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EVALUATION OF ECOLOGICAL EXTREMES OF VEHICLES IN ROAD EMISSION TESTS

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Abstract:

New testing procedures for determining road emissions of exhaust pollutants for passenger vehicles were established in 2018. New road testing procedures are designed to determine actual exhaust emissions, which may not always reflect laboratory emissions. Test procedures for the emission of pollutants in real traffic conditions are divided into four stages. The latest research on the emission of pollutants from motor vehicles in road traffic conditions, carried out using mobile measuring systems, reflects the actual ecological state of vehicles. The article compares the results of exhaust emissions obtained in road tests using the latest legislative proposals for passenger cars. Then, an attempt was made to determine the engine operating parameters in which exhaust road emission would be the lowest. Solution scenarios were defined as part of permissible changes to dynamic parameters that are included in European legislation on RDE testing. For this purpose, an optimization tool was used, allowing on the basis of given input data to determine the minimum objective function, defined as the smallest emission value of individual harmful compounds. The results of the exhaust gas emissions in the RDE test were used to determine the road emissions of individual harmful compounds. A thorough analysis of the emission intensity of individual compounds has shown that it is possible to approximate such values using functional relationships or adopting them as a constant value. This division was used to determine the extremes (in this case the minima) of the objective function (minimum road emissions of harmful exhaust components). This task resulted in obtaining (within the permissible tolerances of all driving parameters and durations of individual road test sections) the value of exhaust emissions in the range from 26% to 81% lower than in the actual road test. This means that there is a tolerance range, where you can obtain the value of emissions in road tests. As a result, you can use the process of determining the minimum emissions tests RDE calibration of the drive units already at the stage of preparation so that in the real traffic conditions characterized by the lowest exhaust emissions.

Keywords: *optimization, exhaust emission, passenger cars, real driving emissions*

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1. Introduction

Increasing environmental requirements have resulted in significant changes in regulations regarding motor vehicles exhaust emissions. The tightening of legislation is noticeable all over the world. A rising number of regions in the world are setting new limits on carbon dioxide emissions (Mansour et al, 2018; Merkisz and Rymaniak, 2017). By 2021 the limits on carbon dioxide emissions will have been reduced for cars in Europe to 95 g/km.

Nowadays, two tests to determine exhaust emissions from passenger cars are used – in laboratory conditions and in real driving conditions. The current lab test is the WLTC test (worldwide harmonized light vehicles test cycle), which is performed on a chassis dynamometer as a fixed type approval test. This test is a part of the certification process of the vehicle and it is identical for all passenger cars (Bielaczyc et al, 2019; Busch and Zellbeck, 2019; Chong et al, 2018; Varella et al, 2018) including electric vehicle (Sun et al, 2019). The WTLC test is limited by many requirements that are to simulate real traffic conditions for road vehicles. However, it has been concluded that the lab test does not reflect the actual ecological performance of motor vehicles, and is thus insufficient. As a result, complementary exhaust emissions testing in real traffic conditions has been introduced. Vehicles testing under real driving conditions in RDE tests is currently given increasingly more attention. These test results reflect the level of pollutant emissions much better than laboratory tests. For measuring the exhaust emissions values mobile research equipment referred to as PEMS type (portable emission measurement system) is used (Clenci et al, 2017; Kousoulidou et al, 2013; Lim et al, 2018).

Many publications regarding exhaust emissions from motor vehicles in real driving conditions have been published in the recent years. That is a trend to ascertain if there is the possibility of using such tests to calibrate engines in a way to reduce their pollutant emissions in the entire range of engine operation (not only in the specific operating ranges used during stationary tests) (Kapusta et al, 2016; Pielecha, 2014; Stelmasiak et al, 2017). The authors of articles (Merkisz et al, 2013; Pielecha et al, 2019; Triantafyllopoulos et al, 2018) pointed out that during research in RDE tests, the nitrogen oxides emission from motor vehicles may be higher than expected. They remarked of a need to make some change in the vehicle software, but they claimed that these changes would only be effective on vehicles equipped with gasoline engines. Unfortunately, vehicles fitted with diesel engines will require further investments to increase the efficiency of the exhaust aftertreatment systems. It can be implemented by using the new methods of reducing the nitrogen oxides concentration.

The authors of publication (Fontaras et al, 2014) verified Euro 5 emission norms for passenger cars by performing a research on a chassis dynamometer in various driving tests and came to the same conclusions. It was found that for vehicles with spark-ignition engines the not to exceed carbon monoxide emissions of 1 g/km (acceptable Euro 5 limit was 1 g/km), not to exceed hydrocarbons emission 10% of the limit (i.e. 0.1 g/km) and the nitrogen oxides emission is equivalent to around 20% of the limit (i.e. 0.06 g/km). It was also pointed out that the vehicles with diesel engines far exceed the permissible emission limits of nitrogen oxides – the obtained values exceed the exhaust emissions limit approximately 4 times (emission limit values for nitrogen oxides in Euro 5 was 0.18 g/km).

It should be noted that operating conditions of the vehicle and the engine (such as the speed of other vehicles, road surface, driver's predispositions, and his driving style and other aspects of road traffic) have an impact on the accuracy of measurements in real driving conditions. The unpredictability of these conditions can significantly affect the results of exhaust emissions measurements. Referring to the content of publications (Giechaskiel et al, 2016; Gis, 2019; Gis and Bednarski, 2019), the greatest impact on the obtained emission results has the thermal state of the vehicle (and the engine), average vehicle speed, driving dynamics, and road topography.

Authors of the article (Merkisz and Pielecha, 2018; Merkisz et al, 2016) focused on the qualitative and quantitative analysis of exhaust emissions in various tests. They have shown that the distance travelled in the test has a larger impact on the values of relative road emissions than its duration. The determined values of emissions for a specific distance in various tests depend mainly on the type of test. For exhaust compounds such as carbon monoxide and hydrocarbons, they are higher in shorter tests than in the RDE test. This situation occurs when the share of urban and rural section of RDE test is greater. For specific

distance emissions of nitrogen oxides and the number of solid particles the situation is opposite. According to the analysis of the tests there is a possibility to shorten the RDE test distance by about 20%. It will not affect the results of specific distance exhaust emission measurements in a significant way.
Another example of the exhaust emission measurement use in both laboratory tests and road tests was described in (Pielecha and Andrych-Zalewska, 2018). The authors reviewed the possibility of using innovative glow plugs, which would allow reducing the exhaust emissions in an initial phase after the engine start-up.
The aim of this publication was in reference to the article (Merkisz and Pielecha, 2018; Köhl et al, 2018) and verify the possibility of slight RDE test modernization. The procedure of determining the exhaust emissions from a gasoline engine in line with Euro 6d-Temp emission norms enabled its subsequent optimization in terms of obtaining the smallest values from the range of acceptable solutions. It should be noted, that the proposed solution scenarios were defined within the range of changes in conditions that are permitted in European legislation regarding RDE research.
The aim of the article was in order to reference the assumptions contained in articles (Merkisz and Pielecha, 2018) and to verify the results obtained in road tests. As a result of the significantly formalized assumptions of road emission tests, the authors of this article referred to the possibility of obtaining different road emission results in the same test drives. In accordance with the RDE requirements, such tests cannot be freely configured or changed. The results of road emissions are determined in line with the guidelines of the procedure for determining emissions in the defined measurement windows. The article assumes the immutability of parameters concerning the vehicle and driver in such tests. The only reference was made to various possibilities of a driving time share in subsequent parts of the road test (urban/rural/motorway) and the related different average speed, which resulted in obtaining different road emissions for each compound.

2. The RDE test procedure according to the latest requirements of the European Commission

The European Commission has therefore made two major changes to improve the lab tests and to introduce testing in real traffic conditions (CR 715, 2007; CR 692, 2008; CR 427, 2016; CR 1154, 2017). Starting from 2017, the process of type approval of new passenger car models in the European Union has included a new and improved lab test WLTC – the successor to the NEDC test, along with the RDE test procedure. These changes are a response to the research results (Gao and Checkel, 2007; Korniski et al, 2007) relating to increased nitrogen oxides emission from vehicles equipped with compression-ignition engines. Although these vehicles met all the limit values set in the legislation when measured in laboratory tests, in road tests they exceeded the acceptable limit. The RDE test procedure consists of four legislative acts (three of them are already in force) (CR 427, 2016; CR 1154, 2017). The changes in regulations that European Commission has already introduced, or whose implementation is planned in the coming years are presented in Table 1.
The RDE test is essentially formalized. It is limited by many requirements set by the European Commission. The most important guidelines of RDE test procedure are listed in Table 2. The test route is designated in accordance with the RDE test requirements and divided into 3 sections based on the velocity range: urban, rural and motorway. The test duration can range from 90 minutes to 120 minutes. The test drive is carried out continuously, with no intermissions. The rural drive section can be interrupted by short periods of urban driving if urban areas are on the route. Driving on the motorway can be interrupted by short driving periods in urban or rural areas. The PEMS installation should be carried out in such a way as to minimize its impact on pollutant emissions, vehicle operation, mass and aerodynamic conditions of the vehicle. For this reason, electricity for the measuring devices is supplied from an external power source.

Table 1. RDE test requirements in Europe (Type Approval) (CR 646, 2016; CR 1151, 2017)

2015	2016	2017	2018	2019	2020	2021	2022
Euro 6b			Euro 6d-Temp		Euro 6d		
NEDC			WLTC				
Research and concept phase			Conformity Factor (CF)				
			$CF_{NOx} = 2.10$	$CF_{NOx} = 2.10$ $CF_{PN} = 1.50$	$CF_{NOx} = 1.43$ $CF_{PN} = 1.50$		

Table 2. Specific requirements for RDE tests (CR 1154, 2017; Giechaskiel et al, 2016; Weiss et al, 2017)

Parameter	Requirement
Ambient temperature (t_a)	– normal range: 0 ºC ≤ t_a ≤ 30 ºC – lower extended range: –7 ºC ≤ t_a < 0 ºC (emission corrective factor 1/1.6) – upper extended range: 30 ºC < t_a ≤ 35 ºC (emission corrective factor 1/1.6)
Driving test altitude (h)	– normal range: h ≤ 700 m a.s.l. – extended range: 700 < h ≤ 1300 m a.s.l.
Impact evaluation of ambient weather and road conditions as well as the driving style	– total altitude increase: less than 1200 m / 100 km – relative positive acceleration (RPA): move than RPA_{min} (for all road conditions) – the product of velocity and acceleration (V a_{pos}): less than V $a_{pos\ max}$ (for all road conditions)
Cold start	– duration of the cold start period is defined from engine start to the first 5 minutes or until coolant temp ≥ 70 °C – max velocity during cold start ≤ 60 km/h – the average speed (including stops) shall be between 15 km/h and 40 km/h – total stop time during cold start < 90 s – idling after ignition < 15 s
Any vehicle stop	– no longer than 180 s
Vehicle aftertreatment systems operation	– a single regeneration of the particulate filter justifies repeating the RDE test; the occurrence of two filter regenerations is to be included in the results of the RDE test
Driving comfort systems operation	– regular use as intended by the manufacturer (for example: use of the air conditioning)
Vehicle load	– vehicle mass: driver (and passenger) along with the PEMS equipment; maximum load < 90% of the sum of the mass of the passengers and the vehicle curb weight
Test requirements	– duration 90–120 min
Urban test portion requirements	– 29%–44% share of the whole test time – distance: more than 16 km – vehicle speed: up to 60 km/h – average speed: 15 km/h–40 km/h – vehicle stop: 6%–30% of the urban portion of the test time
Rural test portion requirements	– 23%–43% share of the whole test time – distance: more than 16 km – vehicle speed (V): 60 km/h < V ≤ 90 km/h
Motorway test portion requirements	– 23%–43% share of the whole test time – distance: more than 16 km – vehicle speed: more than 90 km/h – vehicle speed over 100 km/h for at least 5 min – vehicle speed over 145 km/h no more than 3% of the test section time

3. Research methodology

3.1. Research object

The tested object was a passenger car, whose drive unit characteristics were shown in Table 3. The vehicle was equipped with a gasoline engine with a DI (direct injection), characterized by exhaust emissions in line with the Euro 6d-Temp emissions norm. A Semtech DS mobile analyzer by Sensors was used to perform the measurement of the exhaust compounds concentration along with a measuring apparatus for determining particle number. It allowed the measurement of exhaust emissions in accordance with the RDE test guidelines mentioned earlier. Furthermore, data directly from the vehicle's diagnostic system and a GPS location signal were transmitted to the central unit of the analyzer and recorded.

3.2. Test route

The test route has been chosen so that it meets the requirements of the European Commission as described in the Regulation (CR 1151, 2017; CR 1154, 2017), with particular attention paid to its topography. Table 4 shows the characteristics of the research route in terms of terrain. The analysis of route topography confirms its compliance with the RDE test requirement regarding the difference in the altitude of the test start and end points which is not to exceed 100 m.

Road emission measurements were made three times in the actual traffic conditions when driving in urban, rural and motorway conditions. The presented results are examples. The final results are the averages of all the results obtained.

3.3. The optimization method adopted

In the search for the smallest exhaust emission values in the RDE test, a command was used to search for the minimum value of the function of several variables while meeting the imposed conditions. This task was formulated in the form of:

$$\min \boldsymbol{f}(\boldsymbol{x}) \tag{1}$$

while meeting the limitations of:

$$\boldsymbol{h}(\boldsymbol{x}) = 0 \tag{2}$$

$$\boldsymbol{g}(\boldsymbol{x}) \le 0 \tag{3}$$

where:
$\boldsymbol{f}$ – objective function of the optimization task,
$\boldsymbol{h}(\boldsymbol{x})$ – vector of equality constraints,
$\boldsymbol{g}(\boldsymbol{x})$ – vector of inequality constraints.

The general form of the objective function and the constraints presented above required specific modification of the objective function and constraints to be used so that it was possible to use the conjugate gradient method. The conjugate gradient method belongs to the group of methods for searching for the minimum function value of many variables without constraints. Equality and inequality constraints can be considered by including them in the objective function.

$$K(\boldsymbol{x}) = f(\boldsymbol{x}) + \frac{1}{2\mu}\sum_i h_i^2(\boldsymbol{x}) + \\ + 1/(2\mu)\sum_i W(\boldsymbol{g}) \tag{4}$$

where:
$W(\boldsymbol{g}) = g(x) - g^{(\min)}$ for $g \le g^{(\min)}$
μ – parameter modified in the optimization process.
In the conjugate gradient method, a new direction of the minimum function search is selected so that it is conjugated to all previous ones. The calculation process stages are as follows:
Stage 1.

Table 3. Characteristics of engine/vehicle used in testing

Parameter	Description
Cylinder number, arrangement	4, in series
Displacement [cm^3]	1984
Emissions norm	Euro 6d-Temp
Max. power [kW] at [rpm]	169 / 4700-6200
Max. torque [Nm] at [rpm]	350 / 1500-4400
Fuel injection	direct injection
Vehicle curb weight [kg]	1349

Table 4. Characteristics of the research route in terms of terrain

Parameter	Value	Route map
Distance of the test: – Urban [km] – Rural [km] – Motorway [km]	 27.2 25.1 22.4	
Altitude: – minimum [m] – average [m] – maximum [m]	 52 82 109	
Maximum road grade: – increase [%] – decrease [%]	 4.1 –3.7	

The iteration counter i is reset, and the starting point $X^{(0)}$ is selected, then the first direction of the solution search is determined:

$$KD^{(0)} = -\nabla K(X^{(0)}) \tag{5}$$

Stage 2.
The function $K(X)$ is minimized in the direction $D^{(i)}$ with the step λ in accordance with the relation:

$$X^{(x+1)} = X^{(i)} + \lambda D^{(i)} \tag{6}$$

Stage 3.
The gradient of the function at point $X^{(i+1)}$ is calculated:

$$D^{(i+1)} = \nabla K(X^{(i+1)}) \tag{7}$$

Stage 4.
If $||D^{(i+1)}|| < \varepsilon$, then calculations are finished, and the point $X^{(i+1)}$ is the solution. If the condition is not met and the maximum number of iterations has not been exceeded, then a new search direction is determined:

$$D^{(i+1)} = -\nabla K(X^{(i+1)}) + \beta D^{(i+1)} \tag{8}$$

It is incremented by one iteration counter i, and returned to stage 2. The coefficient β in the formula is defined by the relation (e.g. Fletcher-Reeves):

$$\beta^{(i)} = [(D^{(i+1)})^T D^{(i+1)}]/[(D^{(i)})^T D^{(i)}] \tag{9}$$

If the number of iterations has been exceeded, the calculations were deemed unsuccessful. Then a different starting point should be selected and the calculations should be carried out again.

The following subsections will present the process of determining the minimum road emission of discussed compounds for two adopted cases:

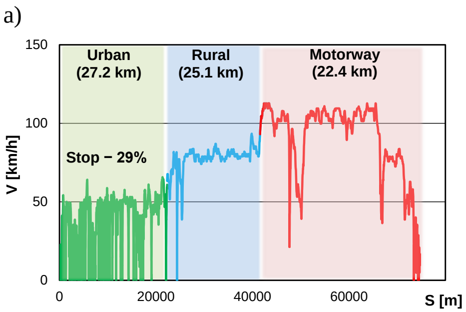
1) constant emissions intensity of exhaust compounds in the relevant part of the RDE test (regardless of the distance traveled),
2) variable emissions intensity of exhaust compounds in the relevant part of the RDE test, which will be depended on the distance traveled.

4. Research results

4.1. RDE test verification

The velocity profile obtained in the tests (Fig. 1a) allowed for the separation of the urban (U), rural (R) and motorway (M) sections. The shares of individual sections of the route were respectively: 36.4% (U), 33.6% (R) and 30.0% (M). The average velocity in the urban part was 21.6 km/h, and the share of vehicle stop duration in this part was 28%. Test duration with the velocity above 100 km/h in the motorway conditions was 10.4 minutes, and the maximum value of the velocity in this part did not exceed 145 km/h. Total test duration was 108 minutes. All considered parameters and others which are not included in this article (e.g. regarding cold start) met the RDE test requirements.

Considering the carbon dioxide road emissions determined in the measuring windows, it should be stated that the character of these results is valid, which confirms their location in the area of the main curve designated by points P_1–P_3, related to the road emission in individual parts of the WLTC test (Fig. 1b), and at the same time, these values are within the tolerance of ±25% from the curve value determined by points P_1–P_3.



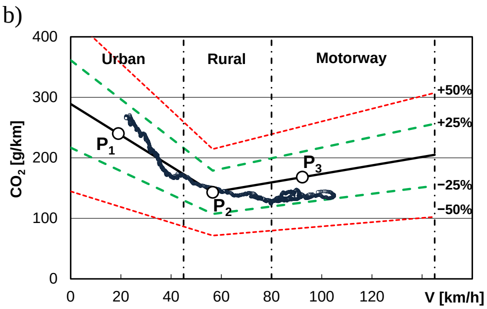


Fig. 1. The vehicle velocity profile with selected urban, rural and motorway driving phases (a), and carbon dioxide road emission curve with marked tolerance areas (b)

The analysis of dynamic driving parameters (Fig. 2), i.e. the relative positive acceleration and the 95th percentile of the velocity and positive acceleration product $(V \cdot a_{pos})_{95}$, also indicates the validation of the test execution in each of the phases. The obtained values of relative positive acceleration were as follows:

– in the urban part: 0.22 m/s^2 (with the minimum limit of 0.14 m/s^2),
– in the rural part: 0.07 m/s^2 (with the minimum limit of 0.05 m/s^2),
– in the motorway part: 0.08 m/s^2 (with the minimum limit of 0.025 m/s^2).

The values of the 95th percentile of the velocity and positive acceleration product in each test phase were as follows:

– in urban part: 11.4 m^2/s^3 (at the maximum limit of 17.4 m^2/s^3),
– in rural part: 14.3 m^2/s^3 (at the maximum limit of 24.7 m^2/s^3),
– in motorway part: 13.8 m^2/s^3 (at the maximum limit of 26.7 m^2/s^3).

The emissions of carbon dioxide, carbon monoxide, nitrogen oxides and the number of particulates were determined and shown in Fig. 3. These emissions were established for each test phase and the value related to the emission in the entire RDE test. Based on the compared results, it can be noticed that the largest road emissions of carbon dioxide, carbon monoxide, and nitrogen oxides occur in the urban part, while in the other two parts of the RDE test it is much smaller (not applicable to road emissions of carbon monoxide).

In order to determine the conformity factor (CF) values, which are the reference point for the obtained results, the recorded values were divided by the emission limit values for individual exhaust compounds (CO – 1000 mg/km, NO_x – 60 mg/km, PN – $6 \cdot 10^{11}$ 1/km). Analyzing the obtained results (Fig. 4), none of the permissible limits were exceeded. The conformity factors (for the entire RDE test) are as follows:

– for carbon monoxide CF_{CO} = 0.57,
– for nitrogen oxides CF_{NOx} = 0.35,
– for particles number CF_{PN} = 0.34.

Obtained values of road exhaust emissions in individual parts and the entire RDE test were used to optimize pollutant emissions in subsequent sections of this article.

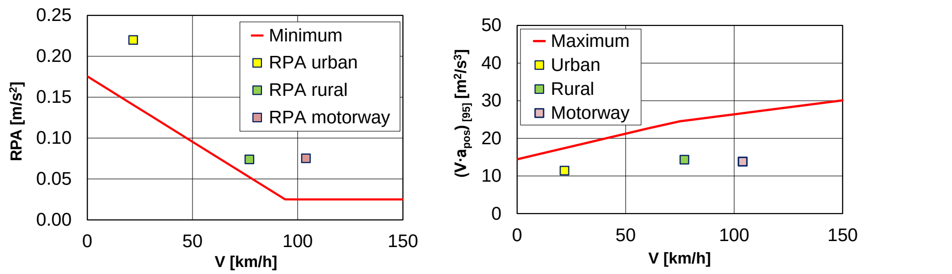


Fig. 2. The relative positive acceleration and 95th percentile of the velocity and positive acceleration product for each phase of the RDE test

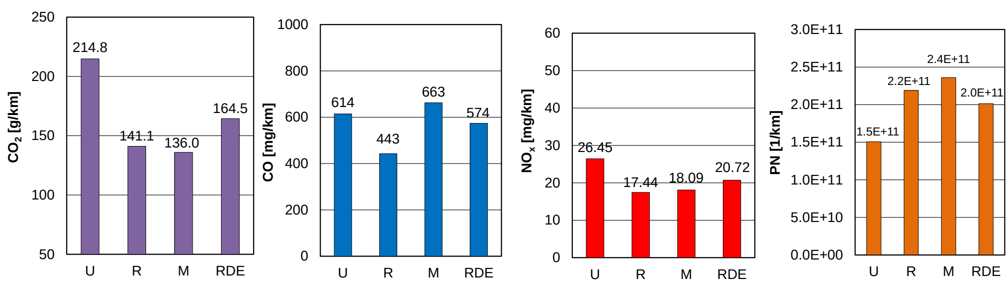


Fig. 3. The values of carbon dioxide, carbon monoxide, nitrogen oxides, and the number of particulates road emissions obtained in individual parts and the entire RDE test

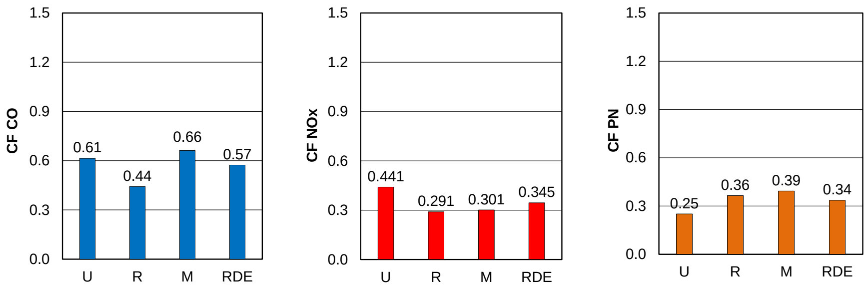


Fig. 4. Conformity factor values for road emissions of carbon monoxide, nitrogen oxides and the number of particulates obtained in individual parts and for the entire RDE test

4.2. Optimization for constant exhaust emissions intensity in the RDE test sections

The previously obtained results of the exhaust emissions in individual parts of the test for a vehicle equipped with a gasoline engine were used to optimize the road emissions in the entire RDE test.

The target function was as follows:

$$b_{j,\mathrm{RDE}} = 0.34\, b_{j,\mathrm{U}} + 0.33\, b_{j,\mathrm{R}} + 0.33\, b_{j,\mathrm{M}} \quad (10)$$

and after taking into account the constant emissions intensity $E_{j,k}$, in each test section it became:

$$b_{j,\mathrm{RDE}} = 0.34\, \frac{E_{j,\mathrm{U}} t_{\mathrm{U}}}{S_U} + 0.33\, \frac{E_{j,\mathrm{R}} t_{\mathrm{R}}}{S_R} + + 0.33\, \frac{E_{j,\mathrm{M}} t_{\mathrm{M}}}{S_M} \quad (11)$$

The input quantities were the compound emission intensity values $E_{j,k}$ (determined from the road emissions $b_{j,k}$; j = CO_2, CO, NO_x, PN, k = Urban, Rural, Motorway).

The variable quantities of the algorithm were:

– test duration in urban, rural and motorway sections t_k,
– test distance in urban, rural and motorway sections S_k,

The limitations were as follows:

– total time of the test $t_{\mathrm{U}} + t_{\mathrm{R}} + t_{\mathrm{M}} \in (90\text{–}120\ \mathrm{min})$,
– average vehicle velocity in urban section $S_{\mathrm{U}}/t_{\mathrm{U}} \in (15\text{–}40\ \mathrm{km/h})$,
– average vehicle velocity in rural section $S_{\mathrm{R}}/t_{\mathrm{R}} \in (40\text{–}80\ \mathrm{km/h})$,
– average vehicle velocity in motorway section $S_{\mathrm{M}}/t_{\mathrm{M}} \in (80\text{–}140\ \mathrm{km/h})$,

The initial values were: $t_{\mathrm{U}} = t_{\mathrm{R}} = t_{\mathrm{M}} = 30$ min and $S_{\mathrm{U}} = S_{\mathrm{R}} = S_{\mathrm{M}} = 16$ km.

Based on the comparison of the emissions intensity for individual compounds with the cumulative of the normal distribution with the appropriate average value and the variance (Fig. 5), a decision was made to determine its mean value (in each test section) and to use it (Fig. 6) when searching for the minimum road emission of compounds in the entire RDE test.

The provided function represented the road exhaust emission of exhaust components, where the variables were:

– the duration of an individual test section,
– the test travel distance in each test section.

The solution had to be found for each exhaust component, resulting in the data listed in Table 5.

The presented values of each test section duration (*t*) and the test distance (*S*), as well as the share of a particular section (*u*) in the entire exhaust emissions test were calculated. It should be noted that all the obtained results meet the criteria described in the norms. It is significant that, for all the exhaust compounds, the RDE test should be characterized by the smallest exhaust emission share of the urban test section to the entire test and at the same time the longest time duration. The motorway section should have the shortest test duration due to the highest average vehicle velocity. All of these relations have been met for each of the exhaust compounds.

4.3. Optimization for variable emissions in the RDE test sections

After taking into account the variable emissions intensity (depending on the distance traveled in each test section), the objective function takes the form:

$$b_{j,\mathrm{RDE}} = 0.34\,\frac{E_{j,\mathrm{U}}(S_\mathrm{U})t_\mathrm{U}}{S_\mathrm{U}} + 0.33\,\frac{E_{j,\mathrm{R}}(S_\mathrm{R})t_\mathrm{R}}{S_\mathrm{R}} + 0.33\,\frac{E_{j,\mathrm{M}}(S_\mathrm{M})t_\mathrm{M}}{S_\mathrm{M}} \tag{12}$$

Other input values and constraints remained unchanged. The determination of the individual exhaust components as a function of the distance traveled by the vehicle proceeded in the following stages:

– determination of the exhaust emission intensity of components in measuring windows in individual sections of the RDE test,
– determination of the distance of the test sections (it was assumed that each section started at zero distance),
– approximation with an exponential function of the obtained emissions intensity relative to the distance traveled (Fig. 7).

In order to preserve the character of changes in the emissions intensity, the individual compounds emission intensity curve is characterized by an exponential function, which corresponds to the physical character of the described phenomena. Sometimes, such a description was characterized by a lower coefficient of determination (R^2) than could be obtained by using a different character of changes. Detailed input data for the objective function are included in Table 6. It contains a record of the exponential function for each exhaust compound (j) depending on the section (k) of the RDE test.

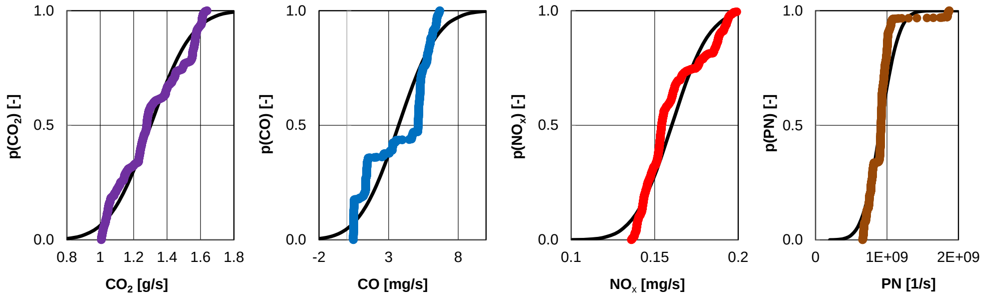


Fig. 5. The comparison of the emission intensity values with the cumulative of normal distribution – example data for the urban section of the RDE test

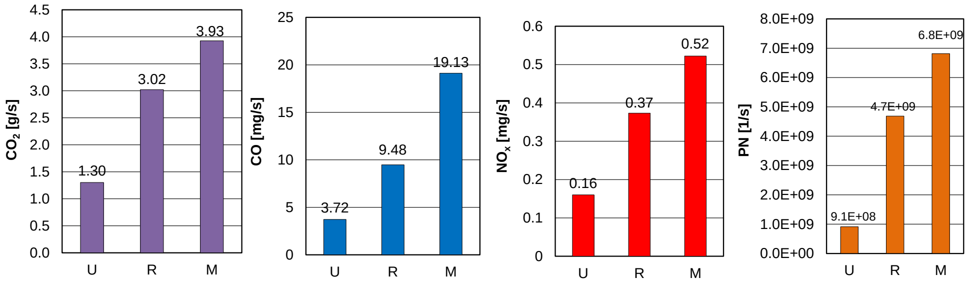


Fig. 6. The conversion values of compounds emission intensity from road emissions (the average vehicle velocity in the given test sections was used)

Table 5. The exhaust emissions results in the RDE test optimization assuming their constant intensity in each of the test sections

	t			S			u			b
	U	R	M	U	R	M	U	R	M	RDE
	[s]	[s]	[s]	[km]	[km]	[km]	[–]	[–]	[–]	[g/km]
CO_2	3234	2293	952	35.90	50.90	37.10	0.290	0.411	0.299	117.9
CO	2781	1570	1048	30.90	34.87	40.79	0.290	0.327	0.383	416.9
NO_x	2963	1489	948	32.93	33.09	36.85	0.320	0.322	0.358	14.8
PN	2814	1443	1144	31.26	32.06	44.48	0.290	0.297	0.413	1.55E+11

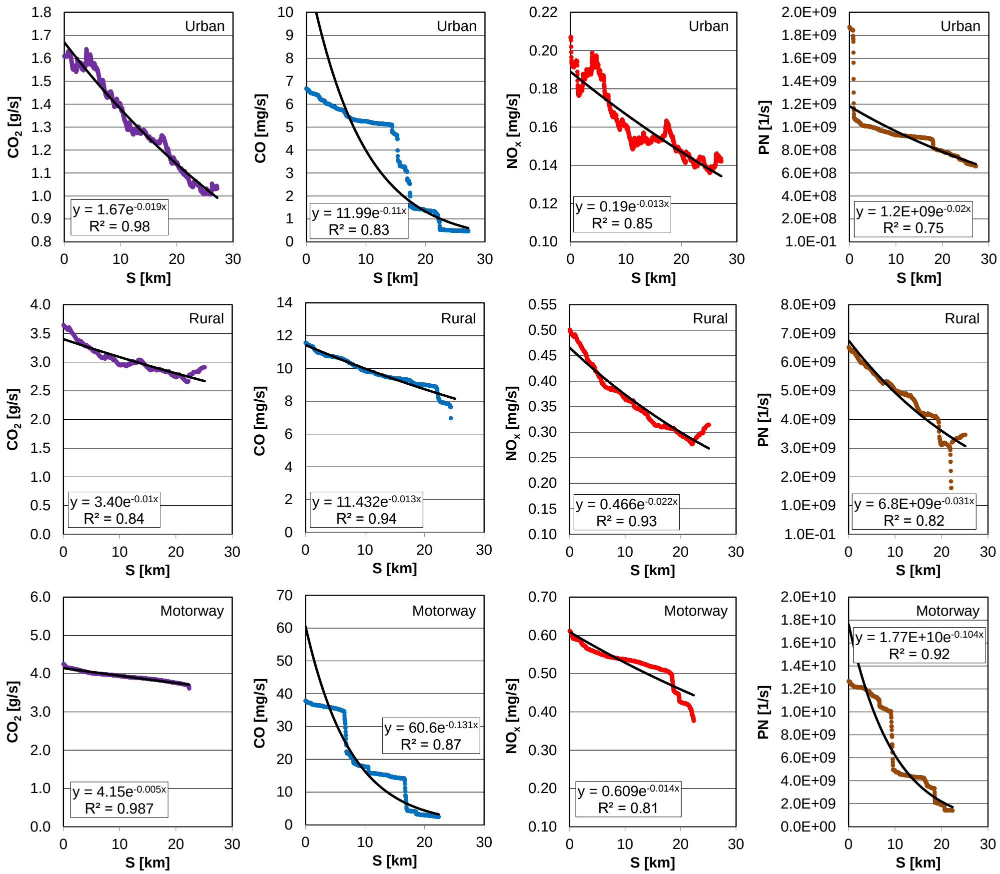


Fig. 7. The approximation of the emission intensity of exhaust compounds (CO_2, CO, NO_x, PN) by an exponential function for individual sections of the RDE test (Urban, Rural, Motorway)

Table 6. The input data for the objective function (2) in which the emission intensity depends on the distance traveled for each test phase (k)

	The compounds emission intensity $E_{j,k}$		
j \ k	U	R	M
CO_2	$1.67e^{-0.019 \cdot S_k}$	$3.4e^{-0.01 \cdot S_k}$	$4.15e^{-0.005 \cdot S_k}$
CO	$11.99e^{-0.11 \cdot S_k}$	$11.43e^{-0.013 \cdot S_k}$	$60.6e^{-0.13 \cdot S_k}$
NO_x	$0.19e^{-0.013 \cdot S_k}$	$0.466e^{-0.022 \cdot S_k}$	$0.61e^{-0.014 \cdot S_k}$
PN	$1.2 \cdot 10^9 e^{-0.02 \cdot S_k}$	$6.8 \cdot 10^9 e^{-0.031 \cdot S_k}$	$1.77 \cdot 10^{10} e^{-0.104 \cdot S_k}$

The calculation was carried out in a similar way to determine the minimum function as in point 3.3. However, the emissions intensity was dependent on the distance traveled in each section of the road test and the corresponding equations from Table 6. The search for a minimum function was carried out for each compound. The optimization results are presented in Table 7.

As a result of the optimization, the obtained values of exhaust emissions were as follows (Fig. 8):

a) for a constant exhaust emission intensity in particular RDE test sections:
   - reduction of carbon dioxide road emissions by 28%,
   - reduction of carbon monoxide road emissions by 27%,
   - reduction of nitrogen oxides road emissions of 29%,
   - reduction of particles number by 26%,

b) for variable exhaust emission intensity in particular RDE test sections (approximated by the exponential function):
   - reduction of carbon dioxide road emissions by 40%,
   - reduction of carbon monoxide road emissions by 81%,
   - reduction of nitrogen oxides road emissions by 48%,
   - reduction of particles number by 75%.

Table 7. Results of the road exhaust emissions optimization in the RDE test assuming their variable intensity in individual test sections

	t			S			$u = S_{U,R,M}/S_{RDE}$			b
	U	R	M	U	R	M	U	R	M	RDE
	[s]	[s]	[s]	[km]	[km]	[km]	[–]	[–]	[–]	[g/km]
CO_2	4047	2251	902	33.73	50.01	32.57	0.290	0.430	0.280	98.7
CO	4061	2195	944	33.84	48.78	34.08	0.290	0.418	0.292	108.4
NO_x	4128	1925	1147	34.39	42.78	41.43	0.290	0.361	0.349	10.8
PN	4056	2217	927	33.80	49.27	33.48	0.290	0.423	0.287	$5.18 \cdot 10^{10}$

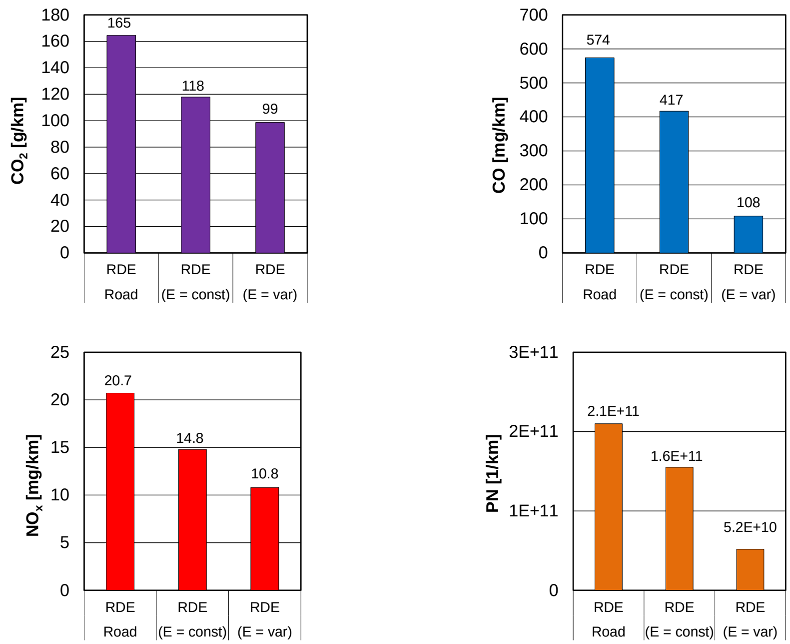


Fig. 8. The results of road emissions in the RDE test, and the obtained values as a result of optimization assuming constant and variable emission intensity in specific test sections

5. Conclusions

Despite the significant formalization of the RDE testing procedures they can be used to optimize not only the operation of the vehicle propulsion system but also the operation of the exhaust aftertreatment system. It is possible to use the optimization of the RDE tests exhaust emissions to calibrate drive units as early as at the stage of their production, so that they can be characterized by the smallest exhaust emission values in real driving conditions.

From the obtained optimization data for the variable emissions intensity (depending on the test drive distance) shows that the final value of the exhaust emissions can be minimized depending on the character of the emission intensity changes. In this case (a vehicle fitted with a spark-ignition engine with Euro 6 emission norm) all emission intensity characteristics of the exhaust components could be described by the general equation $E_{j,k} = A\mathrm{e}^{BS}$ where A is a positive value and B is a negative value.

As a result, with the increasing driving distance of any test section, the exhaust emission intensity value decreased. Therefore, the minimum function search algorithm sought to increase the distance, resulting in reaching a maximum test time of 120 minutes. Another common feature of the optimization results is minimizing the share of the urban section and maximizing the rural section of RDE test. The presented research is a part of the research on the determination of exhaust emissions in RDE tests, not only for vehicles with a conventional drive but also for hybrid vehicles and a contribution to the optimization of energy consumption in electric vehicles.

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References

[1] BIELACZYC, P., SZCZOTKA, A., WOODBURN, J., 2019. *Carbon dioxide emissions and fuel consumption from passenger cars tested over the NEDC and WLTC – an overview and experimental results from market-representative vehicles.* IOP Conf. Series: Earth and Environmental Science, 214, 012136. DOI: 10.1088/1755-1315/214/1/012136.

[2] BUSCH, S., ZELLBECK, H., 2019. *Particle emission of the direct-injection gasoline engine under real driving emissions conditions*. MTZ worldwide, 80, 60-65. DOI: 10.1007/s38313-018-0122-5.

[3] CHONG, H. S., PARK, Y., KWON, S., HONG, Y., 2018. *Analysis of real driving gaseous emissions from light-duty diesel vehicles*. Transportation Research Part D: Transport and Environment, 65, 485-499. DOI: 10.1016/j.trd.2018.09.015.

[4] CLENCI, A., SĂLAN, V., NICULESCU, R., IORGA-SIMĂN, V., ZAHARIA, C., 2017. *Assessment of real driving emissions via portable emission measurement system*. IOP Conference Series: Materials Science and Engineering, 252, 012084, DOI: 10.1088/1757-899X/252/1/012084.

[5] CR 715, 2007. Commission Regulation, 2007. *No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information*. Official J. European Union, L 171. http://data.europa.eu/eli/reg/2007/715/oj.

[6] CR 692, 2008. Commission Regulation, 2008. *No. 692/2008 of 18 July 2008 implementing and amending Regulation (EC) 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information*. European Commission (EC), Official J. European Union, L 199. http://data.europa.eu/eli/reg/2008/692/oj.

[7] CR 427, 2016. Commission Regulation, 2016. *No. 2016/427 of 10 March 2016 amending Regulation (EC) No. 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6), Verifying Real Driving Emissions*. Official J. European Union, L 82. http://data.europa.eu/eli/reg/2016/427/oj.

[8] CR 646, 2016. Commission Regulation, 2016. *No. 2016/646 of 20 April 2016 amending Regulation (EC) No. 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6), Verifying Real Driving Emissions*. Official J. European Union, L 109. http://data.europa.eu/eli/reg/2016/646/oj.

[9] CR 1151, 2017. Commission Regulation, 2017. *No. 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008*. Official J. European Union, L 175. http://data.europa.eu/eli/reg/2017/1151/oj.

[10] CR 1154, 2017. Commission Regulation, 2017. *No. 2017/1154 of 7 June 2017 amending Regulation (EU) 2017/1151 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC of the European Parliament and of the Council as regards real-driving emissions from light passenger and commercial vehicles (Euro 6)*. Official J. European Union, L 175. http://data.europa.eu/eli/reg/2017/1154/oj.

[11] FONTARAS, G., FRANCO, V., DILARA, P., MARTINI, G., MANFREDI, U., 2014. *Development and review of Euro 5 passenger car emission factors based on experimental results over various driving cycles*. Science of The Total Environment, 468-469, 1034-1042. DOI: 10.1016/j.scitotenv.2013.09.043.

[12] GAO, Y., CHECKEL, M. D., 2007. *Emission factors analysis for multiple vehicles using an on-board, in-use emissions measurement system*. SAE Technical Paper 2007-01-1327. DOI: 10.4271/2007-01-1327.

[13] GIECHASKIEL, B., VLACHOS, T., RICCOBONO, F., FORNI, F., COLOMBO, R., MONTIGNY, F., LE-LIJOUR, P., CARRIERO, M., BONNEL, P., WEISS, M., 2016. *Implementation of portable emissions measurement systems (PEMS) for the real-driving emissions (RDE) regulation in Europe*. JoVE Video Journal, 118, e54753. DOI: 10.3791/54753.

[14] GIS, M., 2019. *Assessment of exhaust emissions from vehicles in real traffic conditions*. IOP Conference Series: Earth and Environmental Science, 214, 012035. DOI: 10.1088/1755-1315/214/1/012035.

[15] GIS, M., BEDNARSKI, M., 2019. *Comparative studies of harmful exhaust emission from a hybrid vehicle and a vehicle powered by spark ignition engine.* IOP Conference Series: Earth and Environmental Science, 421 (4), 042022. DOI: 10.1088/1757-899X/421/4/042022.

[16] KAPUSTA, L. J., PIELECHA, I., WISLOCKI, K., TEODORCZYK, A., 2016. *Autoignition and combustion of n-hexane spray in subcritical and supercritical environments.* Journal of Thermal Analysis and Calorimetry, 123, 819-828. DOI: 10.1007/s10973-015-4927-z.

[17] KORNISKI, T., GIERCZAK, C., WALLINGTON, T., 2007. *Laboratory evaluation of the 2.5 inch diameter Semtech® exhaust flow meter with gasoline fueled vehicles*. Sensors 4th Annual SUN Conference, Ann Arbor.

[18] KOUSOULIDOU, M., FONTARAS, G., NTZIACHRISTOS, L.. BONNEL, P., SAMARAS, Z., DILARA, P., 2013. *Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors.* Atmospheric Environment, 64, 329-338. DOI: 10.1016/j.atmosenv.2012.09.062.

[19] KÖHL, M. A., HERMANNS, H., BIEWER, S., 2018. *Efficient monitoring of real driving emissions.* In: COLOMBO, C., LEUCKER, M. (eds) Runtime Verification. Lecture Notes in Computer Science, 11237, Springer, Cham. DOI: 10.1007/978-3-030-03769-7_17.

[20] LIM, J. H., HAN, S. W., KIM, J., JANG, Y. K., CHON, M. S., HWANG, S. C., KIM, J. H., JUNE, S. W., KIM, J. S., HAN, J. S., 2018. *Emission factor of hazardous air pollutants in gas-phase from light commercial vehicle using PEMS on real-road driving*. Journal of Korean Society for Atmospheric Environment, 34 (2), 191-206. DOI: 10.5572/KOSAE.2018.34.2.191.

[21] MANSOUR, C., HADDAD, M., ZGHEIB, E., 2018. *Assessing consumption, emissions and costs of electrified vehicles under real driving conditions in a developing country with an inadequate road transport system*. Transportation Research Part D: Transport and Environment, 63, 498-513. DOI: 10.1016/j.trd.2018.06.012.

[22] MERKISZ, J., PIELECHA, J., 2018. *Comparison of real driving emissions tests*. IOP Conference Series: Materials Science and Engineering, 421 (4), 042055. DOI: 10.1088/1757-899X/421/4/042055.

[23] MERKISZ J., PIELECHA J., JASIŃSKI R., 2016. *Remarks about real driving emissions tests for passenger cars.* Archives of transport, 39 (3), 51-63. DOI: 10.5604/08669546.1225449.

[24] MERKISZ, J., PIELECHA, J., LIJEWSKI, P., MERKISZ-GURANOWSKA, A., NOWAK, M., 2013. *Exhaust emissions from vehicles in real traffic conditions in the Poznan agglomeration.* Air Pollution XXI Book Series: WIT Transactions on Ecology and the Environment, 174, 27-38. DOI: 10.2495/AIR130031.

[25] MERKISZ, J., RYMANIAK, L., 2017. *The assessment of vehicle exhaust emissions referred to CO2 based on the investigations of city buses under actual conditions of operation*. Eksploatacja i niezawodnosc – Maintenance and reliability, 19(4), 522-529. DOI: 10.17531/ein.2017.4.5.

[26] PIELECHA, I., 2014. *Diagnostics of stratified charge combustion under the conditions of multiple gasoline direct injection*. Journal of Thermal Analysis and Calorimetry, 118, 217-225. DOI: 10.1007/s10973-014-3956-3.

[27] PIELECHA, J., ANDRYCH-ZALEWSKA, M., 2018. *The influence of internal catalyst on exhaust emission in dynamic conditions*. E3S Web of Conferences, 44, 00141. DOI: 10.1051/e3sconf/20184400141.

[28] PIELECHA, J., MAGDZIAK, A., BRZEZINSKI, L., 2019. *Nitrogen oxides emission evaluation for Euro 6 category vehicles equipped with combustion engines of different displacement volume.* IOP Conference Series: Earth and Environmental Science, 214, 012010. DOI: 10.1088/1755-1315/214/1/012010.

[29] STELMASIAK, Z., LARISCH, J., PIELECHA, J., PIETRAS, D., 2017. *Particulate matter emission from dual fuel diesel engine fuelled with natural gas.* Polish Maritime Research, 24 (2), 96-104. DOI: 10.1515/pomr-2017-0055.

[30] SUN, B., ZHANG, T., GE, W., TAN, C., GAO, S., 2019. *Driving energy management of front-and-rear-motor-drive electric vehicle based on hybrid radial basis function*. Archives of Transport, 49 (1), 47-58. DOI: 10.5604/01.3001.0013.2775.

[31] TRIANTAFYLLOPOULOS, G., KATSAOUNIS, D., KARAMITROS, D., NTZIACHRISTOS, L., SAMARAS, Z., 2018. *Experimental assessment of the potential to decrease diesel NOx emissions beyond minimum requirements for Euro 6 real drive emissions (RDE) compliance.* Science of The Total Environment, 618, 1400-1407. DOI: 10.1016/j.scitotenv.2017.09.274.

[32] VARELLA, R. A., GIECHASKIEL, B., SOUSA, L., DUARTE, G., 2018. *Comparison of portable emissions measurement systems (PEMS) with laboratory grade equipment*. Applied Sciences, 8(9), 1633. DOI: 10.3390/app8091633.

[33] WEISS, M., PAFFUMI, E., CLAIROTTE, M., DROSSINOS, Y., VLACHOS, T., BONNEL, P., GIECHASKIEL, B., 2017. *Including cold-start emissions in the real-driving emissions (RDE) test procedure*. Publications Office of the European Union. https://doi.org/10.2760/70237.