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The Issues of the Air-Fuel Ratio in Exhaust Emissions Tests Carried out on a Chassis Dynamometer

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Abstract: Vehicle exhaust emission tests use exhaust sampling systems that dilute the exhaust gas with ambient air. The dilution factor *DF* is calculated assuming that the combustion is complete, and that the engine is operated at a stoichiometric air-fuel ratio (AFR). These assumptions are not always met. This is especially true for diesel engines. This article discusses the tests to find out what the average lambda (λ) over the ARTEMIS, WLTC and NEDC driving cycles is and how this affects the result of the emission measurements. Measurements were carried out on a chassis dynamometer equipped with a standard emission measurement system used during the homologation. The λ was calculated using the Brettschneider equation. The dilution ratio *DR* was also determined by measuring the CO_2 concentration in the raw exhaust gas. The CO_2-tracer method used for this was modified. The median of the λ for a CI vehicle was 1.23–3.31, which makes the relative percentage difference between the *DF* and *DR* (Δ_{DF}) in the range of 28–167%. For a SI vehicle homologated under the WLTP procedure, the median of the λ for the WLTC and ARTEMIS cycles was close to one and Δ_{DF} for most cycles does not exceed 10%. In order to reduce the influence of the error of *DF* determination on the result of the emission measurement, it is recommended to use exhaust gas sampling systems that allow to determine the actual dilution ratio or to use the lowest possible dilution. The PAS-CVS system seems to be the most promising.

Keywords: pollutant emissions; emissions regulations; real driving emissions

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Citation: Gis, W.; Taubert, S. The Issues of the Air-Fuel Ratio in Exhaust Emissions Tests Carried out on a Chassis Dynamometer. *Energies* **2021**, *14*, 2360. https://doi.org/10.3390/en14092360

Academic Editor: Ivan Arsie

Received: 20 February 2021
Accepted: 13 April 2021
Published: 21 April 2021

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1. Introduction

In order to calculate the mass of the pollutants emitted from a vehicle exhaust system, it is necessary to know three parameters: the concentration of the pollutant in the exhaust gas, the density of that concentration and the volume of exhaust gases in which the concentration is determined (1).

Direct measurement of the volume of exhaust gases is not applied in vehicle tests on the chassis dynamometer. Instead, a constant volume sampling system is used. Because an exhaust gas flow changes during the repetition of the driving cycle, it is necessary to bring an additional gas stream into the sampling system, which in this case is ambient air. It dilutes the raw exhaust gases with ambient air. The concentration is measured in diluted exhaust gases, while the volume is calculated as the product of the known constant flow rate of the diluted exhaust gases in sampling system and the duration of the measurement.

$$m = \rho \times C^{c}_{CVS,DF} \times V_{CVS}, \quad (1)$$

In order to calculate the mass of the pollutant emitted from the exhaust system, it is necessary to know the extent to which the raw gases have been diluted. This dilution ratio *DR* is defined as the ratio of the volume of the diluted exhaust gas to the raw exhaust gas (2):

$$DR = \frac{V_{cvs}}{V_{exh}}, \quad (2)$$

For its calculation, a dilution factor (*DF*) determined by Equation (3) is used instead of dilution ratio (*DR*). It first appeared in the Code of Federal Regulations (CFR) [1]. The formula for this indicator has been derived on the assumptions that the combustion is complete and that the air-fuel mixture in the engine has stoichiometric a composition:

$$DF = \frac{a}{C_{CO2,CVS} + C_{CO,CVS} + C_{THC,CVS}}, \quad (3)$$

The factor *a* in Equation (2) represents the concentration of carbon dioxide in undiluted (wet) exhaust gases determined under the abovementioned assumptions. The general formula for calculating the value of the factor a for fuel composed of $C_XH_YO_Z$ (C—carbon, H—hydrogen, O—oxygen) is as follows: [2]:

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

At the time when the CFRwas published [1], the adoption of the above simplification assumptions had a little effect on the accuracy of determining the dilution factor since most vehicles were powered by gasoline engines which, in terms of the operation of the engine subject to approvaltests, were powered by astoichiometric or near-stoichiometric mixture andtheconcentrations measured inthedilutedexhaust gas were significantly higher than those measured in thedilution air.

Reducing exhaust emissions leads to a decrease in the measured concentrations in the exhaust gases, which in turn increases the impact of the adopted simplification assumptions on the accuracy of determining the dilution ratio. In the case of vehicle approval tests, the resulting method errors are irrelevant because the essence of those tests is to compare the measured values with the limit values laid down in the legislation, and since all laboratories apply the same calculation methodology, they make the same systematic error. That is not the case with tests conducted to determine emission factors, which are then used to estimate emissions from vehicles. In this case, we want to determine the actual value of the emissions and should, therefore aim to obtain the most accurate result without systemic errors.

The assumption of the stoichiometric composition of the air-fuel mixture used to calculate the dilution of the exhaust gas during the pollutant emissions measurements performed on the chassis dynamometer is not always met. This applies in particular to the following cases [3]:

- the vehicles with CI engines,
- warming the SI engines after a cold start,
- driving at high acceleration values, especially in cars with low power to weight ratio,
- braking with switched off fuel supply,
- turning off the engine in vehicles with the start-stop system.

In the 1990s, new formulas were developed for the exhaust gas dilution factor, which eliminated the primary sources of errors in determining *DF* using Equation (2) [4–7]. In [8] shown the results of a comparison of dilution factor (*DF*) and dilution ratio (*DR*) depending on the different values of the air-fuel ratio. It analysed only the composition of the air-fuel mixture corresponding to a stoichiometric or rich mixture. The relative error Δ_{DF} in the determination of *DF* changed from zero for the stoichiometric mixture to −33% for the λ = 0.70 (Figure 1).

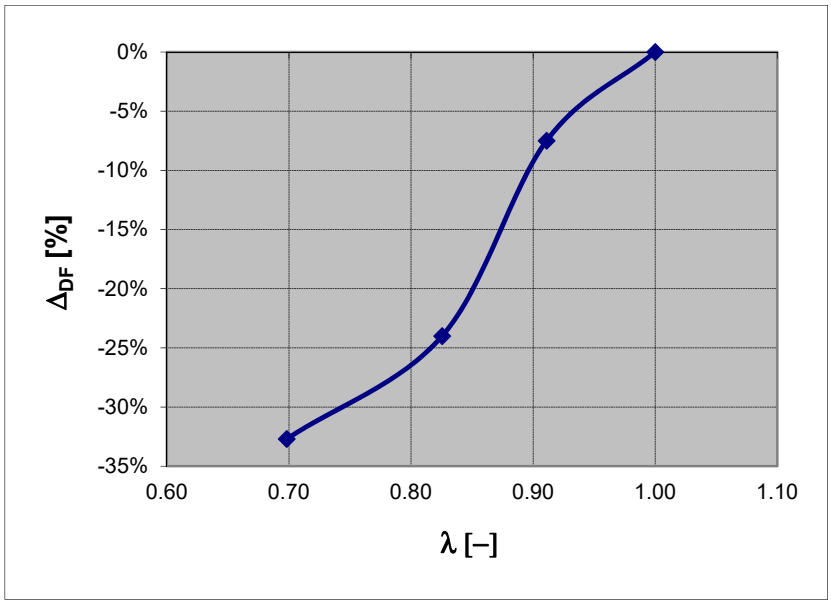


Figure 1. Error in determining the dilution factor *DF* depending on the λ [8].

In real driving conditions of a vehicle, the engine of the tested car operates in a broader range of engine speeds and loads than in the NEDC cycle used during approval tests. This may result in entering operating areas of the engine for which the optimisation criterion was not to meet exhaust emission requirements, but rather to achieve low fuel consumption (mixture depletion) or the assumed engine power (mixture enrichment), which in the case of spark-ignition engines requires that they be powered by an air-fuel mixture with a composition deviating from the stoichiometric composition. It may lead to an incorrect determination of the dilution factor *DF* and, as a result, to the determination of the value of emissions subject to a systemic error. Figures 2–4 show the required road load power versus engine speed for phases of the ARTEMIS, WLTC and NDEC driving cycles corresponding to urban, rural and motorway traffic conditions. It was calculated for Vehicle 3 (see Table 1). The ARTEMIS and WLTC driving cycles are considered representative of the real driving conditions.

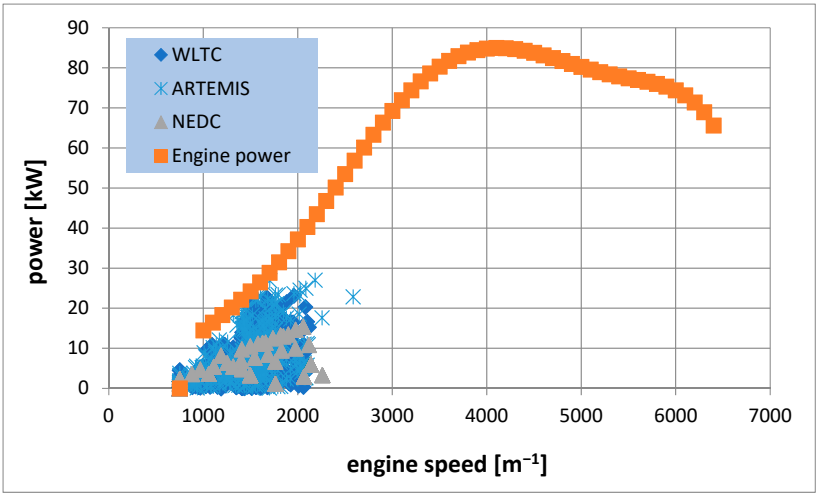


Figure 2. The required road load power versus engine speed for phases of ARTEMIS, WLTC and NDEC driving cycles corresponding to urban traffic conditions.

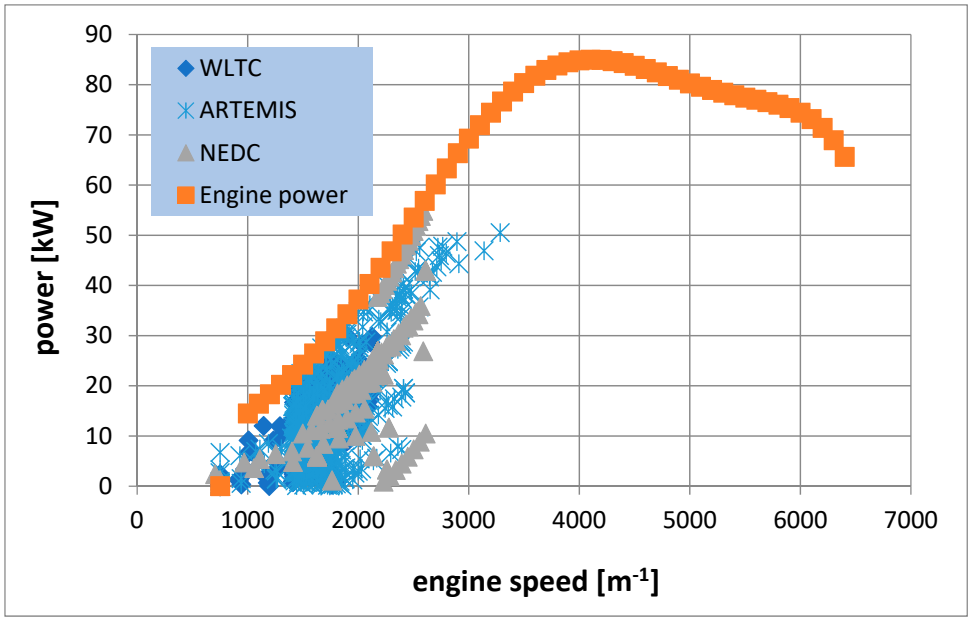


Figure 3. The required road load power versus engine speed for phases of ARTEMIS, WLTC and NDEC driving cycles corresponding to road traffic conditions.

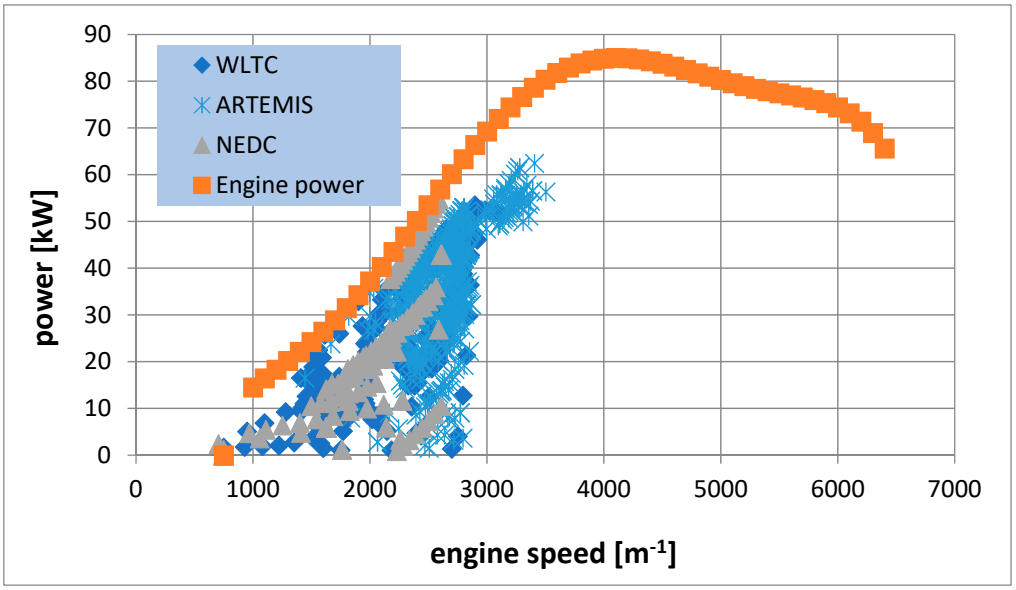


Figure 4. The required road load power versus engine speed for phases of ARTEMIS, WLTC and NDEC driving cycles corresponding to expressway and motorway traffic conditions.

Table 1. Essential data of the tested vehicles

Parameter	Vehicle 1	Vehicle 2	Vehicle 3
Engine	CI	SI	SI
Engine capacity	1995 cm^3	1596 cm^3	1197 cm^3
Maximum engine power	160 kW	77 kW	85 kW
Power to capacity ratio	80.2 W/cm^3	48.2 W/cm^3	71.0 W/cm^3
Power to mass ratio	94.1 W/kg	52.4 W/kg	62.5 W/kg
Emission level	Euro 5	Euro 6 NEDC	Euro 6 WLTP
Injection system	Common Rail	GI	GDI
After-treatment system	DPF + DOC	TWC	TWC

There are several methods to avoid this error. The first method is to eliminate the measured pollutants from the dilution air. As a result, the concentration of C_{dil} in Equation (5) is equal to or very close to zero. Thanks to this, the error resulting from the method of determining the *DF* factor becomes negligible. In order to remove pollutants from the dilution air, exhaust gas sampling systems of the DAR-CVS type are used [6,9,10]:

$$C^{C}_{CVS,DF} = C_{CVS} - C_{dil} \times \left(1 - \frac{1}{DF}\right) \quad (5)$$

The second method is to use the lowest possible dilution of the exhaust gas. As a result, the difference between the concentration of the pollutant measured in the diluted exhaust gas and its concentration in the dilution air increases, which leads to a reduction in the error of emission determination (Figure 1), [11,12]. However, the reduction in the dilution ratio is limited due to the possibility of condensation of water vapor contained in the exhaust gas. That is why the so-called heated exhaust gas sampling systems are used [13,14]. These systems heat both the dilution air and all sampling lines.

The last method is to determine the actual dilution ratio. For this, it is sufficient to measure either the raw exhaust gas volume V_{exh} or the dilution air volume V_{dil} by substituting Equation (6) in Equation (2):

$$V_{exh} = V_{CVS} - V_{dil} \quad (6)$$

The volume V_{exh} can be measured with the PEMS flow meter operates under Bernoulli's principle using averaging pitot tubes [15], or with ultrasonic exhaust flow meter or with the CO_2-tracer method by measuring the concentration of carbon dioxide in the exhaust gas [16–18]. For the measurement of the dilution air volume, exhaust gas sampling systems equipped with an ultrasonic flow meter are most often used. This flow meter is installed at the dilution air inlet to the sampling system [19].

The research was focused on two issues. The first issue was the checking the correctness of the assumption about the stoichiometric composition of the air-fuel mixture in various driving cycles considered representative for road traffic conditions and the measuring of the dilution ratio *DR* in these cycles. The second issue was to estimate the error resulting to not meet this assumption on the exhaust emission measured in these cycles.

2. Materials and Methods

Three driving cycles were selected to analyse the changes in the instantaneous values of the air-fuel ratio: the ARTEMIS cycle considered representative for real driving conditions [20,21], the WLTC cycle introduced in 2017 [22], which, according to the authors, also accurately reflects the real driving conditions and, for comparison, the NEDC cycle used in approval tests until 2017. The tests were conducted on three cars belonging to segment C. Two of them were equipped with a spark-ignition engine, the third with a compression ignition engine. The vehicle with a compression ignition engine had an emission approval confirming the fulfilment of Euro 5 emission requirements, whereas vehicles with spark-ignition engine—Euro 6. The first gasoline vehicle was approved under the previous procedure according to which exhaust emissions are measured in the NEDC cycle, the second according to the latest WLTP procedure. This article uses further the terms Euro 6 NEDC and Euro 6 WLTP respectively (Table 1).

The tests were carried out on a chassis dynamometer equipped with a system for measuring emissions from the exhaust system, meeting the requirements of the normative documents for approval tests within the scope of exhaust emissions. The tests was performed at the Motor Transport Institute, Warsaw, in the laboratory equipped with the following measuring devices (Figure 5):

- type RPL 1220/12 C 221 113/GPM 200 one roller chassis dynamometer with adjustable resistance curve by AVL-Zoellner (Bensheim, Germany),

- 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 Venturies allowing for flow rates from 2 to 30 m^3/min,
  - type PSS i60 SD particulate sampling system by AVL equipped with a heated FID i60 LH type analyzer by AVL, measuring the concentration of the sum of hydrocarbons in the diluted exhaust gas, the sample of which is taken from the dilution tunnel using a heated line. The analyzer was used for measuring THC concentration in the diluted exhaust gases from CI engines,
  - 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 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 equipped with to detectors enabling the simultaneous measurement of low NO_x and NO concentrations;
    - type CUTTER FID i60 CLD two-channel analyzer by AVL, equipped with to detectors enabling the simultaneous measurement of the low total hydrocarbon (THC) and CH_4 concentrations;
  - set of AMA i60 R2-EGR analyzers by AVL equipped with two-range analyzers for analyzing the raw exhaust, consisting of:
    - type IRD i60 CO_2/COH two-channel analyzer by ABB measuring the CO_2 and high CO concentrations in the dry exhaust gases;
    - type COMBI i60 CO_2/COL/O_2 three-channel analyzer by AVL measuring the CO_2, low CO and O_2 concetration in the dry exhaust gases;
    - type CUTTER FID i60 HHD two-channel, heated analyzer by AVL measuring the high total hydrocarbon (THC) and CH_4 concentrations;
    - type CLD i60 HDD two-channel, heated analyzer by AVL with to detectors enabling the simultaneous measurement of high NO_x and NO concentrations;
- a set of calibration gases with accuracy of 1% used for calibration of the analyzers,
- PTU303 weather station (VAISALA, Helsinki, Finland) 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.

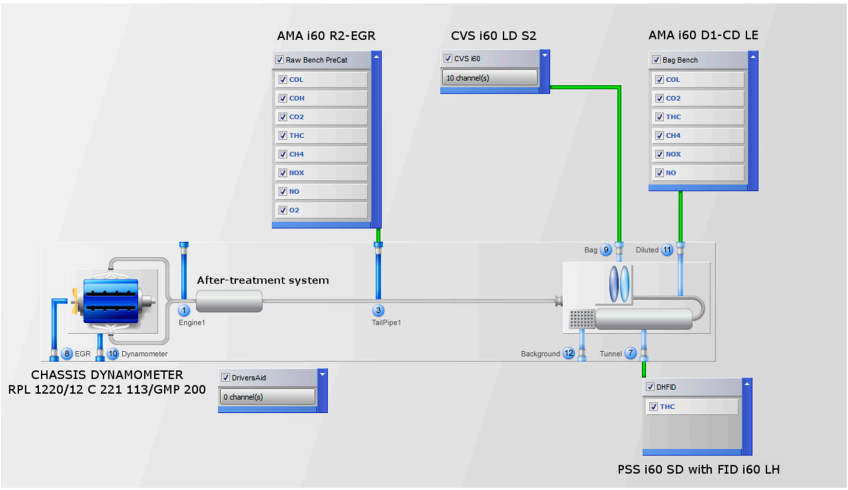


Figure 5. Chart of the measuring system used in the tests.

The used measurement equipment allowed to ensure the accuracy of emission measurements of 4%. During the measurements, instantaneous concentrations of the pollutants in diluted exhaust gases and wet raw exhaust gases were recorded. The raw exhaust gas sample point was behind the after-treatment system (Figure 5).

Based on the recorded instantaneous concentration values in raw exhaust gases, the instantaneous value of λ was calculated using a simplified Brettschneider Equation (7) [2]:

$$\lambda = \frac{[CO_2]+\frac{[CO]}{2}+[O_2]-\frac{[NO]}{2}+\left(\frac{H_{CV}}{4}\times\frac{3{,}5}{3{,}5+\frac{[CO]}{[CO_2]}}-\frac{O_{CV}}{2}\right)\times([CO_2]+[CO])}{\left(1+\frac{H_{CV}}{4}-\frac{O_{CV}}{2}\right)\times([CO]+[CO_2]+[THC])}, \quad (7)$$

H_{CV} and O_{CV} values corresponding to reference fuels E5 and B5 with fuel molecule structure were used for the calculation of the air-fuel ratio: $C_1H_{1.89}O_{0.016}$ and $C_1H_{1.86}O_{0.005}$, i.e., $H_{CV,E5}$=1.89, $O_{CV,E5}$=0.016, $H_{CV,B5}$=1.86 and $O_{CV,B5}$=0.005.

The real exhaust gas dilution factor DR was calculated on the basis of the CO_2-tracer method. In order to derive the formula for the dilution ratio of the exhaust gas DR as a function of the pollutant concentration, a mass balance shall be used. It will be most convenient to use the mass of carbon dioxide due to the high concentration values of this compound. Based on Figure 6, it can be written that:

$$m_{exh,CO_2} + m_{dil,CO_2} = m_{CVS,CO_2} + m_{s,CO_2} + m_{a,CO_2} + m_{e,CO_2}, \quad (8)$$

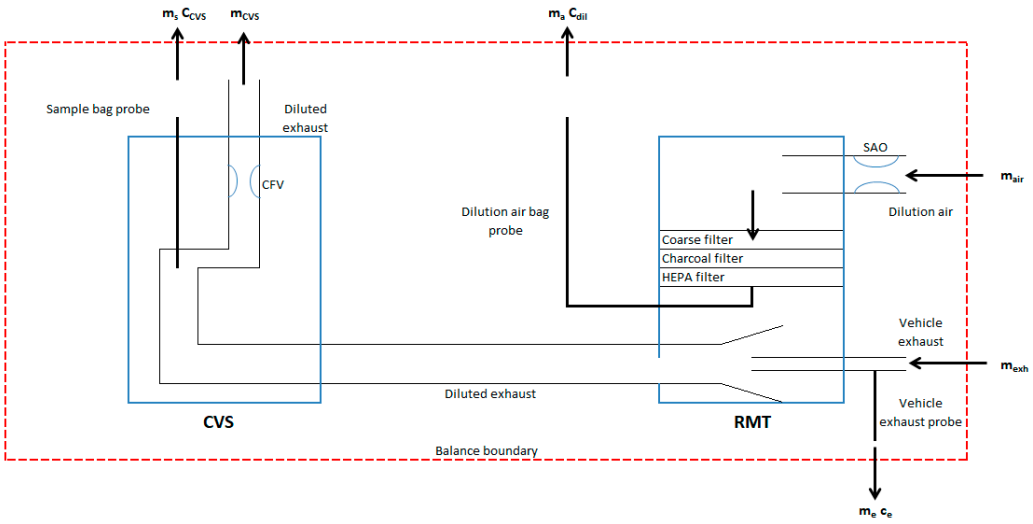


Figure 6. Mass balance area for the method of determining the DR dilution ratio by measuring the CO_2 concentration in the raw exhaust gas.

The left side of the equation shows the mass of CO_2 entering the mass balance area shown in Figure 6, while the right side of the equation shows the mass of CO_2 coming out of this area. Substituting the dependence (1) on the mass of the pollutant into the formula (8) we get:

$$\rho_{CO_2}\times C_{CO_2,exh}\times V_{exh}+\rho_{CO_2}\times C_{CO_2,dil}\times V_{dil}=\rho_{CO_2}\times C_{CO_2,CVS}\times V_{CVS} \\ +\rho_{CO_2}\times C_{CO_2,CVS}\times V_s+\rho_{CO_2}\times C_{CO_2,dil}\times V_a+\rho_{CO_2}\times C_{CO_2,exh}\times V_e, \quad (9)$$

Dividing both sides of the equation by the density of CO_2 and grouping according to CO_2 concentration we get:

$$C_{CO_2,exh} \times (V_{exh} - V_s) + C_{CO_2,dil} \times (V_{dil} - V_a) = C_{CO_2,CVS} \times (V_{CVS} + V_s), \quad (10)$$

In most sampling systems, the volumes V_s and V_a are neglected due to their small values relative to the total dilute exhaust volume V_{CVS} and dilution air volume V_{dil}. The newest systems include taking into account the volume V_s. in the calculation of the mass of the emitted pollutant. However, the volume of V_a is neglected. This solution was used in the sampling system used in the research.

The total volume of diluted exhaust gas passed through the sampling system over the cycle, corrected for the amount of diluted exhaust gas collected in the bag, can be defined as:

$$V^c_{CVS} = V_{CVS} + V_s, \quad (11)$$

If we define the exhaust gas volume corrected by the volume taken by the raw exhaust gas sampling probe, as:

$$V^c_{exh} = V_{exh} - V_e, \quad (12)$$

and taking into account that we assumed that V_a = 0, we get:

$$C_{CO_2,exh} \times V^c_{exh} + C_{CO_2,dil} \times V_{dil} = C_{CO_2,CVS} \times V^c_{CVS}, \quad (13)$$

Taking into account the correction of the diluted exhaust gas and raw exhaust gas volumes with volumes taken for analysis, the Equation (2) on the dilution ratio *DR* takes the form:

$$DR = \frac{V^c_{CVS}}{V^c_{exh}}, \quad (14)$$

Dividing both sides othe Equation (13) by V^c_{exh} we get:

$$C_{CO_2,exh} + C_{CO_2,dil} \times \frac{V_{dil}}{V^c_{exh}} = C_{CO_2,CVS} \times \frac{V^c_{CVS}}{V^c_{exh}}, \quad (15)$$

Taking into account that:

$$V^c_{CVS} = V^c_{exh} + V_{dil}, \quad (16)$$

we get:

$$C_{CO_2,exh} + C_{CO_2,dil} \times \frac{V^c_{CVS} - V^c_{exh}}{V^c_{exh}} = C_{CO_2,CVS} \times \frac{V^c_{CVS}}{V^c_{exh}}, \quad (17)$$

Substituting Equation (14) into Equation (17) and transforming, we get:

$$C_{CO_2,exh} + C_{CO_2,dil} \times (DR - 1) = C_{CO_2,CVS} \times DR, \quad (18)$$

Hence, the formula for determining the dilution ratio DR expressed in terms of carbon dioxide concentrations measured in the diluted exhaust gas ($C_{CO2,CVS}$), raw exhaust gas ($C_{CO2,exh}$) and in the dilution air ($C_{CO2,dil}$) is as follows:

$$DR = \frac{C_{CO2,exh} - C_{CO2,dil}}{C_{CO2,CVS} - C_{CO2,dil}}, \quad (19)$$

In order to accurately determine the *DR* dilution ratio, it is necessary to measure the CO_2 concentration in the dilution air. In some studies [12], this value has been neglected. In order to assess the error caused by adopting such a simplification, the following analysis was performed. For the measurements made in this research, the value of the *DR* dilution ratio was calculated based on the relationship (19). The CO_2 concentrations in the raw exhaust gas, the diluted exhaust gas, and the dilution air were calculated as the average value of the instantaneous values recorded during the driving cycles. The value for the

DR dilution ratio was then calculated using two methods: taking into account the CO_2 concentration in the dilution air and assuming that this concentration is equal to 0. Table 2 shows the values for the *DR* dilution ratio calculated by the two methods. The table also shows the relative percentage difference in determining the value of the dilution ratio $_{\Delta DR}$.

Table 2. The dilution ratio *DR* calculated with and without considering the CO_2 concentration in the dilution air.

Cycle	with $CO_{2,dil}$	without $CO_{2,dil}$	Δ_{DR}
Urban NEDC	21.86	20.11	−8.0%
Extra-urban NEDC	17.45	16.34	−6.4%
WLTC, Low	34.20	30.41	−11.1%
WLTC, Medium	22.59	21.07	−6.7%
WLTC, High	20.37	19.14	−6.0%
WLTC Extra High	14.54	13.89	−4.5%
ARTEMIS URBAN	32.84	29.35	−10.6%
ARTEMIS ROAD	20.89	19.44	−6.9%
ARTEMIS MOTORWAY	7.92	7.72	−2.5%

The average relative percentage difference in determining the value of the dilution ratio Δ_{DR} is equal −7% and ranged from −2.5% to −11.1%. Therefore, the calculation of the *DR* dilution factor should take into account the CO_2 concentration in the dilution air, the more that this value is measured in standard measurements and does not require modification of the measuring equipment used in the test.

3. Results

3.1. Lambda

Based on the recorded instantaneous concentrations of the measured pollutants, instantaneous values of the λ were calculated. For each phase of respective driving cycles the median of the λ was calculated. The values are presented in Table 3.

Table 3. Median of the λ in each phase of NEDC, WLTC and ARTEMIS cycles.

Cycle	SI, Indirect Injection, Euro 6 NEDC	SI, Direct Injection, Euro 6 WLTP	CI, Common Rail, Euro 5
urban NEDC	1.424	1.225	1.746
extra urban NEDC	1.356	1.198	1.617
WLTC, Low	1.378	1.094	1.809
WLTC, Medium	1.211	1.039	1.230
WLTC, High	1.191	1.031	1.551
WLTC Extra High	1.127	1.022	1.532
ARTEMIS URBAN	1.422	1.081	3.307
ARTEMIS ROAD	1.237	1.038	1.959
ARTEMIS MOTORWAY	1.060	1.010	1.535

Figure 7 shows the instantaneous values of the λ in the time function in the WLTC cycle for a car with a compression ignition engine. The graphs show the phases of increase in the value of the λ above the values corresponding to the flammability limit of the mixture. That occurs during engine braking phases when fuel injection is cut off, which leads to a gradual decrease in concentrations of carbon dioxide, hydrocarbons and nitric oxide and an increase in the oxygen concentration in the exhaust system.

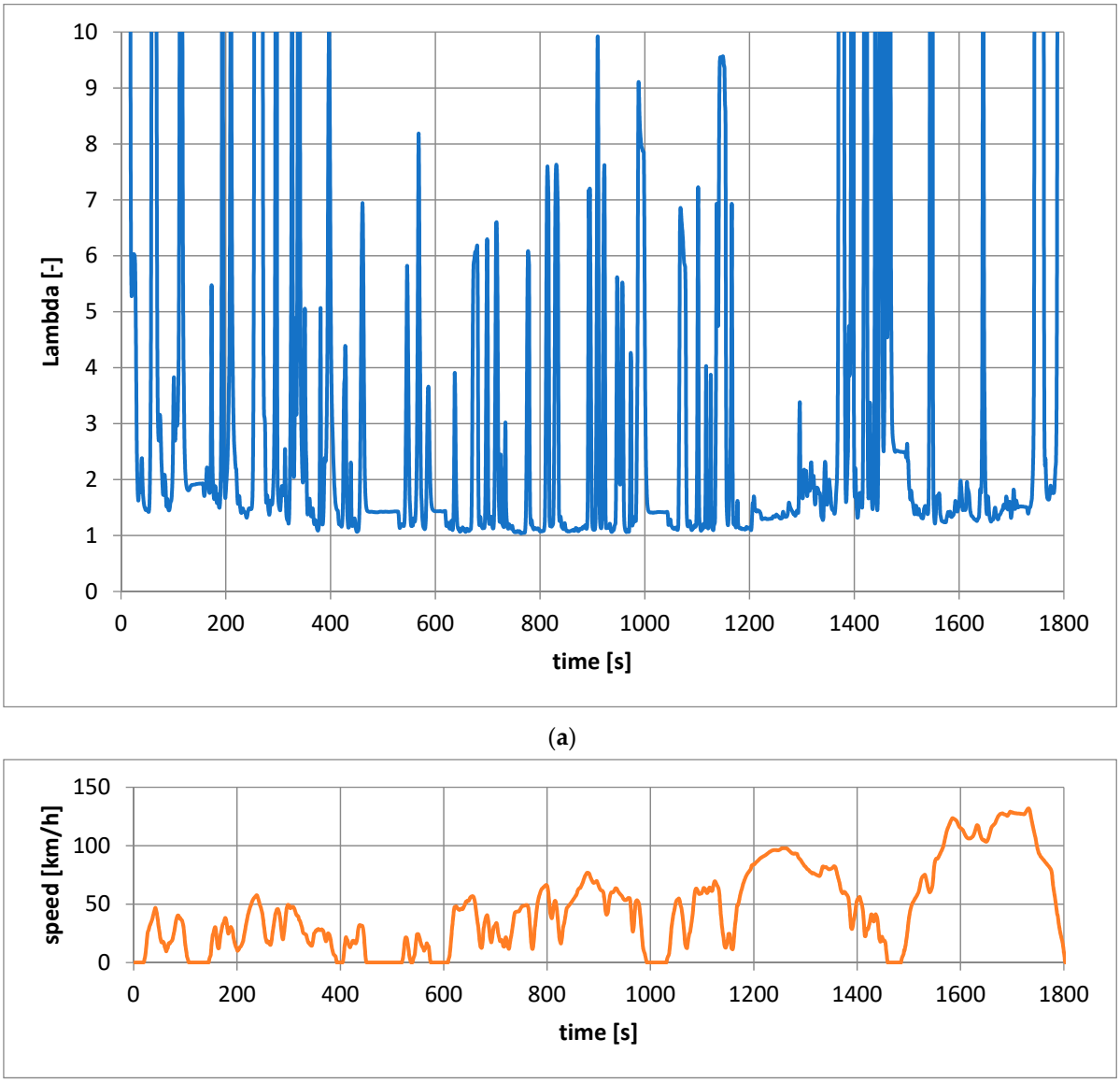


Figure 7. (**a**) Instantaneous values of λ (Lambda) in WLTC for a vehicle equipped with a compression ignition engine, (**b**) real vehicle speed in WLTC cycle.

Figure 8 graphically presents the median of the λ in the different phases of the NEDC, WLTC and ARTEMIS driving cycles for a car with a compression ignition engine with a Euro 5 approval. The median of the λ in each phase of the WLTC, NEDC and ARTEMIS cycles is greater than 1.5 and within the range of 1.532–3.307. Only in the Medium phase of the WLTC cycle, the median is less than 1.5 and equal to 1.230.

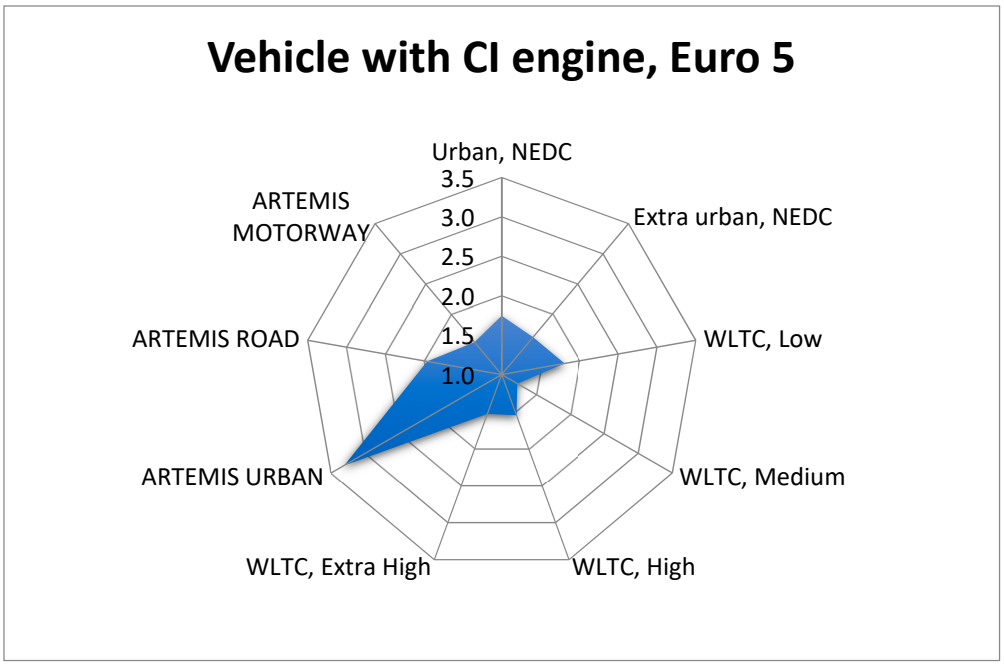


Figure 8. The median λ in driving cycles for a vehicle equipped with compression ignition engine, Euro 5.

Figure 9 graphically shows the median of the λ in the different phases of the NEDC, WLTC and ARTEMIS driving cycles for a car with a spark-ignition engine with a Euro 6 WLTP approval. The median of the λ in each phase of the WLTC cycle is similar to the value corresponding to the stoichiometric composition and within the range of 1.022–1.094. The same is true of the ARTEMIS cycle, for which it falls within the range of 1.010–1.081. In the NEDC cycle, the median of the λ is within 1.198–1.225 and is higher than the values measured for that vehicle in the WLTC and ARTEMIS cycles.

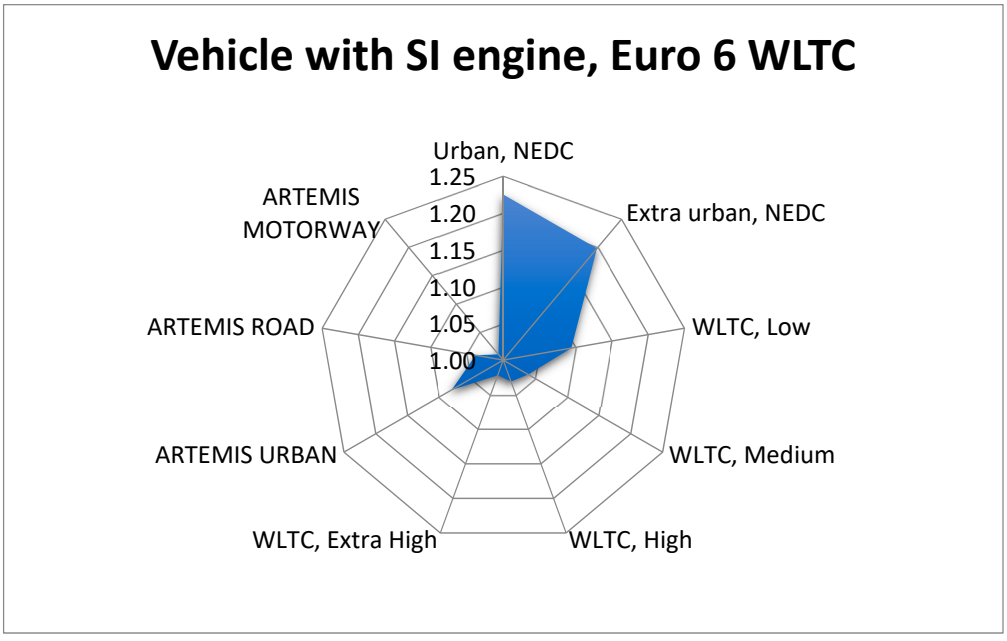


Figure 9. The median of the λ in driving cycles for a vehicle equipped with spark ignition engine, Euro 6 WLTP.

Figure 10 provides a comparison of the median of the λ in respective phases of NEDC, WLTC and ARTEMIS driving cycles for two vehicles with a spark-ignition engine that have

approvals confirming the fulfilment of Euro 6 NEDC and Euro 6 WLTP requirements. For each phase of the WLTC cycles and the URBAN and ROAD phases of the ARTEMIS cycle, the median values of the Euro 6 NEDC vehicle are higher than the corresponding values of the Euro 6 WLTP vehicle. The median of the λ is with the ranges of 1.191–1.422 and 1.022–1.094, respectively. However, for the MOTORWAY phase of the ARTEMIS cycle, the air-fuel ratio was close to the stoichiometric composition and amounted to 1.060 for the Euro 6 NEDC car and 1.010 for the Euro 6 WLTP vehicle.

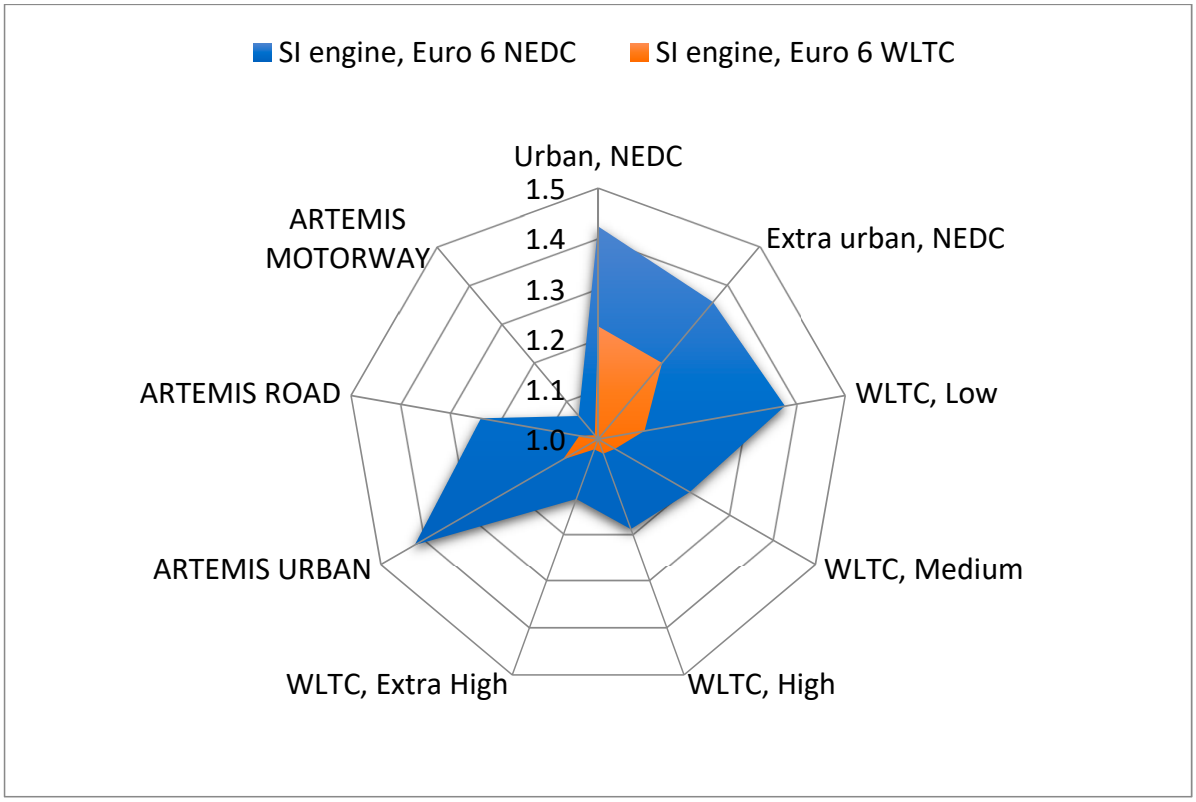


Figure 10. Comparison of the median of the λ in driving cycles for vehicles equipped with a spark ignition engine conforming to exhaust emissions Euro 6 requirements, approved according to NEDC and the new WLTP procedure.

3.2. Dilution Ratio DR

For the purposes of the described research, the real exhaust gas dilution factors *DR* for each phase of the driving cycles were calculated according to the Formula (19). The $C_{CO2,CVS}$, $C_{CO2,exh}$ and $C_{CO2,dil}$ values were calculated as the average of the recorded instantaneous values of CO_2 concentrations in the diluted exhaust gas, the raw exhaust gas and the dilution air. They were compared with the values of the *DF* dilution factor calculated according to Equation (3). The results are shown in Tables 4–6. In these tables also are presented the calculated relative percentage difference of the *DF* dilution factor to the *DR* dilution ratio according to Equation (20):

$$\Delta_{DF} = \frac{DF - DR}{DR} \times 100, \quad (20)$$

Table 4. Dilution ratio (*DR*) and dilution factor (*DF*) in each phase of NEDC, WLTC and ARTEMIS driving cycles for vehicle with SI engine, Euro 6 NEDC.

Cycle	*DR*	*DF*	Δ_{DF}
Urban NEDC	15.37	18.89	22.9%
Extra-urban NEDC	17.45	12.69	−27.3%
WLTC, Low	18.70	22.54	20.5%
WLTC, Medium	13.22	13.93	5.4%
WLTC, High	12.71	13.74	8.1%
WLTC Extra High	7.89	8.44	7.0%
ARTEMIS URBAN	22.23	23.85	7.3%
ARTEMIS ROAD	11.34	12.90	13.8%
ARTEMIS MOTORWAY	4.71	4.50	−4.5%

Table 5. Dilution ratio (*DR*) and dilution factor (*DF*) in each phase of NEDC, WLTC and ARTEMIS driving cycles for vehicle with SI engine, Euro 6 WLTP.

Cycle	*DR*	*DF*	Δ_{DF}
Urban NEDC	21.86	23.68	8.3%
Extra-urban NEDC	17.45	19.14	9.7%
WLTC, Low	34.20	32.07	−6.2%
WLTC, Medium	22.59	20.32	−10.0%
WLTC, High	20.37	18.51	−9.1%
WLTC Extra High	14.17	13.55	−4.4%
ARTEMIS URBAN	31.17	29.10	−6.6%
ARTEMIS ROAD	24.01	18.50	−22.9%
ARTEMIS MOTORWAY	8.32	7.04	−15.4%

Table 6. Dilution ratio (*DR*) and dilution factor (*DF*) in each phase of NEDC, WLTC and ARTEMIS driving cycles for vehicle with CI engine, Euro 5.

Cycle	*DR*	*DF*	Δ_{DF}
Urban NEDC	10.94	19.42	77.5%
Extra-urban NEDC	8.17	13.05	59.7%
WLTC, Low	12.18	21.27	74.6%
WLTC, Medium	7.94	10.19	28.3%
WLTC, High	9.26	13.99	51.1%
WLTC Extra High	6.82	10.84	58.9%
ARTEMIS URBAN	9.28	24.79	167.1%
ARTEMIS ROAD	8.70	14.22	63.4%
ARTEMIS MOTORWAY	5.12	7.06	37.9%

3.3. The Concentration of the Pollutant in the Diluted Exhaust Gas, Corrected for Its Content in the Dilution Air $C_{CVS,corr}$

To calculate the mass emissions of the pollutant, the concentration of the pollutant in the diluted exhaust gas corrected for its content in the dilution air, needs to be known. It is defined by Equation (21).

$$C^{C}_{CVS,DR} = C_{CVS} - C_{dil} \times \left(1 - \frac{1}{DR}\right), \tag{21}$$

According to the regulations [1,2,22], the dilution factor DF (2) is used instead of the *DR* (1). In this case, the $C_{CVS,corr}$ concentration of the pollutant, is determined by the formula (5).

For each test vehicle, the $C_{CVS,corr}$ concentration of the pollutant, was calculated according to Equations (5) and (21). The results are presented in the Tables A1–A15 (Appendix A). In these tables are shown the relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3).

4. Discussion

The median of the λ in each phase of the WLTC, NEDC and ARTEMIS cycles is greater than 1.5 and within the range of 1.532–3.307. This result is consistent with the principle of operation of these engines.

The median of the λ in each phase of the WLTC and ARTEMIS cycles for the Euro 6 WLTP vehicle with SI engine are similar to the value corresponding to the stoichiometric composition. That is due to the need for vehicles to meet the requirements regarding emissions of the exhaust system in the driving cycle, which covers a larger engine operating area than the NEDC cycle (Figures 2–4), and also to introduce RDE (real driving emission) tests into the approval procedure. It has forced vehicle manufacturers to increase the engine's operating areas, where it works with an air-fuel mixture close to the stoichiometric composition, which has a positive effect on the efficiency of the exhaust after-treatment systems of vehicles with spark-ignition engines. In these vehicles, three-way catalytic converters are most commonly used, which achieve a reduction efficiency of not less than 98% in the λ within the range of 0.997–1.003 [23–25].

In the NEDC cycle, the median of the λ is higher than one. This maybe for two reasons. First, in the engine operating areas in the NEDC cycle, the main criterion for optimizing the controller could be to reduce fuel consumption, which is achieved by depleting the air-fuel mixture. Second, the NEDC cycle has more engine braking phases of longer duration than the WLTC and ARTEMIS cycles. The fuel supply is cut off during engine braking. Therefore, in this phase, the actual concentration of CO_2 in the exhaust gas is 0. Due to the response time of the analyzer, the concentration measured by the analyzer decreases more slowly than the concentration in the exhaust gas. The longer the engine braking phase lasts, the closer the CO_2 concentration shown by the analyzer is to 0. This increases the λ calculated from the Equation (7).

For each phase of the WLTC cycles and the URBAN and ROAD phases of the ARTEMIS cycle, the median values of the Euro 6 NEDC vehicle are higher than the corresponding values of the Euro 6 WLTP vehicle. The reason for this probably is because, in the engine operating areas that do not occur in the NEDC cycle, the main criterion for optimizing the engine controller was to reduce fuel consumption, which is achieved by depleting the air-fuel mixture.

The assumption of the stoichiometric composition of the air-fuel ratio is not always met. This introduces an error in the calculation of the exhaust dilution factor *DF*. For a vehicle with a CI engine, the percentage relative error of the dilution factor *DF* in relation to the dilution ratio *DR* ranged from 28% to 167% (Table 6). For this reason, there is an error in determining the $C_{CVS,corr}$ concentration of the pollutant, calculated on the basis of Equation (5).

Figures 11–14 show the minimum, maximum and average value of relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3) for each pollutant.

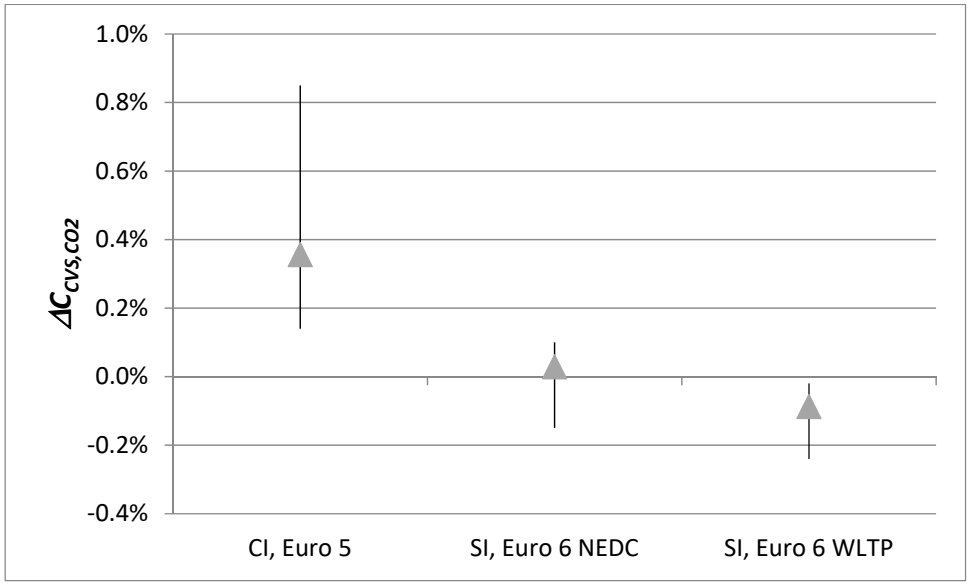


Figure 11. Relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3) for CO_2.

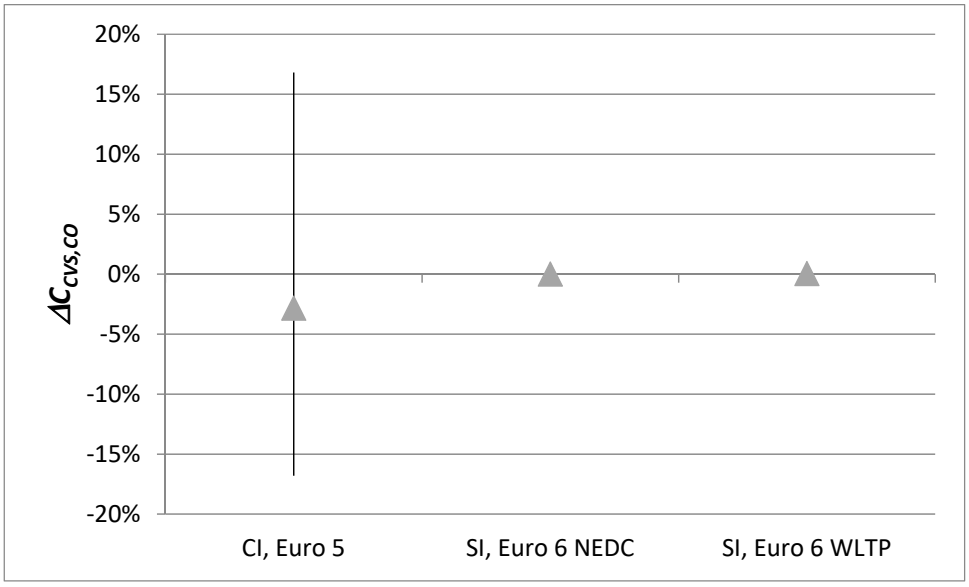


Figure 12. Relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3) for CO.

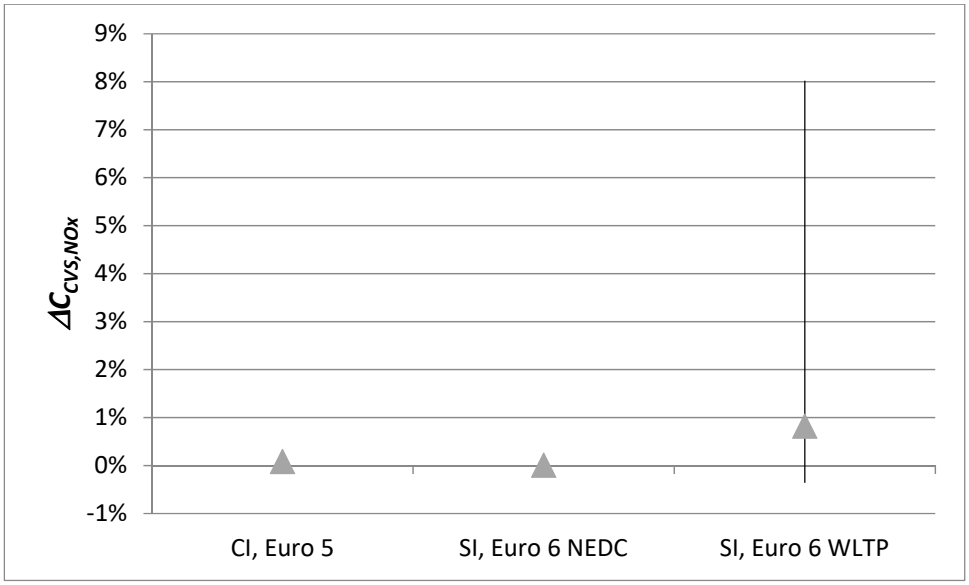


Figure 13. Relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3) for NO_x.

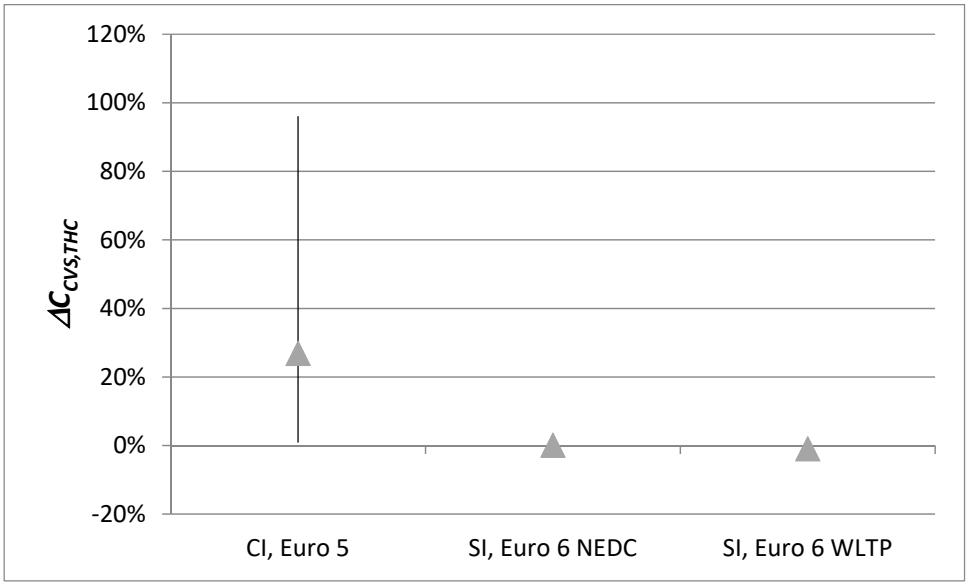


Figure 14. Relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3) for THC.

In the case of CO_2, CO and NO_x, the average relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant was less than one for all tested cars. The value of this error resulted mainly from the concentration values of these pollutants in the dilution air close to zero. In this case, even a large error in determining the dilution factor *DF* has a negligible impact on the error in calculating the pollutant emission. For these pollutants, the error in determining the emissions resulting from calculating the dilution factor *DF* instead of the dilution ratio *DR* is negligible. The second reason is the large difference between the concentration measured in the diluted exhaust gas and the dilution air. It occurs in most phases of the cycles used in the tests.

The smaller is the difference between the concentration in the diluted exhaust gas and that in the dilution air, the greater this error is. Figure 15 shows the change in the error in determining the total hydrocarbon (THC) $C_{CVS,corr}$ concentration as a function of

the difference between the THC concentration in the diluted exhaust gas and that in the dilution air. The calculations were based on a constant THC concentration in the dilution air equal to 3 ppm expressed equivalent to carbon atoms C1 (typical background value in the MTI laboratory) and DR and DF calculated for a vehicle with a CI engine obtained in the Artemis Urban cycle (Table 6).

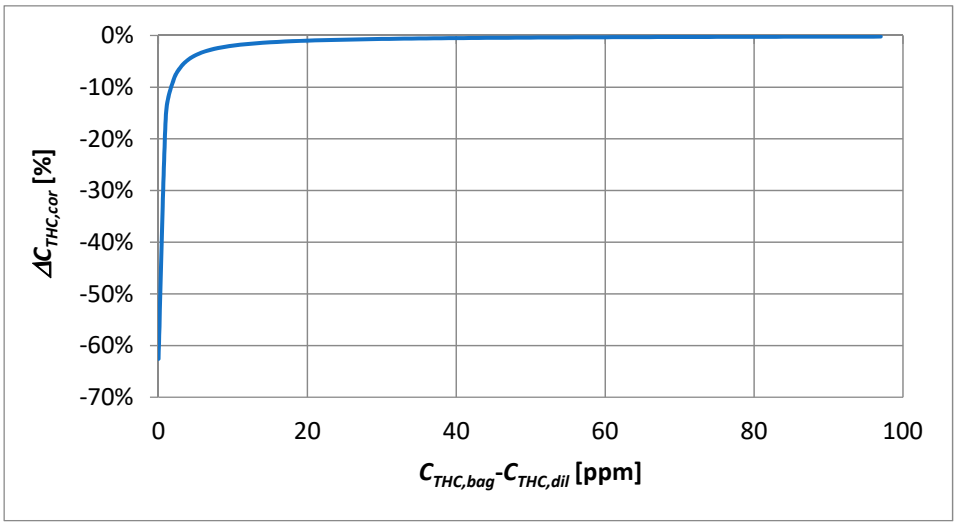


Figure 15. The error of the calculated THC concentration in the diluted exhaust gas, corrected for its content in the dilution air as a function of the difference between the THC concentration in the diluted exhaust gas $C_{THC,bag}$ and the THC concentration in the dilution air $C_{THC,dil}$.

In the case of THC, the relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant for both cars equipped with SI engine is also negligible. The small value of this difference is due to the large difference between the concentration measured in the diluted exhaust gas and the dilution air.

In the case of THC for a car with a CI engine, the relative percentage difference in determining the $C_{CVS,corr}$ concentration of the pollutant ranges from 0.86% to 96.08%, and its average value is 27%. Only for the Urban phase of the NEDC cycle and the Low phase of the WLTC cycle, the value of this error is approximately 1%. In the case of this pollutant, the main reason for the high value of this error is the very little difference in between the concentration in the diluted exhaust gas and that in the dilution air.

Note the CO concentrations in the diluted exhaust gas and dilution air for a diesel car as measured by the NEDC, ARTEMIS Motorway and High phase of the WLTC. In these cycles, the concentration of CO in the diluted exhaust gas is less than that in the dilution air. This is due to the assumption that the intake air does not contain any contaminants (which is not true). In such cases as described above, the exhaust after-treatment systems also remove contaminants that are in the intake air. Therefore, the concentration in the diluted exhaust gas can be less than the concentration in the dilution air.

5. Conclusions

Vehicles with compression ignition engines operate with an air-fuel ratio significantly greater than unity. In the tested car with a compression ignition engine, the median of the λ in most driving cycles was in the range of 1.532–3.307, only in the medium phase of the WLTC cycle was lower and equal to 1.230. Also, the vehicle with a spark-ignition engine, with an approval confirming the fulfilment of Euro 6 NEDC requirements, was powered by an air-fuel mixture with a λ greater than unity. For these vehicles, the assumption of the stoichiometric composition of the air-fuel mixture, which was adopted in determining the formula for calculating the DF dilution factor of exhaust gases, is not met. This may lead

to a systematic error in the calculated value of emissions from the exhaust system, which cannot be ignored in the emission levels measured for modern vehicles.

In 2017, the new World Light Duty Procedure (WLTP) was introduced for the approval of light-duty vehicles in terms of emissions, which put particular emphasis on reproducing the real-driving conditions of the car. This applies both to the course of speed over time and to the reproduction on the chassis dynamometer of driving resistances of a vehicle on the road. Because of the above, the engines of vehicles tested according to the WLTP procedure operate in a much wider engine operating area than in the previous procedure where the NEDC cycle was in force. This leads to the need to increase the engine operating area, where the main optimization criterion is to maintain the high efficiency of the after-treatment systems. For vehicles with spark-ignition engines where three-way catalytic converters are most commonly used, this is achieved by supplying the engine with an air-fuel mixture similar to that of stoichiometric composition. It can be assumed that in these vehicles the systematic error in determining the dilution factor and the calculation of emissions, resulting from the adopted assumption of the stoichiometric composition of the air-fuel mixture in the engine will be negligible.

In order to minimize the error in determining the concentration of the pollutant in the diluted exhaust gas corrected for its content in the dilution air, it is necessary to adjust the exhaust gas sampling system to obtain the lowest possible dilution of the exhaust gas while avoiding condensation of water vapor contained in the exhaust gas. It is advantageous to use exhaust gas sampling systems that reduce the influence of this error on the result of the emission measurement: DAR-CVS, PAS-CVS, Heated CVS. If the expected concentration of a pollutant in the diluted exhaust gas is close to that of that pollutant in the dilution air, it is recommended to use the direct determination of the dilution ratio *DR* instead of the dilution factor *DF* calculated from Formula (3).

Author Contributions: Conceptualization, S.T. and W.G.; methodology, S.T.; software, S.T. and W.G.; validation, S.T. and W.G.; formal analysis, S.T.; investigation, S.T. and W.G.; resources, S.T. and W.G.; data curation, S.T. and W.G.; writing—original draft preparation, S.T. and W.G.; writing—review and editing, W.G.; visualization, S.T. and W.G.; supervision, S.T.; project administration, S.T.; funding acquisition, S.T. and W.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

[CO]	carbon oxide concentration in exhaust gas [% vol.];
[CO_2]	carbon dioxide concentration in exhaust gas [% vol.];
[NO]	nitrogen oxides concentration in exhaust gas [% vol.];
[O_2]	oxygen concentration in exhaust gas [% vol.];
[THC]	total hydrocarbons concentration in exhaust gas [% vol.];
a	concentration of carbon dioxide in undiluted, wet exhaust gas, determined with the assumption that the combustion is complete and perfect and the air-fuel mixture has a stoichiometric composition [% vol.];
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems;
$C^{C}_{CVS,DF}$	llutant concentration of the diluted exhaust gas, corrected for its content in the dilution air, calculated on the basis of the dilution factor DF [ppm or % vol.];
$C^{C}_{CVS,DR}$	pollutant concentration of the diluted exhaust gas, corrected for its content in the dilution air, calculated on the basis of the dilution ratio DR [ppm or % vol.];
$C_{CO,CVS}$	measured concentration of carbon monoxide in the diluted exhaust gas [ppm];
$C_{CO2,CVS}$	measured concentration of carbon dioxide in the diluted exhaust gas [% vol.];
$C_{CO2,dil}$	measured concentration of carbon dioxide in the dilution air [% vol.];
$C_{CO2,exh}$	measured concentration of carbon dioxide in the exhaust gas [% vol.];
$C_{THC,bag}$	concentration of total hydrocarbon in the diluted exhaust gas measured in sample bag [ppm];
$C_{THC,CVS}$	concentration of total hydrocarbon in the diluted exhaust gas [ppm];
$C_{THC,dil}$	concentration of total hydrocarbon in the dilution air measured in dilution bag [ppm];
$C_{THC,cor}$	concentration of total hydrocarbon in the diluted exhaust gas, corrected for its content in the dilution air, calculated on the basis of the Equation (8) [ppm];
C_{CVS}	concentration of the pollutant measured in the diluted exhaust gas collected in the dilution bag [ppm or % vol.];
$C_{CVS,corr}$	concentration of the pollutant in the diluted exhaust gas corrected for its content in the dilution air [ppm or % vol.];
C_{dil}	concentration of the pollutant measured in the dilution air collected in the dilution bag [ppm or % vol.];
CFR	Code of Federal Regulations;
CI	compression ignition;
CVS	Constant Volume Sampling;
DAR-CVS	Dilution air Refinement Constant Volume Sampling;
Δ_{DF}	relative percentage difference of the DF dilution factor to the DR dilution ratio;
DF	dilution factor [-];
DOC	Diesel Oxidation Catalyst;
DPF	diesel particle filter;
DR	dilution ratio [-];
GDI	gasoline direct injection;
GI	gasoline injection;
λ	the ratio of the actual air/fuel ratio to stoichiometric [-];
MTI	Motor Transport Institute;
NEDC	New European Driving Cycle;
H_{CV}	number of hydrogen atoms to number of carbon atoms in a fuel molecule $C_xH_yO_z$ [-];
O_{CV}	number of oxygen atoms to number of carbon atoms in a fuel molecule $C_xH_yO_z$ [-];
PAS-CVS	Proportional Ambient Sampling Constant Volume Sampling;
PEMS	Portable Emission Measurement System;
SI	spark ignition;
TWC	Three Way Catalyst;
V_{CVS}	diluted exhaust volume [m^3];
V_{dil}	dilution air volume [m^3];
V_{exh}	exhaust volume [m^3];
WLTC	World harmonized Light-duty Test Cycle;
WLTP	World harmonized Light-duty Test Procedure;
X	number of carbon atoms in the fuel molecule $C_xH_yO_z$ [-];
Y	number of hydrogen atoms in the fuel molecule $C_xH_yO_z$ [-];
Z	number of oxygen atoms in the fuel molecule $C_xH_yO_z$ [-].

Appendix A

Relative percentage difference in determining the concentration of the pollutant in the diluted exhaust gas corrected for its content in the dilution air $C_{CVS,corr}$ as calculated from dilution ratio *DR* (19) and dilution factor *DF* (3).

Table A1. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 5 vehicle with CI engine, CO_2 pollutant [%].

Cycle	C_{CVS}	C_{dil}	*DR*	$C^{C}_{CVS,DR}$	*DF*	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	0.695	0.047	10.94	0.652	19.42	0.650	0.29%
Extra-urban NEDC	1.034	0.053	8.17	0.987	13.05	0.985	0.25%
WLTC, Low	0.632	0.051	12.18	0.585	21.27	0.583	0.31%
WLTC, Medium	1.323	0.062	7.94	1.269	10.19	1.267	0.14%
WLTC, High	0.964	0.087	9.26	0.886	13.99	0.883	0.36%
WLTC Extra High	1.244	0.105	6.82	1.154	10.84	1.149	0.50%
ARTEMIS URBAN	0.544	0.061	9.28	0.490	24.79	0.485	0.85%
ARTEMIS ROAD	0.949	0.058	8.70	0.898	14.22	0.895	0.29%
ARTEMIS MOTORWAY	1.911	0.075	5.12	1.851	7.06	1.847	0.22%

Table A2. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 5 vehicle with CI engine, CO concentration [ppm].

Cycle	C_{CVS}	C_{dil}	*DR*	$C^{C}_{CVS,DR}$	*DF*	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	0.104	0.243	10.94	−0.117	19.42	−0.126	−7.67%
Extra-urban NEDC	0.053	0.271	8.17	−0.185	13.05	−0.197	−6.29%
WLTC, Low	17.638	0.625	12.18	17.064	21.27	17.042	0.13%
WLTC, Medium	3.511	0.672	7.94	2.924	10.19	2.905	0.64%
WLTC, High	0.423	0.640	9.26	−0.148	13.99	−0.171	−13.65%
WLTC Extra High	0.309	0.529	6.82	−0.142	10.84	−0.171	−16.80%
ARTEMIS URBAN	0.234	0.172	9.28	0.081	24.79	0.069	16.82%
ARTEMIS ROAD	1.150	−0.402	8.70	1.506	14.22	1.524	−1.18%
ARTEMIS MOTORWAY	−0.528	−0.172	5.12	−0.390	7.06	−0.380	2.43%

Table A3. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 5 vehicle with CI engine, NO_x concentration [ppm].

Cycle	C_{CVS}	C_{dil}	*DR*	$C^{C}_{CVS,DR}$	*DF*	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	6.265	0.082	10.94	6.190	19.42	6.187	0.05%
Extra-urban NEDC	16.476	0.182	8.17	16.316	13.05	16.308	0.05%
WLTC, Low	6.678	0.097	12.18	6.589	21.27	6.586	0.05%
WLTC, Medium	20.761	0.237	7.94	20.554	10.19	20.547	0.03%
WLTC, High	17.042	0.615	9.26	16.493	13.99	16.471	0.14%
WLTC Extra High	37.803	1.000	6.82	36.950	10.84	36.895	0.15%
ARTEMIS URBAN	22.470	0.554	9.28	21.976	24.79	21.938	0.17%
ARTEMIS ROAD	34.035	0.511	8.70	33.583	14.22	33.560	0.07%
ARTEMIS MOTORWAY	87.032	1.021	5.12	86.210	7.06	86.156	0.06%

Table A4. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 5 vehicle with CI engine, THC concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	3.689	3.078	10.94	0.892	19.42	0.769	15.97%
Extra-urban NEDC	3.082	3.063	8.17	0.394	13.05	0.254	55.26%
WLTC, Low	10.603	2.951	12.18	7.894	21.27	7.791	1.33%
WLTC, Medium	12.784	3.079	7.94	10.093	10.19	10.007	0.86%
WLTC, High	8.638	3.243	9.26	5.745	13.99	5.627	2.10%
WLTC Extra High	5.005	3.282	6.82	2.204	10.84	2.026	8.81%
ARTEMIS URBAN	3.649	3.064	9.28	0.915	24.79	0.709	29.15%
ARTEMIS ROAD	3.351	3.433	8.70	0.313	14.22	0.159	96.08%
ARTEMIS MOTORWAY	3.564	3.477	5.12	0.766	7.06	0.579	32.20%

Table A5. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 5 vehicle with CI engine, CH_4 concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	2.459	2.064	10.94	0.584	19.42	0.501	16.43%
Extra-urban NEDC	2.178	2.062	8.17	0.368	13.05	0.274	34.44%
WLTC, Low	4.825	1.901	12.18	3.080	21.27	3.013	2.21%
WLTC, Medium	8.463	1.980	7.94	6.732	10.19	6.677	0.82%
WLTC, High	4.544	2.089	9.26	2.681	13.99	2.604	2.93%
WLTC Extra High	1.920	2.087	6.82	0.139	10.84	0.026	444.55%
ARTEMIS URBAN	2.019	1.968	9.28	0.263	24.79	0.130	101.76%
ARTEMIS ROAD	2.258	2.267	8.70	0.252	14.22	0.150	67.24%
ARTEMIS MOTORWAY	1.797	2.239	5.12	−0.005	7.06	−0.125	−96.24%

Table A6. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 NEDC vehicle with SI engine, CO_2 concentration [%].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	0.621	0.048	15.37	0.576	18.89	0.576	0.10%
Extra-urban NEDC	0.931	0.060	17.45	0.874	12.69	0.876	−0.15%
WLTC, Low	0.586	0.052	18.70	0.537	22.54	0.536	0.09%
WLTC, Medium	0.936	0.059	13.22	0.881	13.93	0.881	0.03%
WLTC, High	0.955	0.072	12.71	0.889	13.74	0.888	0.05%
WLTC Extra High	1.494	0.084	7.89	1.421	8.44	1.420	0.05%
ARTEMIS URBAN	0.556	0.075	22.23	0.484	23.85	0.484	0.05%
ARTEMIS ROAD	1.009	0.066	11.34	0.949	12.90	0.948	0.07%
ARTEMIS MOTORWAY	2.812	0.093	4.71	2.739	4.50	2.740	−0.03%

Table A7. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 NEDC vehicle with SI engine, CO concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	63.335	0.828	15.37	62.561	18.89	62.551	0.02%
Extra-urban NEDC	63.689	1.526	17.45	62.250	12.69	62.283	−0.05%
WLTC, Low	63.109	3.232	18.70	60.050	22.54	60.020	0.05%
WLTC, Medium	250.981	4.015	13.22	247.270	13.93	247.254	0.01%
WLTC, High	193.729	7.381	12.71	186.929	13.74	186.885	0.02%
WLTC Extra High	913.930	14.400	7.89	901.355	8.44	901.236	0.01%
ARTEMIS URBAN	56.401	2.885	22.23	53.646	23.85	53.637	0.02%
ARTEMIS ROAD	280.355	3.496	11.34	277.167	12.90	277.130	0.01%
ARTEMIS MOTORWAY	1598.574	20.821	4.71	1582.174	4.50	1582.380	−0.01%

Table A8. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 NEDC vehicle with SI engine, NO_x concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	3.044	0.033	15.37	3.013	18.89	3.013	0.01%
Extra-urban NEDC	10.098	0.091	17.45	10.012	12.69	10.014	−0.02%
WLTC, Low	10.849	0.165	18.70	10.693	22.54	10.691	0.01%
WLTC, Medium	8.631	0.292	13.22	8.361	13.93	8.360	0.01%
WLTC, High	8.423	0.419	12.71	8.037	13.74	8.034	0.03%
WLTC Extra High	20.470	0.537	7.89	20.001	8.44	19.997	0.02%
ARTEMIS URBAN	5.819	0.335	22.23	5.499	23.85	5.498	0.02%
ARTEMIS ROAD	11.652	0.347	11.34	11.336	12.90	11.332	0.03%
ARTEMIS MOTORWAY	42.473	0.864	4.71	41.792	4.50	41.801	−0.02%

Table A9. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 NEDC vehicle with SI engine, THC concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	24.202	3.404	15.37	21.019	18.89	20.978	0.20%
Extra-urban NEDC	7.074	3.558	17.45	3.720	12.69	3.796	−2.01%
WLTC, Low	21.286	3.534	18.70	17.941	22.54	17.909	0.18%
WLTC, Medium	9.213	3.593	13.22	5.892	13.93	5.878	0.24%
WLTC, High	7.345	3.632	12.71	3.999	13.74	3.977	0.54%
WLTC Extra High	22.567	3.796	7.89	19.252	8.44	19.221	0.16%
ARTEMIS URBAN	5.187	3.502	22.23	1.843	23.85	1.832	0.58%
ARTEMIS ROAD	11.680	3.574	11.34	8.421	12.90	8.383	0.45%
ARTEMIS MOTORWAY	36.964	4.276	4.71	33.596	4.50	33.638	−0.13%

Table A10. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 NEDC vehicle with SI engine, CH_4 concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	3.356	2.015	15.37	1.472	18.89	1.448	1.69%
Extra-urban NEDC	2.695	2.046	17.45	0.766	12.69	0.810	−5.43%
WLTC, Low	2.934	1.965	18.70	1.074	22.54	1.056	1.69%
WLTC, Medium	2.876	1.986	13.22	1.040	13.93	1.033	0.74%
WLTC, High	2.666	1.998	12.71	0.825	13.74	0.813	1.45%
WLTC Extra High	4.719	2.016	7.89	2.959	8.44	2.942	0.57%
ARTEMIS URBAN	2.393	2.017	22.23	0.467	23.85	0.461	1.34%
ARTEMIS ROAD	2.977	1.985	11.34	1.167	12.90	1.146	1.85%
ARTEMIS MOTORWAY	6.579	2.027	4.71	4.982	4.50	5.002	−0.40%

Table A11. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 WLTP vehicle with SI engine, CO_2 concentration [%].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	0.563	0.046	34.43	0.518	23.68	0.519	−0.12%
Extra-urban NEDC	0.696	0.078	30.00	0.621	19.14	0.622	−0.24%
WLTC, Low	0.409	0.064	34.20	0.347	32.07	0.347	−0.04%
WLTC, Medium	0.656	0.063	22.59	0.596	20.32	0.596	−0.05%
WLTC, High	0.720	0.057	20.37	0.666	18.51	0.666	−0.04%
WLTC Extra High	0.973	0.064	14.17	0.914	13.55	0.914	−0.02%
ARTEMIS URBAN	0.458	0.046	31.17	0.413	29.10	0.414	−0.03%
ARTEMIS ROAD	0.721	0.063	24.01	0.661	18.50	0.661	−0.12%
ARTEMIS MOTORWAY	1.889	0.098	8.32	1.803	7.04	1.805	−0.12%

Table A12. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 WLTP vehicle with SI engine, CO concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^{C}_{CVS,DR}$	DF	$C^{C}_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	15.788	0.405	34.43	15.395	23.68	15.400	−0.03%
Extra-urban NEDC	32.920	1.461	30.00	31.508	19.14	31.535	−0.09%
WLTC, Low	29.053	1.829	34.20	27.277	32.07	27.281	−0.01%
WLTC, Medium	0.158	1.101	22.59	−0.894	20.32	−0.889	0.61%
WLTC, High	3.564	0.999	20.37	2.614	18.51	2.619	−0.19%
WLTC Extra High	122.537	1.950	14.17	120.725	13.55	120.731	−0.01%
ARTEMIS URBAN	−0.007	0.130	31.17	−0.133	29.10	−0.133	0.22%
ARTEMIS ROAD	25.671	1.610	24.01	24.128	18.50	24.148	−0.08%
ARTEMIS MOTORWAY	123.259	2.444	8.32	121.109	7.04	121.162	−0.04%

Table A13. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 WLTP vehicle with SI engine, NO_x concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^C_{CVS,DR}$	DF	$C^C_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	4.908	0.061	34.43	4.849	23.68	4.850	−0.02%
Extra-urban NEDC	0.178	0.250	30.00	−0.064	19.14	−0.059	8.02%
WLTC, Low	8.190	0.414	34.20	7.788	32.07	7.789	−0.01%
WLTC, Medium	15.543	0.937	22.59	14.647	20.32	14.652	−0.03%
WLTC, High	8.382	0.315	20.37	8.082	18.51	8.084	−0.02%
WLTC Extra High	13.197	0.684	14.17	12.561	13.55	12.563	−0.02%
ARTEMIS URBAN	18.949	0.126	31.17	18.827	29.10	18.827	0.00%
ARTEMIS ROAD	16.950	1.710	24.01	15.311	18.50	15.332	−0.14%
ARTEMIS MOTORWAY	14.014	2.043	8.32	12.217	7.04	12.261	−0.36%

Table A14. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 WLTP vehicle with SI engine, THC concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^C_{CVS,DR}$	DF	$C^C_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	15.070	5.726	34.43	9.510	23.68	9.586	−0.79%
Extra-urban NEDC	7.863	5.214	30.00	2.823	19.14	2.921	−3.38%
WLTC, Low	55.822	5.868	34.20	50.126	32.07	50.137	−0.02%
WLTC, Medium	39.387	5.725	22.59	33.915	20.32	33.944	−0.08%
WLTC, High	37.683	5.912	20.37	32.061	18.51	32.090	−0.09%
WLTC Extra High	40.256	5.879	14.17	34.792	13.55	34.811	−0.05%
ARTEMIS URBAN	6.803	5.746	31.17	1.241	29.10	1.254	−1.05%
ARTEMIS ROAD	12.838	5.757	24.01	7.321	18.50	7.392	−0.97%
ARTEMIS MOTORWAY	9.893	5.782	8.32	4.806	7.04	4.932	−2.56%

Table A15. The $C_{CVS,corr}$ calculated based on Equations (5) and (21) for Euro 6 WLTP vehicle with SI engine, CH_4 concentration [ppm].

Cycle	C_{CVS}	C_{dil}	DR	$C^C_{CVS,DR}$	DF	$C^C_{CVS,DF}$	ΔC_{CVS}
Urban NEDC	3.250	2.052	34.43	1.258	23.68	1.285	−2.11%
Extra-urban NEDC	2.278	1.997	30.00	0.348	19.14	0.385	−9.80%
WLTC, Low	2.997	1.070	34.20	1.958	32.07	1.960	−0.11%
WLTC, Medium	2.739	1.030	22.59	1.755	20.32	1.760	−0.29%
WLTC, High	2.349	1.077	20.37	1.325	18.51	1.330	−0.40%
WLTC Extra High	3.494	1.067	14.17	2.502	13.55	2.506	−0.14%
ARTEMIS URBAN	2.417	1.995	31.17	0.486	29.10	0.491	−0.93%
ARTEMIS ROAD	2.812	1.056	24.01	1.800	18.50	1.813	−0.72%
ARTEMIS MOTORWAY	2.722	1.068	8.32	1.782	7.04	1.806	−1.29%

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