduction is made with 1% resolution, maximum 15% $N_{e\,max}$. Lower value renders the results invalid.

The coefficient of conformity in operation in terms of exhaust emissions *conformity factor* (CF) is determined in all windows for each analyzed exhaust component as per Eq. (1). In order to render the evaluation in a given averaging interval positive, the determined coefficients cannot be greater than 1.5. The vehicle is considered compliant if 90% of the calculated CF values meet this criterion.

$$CF = \frac{e_j}{L_j} \quad (1)$$

where CF—coefficient of conformity in a given averaging window; L_j—admissible emission of a *j*th component in the WHTC test [mg/(kW h)].

The American *United States Environmental Protection Agency* (US EPA) has proposed a test serving the purpose of controlling the exhaust emissions from heavy-duty vehicles under non-test conditions *not-to-exceed* (NTE) that could be applied during the assessment of the actual environmental indexes. The NTE requirements were introduced in 1998 as an ordinance with the consent of the HDV engine manufacturers [25]. The test stringent requirements were gradually extended to other engine categories. As an assumption, the limits and procedures of the test performance were developed as an additional confirmation that exhaust emissions are in conformity with the legislation in the entire range of engine speeds and loads. The NTE test area of an example engine has been shown in **Figure 17**.

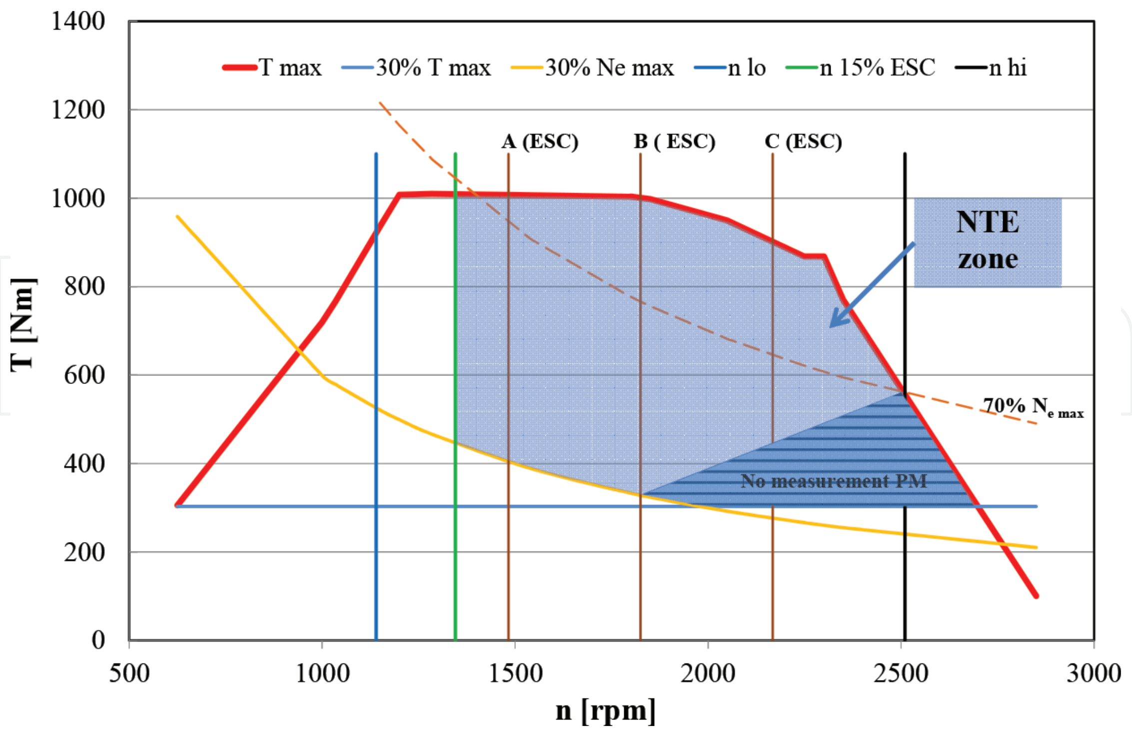

Figure 17. The NTE test area for the engine of a heavy-duty vehicle.

The test procedure does not determine any specific driving cycle, but it contains guidelines related to the determination of the area for which the emission is measured. The tests can be performed under any operating conditions. It is vital that in a certain range, the engine operates for at least 30 s in the control area. In this period, the values of engine speed and load may not exceed a predetermined area. The obtained values of exhaust emissions are averaged and in the final stage compared to the applicable NTE emission limits. In order to determine the control area, it is necessary to determine the basic engine characteristics and meet the following conditions [25]:

- the minimum engine speed (engine A) is analogical to the engine speeds of the European stationary cycle (ESC) test, just as is in the case of engine B;
- engine load is equal or greater than 30% of the maximum engine torque;
- all points of work in which the engine develops power lower than 30% of the maximum power are excluded from the NTE area; and
- the engine manufacturer may apply for an exclusion from the NTE area of engine speeds and loads for which the unit fuel consumption is greater than 5% of the minimum fuel consumption, if he expects that the engine will not work in these areas during regular operation. This does not apply to engines coupled with automatic transmissions of a specified number of speeds and vehicles with manual transmissions.

Due to the obtained maximum engine speeds (2400 rpm), there are small differences in defining the area excluded from the measurement of particulate matter.

6. Testing heavy-duty vehicles

6.1. The route

For the tests, the authors selected a road portion of the length of 27 km (**Figure 18**). The road portion well characterizes the operation of vehicles of the GVW exceeding 16,000 kg (long haulage) in the area where the measurements were carried out. The test route started and ended in the industrial zone (point A) where a production facility is located at which approximately 50 heavy-duty vehicles are handled daily. The test road portion can be divided into two parts: a drive on urban roads (portion A–B) and national and regional roads. The drive on national or regional roads depends on the driving direction from/to the entrance to the A2 expressway (Koło) (point D). In the case of driving to the “Koło” expressway entrance, the route went through points B–C and C–D. In the reverse situation, i.e., exiting the expressway and driving to the production facility via bypasses: points D–C and C–B (on the D–C road portion heavy-duty trucks of the GVW in excess of 7000 kg are not permitted.) The above route can be deemed representative of the national transport and logistic infrastructure—representing the road infrastructure and the distribution of production facilities in small and medium-sized towns.

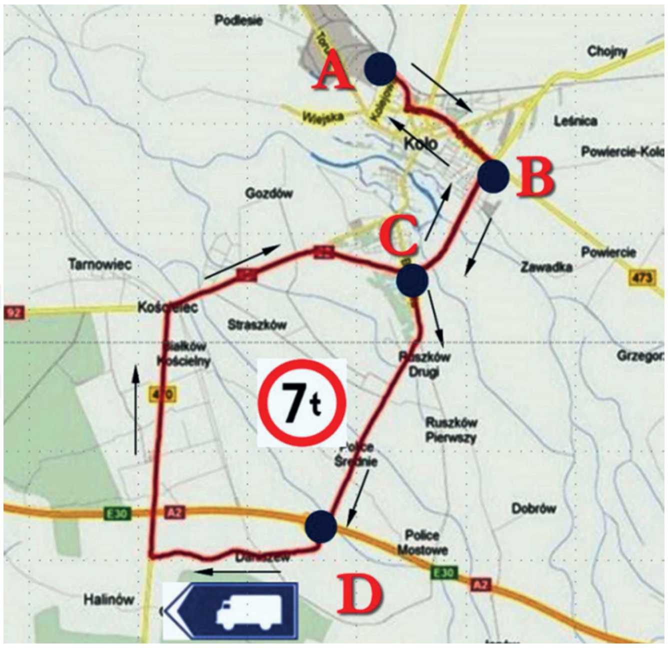

Figure 18. The measurement road portion used in the on-road emission tests [made based on GPSVisualiser.com].

6.2. Research objects

For the research, the authors used two heavy-duty trucks (road tractors with semi-trailers) loaded with a cargo of 20,000 and 24,800 kg (**Figure 19**). The first of the objects was fitted with a 309 kW (420 KM) Euro III engine. The other object had a V8 412 kW (560 KM) Euro V engine. Both vehicles were fitted with an automatic transmission (**Table 4**) of the 12+1 configuration. The second vehicle was also fitted with a driver monitoring system. By a continuous analysis of signals from a series of sensors, the system provides real time suggestions, and upon end of trip generates a report on the driving style. The suggestions and the evaluation are presented on a display and have four categories: driving uphill, predicting, braking, and gearshifts. The idea behind the system is to continuously improve the driving skills in terms of fuel consumption and proper use of modern solutions such as: automatic transmission, retarders, or *electronic braking system* (EBS).

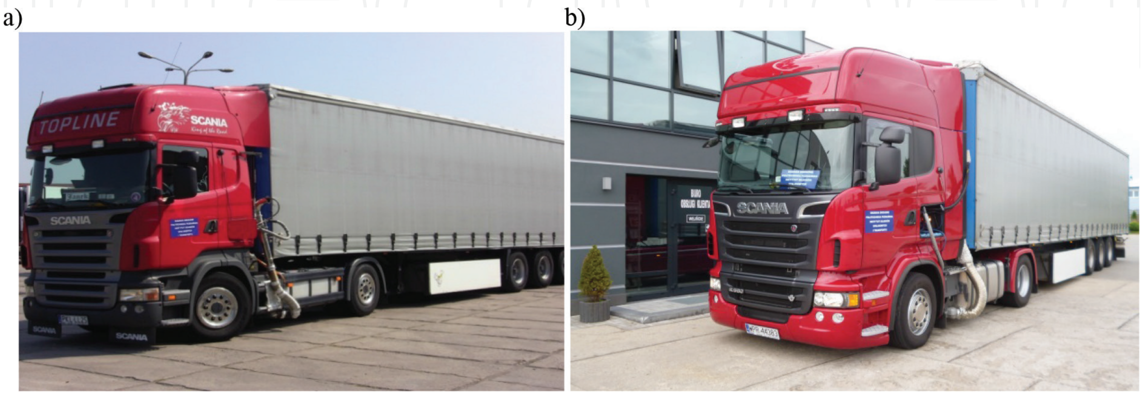

Figure 19. Research objects during the on-road emission tests: (a) vehicle A and (b) vehicle B.

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Parameter	Vehicle A	Vehicle B
Displacement	11.7 dm^3	15.6 dm^3
Number of cylinders/arrangement	6/straight	8/V8
Maximum power output	309 kW @ 1900 rpm	412 kW @ 1900 rpm
Maximum torque	2100 N m @ 1000–1350 rpm	2700 N m @ 1000–1400 rpm
Unit power output index	8.3 kW/t	10.3 kW/t
Emission standard	Euro III	Euro V
Exhaust gas aftertreatment	N/A	SCR
Transmission	Automatic 12 + 1	Automatic 12 + 1
Driver support system	N/A	SDS
Tractor axle configuration	4 × 2	4 × 2
Curb weight including trailer	15,000 kg	15,200 kg
Cargo weight	20,000 kg	24,800 kg
Type of cargo	Big-Bag	Steel
Type of trailer	Canopy	Canopy

Table 4. Characteristics of vehicles used for the tests.

6.3. The exhaust emission correction coefficient

Because the authors could not perform the measurements on two heavy-duty vehicles of the same exhaust emissions standard, the tests were carried out for Euro III and Euro V compliant vehicles. In order to compare the obtained values of the CO emission, the authors decided to define a dimensionless emission correction coefficient C_i [25]:

$$C_i = \frac{e_{\mathrm{EuroV}}}{e_{\mathrm{EuroIII}}} \quad (2)$$

where C_i—correction coefficient of an ith component; e_i, Euro V—a limit of unit emission of a given component in the Euro V standard [g/(kWh)]; e_i, Euro V—a limit of unit emission of a given component in the Euro III standard [g/(kWh)]. Determined values of C_i coefficient are shown in **Table 5**.

	Euro III [g/(kWh)]	Euro V [g/(kWh)]	Coefficient C_i [–]
CO	2.10	1.50	0.72
NO_x	5.00	2.00	0.40
PM	0.1	0.02	0.20

Table 5. Values of the emissions limit and C_i coefficient.

6.4. Analysis of the vehicle driving profiles

In the first, urban part, significant differences in the driving profiles of both vehicles were recorded. Vehicle A had a higher speed than vehicle B (**Figure 20** and **Table 6**). This was caused by higher traffic congestion during the test run of vehicle B. In the rural part, both driving profiles were similar. Vehicle A, during the entire run had a lower average speed (by 5%) than vehicle B. From the analysis of the maximum and average acceleration in the acceleration phase, it results that vehicle B was more dynamic because in both cases its values were higher by 49 and 19%, respectively. The second-by-second emission of CO, NO_x, and PM of vehicle A was multiplied by index C_i and then compared with the course recorded for vehicle B.

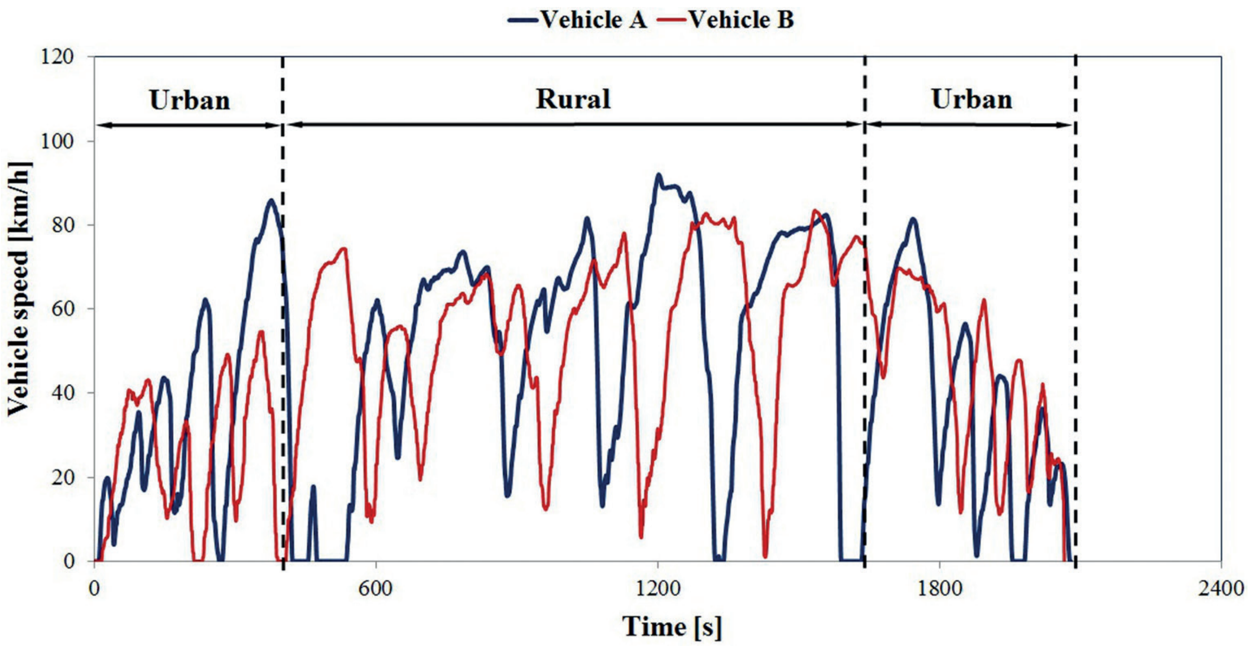

Figure 20. Speed profiles of the tested vehicles obtained during the on-road tests described with function $V = f(t)$.

Parameter	Unit	Vehicle A	Vehicle B	Percentage ratio vehicle A/ vehicle B [%]
Distance, s	km	26.57	26.88	98.84
Maximum speed, V_{max}	km/h	92.00	84.52	108.14
Average speed, V_{ave}	km/h	45.73	48.56	94.17
Minimum acceleration, a_{min}	m/s^2	−2.93	−2.80	104.64
Maximum acceleration, a_{max}	m/s^2	1.28	2.53	50.60
Average acceleration in phase of the ramp-up, $a_{śr}$	m/s^2	0.21	0.26	80.77

Table 6. Parameters characterizing the test runs of both vehicles during the on-road tests.

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Analyzing the second-by-second emission of NO_x, the authors observed that in the first, urban phase vehicle B had higher values of this emission than vehicle A (**Figure 21**). In the further part of the test, this trend changed and vehicle A had higher emissions. Such a situation was caused by the selective catalytic reduction (SCR) system responsible for the control of the NO_x emission, fitted in the exhaust of vehicle B. In the first phase of the test, the SCR system was most likely inhibited, as the tests for both vehicles were initiated from a cold start (a cold start is to be construed in this case as starting the engine at an ambient temperature of over 20°C) and under these conditions, the exhaust gas temperature is too low for the NO_x reduction to take place if a 32.5% water solution of urea is applied. Upon stabilization of the engine thermal state, a growth of the exhaust gas temperature takes place; thus, generating proper conditions for the NO_x reduction. The temperature of the exhaust gas also influences the conversion rate of the SCR catalytic converter where the said reactions take place. In standard SCR converters, the highest conversion rate occurs for 250–400°C. Under such conditions, the SCR control system initiates injection of a 32.5% solution of urea into the vehicle exhaust system, from which, following a series of reactions, ammonia is generated and used in the selective reduction of NO_x. From the recorded course of the second-by-second emission of NO_x, it results that the SCR system had obtained the highest conversion rate after 600 s of the test run, and that vehicle B obtained much lower values of this emission than in the initial phase of the test. In this part of the test, vehicle B also had lower emission of NO_x compared to vehicle A.

Next, based on the carbon balance method [30], the gas mileage for both vehicles was determined (in this method, the on-road emission of CO_2, CO, and HC is taken into account). The HC part has been omitted due to relatively low values of the on-road emission of this component by heavy-duty trucks remaining within the margin of measurement error. **Figure 22** presents the comparison of the on-road emissions of CO, NO_x, CO_2, PM, and the gas mileage. In all cases, vehicle B obtained lower values and a higher gas mileage. It is noteworthy that it had a significant increase

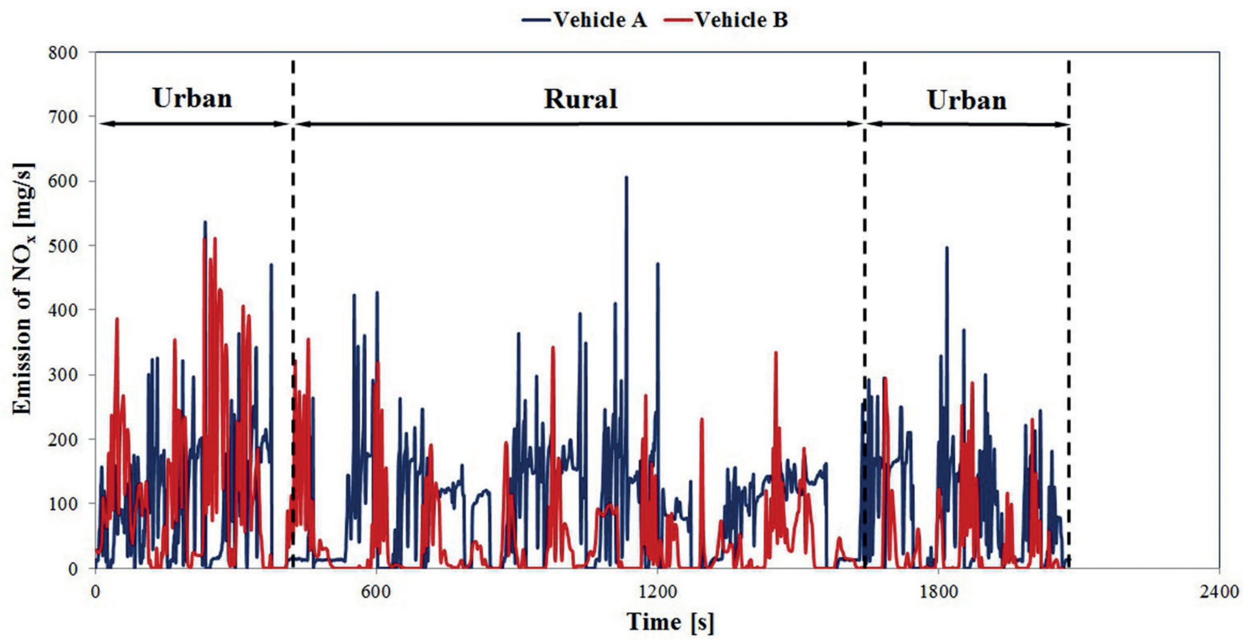

Figure 21. The tracing of the second-by-second emission of NO_x for both vehicles obtained during the on-road tests.

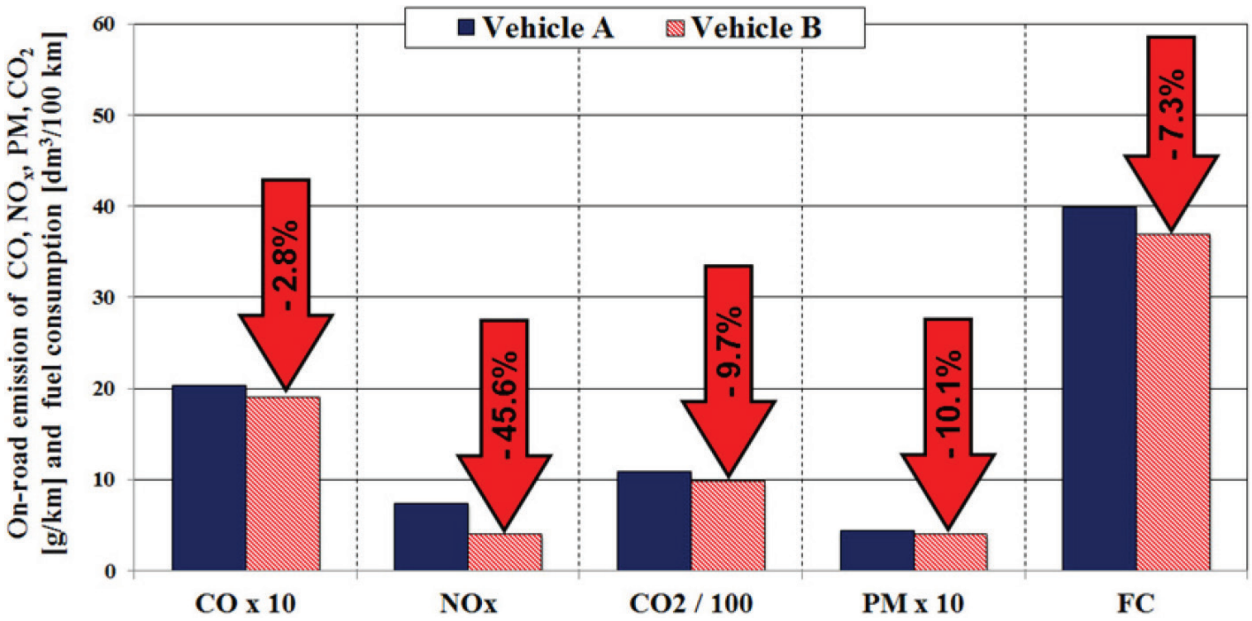

Figure 22. Comparison of the on-road emission of CO, NO_x, CO_2, PM and gas mileage of the tested vehicles.

in the gas mileage (by 2.9 dm^3/100 km). The cost of fuel is currently the main cost of operation of long-haulage trucks. The greatest drop was observed for the on-road emission of NO_x, which mainly resulted from the application of the SCR system in vehicle B.

The reduction of exhaust emissions requires a continuous search for new solutions in terms of both the design of engines/powertrains and the methodology of their testing. A factor stimulating this advancement is the exhaust emissions legislation. The advancement of the exhaust emissions measurement technology has created new possibilities in terms of measurements performed under actual conditions of operation. Supposedly, this particular method will be further developed and will gain in importance. A natural reaction of the legislators and manufacturers should be the recognition of measurements under actual operation as one of the main methods of homologation testing. Relevant works aiming at the introduction of such changes should finish without delay and the resultant legislation should be of global outreach.

The PEMS-based measurements have provided invaluable information regarding the emissions under actual operation of vehicles including their operating parameters. One of the most important observations is the difference in the emissions between the homologation tests and the tests performed under actual operation. The results of the measurements performed on LDV vehicles indicate significant differences, particularly in terms of NO_x and HC. The reasons for that are different parameters in the homologation tests and those under actual operation. The differences for the HDV Euro III and Euro V compliant vehicles are big, particularly in terms of NO_x and PM. They amount to 45 and 10%, respectively. However, referring these results to the Euro III (vehicle A) and Euro V (vehicle B) limits, the differences are smaller—the reduction of the emission of NOx and PM in the Euro V standard compared to the Euro III standard is 60% and over 90%, respectively.

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7. Conclusions

The reduction of exhaust emissions requires a continuous search for new solutions in both engine design and methods of engine testing. A main factor stimulating this development is the exhaust emission legislation in which they are in progress. The advancement of exhaust emission measurement techniques provides new possibilities of engine and vehicle testing particularly under actual conditions of operation (RDE). One may suppose that this method will become prevalent and will gain significance. The aim of the legislators and manufacturers should be the acknowledgment of the RDE measurements as one of the main methods of homologation testing works. The aim of introducing such changes should be completed as soon as possible and the enforceability of the implemented legislation should be global.

Abbreviations

CAN	controller area network
CF	conformity factor
CI	compress ignition
CNG	compressed natural gas
CVS	constant volume sample
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EBS	electronic braking system
EEV	enhanced environmentally friendly vehicle
EFM-HS	exhaust flow meter high speed
EGR	exhaust gas recirculation
ELR	European load response
EPA	environment protection agency
ESC	European stationary cycle
ETC	European transient cycle
FC	fuel consumption
FID	flame ionization detector
GPS	global positioning system
HDV	heavy-duty vehicle
IARC	International Agency for Research of Cancer
LAN	local area network
LDV	light-duty vehicle
LPG	liquefied petroleum gas
MSS	micro soot sensor

NDIR	non-dispersive infrared
NDUV	non-dispersive ultraviolet
NEDC	new European driving cycle
NTE	not-to-exceed
PC	passenger car
PEMS	portable emission measurement system
PM	particulate matter
PN	particle number
RDE	real driving emissions
SI	spark ignition
SCR	selective catalytic reduction
t	time
T	torque
TWC	three way catalyst
V	velocity
WHO	World Health Organization
WHSC	World Harmonized Stationary Cycle
WHTC	World Harmonized Transient Cycle
WLTC	Worldwide harmonized light-duty test cycle
WLTP	Worldwide harmonized light vehicles test Procedures
W	work

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