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Error Analysis of the Normative Calculation Method of the Exhaust Emissions and Fuel Consumption in the Vehicles Fueled with Gaseous Fuels

Paulina Grzelak * and Sławomir Taubert

Environmental Protection Center, Motor Transport Institute, 80 Jagiellonska Str., 03-301 Warsaw, Poland; slawomir.taubert@its.waw.pl

* Correspondence: paulina.grzelak@its.waw.pl; Tel.: +48-22-43-85-267

Abstract: The methodologies for calculating exhaust emissions and fuel consumption, which are given in the normative documents, do not take into account the fact that vehicles equipped with liquefied petroleum gas (LPG) or compressed natural gas (CNG) systems are fueled with petrol after a cold start. When calculating exhaust emissions and fuel consumption of LPG or CNG-powered vehicles, it is assumed that they result from the combustion of gaseous fuel only. This simplification leads to an incorrect determination of the emissions and fuel consumption values, as the formulas for calculating these values differ depending on the fuel type. This article presents the results of tests aimed at checking how that factor affects the value of emissions and fuel consumption calculated in the driving cycles used in the type-approval tests. In order to estimate the error resulting from this simplification, the tests of exhaust emissions and fuel consumption of a vehicle equipped with an LPG system were carried out. The tests were carried out on a chassis dynamometer in the worldwide harmonized light vehicles test cycle (WLTC) used in the type approval tests. In the tested vehicle, the CO, total hydrocarbons (THC), NO_x and CO_2 emissions calculated with the normative method were approx. 7% lower than the values calculated with the corrected method. For this reason, there is a need to develop a measurement method that allows for a separate analysis of the phase in which the vehicle is fueled with gasoline. This will allow the elimination of errors in the current normative method of calculating pollutant emissions from the exhaust system and fuel consumption of vehicles fueled with gaseous fuels.

Keywords: gaseous fuels; exhaust emissions; emissions regulations; emissions calculation; fuel consumption calculation

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1. Introduction

When calculating the pollutant emissions from the exhaust systems of bi-fuel cars, i.e., cars fueled with gasoline and gaseous fuel (liquefied petroleum gas (LPG) or compressed natural gas (CNG)), it is assumed in the normative documents [1–3], that the emission of pollutants and fuel consumption result only from the combustion of gaseous fuel. The fact that after the cold start-up the engine is initially fueled with gasoline is not taken into account, and for this phase also the formulas suitable for gaseous fuels are used instead of those suitable for gasoline. The provisions on the type-approval tests [1,3,4] define the maximum permissible engine operation time on gasoline. In the case of vehicles with spark ignition engines with indirect gasoline injection, it is 90 s for the Euro 5 emission level or lower and 60 s for Euro 6 level.

In the methodology of calculating exhaust emissions and fuel consumption, there are formulas in which the values of some variables depend on the fuel composition.

Those variables are:

- hydrocarbon density ρ_{THC} in exhausts (Table 1),

- concentration of carbon dioxide in undiluted, wet exhaust determined with the assumption that combustion is complete and perfect and the air-fuel mixture has a stoichiometric composition (Equation (5), Table 2), and
- fuel density (Table 3).

Table 1. Total hydrocarbon density (g/dm^3) under the reference conditions of 273.15 K and 1013.25 hPa [1,3].

Hydrocarbons	Density [g/m^3]
Gasoline E5 ($C_1H_{1.89}O_{0.016}$)	0.631
Gasoline E10 ($C_1H_{1.93}O_{0.033}$)	0.646
Diesel B5 ($C_1H_{1.86}O_{0.005}$)	0.622
Diesel B7 ($C_1H_{1.86}O_{0.007}$)	0.625
LPG ($C_1H_{2.525}$)	0.649
CNG / Biomethane (CH_4)	0.716
Ethanol E85 ($C_1H_{2.74}O_{0.385}$)	0.934

Table 2. Values of the "*a*" factor for specific fuels [1,3].

Fuel	Factor "*a*"
Gasoline E5	13.4
Gasoline E10	13.4
Diesel B5	13.5
Diesel B7	13.5
LPG	11.9
CNG/Biomethane	9.5
Ethanol E85	12.5

Table 3. Fuel density (kg/dm^3) [1,3].

Fuel	Density
Gasoline E5 ($C_1H_{1.89}O_{0.016}$)	0.743–0.756
LPG ($C_1H_{2.525}$)	0.538
CNG / Biomethane (CH_4)	0.654

The use of inappropriate values of these variables leads to the determination of an incorrect value of gaseous pollutant emissions and fuel consumption. The emission of gaseous pollutants is determined according to the following Formula (1) [1,3]:

$$m = \frac{V_{CVS} \times \rho \times k_h \times C^C_{CVS} \times 10^{-2}}{d} \quad (1)$$

The parameters C^C_{CVS}, V_{CVS}, and ρ are determined based on the tests, and the density of a given pollutant is specified in the regulations [1–3]. For carbon monoxide, carbon dioxide, and nitrogen oxides, the ρ values are the same regardless of the fuel used, while for hydrocarbons, the density depends on the fuel used to supply the engine (Table 1).

The general equation for calculating total hydrocarbon density for each fuel with composition of $C_XH_YO_Z$ is as follows (2) [1,3]:

$$\rho_{THC} = \frac{MW_C + \frac{H}{C} \times MW_H + \frac{O}{C} \times MW_O}{V_M} \quad (2)$$

The concentration of pollutants in the diluted exhaust gas, corrected due to its content in the dilution air C^C_{CVS}, is calculated based on the concentrations of pollutant in the diluted exhaust and in the dilution air according to Equation (3) [1,3]:

$$C^c_{CVS} = C_{CVS} - C_{dil} \times (1 - \frac{1}{DF}) \quad (3)$$

The dilution factor, which appeared in Equation (3), is determined by Equation (4) [1,3]:

$$DF = \frac{a}{C_{CO_2} + 10^{-4} \times (C_{THC} + C_{CO})} \quad (4)$$

The general formula for calculating the value of the factor "*a*" for the fuel of the composition $C_XH_YO_Z$ (C—carbon, H—hydrogen, O—oxygen) is as follows (Equation (5)) [1,3]:

$$a = 100 \times \frac{X}{X + Y/2 + 3.76 \times (X + Y/4 - Z/2)} \quad (5)$$

Table 2 shows the values of the factor "*a*" for various types of fuels.

Fuel consumption is determined in tests carried out on a chassis dynamometer and based on the carbon balance method. The calculation method is given in Regulation No. 101 ONZ, Revision 3, Supplement 1 to the 01 series of amendments [2]. The formulas for calculating fuel consumption for the selected fuels (6)–(8) are given below:

a. for vehicles with a spark ignition engine fueled with petrol (E5):

$$FC = \left(\frac{0.118}{\rho_{gasoline}}\right) \cdot \left[(0.848 \cdot E_{HC}) + (0.429 \cdot E_{CO}) + \left(0.273 \cdot E_{CO_2}\right)\right] \quad (6)$$

b. for vehicles with a spark ignition engine fueled with LPG:

$$FC_{norm} = \left(\frac{0.1212}{\rho_{LPG}}\right) \cdot \left[(0.825 \cdot E_{HC}) + (0.429 \cdot E_{CO}) + \left(0.273 \cdot E_{CO_2}\right)\right] \quad (7)$$

c. for vehicles with a spark ignition engine fueled with natural gas (CNG) or biomethane (CBG):

$$FC_{norm} = \left(\frac{0.1336}{\rho_{\frac{CNG}{CBG}}}\right) \cdot \left[(0.749 \cdot E_{HC}) + (0.429 \cdot E_{CO}) + \left(0.273 \cdot E_{CO_2}\right)\right] \quad (8)$$

When calculating gasoline consumption, the density measured for a given sample of this fuel is used. The gasoline density value in the type-approval tests should be within the range given in Table 3. This table also shows the density values for gaseous fuels.

In the methodology of calculating the emissions of vehicles running on gaseous fuel, the failure to take into account the fact that after the cold start, the engine is fueled with gasoline, and using formulas appropriate for gaseous fuels causes errors in the measurement results, the sources of which are incorrect values for the following variables:

- factor "*a*" in the Equation (4);
- total hydrocarbon density ρ_{THC} in the Equation (1);
- fuel density used in formulas to calculate the fuel consumption in Equations (6)–(8);
- factor in Equations (6)–(8) depends on the structure of the fuel molecule in the case of hydrocarbon emissions.

A number of publications can be found that present analysis of the sources of errors in the measurement of pollutant emissions from the vehicle exhaust systems and describe the possibilities of reducing or eliminating these errors [5–32]. However, the authors did not find any studies on the error estimation resulting from the skipping of the gasoline supply phase in the measurements of pollutant emissions from the exhaust system and the fuel consumption of bi-fuel vehicles fueled with gaseous fuels. The article describes tests aimed at estimating this error in the world harmonized light-duty test cycle (WLTC driving cycle) used in vehicle approval tests.

2. Methodology

The tests were carried out on a passenger vehicle belonging to the C segment, equipped with a spark ignition engine with indirect gasoline injection system and a capacity of 1.6 dm^3 (Table 4). The tested vehicle was equipped with an LPG system with sequential injection of LPG in the gas phase, into the intake manifold.

Table 4. Essential data of the tested vehicle.

Parameter	Value/Description
Engine	Four stroke spark ignition engine
Engine capacity	1598 cm^3
Maximum engine power	81 kW at 6000 min^{-1}
Fuel system	Bi-fuel; gasoline or LPG
Gasoline injection system	Multipoint indirect gasoline injection
LPG injection system	Multipoint indirect sequential injection in the gas phase
After-treatment system	Three-way catalytic converter

The tests were conducted at the Motor Transport Institute, Warsaw, Poland, on a chassis dynamometer equipped with a system for measuring emissions from the exhaust system, meeting the requirements of the normative documents for the type-approval tests within the scope of exhaust emissions. The chassis dynamometer was equipped with the following devices:

- type RPL 1220/12 C 221 113/GPM 200 one roller chassis dynamometer with adjustable resistance curve by AVL-Zoellner,
- exhaust sampling and emissions analysis system by AVL consisting of:
    - type CVS i60 LD S2 full-flow CFV-CVS exhaust gas sampling system by AVL with critical flow Venturis allowing for flow rates from 2 to 30 m^3/min,
    - set of AMA i60 D1-CD LE analyzers by AVL equipped with two-range analyzers for analyzing the diluted exhaust, consisting of:
        - type AVL IRD i60 CO_2 L/CO SL two-channel analyzer by ABB operating on the principle of infrared absorption (NDIR), measuring the low CO_2 concentration and very low CO concentration in the dry exhaust gases;
        - type AVL CLD i60 LHD two-channel, heated analyzer by AVL operating on the principle of chemiluminescence, equipped with two detectors enabling the simultaneous measurement of low NO_x and NO concentrations;
        - type CUTTER FID i60 CLD two-channel analyzer by AVL operating on the principle of flame ionization detection (FID), equipped with two detectors enabling the simultaneous measurement of low total hydrocarbons (THC) and CH_4 concentrations;
- a set of calibration gases with accuracy of 1%, used for calibration of the analyzers,
- VAISALA PTU303 weather station for measuring air temperature, pressure, and humidity in a chassis dynamometer room,
- iGEM Vehicle measurement automation system produced by AVL, which was responsible for controlling the operation of measuring devices, analyzing exhaust gas samples and recording selected parameters in the database.

The diagram of the measuring system used in the tests is presented in Figure 1.

The chassis dynamometer was adjusted so as to reproduce the total road load measured for the tested vehicle. The measuring equipment met the requirements set out in UN Regulation 83 [1]. The accuracies of the main measuring equipment are given in Table 5.

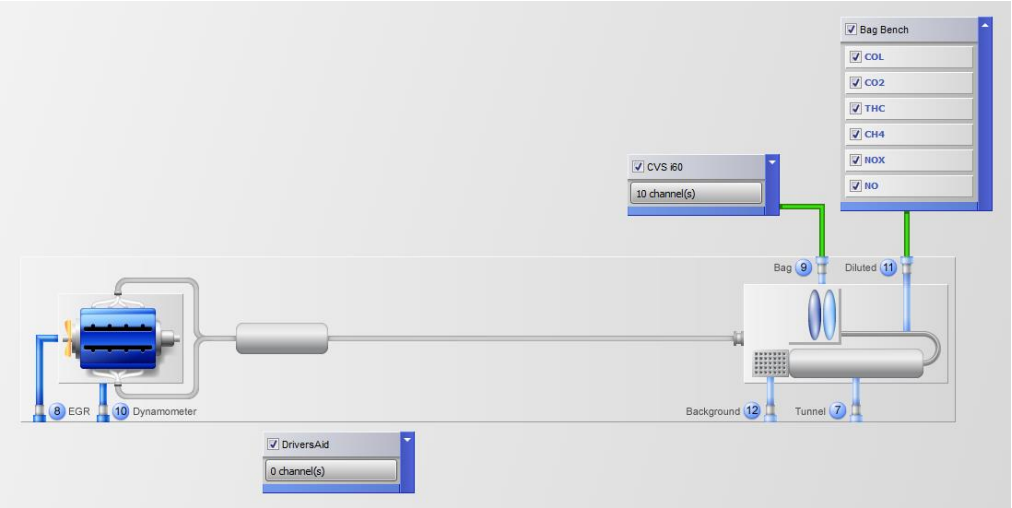


Figure 1. Diagram of the measuring system used in the tests.

Table 5. Accuracy of the measuring equipment.

Measured Parameter	Measuring Equipment	Accuracy
Flow	Exhaust dilution system	±0.5%
Speed	Chassis dynamometer	±0.025%
Distance	Chassis dynamometer	±0.1%
Concentration	Analyzers	±2%

Measurements were made on the WLTC driving cycle. Before the measurements, the vehicle was conditioned for at least 12 h in temperatures +23 °C. During the tests, the vehicle engine was started on gasoline. After reaching the minimum parameters set in the LPG control unit, the LPG controller switched the fuel supply to LPG fuel. During the WLTC driving cycle, instantaneous values of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), methane (CH_4), nitrogen oxides (NO_x), and nitric oxide (NO) in the diluted exhaust gas were recorded. The voltage on the electrovalve installed upstream of the LPG inlet to the LPG pressure regulator was also recorded. The time after which the engine started to run on LPG was considered to be the time elapsed from starting the engine until the voltage appeared on the contacts of this electrovalve, plus the time of switching the LPG system from gasoline to LPG. This time was set in the LPG electronic control unit (ECU) and amounted to 3.1 s (the sum of the switching time and the pressure regulator filling time).

The emissions of pollutants were calculated using two methods.

The first method was based on the instantaneous values of the concentrations of the measured pollutants and the engine operation time while running on gasoline and LPG. Later in this article, this method is called the "corrected method". The engine was switched from gasoline to LPG in the first phase of the WLTC (Low Phase) cycle. This part of the cycle was divided into two phases: the phase in which the engine was running on gasoline (Low_{gas}) and the phase in which the engine was fueled with LPG (Low_{LPG}).

For each of these phases, the formulas appropriate for a given fuel were used. The mean value of the concentrations was determined for each phase to calculate the dilution factor DF. Based on these values, the DF factor was calculated according to Equation (4) using the factor "a" appropriate for the given fuel. With the DF factors calculated, the instantaneous emission was calculated based on the instantaneous concentrations recorded with the frequency of 1 Hz. The instantaneous emission values were then summed for each of the Low_{gas} and Low_{LPG} phases. The obtained summary values were the emission of a given pollutant in the Low_{gas} and Low_{LPG} phases. In the final step of the calculation, the values of the emissions from these two phases were added and divided by the distance

traveled in the Low phase of the WLTC cycle. That way, the emission value of a given pollutant was obtained in the Low phase of the WLTC cycle, taking into account the fact that during part of this phase the engine was powered by gasoline.

The second method was based on a procedure set out in the literature positions [1] and [3]. Later in this article, this method is called the "normative method". This method is based on concentration values measured in the diluted exhaust gas collected in the bags. Proportional samples of the diluted exhaust gas were collected in two bags for each of the four phases of the WLTC cycle. After the test, the concentrations of the pollutants in the diluted exhaust gas and dilution air collected in the bags were analyzed. So the fact that the engine was fueled with gasoline after start-up was not taken into account, and the formulas appropriate for the LPG fuel were used for the whole cycle.

For the calculation of total hydrocarbons (THC) emissions, the following fuel composition and density ρ_{THC} were adopted (in accordance with Section 6.6.2 of Annex 4a to UN Regulation 83, 07 series of amendments [1]):

- for gasoline (E5): $C_1H_{1.89}O_{0.016}$ and ρ_{THC} = 0.631 g/dm^3;
- for LPG: $C_1H_{2.522}$ and ρ_{THC} = 0.649 g/dm^3.

3. Results

3.1. Exhaust Emissions

Five exhaust emissions measurements were performed on the WLTC cycle after a cold start. In each test, switching to LPG was performed in the first phase of the WLTC cycle (Low phase) (Table 6). Therefore, only this phase was analyzed.

Table 6. Working time on gasoline T_{gas} (s) and the distance traveled in the Low phase of the world harmonized light-duty test cycle (WLTC) cycle (km).

T_{gas} [s]	Distance [km]
68	3.172
73	3.136
73	3.109
91	3.076
72	3.082

Table 7 shows the values of pollutant emissions calculated using two methods: normative and corrected for one of the measurements. The table shows the values of the emissions calculated for each of the two Low_{gas} and Low_{LPG} phases and the sum of these two values (Low_{Total}). The Low-phase emission value calculated according to the corrected method is marked as $Emission_{Low}$. The results for all five measurements are provided in Appendix A (Tables A1–A5).

Table 7. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	175.7	96.2	502.2	598.4	188.7
CO	1.271	3.790	0.530	4.320	1.362
NO_x	0.247	0.404	0.443	0.847	0.267
NO	0.153	0.266	0.281	0.547	0.172
THC	0.323	0.977	0.130	1.107	0.349
CH_4	0.021	0.038	0.036	0.074	0.023

Table 8 shows the relative percentage difference between the emission values of individual pollutants calculated using the normative and corrected methods, calculated according to Formula (9). Figure 2 shows the average value of this difference.

$$\Delta E = \frac{E_{normative} - E_{corrected}}{E_{corrected}} \times 100 \quad (9)$$

Table 8. Relative percentage difference between the pollutant emissions as calculated by the normative method and the corrected method.

Pollutant	ΔE_1	ΔE_2	ΔE_3	ΔE_4	ΔE_5	$\Delta E_{average}$
CO_2	−6.9%	−6.7%	−6.9%	−6.5%	−6.5%	−6.7%
CO	−6.7%	−6.8%	−6.7%	−6.5%	−6.4%	−6.6%
NO_x	−7.5%	−6.9%	−7.4%	−6.9%	−6.8%	−7.1%
NO	−11.3%	−20.7%	−11.3%	−5.5%	−16.2%	−13.0%
THC	−7.4%	−7.4%	−6.7%	−6.5%	−4.3%	−6.5%
CH_4	−10.0%	−18.7%	−6.7%	4.1%	12.5%	−3.8%

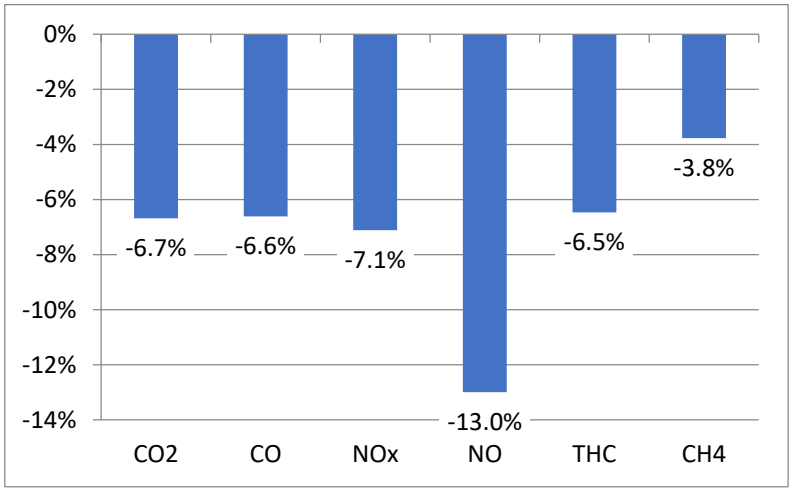


Figure 2. Average relative percentage difference between the pollutant emissions as calculated by the normative method and the corrected method.

For all pollutants, the relative percentage difference between the emission values of individual pollutants calculated with the normative and corrected methods was negative. For the limited pollutants (CO, NO_x, THC), the Low phase emissions of the WLTC calculated by the normative method were 6.5% to 7.1% lower than the values calculated by the corrected method.

3.2. Fuel Consumption

Table 8 shows the fuel consumption values calculated in accordance with the normative and corrected methods. For the corrected method, the consumption values of both gasoline and LPG are given. For their calculation, Formulas (6) and (7) were used respectively, taking into account the measured densities of these fuels, amounting to 0.737 kg/dm^3 for gasoline and 0.5206 kg/dm^3 for LPG. The mass emissions of CO_2, CO, and THC (see Tables A1–A5) were divided by the distance traveled with the fuel in question (Table 6). Table 9 also shows the relative percentage difference ΔFC_{LPG} between LPG consumption calculated according to the normative method and consumption of this fuel calculated according to the corrected method.

Table 9. Fuel consumption (dm^3/100 km) in Low phase of WLTC cycle, calculated by both normative and corrected methods.

Lp.	Normative	Corrected		ΔFC_{LPG}
		Gasoline	LPG	
1	10.99	11.85	11.49	4.5%
2	11.13	11.71	11.61	4.3%
3	11.10	12.16	11.53	3.9%
4	11.63	11.74	11.89	2.2%
5	11.33	13.61	11.46	1.1%

4. Discussion

In the normative method of calculating emissions of pollutants from the exhaust system of vehicles fueled with gaseous fuels, there are two sources of error resulting from the use of values appropriate for gaseous fuel also in the phase in which the engine is actually running on gasoline. This applies to the following parameters:

- Hydrocarbon density in Equation (1)—only for emissions of total THC;
- Factor "*a*" in Equation (2).

For the tested vehicle, the emissions of total hydrocarbons in the Low phase of the WLTC cycle, which occurred in the phase in which the engine was running on gasoline, accounted for 88.6% of total emissions of total hydrocarbons in the Low phase. The relative percentage difference in THC density for both fuels was 2.9%. Therefore, the error resulting from the application of the THC density appropriate for the gaseous fuel also in the phase in which the engine is fueled with gasoline was 2.5% and made the THC emissions calculated in accordance with the normative method, due to this error, higher by this value.

The Low phase carbon dioxide emissions of the WLTC cycle calculated according to the corrected method were 6.7% higher on average than the value calculated according to the normative method. As a result, the weighted average emissions of this pollutant in the WLTC cycle were higher by 1.6% on average. The values of CO_2 emissions in the individual phases of the WLTC cycle and the weighted average value of these emissions are provided in the vehicle type-approval certificate. In view of the above, it can be assumed that for bi-fuel vehicles these values may be too low. This may have an impact on the average carbon dioxide emissions of a manufacturer's newly launched vehicles, which are calculated from [33]. However, the share of new vehicles factory-equipped with LPG or CNG installations in total vehicle production is small and therefore it should be expected that providing the CO_2 emissions value calculated in accordance with the normative method will have a slight impact on the average emissions of this pollutant from vehicles of a given manufacturer.

When calculating fuel consumption, in addition to the two above-mentioned values that affect the emissions values of carbon dioxide, carbon monoxide, and total hydrocarbons, there are also the following values:

- fuel density in Formulas (6)–(8);
- THC emissions factor, which depends on the structure of the fuel molecule.

The average relative percentage difference in LPG fuel consumption during the Low phase of the WLTC cycle calculated with both methods is 3.2%. The consumption of LPG calculated with the corrected method is higher than that calculated with the normative method. In the case of bi-fuel vehicles, gasoline consumption should also be considered.

In order to eliminate the error resulting from the application of the normative method for the calculation of pollutant emissions and fuel consumption, there should be a measurement method developed that allows for a separate analysis of the phase during which the tested vehicle is fueled with gasoline. This will be the subject of further research.

5. Conclusions

The methods of calculating emissions of pollutants from the exhaust system and the fuel consumption of vehicles fueled with gaseous fuels, described in the normative documents, do not take into account the fact that after the cold start, the engine is initially fueled with gasoline. The formulas used in the calculations include quantities that depend on the type of fuel used by the engine. This results in incorrect emissions and fuel consumption values. In the tested vehicle, the relative percentage difference of emissions in the Low phase of the WLTC cycle calculated with the normative and corrected method was approx. 7% for the limited pollutants CO, THC, and NO_x. Additionally, carbon dioxide emissions calculated with the normative method were 6.7% lower than the value calculated with the corrected method.

The CO_2 emission values are given in the vehicle type-approval certificate. Based on those values, the average emissions of new vehicles placed on the market by a given manufacturer are calculated and compared with the limit value. If the manufacturer exceeds this value, a financial penalty is imposed, depending on the size of the excess. Therefore, one should strive to reduce errors in determining these emission values.

There is a need to develop a measurement method that allows for a separate analysis of the phase in which the vehicle is fueled with gasoline. This will allow for the elimination of errors in the current normative method of calculating pollutant emissions from the exhaust system and fuel consumption of vehicles fueled with gaseous fuels.

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Nomenclature

a	concentration of carbon dioxide in undiluted, wet exhaust gas, determined with the assumption that the combustion is complete and perfect and the fuel-air mixture has a stoichiometric composition (% vol.);
C_{CO}	measured concentration of carbon monoxide in the diluted exhaust gas (ppm);
C_{CO_2}	measured concentration of carbon dioxide in the diluted exhaust gas (% vol.);
C^C_{CVS}	concentration of pollutant in the diluted exhaust gas corrected according to its content in the dilution air (ppm);
C_{CVS}	concentration of pollutant in the diluted exhaust gas;
C_{dil}	concentration of pollutant in the dilution air,
CNG	compressed natural gas;
C_{THC}	measured concentration of total hydrocarbons in the diluted exhaust gas (ppm);
d	distance traveled during the test (km);
DF	dilution factor;
E_{CO}	measured emission of carbon monoxide (g/km);
E_{CO_2}	measured emission of carbon dioxide (g/km);
$E_{corrected}$	corrected emission, taking into account the gasoline supplying phase in the calculations;
ECU	electronic control unit;
E_{HC}	measured emission of hydrocarbons (g/km);

$E_{normative}$	emissions calculated in accordance with Regulation 83 and European regulation 2017/1151, i.e., without taking into account that part of the emissions results from gasoline consumption;
FC	fuel consumption in dm^3 per 100 km (in the case of gasoline, LPG, diesel or biodiesel) or in m^3 per 100 km (in the case of natural gas);
H/C	hydrogen to carbon ratio for specific fuel CxHyOz;
k_h	correction factor depending on air humidity (only for nitrogen oxides NOx);
LPG	liquefied petroleum gas;
m	mass of the pollutant's emission (g/km);
MW_C	molar mass of carbon (12,011 g/mol);
MW	molar mass of hydrogen (1008 g/mol);
MW_O	molar mass of oxygen (15,999 g/mol);
NOx	nitrogen oxides that are most relevant for air pollution (NO and NO_2);
O/C	oxygen to carbon ratio for specific fuel CxHyOz;
THC	total hydrocarbons;
V_{CVS}	volume of diluted exhaust gas, corrected for reference conditions (dm^3);
V_M	molar volume of an ideal gas at 273.15 K and 1013.25 hPa (22,413 dm^3/mol);
WLTC	world harmonized light-duty test cycle;
$\rho_{CNG/CBG}$	CNG/biomethane density.
$\rho_{gasoline}$	gasoline density;
ρ	density of pollutant under the reference conditions (g/dm^3);
ρ_{LPG}	LPG density;
ρ_{THC}	the density of total hydrocarbons including non-methane hydrocarbons (g/dm^3);

Appendix A

Tables A1–A5 show the values of pollutant emissions calculated using two methods: normative and corrected for all five measurements. The tables show the values of the emissions calculated for each of the two Low_{gas} and Low_{LPG} phases and the sum of these two values (Low_{Total}). The low-phase emission value calculated according to the corrected method is marked as $Emission_{Low}$.

Table A1. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC cycle—measurement No. 1.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	175.7	96.2	502.2	598.4	188.7
CO	1.271	3.790	0.530	4.320	1.362
NO_x	0.247	0.404	0.443	0.847	0.267
NO	0.153	0.266	0.281	0.547	0.172
THC	0.323	0.977	0.130	1.107	0.349
CH_4	0.021	0.038	0.036	0.074	0.023

Table A2. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC cycle—measurement No. 2.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	177.9	102.7	495.3	598.0	190.7
CO	1.348	3.822	0.716	4.538	1.447
NO_x	0.242	0.349	0.466	0.815	0.260
NO	0.149	0.299	0.290	0.589	0.188
THC	0.291	0.874	0.111	0.985	0.314
CH_4	0.021	0.038	0.043	0.081	0.026

Table A3. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC cycle—measurement No. 3.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	176.2	100.8	487.2	588.0	189.1
CO	2.113	4.278	2.761	7.039	2.264
NO_x	0.145	0.373	0.114	0.487	0.157
NO	0.091	0.247	0.072	0.319	0.103
THC	0.320	0.947	0.119	1.066	0.343
CH_4	0.024	0.038	0.042	0.080	0.026

Table A4. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC cycle—measurement No. 4.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	185.0	140.5	468.1	608.6	197.9
CO	1.884	5.741	0.455	6.196	2.014
NO_x	0.157	0.361	0.158	0.519	0.169
NO	0.098	0.235	0.084	0.319	0.104
THC	0.350	1.074	0.078	1.152	0.375
CH_4	0.022	0.046	0.019	0.065	0.021

Table A5. Comparison of exhaust emissions calculated by the normative and corrected method for the Low phase of the WLTC cycle—measurement No. 5.

Pollutant	Normative [g/km]	Corrected			
		Low_{gas} [g]	Low_{LPG} [g]	Total [g]	$Emission_{Low}$ [g/km]
CO_2	180.3	110.5	483.5	594.0	192.7
CO	1.959	5.836	0.614	6.450	2.093
NO_x	0.542	0.251	1.541	1.792	0.581
NO	0.307	0.167	0.962	1.129	0.366
THC	0.281	0.761	0.144	0.905	0.294
CH_4	0.027	0.041	0.033	0.074	0.024

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