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Determining the route for the purpose light vehicles testing in Real Driving Emissions (RDE) test

In the regulations concerning approval of light vehicles starting from September 2019 it will be necessary to conduct exhaust emissions tests both on a chassis dynamometer and for real driving emissions. It is a legislative requirement set forth in EU regulations for the purpose of the RDE (Real Driving Emissions) procedure.

To decide on the RDE route for the purpose of the LV exhaust emissions tests many requirements must be fulfilled, regarding for example external temperature and the topographic height of the tests, driving style (driving dynamic parameters), trip duration, length of respective test sections (urban, rural, motorway, etc.). The works on outlining RDE routes are continued across the country in various research centres. Specifying the RDE route for test purposes, i.e. works in which the authors of this article are actively involved, has become a major challenge for future approval surveys concerning the assessment of hazardous emissions from light vehicles and for development studies focusing on – for example – the consumption of energy in electric and hybrid vehicles.

The test route has been chosen to ensure that the test is performed on a continual basis. Data were recorded on a constant basis with the minimum duration of the test achieved. The test involved light vehicles and PEMS device for measuring the exhaust emissions, vehicle's speed, completed route, etc. The device was installed in such manner as to ensure that its impact on the exhaust emissions from the tested vehicle and on the device's operation is the least.

The vehicle load was consistent with the requirements of the standard and included the aforesaid measurement device, the driver and the operator of PEMS. The tests were carried out on working days. The streets and roads used for the tests were hard-surfaced. Measurements were performed in accordance with the requirements of RDE packages (Package 1–4), i.e. taking into account – among others – the engine cold start.

The article discusses the method of outlining the test route fulfilling the specific requirements for RDE testing. Chosen results of exhaust emissions from a passenger car with a spark-ignition engine along the defined RDE test route have been provided.

The tests discussed in the article are introductory in the area of RDE tests and provide an introduction into further studies of exhaust emissions and energy consumption in real driving conditions in conventional vehicles and vehicles with alternative engines, e.g. hybrid and electric vehicles.

Key words: *RDE, vehicle, transport, passenger cars, test, ecology, homologation*

1. Introduction

The approval process of light vehicles in the European Union comprises a procedure for the measurement of real driving emissions generated by those vehicles. In accordance with the requirements (Commission Regulation (EU) no. 582/2011, Commission Regulation (EU) no. 2018/932) for all new approvals the emissions of CO, THC, NMHC, CH_4, NO_x is measured in RDE, which cannot exceed 1.5 times the maximum Euro VI limit [1–4].

The parameters of road tests cannot be any parameters. It is necessary to select adequately the test route. The route must include driving in urban, rural and motorway areas. It is only one of the many requirements that must be met. The scope of those requirements is presented in Table 1.

2. Moving Averaging Window method for exhaust emissions

The Moving Averaging Window method provides an insight on the real-driving emissions (RDE) occurring during the test at a given scale. The test is divided in subsections (windows) and the subsequent statistical treatment aims at identifying which windows are suitable to assess the vehicle RDE performance.

The "normality" of the windows is conducted by comparing their CO_2 distance-specific emissions with a reference curve. The test is complete when the test includes a sufficient number of normal windows, covering different speed areas (urban, rural, motorway). It consists of the following steps:

– calculation of emissions by sub-sets or "windows,
– identification of normal windows,
– verification of test completeness and normality,
– calculation of emissions using the normal windows,
– specifying dynamic trip parameters.

The instantaneous emissions must be integrated using a Moving Averaging Window method, based on the reference CO_2 mass (Fig. 2). The principle of the calculation is as follows: the mass emissions are not calculated for the complete data set, but for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the CO_2 mass emitted by the vehicle over the reference laboratory cycle (WLTC). The moving average calculations are conducted with a time increment corresponding to the data sampling frequency (usually 1 Hz). These sub-sets used to average the emissions data are referred to as "averaging windows". The calculation described in the present point may be run from the last point (backwards) or from the first point (forward).

Table 1. Specific requirements regarding RDE tests [1–4]

Parameter	Requirements
Ambient temperature (T_z)	– normal range: $0^oC \le T_z < 30^oC$
	– lower extended range: $-7^oC \le T_z < 0^oC$
	– upper extended range: $30^oC < T_z \le 35^oC$
Topographic height of test areas (h)	– normal range: h ≤ 700 m a.s.l.
	– extended range: 700 < h ≤ 1300 m a.s.l.
Impact of external weather and road parameters and the driving style	– accumulated height increase: less than 1200 m/100 km
	– (RPA): greater than RPA_{min} (in all driving conditions)
	– product of acceleration and speed ($v \cdot a_{pos}$): less than $v \cdot a_{pos\ min}$ (in all driving conditions)
Thermal condition of the vehicle prior to tests	– cold start: coolant less than 70^oC, time of at least 300 s
	– emission upon cold start not included in RDE test
Single vehicle downtime	– no more than 180 s
Exhaust after-treatment system's operation	– single regeneration of PM filter can result in RDE test repetition; two regenerations are included in the results of exhaust emissions in RDE test
Driving comfort system operation	– used normally according to purpose (e.g. air-conditioning system)
Vehicle load	– weight of vehicle: driver (and passenger) and test equipment; max. load < 90% of the sum of weight of passengers and vehicle's usable mass
Test requirement	– duration 90–120 min
Requirements for the urban test part	– 29–44% of the entire test length
	– distance more than 16 km
	– speed (v): v ≤ 60 km/h
	– average speed: 15–40 km/h
	– break: 6–30% of the total urban time
Requirements for the rural part	– 23–43% of the entire test length
	– distance: greater than16 km
	– vehicle's speed (v): 60 km/h < v ≤ 90 km/h
Requirements for the motorway part	– 23–43% of the entire test length
	– distance: greater than16 km
	– vehicle's speed (v): v > 90 km/h
	– driving speed of more than 100 km/h for at least 5 min
	– driving speed of more than 145 km/h for at least 3% of the time

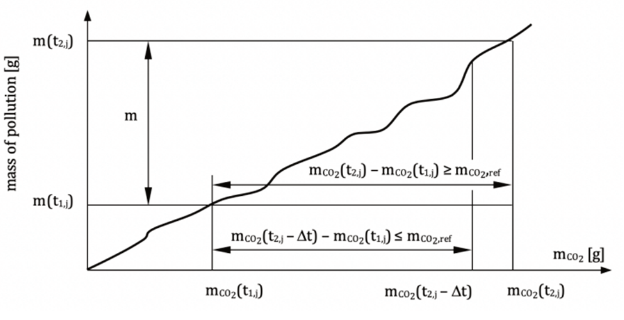

Fig. 2. Definition of CO_2 mass based averaging windows [1–4]

Duration of i-window average ($t_{2,j} - t_{1,j}$) is determined according to the following formula (Fig. 2):

$$m_{CO_2}(t_{2,j}) - m_{CO_2}(t_{1,j}) \ge m_{CO_2,ref} \quad (1)$$

where: $m_{CO_2}(t_{i,j})$ – is the CO_2 mass measured between the test start and time ($t_{i,j}$), [g]; $m_{CO_2,ref}$ – is the half of the CO_2 mass [g] emitted by the vehicle over the WLTP cycle (type I test, including cold start); $t_{2,j}$ – shall be selected such as:

$$m_{CO_2}(t_{2,j} - \Delta t) - m_{CO_2}(t_{1,j}) < m_{CO_2,ref} \le m_{CO_2}(t_{2,j}) - m_{CO_2}(t_{1,j}) \quad (2)$$

where Δt is the data sampling period (1 s or less).

The reference points P_1, P_2 and P_3 (Fig. 3) required to define the curve shall be established as follows:

- P_1: v_{P_1} = 19 km/h (average speed of the 1 Low Speed phase of the WLTP cycle),
- b_{CO_2,P_1} – on-road emission of CO_2 [g/km] of 1 Low Speed phase of the WLTC phase increased by 20%,
- P_2: v_{P_2} = 56.6 km/h (average speed of the 3 High Speed phase of the WLTP cycle),
- b_{CO_2,P_2} – on-road emission of CO_2 [g/km] of 3 Low Speed phase of the WLTC phase increased by 10%,
- P_3: v_{P_3} = 92.3 km/h (average speed of the 4 Extra High Speed phase of the WLTP cycle),
- b_{CO_2,P_3} = on-road emission of CO_2 [g/km] of 4 Low Speed phase of the WLTC phase increased by 5%.

The CO_2 emissions are calculated as a function of the average speed using two linear sections (P_1, P_2) and (P_2, P_3).

The section (P_2, P_3) is limited to 145 km/h on the vehicle speed axis.

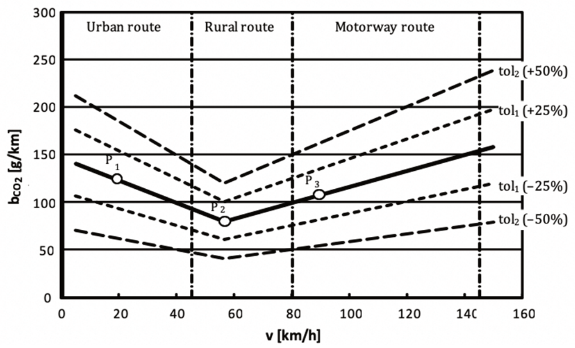

Fig. 3. Vehicle CO_2 characteristic curve

Urban windows are characterized by average vehicle ground speeds smaller than 45 km/h, rural windows are characterized by average vehicle ground speeds greater than or equal to 45 km/h and smaller than 80 km/h, motorway windows are characterized by average vehicle ground speeds greater than or equal to 80 km/h and smaller than 145 km/h. The primary tolerance and the secondary tolerance of the vehicle CO_2 characteristic curve are respectively $tol_1 = 25\%$ and $tol_2 = 50\%$. The test shall be complete when it comprises at least 15% of urban, rural and motorway windows, out of the total number of windows. The test shall be normal when at least 50% of the urban, rural and motorway windows are within the primary tolerance defined for the characteristic curve. If the specified minimum requirement of 50% is not met, the upper positive tolerance tol_1 may be increased by steps of 1% until the 50% of normal windows target is reached. When using this mechanism, tol_1 shall never exceed 30%.

Having ascertained that the test is complete, the weighing factor for each window shall be determined in the following tolerance ranges:

- if the window falls within the 1st degree tolerance, i.e.:

$$b_{CO_2}\left(1-\frac{tol_1}{100}\right) \le b_{CO_2,i} \le b_{CO_2}\left(1+\frac{tol_1}{100}\right) \quad (3)$$

the weighing factor *shall be equal 1.*

- if the window falls within the tolerance range from +25% to +50%, i.e.:

$$b_{CO_2}\left(1+\frac{tol_1}{100}\right) \le b_{CO_2,i} \le b_{CO_2}\left(1+\frac{tol_2}{100}\right) \quad (4)$$

its weighing factor shall be determined with the following formula:

$$w = k_{11}\, h + k_{12} \quad (5)$$

where: $k_{11} = \dfrac{1}{tol_1 - tol_2}$, a $k_{12} = \dfrac{tol_2}{tol_2 - tol_1}$,

– if the window falls within the tolerance range from –50% to –25%, i.e.:

$$b_{CO_2}\left(1-\frac{tol_2}{100}\right) \le b_{CO_2,i} \le b_{CO_2}\left(1-\frac{tol_1}{100}\right) \quad (6)$$

its weighing factor shall be determined with the following formula:

$$w = k_{21}\, h + k_{22} \quad (7)$$

where: $k_{21} = \dfrac{1}{tol_2 - tol_1}$, a $k_{22} = \dfrac{tol_2}{tol_2 - tol_1}$,

– if the window falls below tolerance range –50% or above +50%, i.e.:

$$b_{CO_2,i} \le b_{CO_2}\left(1-\frac{tol_2}{100}\right) \text{ or } b_{CO_2,i} \ge b_{CO_2}\left(1+\frac{tol_2}{100}\right) \quad (8)$$

its weighing factor is w = 0.

The value of h for every window is determined based on the following formula:

$$h = 100\left(\frac{b_{CO_2,i} - b_{CO_2}}{b_{CO_2}}\right) \quad (9)$$

After the weighing factor for every window is determined, it is marked on the chart where every weighing factor (w) is marked on the y axis, tolerance percentage (h) on x axis (Fig. 4).

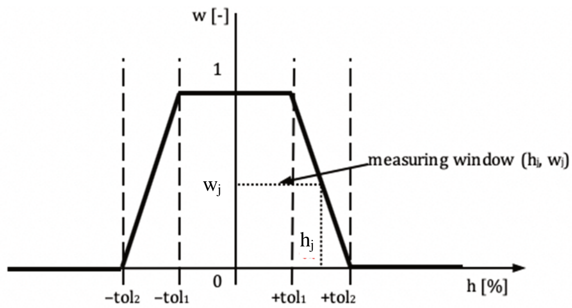

Fig. 4. Averaging window weighing function [1–4]

After all those steps are performed, the CO_2 on-road emissions for every window are illustrated on the characteristic curve chart (Fig. 5).

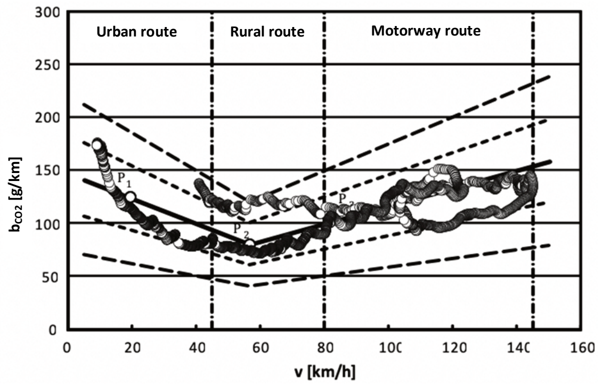

Fig. 5. Vehicle CO_2 characteristic curve with CO_2 emissions in respective windows, during on-road tests [1–4]

Next the severity indices shall be calculated separately for the urban (m), rural (p) and motorway (a) categories by summarising windows for a particular category (h_k) and dividing by the total number (N), e.g. for the urban category:

$$u = \frac{\sum h_k}{N}, \; k = m, p, a \tag{10}$$

and the complete trip:

$$u = \frac{f_m h_m + f_p h_p + f_a h_a}{f_m + f_p + f_a} \tag{11}$$

where: $f_m = 0.34$, $f_p = 0.33$, a $f_a = 0.33$.

In the end the distance-specific emissions in [mg/km] are calculated for the complete trip each gaseous pollutant in the following way:

$$b_j = 1000 \cdot \frac{f_m b_{j,m} + f_p b_{j,p} + f_a b_{j,a}}{f_m + f_p + f_a} \tag{12}$$

and for the on-road emission of particulate matter:

$$b_{PN} = \frac{f_m b_{PN,m} + f_p b_{PN,p} + f_a b_{PN,a}}{f_m + f_p + f_a} \tag{13}$$

To determine dynamic trip parameters the following must be determined: value of 95 centile of the product of driving speed and positive acceleration greater than 0.1 m/s^2 (expressed in m^2/s^3) and relative positive acceleration (expressed in m/s^2) for urban, rural and motorway shares.

The value of the 95th centile of the product $(v \cdot a_+)$ – formulated as $(v \cdot a_+)_{k\_[95]}$ – is determined in the following manner: value of products $(v \cdot a_+)_{i,k}$ in every test part (k – urban, rural and motorway share) is categorised in a growing order for all data sets of $a_{i,k} \geq 0.1$ m/s^2 (number of data sets must be greater than 150) and the total number of windows N_k is determined.

In the next step the centile values are allocated to the product $(v \cdot a_+)_{i,k}$ in the following manner: the lowest value of the product $(v \cdot a_+)$ has centile of $1/N_k$, the second lowest – $2/N_k$, the third lowest – $3/N_k$, and the highest value – $N_k/N_k = 100\%$. Value $(v \cdot a_+)_{k\_[95]}$ stands for $(v \cdot a_+)_{i,k}$, for which $j/N_k = 95\%$ (j – successive value of product of speed and positive acceleration). If $j/N_k = 95\%$ cannot be achieved, then $(v \cdot a_+)_{k\_[95]}$ is determined based on line interpolation of successive samples j and (j + 1), for which $j/N_k < 95\%$ and $(j + 1)/N_k > 95\%$.

The validity of the trip is verified for every urban, rural and motorway share. If the value of $(v \cdot a_+)_{k\_[95]}$ meets the equation for every test step (Fig. 6a):

$$(v \cdot a_+)_{k\_[95]} < 0{,}136 \cdot \bar{v}_k + 14{,}4 \quad \text{for } \bar{v}_k \leq 74{,}6 \text{ km/h} \tag{15}$$

$$(v \cdot a_+)_{k\_[95]} < 0{,}0742 \cdot \bar{v}_k + 18{,}966 \quad \text{for } \bar{v}_k > 74{,}6 \text{ km/h} \tag{16}$$

the trip is valid.

RPA – relative positive acceleration for every step of the test is determined based on the following formula:

$$RPA_k = \frac{\sum_{j=1}^{N_k} \Delta t \cdot (v \cdot a_+)_{j,k}}{\sum_{j=1}^{L} d_{i,k}} \tag{14}$$

where: RPA_k – relative positive acceleration for urban, rural and motorway shares, m/s^2, Δt – data sampling period (1 s), N_k – number of windows for urban, rural, and motorway shares with positive acceleration, L – total number of windows for urban, rural, and motorway shares.

If RPA_k value meets the equation for every test step – Eq. (14):

$$RPA > -0{,}0016 \cdot \bar{v}_k + 0{,}1755 \quad \text{for } \bar{v}_k \leq 94{,}05 \text{ km/h} \tag{15}$$

$$RPA > 0{,}025 \quad \text{for } \bar{v}_k > 94{,}05 \text{ km/h} \tag{16}$$

the trip is valid.

3. Determing the test route

Several driving trips were performed in order to outline the test route. Three test vehicles were used to perform the trips. Technical data of those vehicles are presented in Table 2 below.

Table 2. Parameters of vehicles used to delineate RDE route

	Vehicle I	Vehicle II	Vehicle III
Production year	2017	2008	2017
Engine displacement	1598 cm^3	1798 cm^3	1502 cm^3
Drive unit power	100 kW	92 kW	105 kW
Type of fuel	Diesel oil	Petrol	Petrol
Vehicle category	M1	M1	M1
Vehicle mass	1375 kg	1340 kg	1690 kg

After every attempt to outline the trip route, an analysis of the resulting data was performed, based on which it was determined whether its requirements were met. PEMS-Semtech DS measuring equipment – among others – was used for this purpose [5–7]. Table 3 and Table 4 presents parameters of the test trips.

Having fulfilled requirements for a route, a series of measurements was carried out to verify the accuracy of the obtained results. The outlined test route is shown in Fig. 6 below.

Fig. 6. Test route

Table 3. RDE test parameters – test example (unfulfilled test)

Test accuracy			
Test parameter	Result	Requirement	Correctness
Urban route [km]	27.78	> 16	Correct
Rural route [km]	20.76	> 16	Correct
Motorway route [km]	14.49	> 16	Incorrect
Overall route [km]	63.04	> 48	Correct
Urban share [%]	44.07	29–44	Incorrect
Rural share [%]	32.94	33 ±10	Correct
Motorway share [%]	22.99	33 ±10	Incorrect
Average speed in urban route [km/h]	31.80	15–40	Correct
Share of downtime in urban route [%]	16.18	6–30	Correct
Trip time above 100 km/h [min]	7.13	> 5	Correct
Max. driving speed [km/h]	126.00	< 160	Correct
Trip time above 145 km/h	0.00	< 3	Correct
Duration of trip [min]	77.97	90–120	Incorrect
Dynamic test conditions			
Urban: number of data $a > 0.1$ m/s^2	956	> 150	Correct
Rural: number of data $a > 0.1$ m/s^2	272	> 150	Correct
Motorway: number of data $a > 0.1$ m/s^2	140	> 150	Incorrect
Urban: average speed [km/h]	31.80		
Rural: average speed [km/h]	70.26		
Motorway: average speed [km/h]	111.24		
Urban: 95th centile $V.a_{pos}$ [m^2/s^3]	12.27	< 18.765	Correct
Rural: 95th centile $V.a_{pos}$ [m^2/s^3]	16.42	< 23.995	Correct
Motorway: 95th centile $V.a_{pos}$ [m^2/s^3]	15.43	< 27.220	Correct
Urban: RPA [m/s^2]	0.14	> 0.125	Correct
Rural: RPA [m/s^2]	0.06	> 0.063	Correct
Motorway: RPA [m/s^2]	0.06	> 0.025	Correct

Table 4. RDE test parameters – test example (fulfilled test)

Test accuracy			
Test parameter	Result	Requirement	Correctness
Urban route [km]	32.51	> 16	Correct
Rural route [km]	28.42	> 16	Correct
Motorway route [km]	29.21	> 16	Correct
Overall route [km]	90.14	> 48	Correct
Urban share [%]	36.06	29–44	Correct
Rural share [%]	31.53	33 ±10	Correct
Motorway share [%]	32.41	33 ±10	Correct
Average speed in urban route [km/h]	33.29	15–40	Correct
Share of downtime in urban route [%]	13.54	6–30	Correct
Trip time above 100 km/h [min]	14.57	> 5	Correct
Max. driving speed [km/h]	128.00	< 160	Correct
Trip time above 145 km/h	0.00	< 3	Correct
Duration of trip [min]	97.95	90–120	Correct
Dynamic test conditions			
Urban: number of data $a > 0.1$ m/s^2	1039	> 150	Correct
Rural: number of data $a > 0.1$ m/s^2	393	> 150	Correct
Motorway: number of data $a > 0.1$ m/s^2	309	> 150	Correct
Urban: average speed [km/h]	33.29		
Rural: average speed [km/h]	71.54		
Motorway: average speed [km/h]	112.84		
Urban: 95th centile $v.a_{pos}$ [m^2/s^3]	13.92	< 18.968	Correct
Rural: 95th centile $v.a_{pos}$ [m^2/s^3]	18.36	< 24.170	Correct
Motorway: 95th centile $v.a_{pos}$ [m^2/s^3]	18.60	< 27.338	Correct
Urban: RPA [m/s^2]	0.14	> 0.122	Correct
Rural: RPA [m/s^2]	0.07	> 0.061	Correct
Motorway: RPA [m/s^2]	0.08	> 0.025	Correct

The specified test route fulfils the requirements imposed by the legislator. It supplements the WLTC test procedure. The test route is characteristic for Warsaw and allows for conducting studies on emissions consistent with the requirements of the prevailing WLTC procedure.

4. Summary

Further RDE tests along the outlined route shall be performed to compare the results obtained from the Averaging Window Method and from other methods of determining exhaust emissions in on-road tests, i.e. the method using all measurement data and power binning method.

Nomenclature

BEV	Battery Electric Vehicle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
NEDC	New European Driving Cycle
RDE	Real Driving Emissions
WLTP	Worldwide harmonised Light Duty Vehicle Test Procedure

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