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Article

Alternative Exhaust Emission Factors from Vehicles in On-Road Driving Tests

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Abstract: On-road driving tests are performed to determine the emission of harmful exhaust compounds from vehicles. These primarily include carbon dioxide, nitrogen oxides, and particle number. However, there is a lack of indicators that combine the first three substances that are the most important in assessing the environmental aspects of vehicles. The purpose of this article is to indicate the possibility of assessing emissions in real driving conditions from light-duty and heavy-duty vehicles of different categories. In order to do so, a portable emissions measurement system (PEMS) and an instrument for measuring the particle number were used. The tests were carried out on routes designed to comply with the requirements and regulations laid down in the European Union legislation. On-road emissions of carbon dioxide, nitrogen oxides and particle number have been determined. Factors have been determined as the multiplication of these compounds for each vehicle category in three phases of the test: urban, rural, and motorway. A new way of assessing emissions from vehicles using new factors has been proposed.

Keywords: real driving emissions; exhaust emission; portable emissions measurement system; light-duty vehicles; heavy-duty diesel vehicles

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1. Introduction

The use of advanced technologies in internal combustion engines and their usage in all means of transport exacts a continuous reduction of emissions from these sources of propulsion. The new procedures for emissions testing introduced by, among others, the European Union are the result of the negative impact of motor vehicles on human health and the environment. As part of its strategy to reduce greenhouse gas emissions, the European Union has introduced carbon dioxide limits for new passenger vehicles and light commercial vehicles. Carbon dioxide is the key compound (in addition to nitrogen oxides and particle number) taken into account in both on-road driving tests and tests performed on the dynamometer.

Passenger vehicles and light commercial vehicles are responsible for, respectively, roughly 12% and 2.5% of total carbon dioxide emissions in the EU [1]. In 2019, The European Parliament and Council adopted Regulation (EU) 2019/631 [2] setting carbon dioxide emission performance standards for new passenger vehicles and for new light commercial vehicles. The EU's main objective is to achieve climate neutrality by 2050, and its indirect objective is to reduce greenhouse gas emissions by at least 55% by 2030. The anticipated benefits will include, among others, a 23% reduction in greenhouse gas emissions from road transport in 2030 compared to the year 2005. In the period 2021–2026, the Commission will monitor the discrepancies in this respect and, on this basis, will assess the possibility of adapting to the required carbon dioxide emission levels for a given manufacturer from 2030 onwards. By 2023 the Commission will evaluate the possibility of developing a common method for assessing and reporting carbon dioxide emissions in the whole life cycle of passenger vehicles and light commercial vehicles [1].

Lorries, buses, and coaches currently account for approximately 25% of carbon dioxide emissions in road transport. It is predicted that they will have an even greater share in the future. In order to reduce CO_2 emissions from transport by 2050, it is necessary to introduce effective measures to reduce it from heavy-duty vehicles.

In order to achieve the EU's target of reducing greenhouse gas emissions by 30% below 2005 levels, in 2030, in the sectors covered by Regulation (EU) 2018/842 [3] and to achieve the objectives of the Paris Agreement, and to ensure the proper functioning of the internal market, the aforesaid Regulation lays down carbon dioxide emission requirements for new heavy-duty vehicles.

2. Review of the Literature on the Subject

Clairotte et al. in their paper [4] presented the work of the 2019 JRC on market surveillance activities conducted in emissions testing and compliance for light-duty vehicles. In this paper, the exhaust emissions of 35 light-duty vehicles were evaluated through laboratory emissions testing and real driving emissions. The on-road nitrogen oxide emission levels obtained in the RDE-compliant tests mostly coincided with the emission levels measured in the laboratory. On-road nitrogen oxide emissions were below the limit set for laboratory testing on a chassis dynamometer. The same findings and conclusions apply largely to on-road carbon monoxide emissions under actual driving conditions. However, the deviations were larger in real driving conditions, where the average deviation value is 20% higher than the declared values in the WLTC test.

Suarez-Bertoa et al. [5] presented aggregated on-road emissions results obtained under real-world driving conditions from a fleet of 19 Euro 6b, 6c, and 6d-Temp vehicles. The fleet included vehicles with engines powered by diesel, gasoline, and compressed natural gas. Low particle number and carbon monoxide emissions were recorded for all diesel vehicles. In addition, the diesel vehicles tested met the nitrogen oxide emission limits required by the RDE tests. At the same time, the results suggest that attention should be paid to carbon monoxide and particle number emissions from certain types of vehicles under dynamic conditions.

Papadopoulos et al. [6] report emission factors for the design of medium-duty diesel trucks equipped with diesel particulate filters (DPFs), for which tests were conducted under real driving conditions. Gaseous and particulate emissions and fuel consumption of 14 trucks with Euro IV, Euro V, and Euro VI diesel engines were analyzed, evaluating the effectiveness of various emission control technologies used. In terms of on-road emissions, nitrogen oxide emissions were higher than the Euro limits, while on-road carbon monoxide emissions and on-road hydrocarbon and particulate emissions were within the specified limits.

The EU regulations refer to the testing of exhaust emissions under real driving conditions using PEMS for such measurements as part of the type approval of a vehicle under in-service conformity testing. The comprehensive study of on-road emissions of nitrogen oxides, ammonia, and particle number presented in [7] concerns measurements under real driving conditions of a truck with Euro 6 emission standard. Euro VI emission class trucks generally meet the accepted requirements for exhaust emissions in real driving conditions. Compared to Euro V trucks, the emission of nitrogen oxides from these vehicles decreased by approximately 89%. The average emission of nitrogen oxides in RDE testing for Euro VI trucks is lower than the average for such RDE testing of light-duty trucks with a diesel engine (Euro 6b—0.56 g/km) [8].

Grigoratos et al. in their paper [9] also presented the results of exhaust emission tests under real driving conditions of Euro VI vehicles. Five heavy vehicles were tested—four trucks and one bus. The tests were carried out in real driving conditions at low, medium and high vehicle speeds in order to examine the effectiveness of the exhaust after-treatment systems used. All the tested vehicles showed better emission results compared to "older" diesel HDVs, which confirms the technical improvements of engines and aftertreatment systems introduced in recent years. Emissions of some exhaust pollutants were found to be relatively high at low speeds due to the lower efficiency of the respective emission control systems. All vehicles emitted NO_x at low levels—much lower than previous vehicles of this type meeting previous Euro standards. Carbon monoxide emissions from the tested vehicles were low, which proves high efficiency of the applied technologies limiting carbon monoxide emissions.

The study [10] summarized the analysis of data submitted to the European Commission's Joint Research Centre (JRC) by truck manufacturers. The data covered the structure of the 2016 truck fleet and carbon dioxide emissions. The results include key indicators and a representative baseline distribution of CO_2 emissions for the entire vehicle fleet for 2016. The JRC undertook a detailed analysis and validation of the data, followed by the development of a methodology to standardize the results. Target groups included Class 4 and Class 9 trucks and Class 5 and Class 10 tractor-trailers. On-road carbon dioxide emissions data from vehicles in the classes mentioned earlier were provided.

Vermeulen et al. in their study [11] confirmed that Euro 6 trucks are not always ecological under urban driving conditions. When these vehicles are operated at low driving speeds, on-road NO_x emissions depend on the existing actual driving conditions. A study of the contribution of cold-start emissions to total NO_x emissions showed that about 17% of total NO_x emissions occur during or immediately after cold-start (at an ambient temperature of about 10 °C). The average test NH_3 concentration ranged from 1 to 18 ppm. The paper reports actual on-road NO_x emissions from heavy-duty diesel trucks of category N3, medium-duty vehicles of category N3, and heavy-duty vehicles of category N2, expressed as the ratio of on-road NO_x emissions to CO_2 emissions.

In the work of Leach et al. [12], NO_x emissions from three vehicles (a Euro 5 car, a Euro V hybrid bus, and a Euro VI) were measured under real driving conditions. The results show that vehicle acceleration events play a significant role affecting their total NO_x emissions. The temperature of any aftertreatment system to reduce NO_x emissions was also observed to be significant. At idling speed, it has been observed that a passenger car almost doubles its NO_x emissions when air conditioning is turned on. Actual driving conditions are compared to compliance cycles for bus certification.

The literature review that the authors of this article were able to perform allows for a conclusion that in driving emission tests of passenger vehicles and lorries, the main emphasis is given to assessing on-road emissions of nitrogen oxides, particle number, and carbon dioxide. There are also—however, fewer—references to on-road emissions of other exhaust pollutants, including, among others, e.g., carbon monoxide emissions on the road. There is no indicator combining the aforesaid three values essential to the environmental performance of cars. For that reason, the authors of the article propose a novel approach to that issue and suggest adopting one indicator for the assessment of the environmental performance of vehicles that would combine the three values described above.

3. Materials and Methods

3.1. Passenger Cars

The tested objects comprised passenger vehicles of category M1 (Euro 6d-Temp emission class): powered by gasoline, diesel and hybrid plug-in engines. Comparative tests of gaseous emissions of exhaust pollutants (CO, CO_2, NO_x) and particle number (PN) emissions in light vehicles (passenger vehicle with gasoline, diesel, hybrid plug-in engine) were carried out in real driving conditions according to the most recent RDE procedure. The possibilities available for obtaining the vehicles mentioned above have enabled the testing in the RDE procedure of the said vehicles with the following basic parameters (Table 1).

Table 1. Technical parameters of the tested passenger vehicles.

Technical Parameters	Vehicle A (Gasoline)	Vehicle B (Diesel)	Vehicle C (Hybrid)
Engine	Gasoline, Turbo, R4, 16 V	Gasoline, Turbo, R4, 16 V	Gasoline, Turbo, R4, 16 V
Fuel system	direct injection	direct injection	direct injection
Engine displacement	1591 cm^3	1598 cm^3	1999 cm^3
Max. power	132 kW at 5500 rpm	100 kW at 4000 rpm	113 kW at 6000 rpm +50 kW (electric motor)
Transmission	automatic, six gears	automatic, six gears	automatic, six gears
Aftertreatment system	TWC + GPF	DOC + DPF + SCR	TWC + GPF
Curb weight	1540 kg	1635 kg	1815 kg
Maximum weight	2050 kg	2150 kg	2270 kg
Euro standard	Euro 6d-Temp	Euro 6d-Temp	Euro 6d-Temp
Mileage	25,000 km	15,000 km	18,000 km
Battery	-	13.6 kWh	13.6 kWh; SOC = 100%

Despite the differences in the engine displacement and types of engines, a common feature was the similar maximum weight of the vehicles.

The studies were conducted in the following external weather conditions: temperature 20–22 °C, relative humidity equal to 82–84%, and an atmospheric pressure of 1015–1020 hPa. The measurements of the previously mentioned vehicles were conducted from 10 a.m. to 3 p.m. on three consecutive business days. The tests were carried out from the cold start of the tested cars, after 24 h of laboratory conditioning of the vehicles. The Semtech DS equipment was used for gaseous exhaust components, and the particle number was measured with the Engine Exhaust Particle Sizer Model 3090. To ensure the proper measurement of the gaseous compounds, calibration and zeroing of the analyzers was performed. The Semtech DS device was mounted inside the vehicle, and the measurements were performed with an independent power source. The apparatus was connected to the exhaust pipe of the vehicle, and the exhaust gases are collected through a heated gas path (191 °C). The gases were filtered of particulate matter and measurements are made, successively, of hydrocarbons, nitrogen oxides, carbon monoxide and carbon dioxide. In the final stage, the oxygen concentration is measured. Thanks to the data from the diagnostic system, it was possible to record the operating parameters of the vehicle.

The load on the vehicles comprised the driver and the passenger (approx. 75 kg each), the fuel tank filled at 75% of the maximum volume, the test instruments (35 kg), two batteries (approx. 10 kg each). The tests were conducted along a route designated for RDE testing (Figure 1). The requirements for the cars' journey along the RDE route have been met in accordance with [13–16]. Table A1 (Appendix A) provides detailed data regarding one of the RDE tests carried out in the vehicle equipped with a gasoline engine.

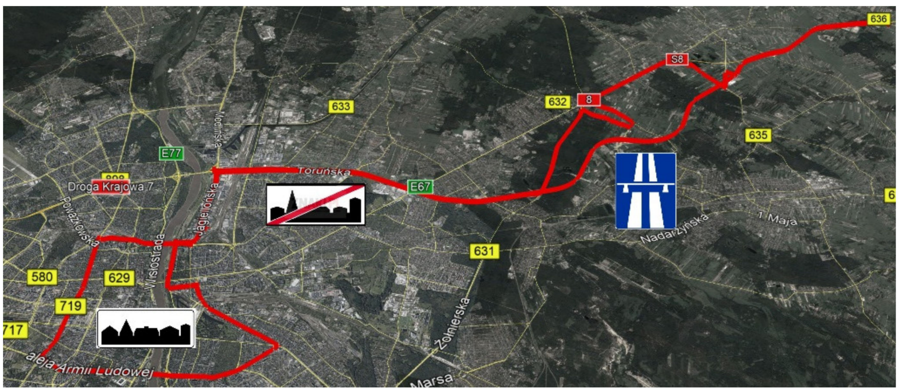


Figure 1. RDE trip route for tests of passenger cars.

3.2. Heavy-Duty Vehicles

The ability to obtain heavy-duty vehicles has enabled RDE testing of vehicles of categories N2 and N3 with the following basic parameters (Table 2).

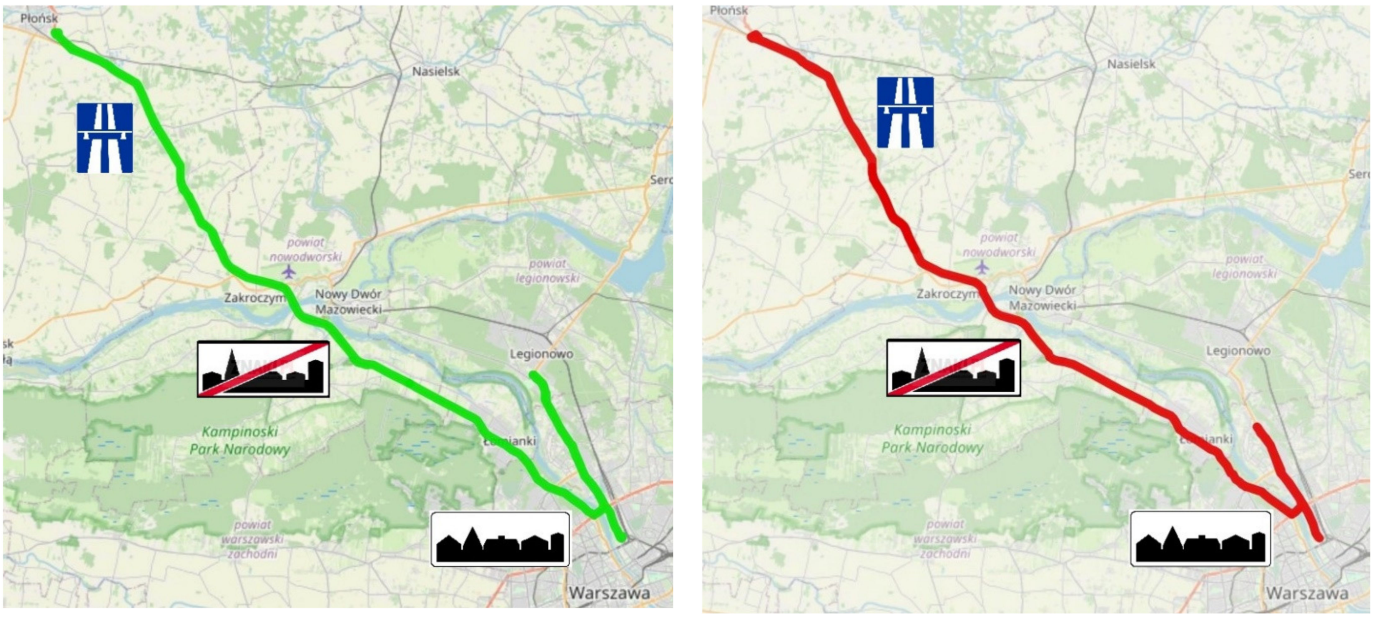
Table 2. Technical parameters of the tested heavy-duty vehicles.

Technical Parameters	Category N2	Category N3
Engine	Diesel, R4	Diesel, R6
Fuel system	direct injection/common rail	direct injection/common rail
Engine displacement	1968 cm^3	12,419 cm^3
Max. power	177 kW at 3600 rpm	375 kW at 1800 rpm
Transmission	automatic, six gears	automatic, six gears
After-treatment system	DOC + DPF + SCR	DOC + DPF + SCR
Curb weight	2915 kg	7778 kg
Load	5000 kg	40,000 kg
Euro standard	Euro VI	Euro VI
Mileage	83,000 km	65,000 km

The tests were conducted on a designated route for RDE testing (Figure 2). The requirements for the cars' journey on the following RDE routes have been met, in accordance with the requirements [2], which are as follows:

- in the case of N2 category vehicles, the trip comprised driving approximately 45% in urban areas, 25% in rural areas, and 30% on a motorway;
- in the case of N3 category vehicles, the trip comprised driving approximately 30% in urban areas, 25% in rural areas, and 45% on a motorway.

All vehicle tests were repeated several times (as a minimum three times) on a given route, and the results obtained are representative for the most common vehicles in the particular category.



(**a**) (**b**)

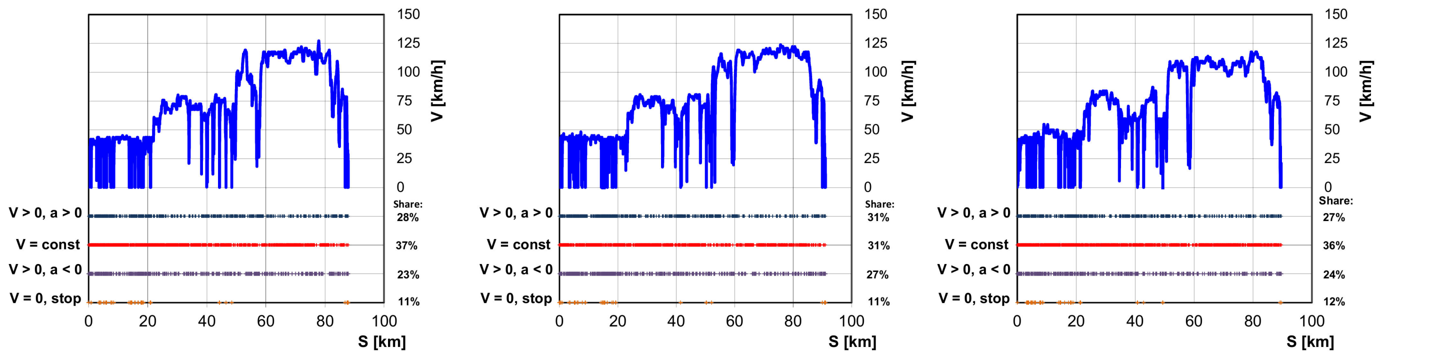
Figure 2. RDE trip route in tests of (**a**) N2 category vehicle; (**b**) N3 category vehicle.

A PEMS device (Semtech DS) was used to measure the concentration of exhaust compounds, and the particle number was measured with the use of the Engine Exhaust Particle Sizer Model 3090. The studies were conducted under the following external weather conditions: temperature of 16–18 °C, relative humidity equal to 85–90% and an atmospheric pressure of 1005–1015 hPa. The measurements of the vehicles as mentioned above were carried out from 10 a.m. to 3 p.m. on consecutive business days. The tests were carried out from the cold start of the engines of the tested cars, after 24 h of laboratory conditioning of the vehicles. The tests were repeated 3 times on the same measuring route (without changing the direction). The final values of unit emissions did not differ by more than 10%. The values shown in the article are representative values for the given parameter category. The load on the vehicles was as follows: maximum weight 5000 kg (category N1) and 40,000 kg (category N3), the driver and the passenger (approximately 75 kg each), filled fuel tank (75%), test instruments (35 kg), and two batteries (approximately 10 kg each).

4. Results

4.1. Light-Duty Vehicles

The characteristics of speed in passenger vehicles with gasoline diesel engines, as well as hybrid plug-in vehicles in the RDE test, together with marked shares of acceleration, constant speed, braking, and stopping are shown in Figure 3.



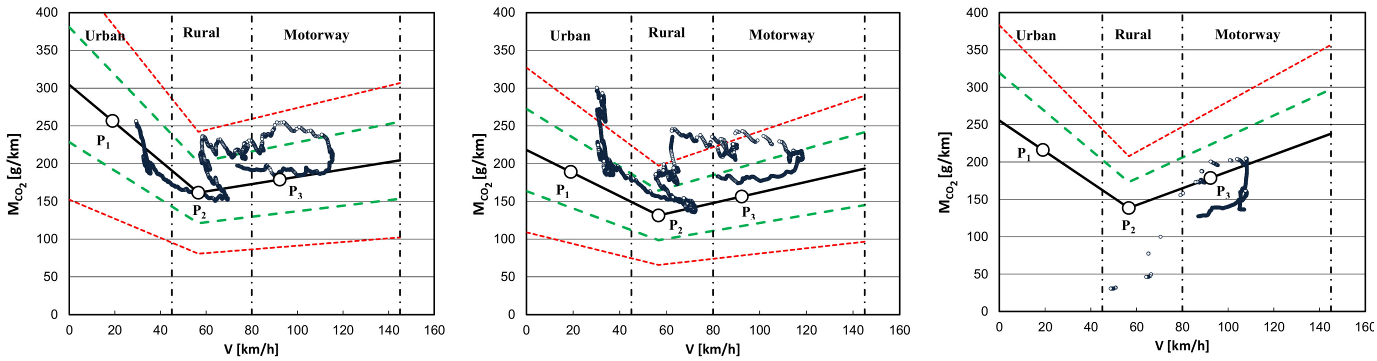
(**a**) (**b**) (**c**)

Figure 3. Characteristics of speed in passenger vehicles with a spark ignition engine (**a**), diesel engine (**b**), PHEV (**c**), in RDE tests with the marked shares of acceleration, constant speed, braking and stop.

In the case of the passenger vehicle with a gasoline engine (Figure 3a), the share of acceleration (driving with parameters v > 0 and a > 0) was equal to 28%, driving with constant speed—37%, while the share of braking (driving with parameters v > 0 and a < 0) accounted for 23%, and the share of stop—11%. In the case of a passenger vehicle with a diesel engine (Figure 3b), the share of driving with parameters v > 0 and a > 0 was slightly higher than before and equal to 31%; the share of driving at constant speed was 31%, while the share of driving at v > 0 and a < 0 was 27%, whereas the share of speed v = 0 (vehicle stop) was—as before—11%. The shares of the hybrid vehicle (Figure 3c) were more similar to that of the gasoline-fuelled car, with v > 0 and a > 0 accounting for 27%, constant speed was 36%, v > 0 and a < 0 accounting for 24% and the share of the vehicle's braking was equal to 12%. The discussed shares of driving phases in the tested passenger vehicles are similar, which allows for comparing other test parameters and exhaust emissions.

The route of the passenger vehicle with a gasoline engine was 87.9 km long (limit > 48 km). The share of the urban route accounted for 34.1% (limit 29–44%), the share of the rural route was equal to 31.9% (limit 33% ± 10%), whereas the share of the motorway route was 34% (limit 33% ± 10%). The route of the passenger vehicle with a diesel engine was 91 km long. The share of the urban route accounted for 33.5%, the share of the rural route was equal to 30.7%, and the share of the motorway route—35.8%. The route of the PHEV passenger vehicle was 89.6 km long. The share of the urban route accounted for 38.6%, the share of the rural route was equal to 25.9%, and the share of the motorway route was 35.5%. The abovementioned parameters were consistent with the limits set out in the standard and positioned within the mid-range of acceptable variability.

Figure 4 shows, as an example, the characteristic curves of on-road emissions of carbon dioxide with marked carbon dioxide emission values obtained in separate measuring windows during road tests of passenger cars. The test is important because more than 50% of the measuring windows in the urban, rural, and motorway ranges fell within the original tolerance (±25%) specified for the characteristic curve.

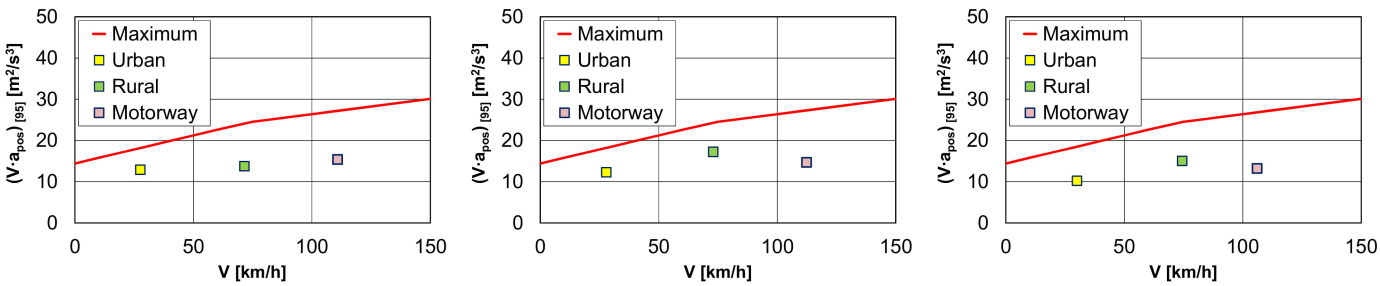


(**a**) (**b**) (**c**)

Figure 4. Characteristic curve of on-road carbon dioxide emission with the marked values of CO_2 emission in respective measuring windows, achieved in road tests in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), and PHEV (**c**); legend: P_1, P_2, P_3—WLTP CO_2, green line—±25%, red line—±50%, solid line—mowing average window CO_2.

Urban driving ranges are characterised by average speeds of less than 45 km/h (as determined in the measuring windows), the rural range is characterised by average speeds equal to or greater than 45 km/h and less than 80 km/h, while the motorway driving range is characterised by average vehicle speeds equal to or greater than 80 km/h and less than 145 km/h. The primary and secondary tolerances for the CO_2 characteristic curve of the vehicle are respectively: tol1 = ±25% (green-coloured curve in Figure 4) and tol2 = ±50% (red-coloured curves in Figure 4). A distinctive feature of the PHEV passenger vehicle was the lack of lower limits.

The evaluation of the dynamic conditions of the RDE test confirmed the correctness of its execution (Figures 5 and 6). This refers to the value of the 95th centile of the product of the vehicle's speed and positive acceleration (expressed in m^2/s^3), for acceleration greater than 0.1 m/s^2 and relative positive acceleration (expressed in m/s^2) for the part of the trip in the urban, rural, and motorway areas.



(**a**) (**b**) (**c**)

Figure 5. Evaluation of the dynamic conditions of the RDE test—the 95th centile ($v \cdot a_{pos}$)—for a passenger vehicle with a gasoline engine (**a**), diesel engine (**b**), PHEV (**c**).

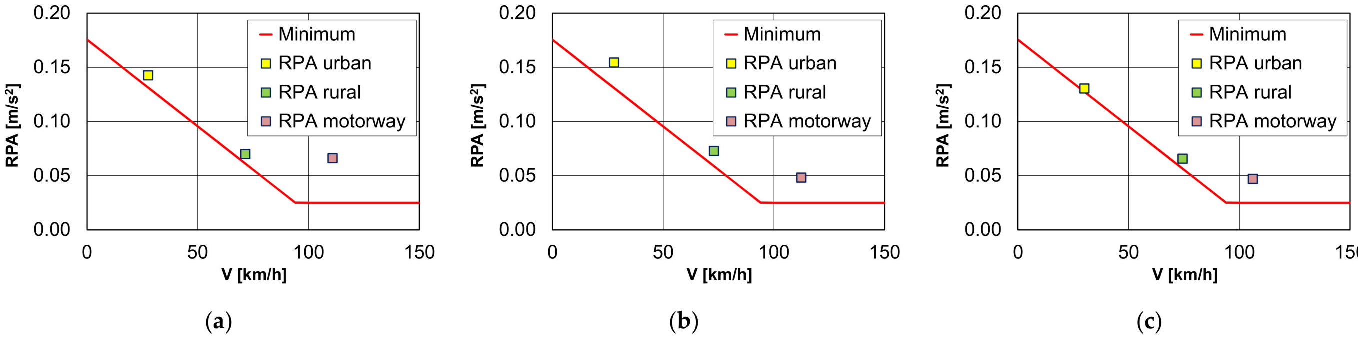


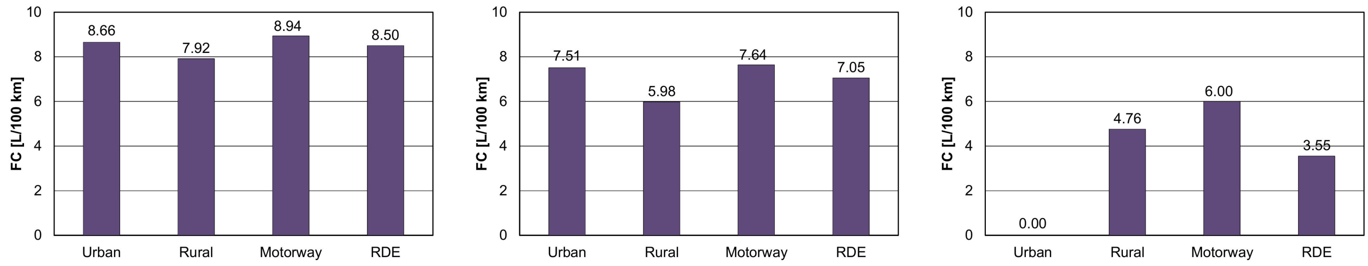
Figure 6. Evaluation of the dynamic conditions of the RDE test—the relative positive acceleration (RPA)—for a passenger vehicle with a gasoline engine (**a**), diesel engine (**b**), PHEV (**c**).

In the case of the passenger vehicle with a gasoline engine, the 95th centile ($v \cdot a_{pos}$) was, respectively, (Figure 5a) for urban traffic 12.9 m^2/s^3 (limit < 18.198 m^2/s^3), for rural traffic 13.8 m^2/s^3 (limit < 24.166 m^2/s^3), and for the motorway traffic 15.4 m^2/s^3 (limit < 27.194 m^2/s^3). In the case of the diesel passenger car, the 95th centile ($v \cdot a_{pos}$) was respectively (Figure 5b) for urban traffic 12.3 m^2/s^3 (limit < 18.228 m^2/s^3), for rural traffic 17.2 m^2/s^3 (limit < 24.361 m^2/s^3), and for the motorway traffic 14.7 m^2/s^3 (limit < 27.304 m^2/s^3). In the case of the PHEV passenger vehicle the 95th centile ($v \cdot a_{pos}$) was respectively (Figure 5c): for urban traffic 10.2 m^2/s^3 (limit < 18.525 m^2/s^3), for rural traffic 15.1 m^2/s^3 (limit < 24.559 m^2/s^3), and for motorway traffic 13.2 m^2/s^3 (limit < 26.837 m^2/s^3).

In the case of the passenger vehicle with a gasoline engine, the relative positive acceleration (RPA) (Figure 6a) was equal to, respectively, for urban traffic 0.14 m/s^2 (limit > 0.131 m/s^2), for rural traffic 0.07 m/s^2 (limit > 0.061 m/s^2), and for motorway traffic 0.07 m/s^2 (limit > 0.025 m/s^2). In the case of the diesel passenger vehicle the relative positive acceleration was (Figure 6b) for urban traffic 0.15 m/s^2 (limit > 0.131 m/s^2), for rural traffic 0.073 m/s^2 (limit > 0.059 m/s^2), and for motorway traffic 0.048 m/s^2 (limit > 0.025 m/s^2). In the case of the PHEV passenger vehicle the relative positive acceleration (Figure 6c) was respectively for urban traffic 0.13 m/s^2 (limit > 0.127 m/s^2), for rural traffic 0.066 m/s^2 (limit > 0.056 m/s^2), and for motorway traffic 0.047 m/s^2 (limit > 0.025 m/s^2).

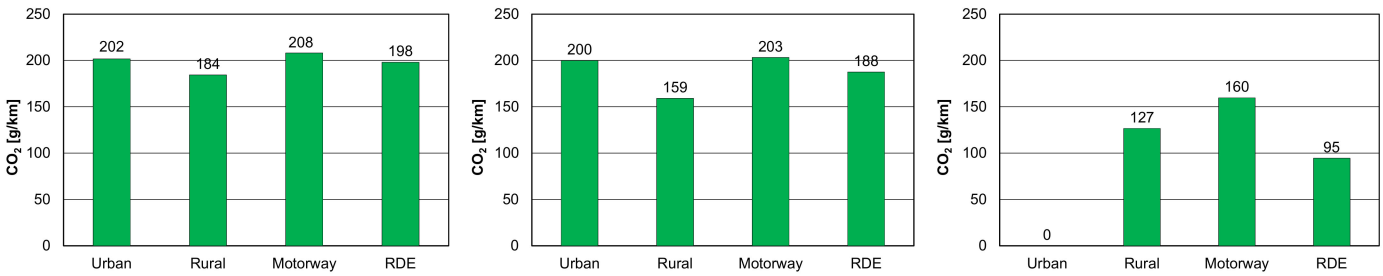
Figures 7–11 show the results of the tests of fuel consumption and on-road emissions of CO, NO_x, PN, and CO_2 for the passenger vehicle with a gasoline engine, diesel engine, and PHEV. The highest fuel consumption and CO_2 on-road emissions occur in motorway and urban traffic in the case of the passenger vehicle with a gasoline engine (respectively, in the case of fuel consumption of 8.94 L/100 km and 8.66 L/100 km), as well as CO_2 on-road emissions—208 g/km and 202 g/km (Figures 7a and 8a), and with a diesel engine (respectively, for fuel consumption of 7.64 L/100 km and 7.51 L/100 km), as well as CO_2 on-road emissions—203 g/km and 200 g/km (Figures 7b and 8b). In the case of a PHEV passenger car, the highest fuel consumption and CO_2 emission occurred in the motorway phase, respectively, in the case of fuel consumption—6.0 dm^3/100 km and CO_2 emissions—160 g/km (Figures 7c and 8c). In the rural traffic and the entire RDE test, fuel consumption in the tested vehicles was as follows:

- Gasoline: 7.92 L/100 km (rural), 8.50 L/100 km (total RDE), 184 gCO_2/km (rural), and 198 gCO_2/km (total RDE),
- Diesel: 5.98 L/100 km (rural), 7.05 L/100 km (total RDE), 159 gCO_2/km (rural), and 188 gCO_2/km (total RDE),
- Hybrid plug-in: 4.76 L/100 km (rural), 3.55 L/100 km (total RDE), 127 gCO_2/km (rural), and 95 gCO_2/km (total RDE).



(**a**) (**b**) (**c**)

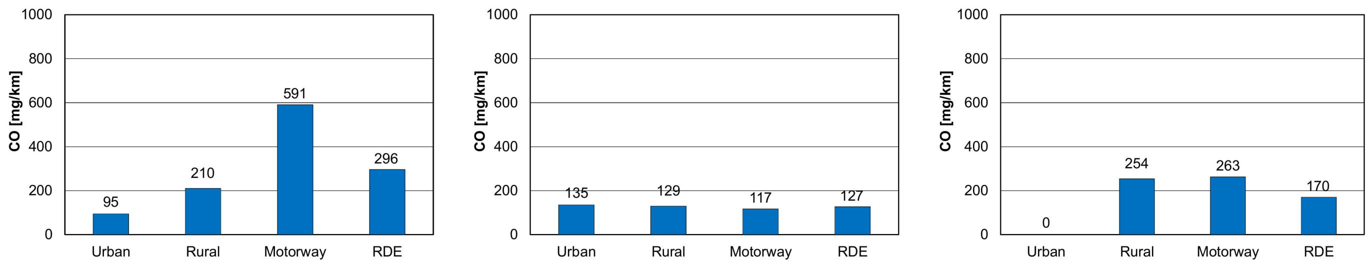
Figure 7. Results of tests of fuel consumption in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).



(**a**) (**b**) (**c**)

Figure 8. Results of tests of carbon dioxide on-road emission in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

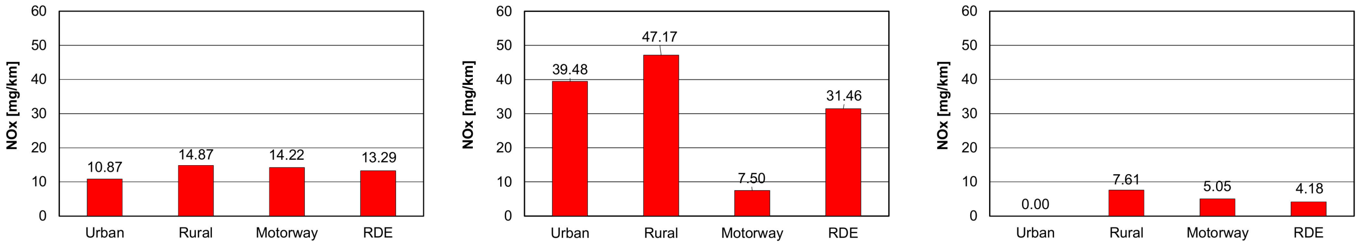
In the case of on-road emission of carbon monoxide, it is the largest for the passenger vehicle with a gasoline engine and a PHEV passenger vehicle in motorway traffic (591 mg/km and 263 mg/km), and in the case of the passenger vehicle with a diesel engine—in urban traffic (135 mg/km). In the vehicle with a gasoline engine, the following values were obtained in urban, rural traffic, and the entire RDE test: 95 mg/km, 210 mg/km, and 296 mg/km. For the diesel vehicle, values of 129 mg/km, 117 mg/km, and 127 mg/km were obtained, respectively, in rural traffic, motorway traffic, and throughout the entire RDE test. In the case of the PHEV car, the following values were obtained: in urban traffic 0 mg/km, in rural traffic 254 mg/km, and the entire RDE test 170 mg/km (Figure 9).



(**a**) (**b**) (**c**)

Figure 9. Results of tests of carbon monoxide emission in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

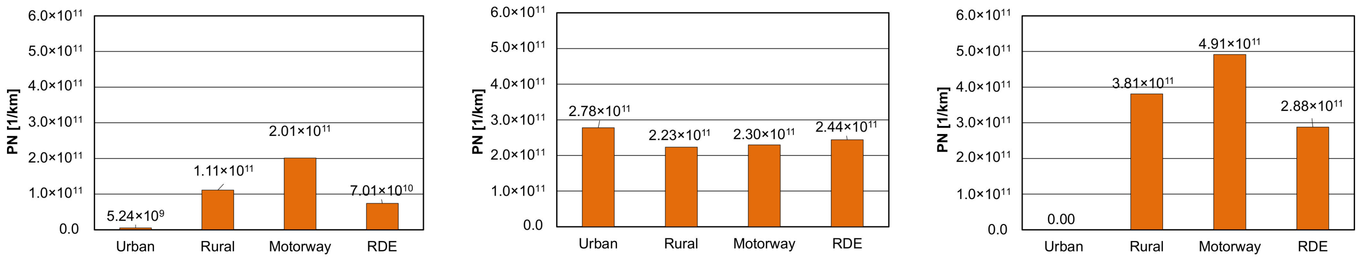
In the case of NO_x on-road emissions (Figure 10), it is the largest in rural traffic in all tested passenger vehicles (the vehicle with a gasoline engine—14.87 mg/km, the diesel vehicle—47.17 mg/km and PHEV—7.61 mg/km). What is noticeable is also the relatively high emissions in urban traffic (in the case of the vehicle with a gasoline engine (10.87 mg/km) and especially in the case of the diesel vehicle (39.48 mg/km). The considerable road emissions of the component in question, which occur during the cold start, are most likely to have a significant impact here. The other NO_x road emissions are as follows—for the vehicle with a gasoline engine: 14.22 mg/km in rural traffic and 13.29 mg/km in the entire RDE test (Figure 10a). Regarding the diesel car, it is 7.50 mg/km in rural traffic and 31.46 mg/km in the whole RDE test (Figure 10b). In PHEV, the road emission in urban traffic did not occur, while in rural traffic it amounted to 5.05 mg/km, and in the entire RDE test to 4.18 mg/km (Figure 10c).



(**a**) (**b**) (**c**)

Figure 10. Results of tests of nitrogen oxides on-road emission in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

Concerning the particle number, the highest emissions occur in motorway traffic (the vehicle with a gasoline engine and PHEV, respectively 2.01 × 10^{11} 1/km and 4.91 × 10^{11} 1/km), and in urban traffic (diesel engine) respectively 2.78 × 10^{11} 1/km (Figure 11). In the passenger vehicle with a gasoline engine, the other road emissions are: 5.24 × 10^9 1/km in urban traffic, 1.11 × 10^{11} 1/km in rural traffic, and 7.01 × 10^{10} 1/km in the entire RDE test (Figure 11a). For the diesel passenger car, it is 2.23 × 10^{11} 1/km (rural traffic), 2.30 × 10^{11} 1/km (motorway traffic), and 2.44 × 10^{11} 1/km in the whole RDE test (Figure 11b). In the case of the PHEV passenger car, the road emission of PN did not occur in urban traffic, whereas in rural traffic, it was 3.81 × 10^{11} 1/km, and in the whole RDE test it was equal to 2.88 × 10^{11} 1/km (Figure 11c).



(**a**) (**b**) (**c**)

Figure 11. Results of tests of particle number on-road emission in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

The conformity factors (CF) of nitrogen oxides and the particle number obtained in respective parts of the test for the tested passenger vehicles are shown in Figures 12 and 13. The analysis of the results confirms that in the passenger vehicle with a gasoline engine, the conformity factor of nitrogen oxides in urban traffic is equal to 0.18, in rural traffic 0.25, in motorway traffic—0.24, and in the entire RDE test—0.22. These values are greater than the relevant conformity factors for PHEV passenger car, i.e., 1.9 times (rural traffic), three times (motorway traffic), and 3.1 times (in the entire RDE test). Even more significant differences were recorded when comparing factors in the vehicle with a gasoline engine and the diesel car. In the diesel car, the conformity factors were higher: 66 times in the urban phase, 6.1 times in the rural phase, 1.5 times in the motorway phase, and 7.4 times in the entire RDE test. The PHEV passenger vehicle fulfilled the requirements regarding the emission of nitrogen oxides to the greatest extent compared to the vehicles powered with a conventional gasoline engine and a diesel engine.

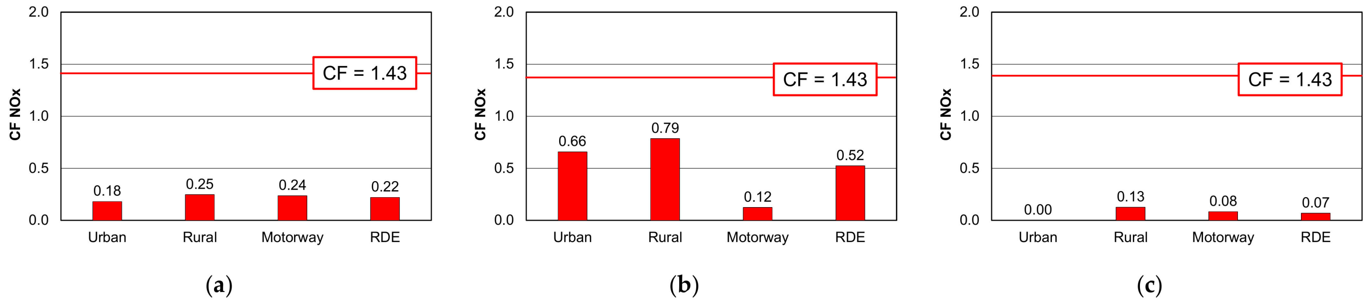


Figure 12. Conformity factors for nitrogen oxides emission achieved in respective parts of the tests in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

Noticeable is that the requirements concerning particle number are exceeded in the passenger vehicle with a gasoline engine in motorway traffic. In the other cases analysed, the requirements for the particle number—and the requirements concerning nitrogen oxides—are met. On the other hand, in the case of CF for the particle number in the passenger vehicle with a gasoline engine and that conformity factor for the PHEV in urban traffic, the recorded values are close to zero (Figure 13a). In the rural traffic, that factor (in the vehicle with a gasoline engine) is 3.3 times smaller, in motorway traffic—2.4 times smaller, and in the entire RDE test—four times smaller compared to the PHEV. The conformity factor for the diesel passenger vehicle (Figure 13b) in rural traffic is 1.7 times smaller, in motorway traffic 2.2 times smaller, and in the entire RDE test smaller by 10% compared to the PHEV (Figure 13c).

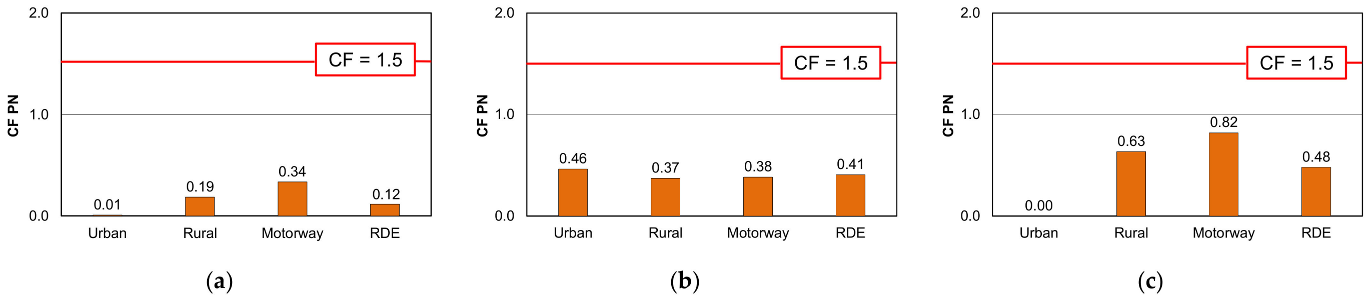


Figure 13. Conformity factors for PN emission achieved in respective parts of the tests in a passenger vehicle with a gasoline engine (**a**), a diesel engine (**b**), PHEV (**c**).

The obtained road emissions results for passenger vehicles will be used later in the article to determine the emission factor that will be a multiplication of the individual emission factors.

4.2. Tests of Heavy-Duty Vehicles

Similar tests in real driving conditions were performed for heavy-duty vehicles. The speed-over-time characteristics for a heavy-duty diesel vehicle of category N2 (Figure 14) reveals three speed ranges: urban phase (v < 50 km/h), rural phase (v < 75 km/h) and motorway phase (v > 75 km/h). In the case of the tested heavy-duty category N2 vehicle with a diesel engine, the share of driving at v > 0, a > 0 was 48%, with constant speed—3%, share of driving at v > 0, a < 0 was equal to 49%, and for v = 0 (stop) was close to zero.

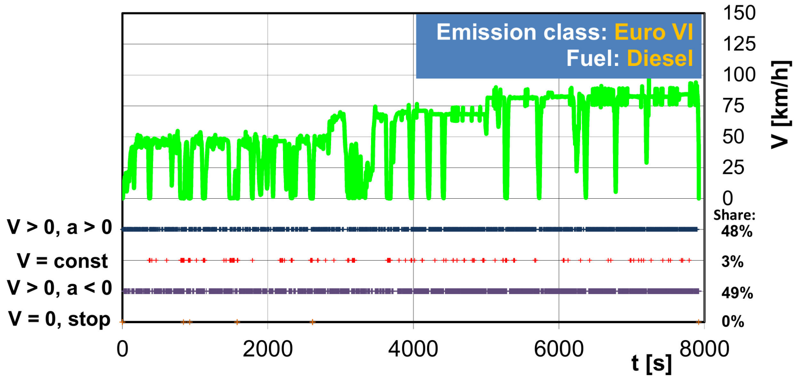


Figure 14. Distribution of speed over time in N2 category vehicle.

When considering the intensity of exhaust emissions in the vehicle speed–acceleration coordinates, it is possible to identify areas of the vehicle's operation where the environmental impact is significant (Figure 15). Unfortunately, such analyses are not required during standard emission tests. However, it is vital to know the operating ranges of the engine and their environmental impact in development studies.

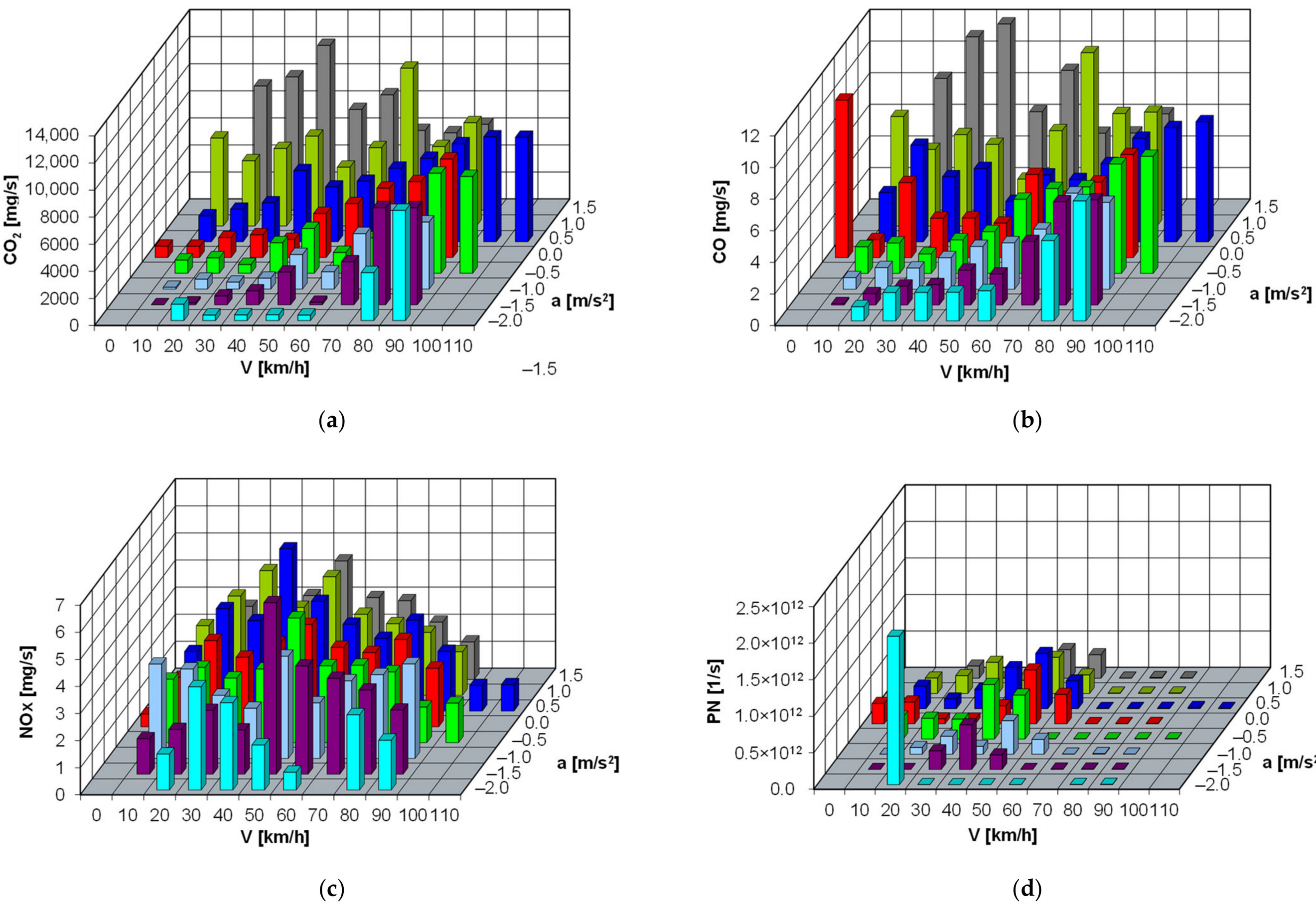


Figure 15. Two-dimensional distribution of flow rate of CO_2 (**a**), CO (**b**), NOx (**c**) and PN (**d**) in vehicle speed-acceleration coordinates (N2 category).

When examining the carbon dioxide flow rate in the vehicle of category N2, it can be concluded that the largest (8000 mg/s–10,000 mg/s) occurs in the vehicle's speed range of 18 m/s–20 m/s and acceleration of 0.6 m/s^2–1.0 m/s^2. It is almost linearly dependent on the vehicle's speed but increases very strongly as the vehicle accelerates (Figure 15a).

Regarding the intensity of carbon monoxide emission, the largest (6–8 mg/s) occurs in a similar range as the intensity of carbon dioxide emission, while its high values are noticeable in the low speed and high acceleration range of the vehicle (Figure 15b). When considering the nitrogen oxides emission, the highest intensity occurs in the range of average vehicle speed (6 m/s–14 m/s) and acceleration in the range of 0.6 m/s^2–1.0 m/s^2 (Figure 15c). That is characteristic of vehicles equipped with advanced after-treatment systems, the effectiveness of which depends on the temperature of the exhaust gases. The operating temperature of these systems increases with the increase of the engine load and the vehicle's speed and acceleration. In the case of the particle number, the greatest intensity occurs in the vehicle speed range of 10–12 m/s^2 and its acceleration of 0.2 m/s^2–0.6 m/s^2 (Figure 15d). These data are determined along the entire trip. Therefore, it can be concluded that most of the particulate matter was emitted in low-speed driving conditions (urban and rural phases), while in the motorway driving phase, due to the high temperature of the exhaust gases, the efficiency of the particulate filter is much higher than in other areas of the vehicle's operation.

Using the flow rate of the relevant harmful component of exhaust gases and knowing the share of time for each phase of the vehicle's movement, the mass of exhaust components was determined (Table 3).

Table 3. Results of tests of unit emission from a heavy-duty vehicle of N2 category.

Phase	V [km/h]	Time [s]	Share [%]	Value [%]	CO [g/kWh]	NOx [g/kWh]	PN [1/kWh]	CO_2 [g/kWh]
Urban	0–50	3566	45 ± 5	45%	0.787	0.526	1.37×10^{12}	857
Rural	50–75	1816	25 ± 5	23%	0.623	1.269	6.61×10^{10}	772
Motorway	75–90	2539	30 ± 5	32%	0.677	0.010	5.91×10^{9}	743
Total		7921	100	100%	0.693	0.460	3.78×10^{11}	780

The highest unit carbon monoxide emission occurred in urban traffic and was equal to 0.787 g/kWh. In the case of unit emission of nitrogen oxides, the largest occurred in rural traffic (1.269 g/kWh), but high values were also recorded in urban traffic (0.526 g/kWh). The highest unit emission of particle number occurs in urban traffic and amounts to 1.37×10^{12} 1/kWh, and the unit emission of carbon dioxide is also the highest in urban traffic at 857 g/kWh. Most likely, the highest values of unit emissions in urban traffic and also in rural traffic (PN) are influenced by the emission of these pollutants during cold start.

The test results of a diesel N3 category truck are shown below. The characteristics of speed changes of the said vehicle are shown in Figure 16. The route was divided into three parts. However, due to a different vehicle category, the share of the respective driving sections was different (a smaller share of urban driving at the expense of increasing the share of motorway driving). Nevertheless, a detailed analysis shows that the share of driving at v > 0, a > 0 accounted for 41%, with constant speed—22%, while the share of driving during the braking (v > 0, a < 0) was equal to 35% and the vehicle stop (v = 0) was 1%.

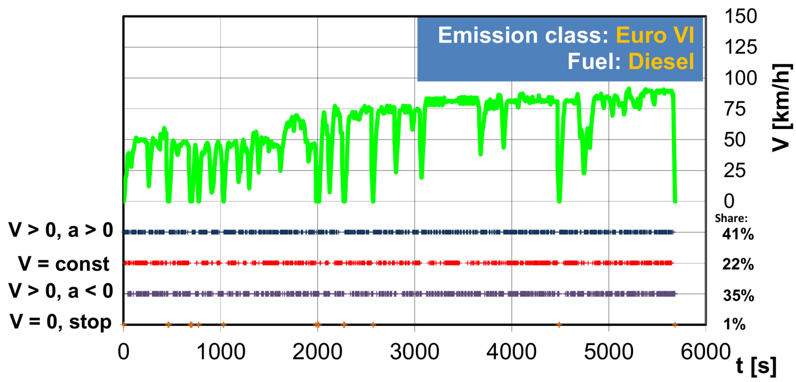
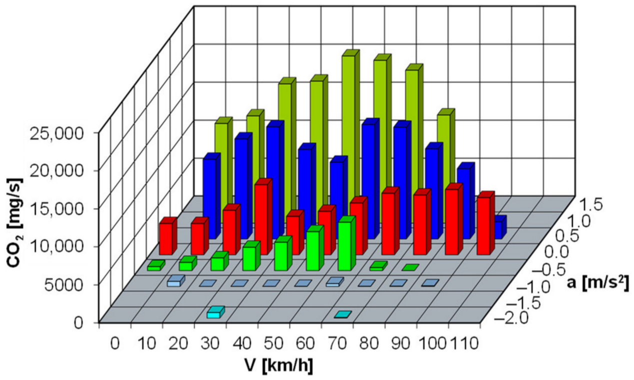


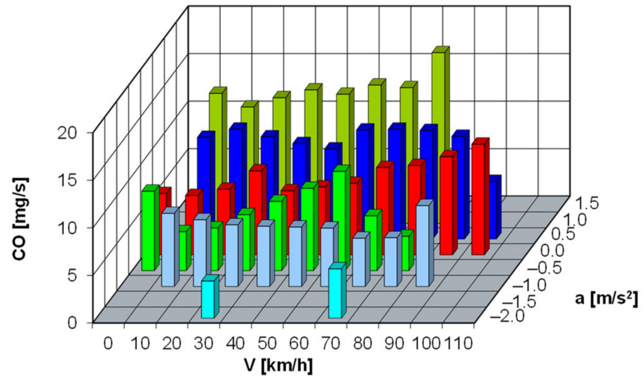
Figure 16. Distribution of speed over time for N3 category vehicle.

The analysis of exhaust emissions from the N3 category vehicle is characterised by a different specificity from that of the N2 category vehicle. The intensity of carbon dioxide emission is linearly dependent on the vehicle's speed only for acceleration slightly different from zero (Figure 17a). There were virtually no traffic conditions in which the vehicle would be violently braked. For a greater acceleration of the vehicle, the intensity of carbon dioxide emission is 16,000–18,000 m/s, which is twice the value of the vehicle of category N2. In the case of the intensity of carbon monoxide emission, the characteristics are similar (Figure 17b), except that as regards braking noticeable is an increase in the emission of this compound, due to, among others, the cooling of the exhaust system (after-treatment systems) and at the same time a rapid reduction in the amount of air. When considering the intensity of nitrogen oxides emission, it should be concluded that the reduction system of this compound (SCR) worked with high efficiency and the maximum emission intensity values did not exceed 20–30 mg/s. Attention should also be given to lower emission levels for higher vehicle speeds and a lack of sensitivity to the change in acceleration (Figure 17c). For the particle number, its highest intensity (1×10^{12}–2×10^{12} 1/kWh) occurs within the maximum speed and acceleration range (Figure 17d).

Using the flow rate of the relevant harmful component of the exhaust gas and knowing the share of time for each phase of the vehicle's movement, the unit emissions of the respective pollutants (Table 4) were determined—as in the case of the N2 category heavy-duty vehicle—for the heavy-duty vehicle of category N3. The highest unit emission of carbon monoxide occurred during the urban test phase and amounted to 0.79 g/kWh. In the case of unit emission of nitrogen oxides, the largest also occurred in urban traffic (0.71 g/kWh). The highest unit emission of particle number appears in the motorway test phase and is equal to 8.6×10^{11} g/kWh, and that emission for carbon dioxide is the highest in the urban test phase and amounts to 775 g/kWh. Most likely, the highest values of the unit emissions mentioned earlier in urban traffic (CO, NO_x, CO_2) are influenced by pollutant emissions during cold start.



(**a**)



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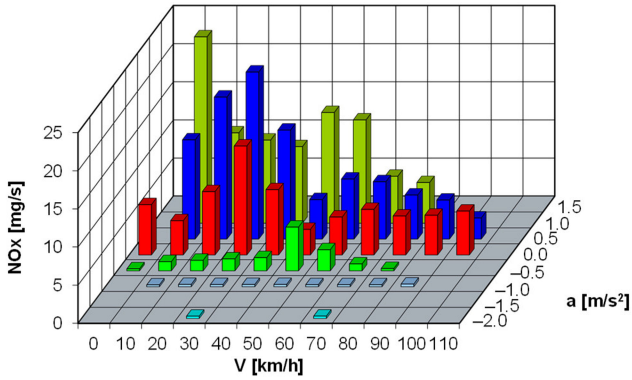
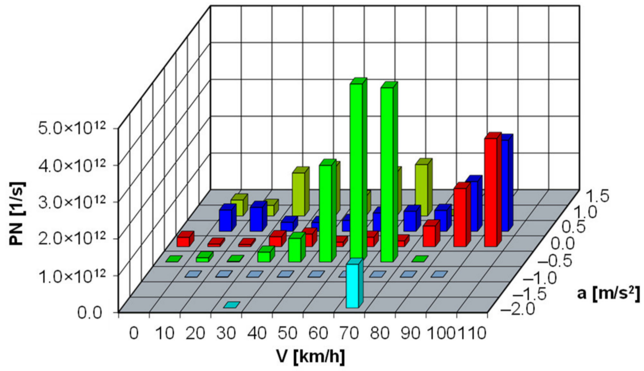


(**c**)



(**d**)

Figure 17. Two-dimensional distribution of flow intensity of CO_2 (**a**), CO (**b**), NO_x (**c**) and PN (**d**) in the speed–acceleration coordinates in N3 category vehicle.

Table 4. Results of tests of road emissions from N3 category heavy-duty vehicle.

Phase	V [km/h]	Time [s]	Share [%]	Value [%]	CO [g/kWh]	NOx [g/kWh]	PN [g/kWh]	CO_2 [g/kWh]
Urban	0–50	2014	30 ± 5	35%	0.790	0.710	2.29×10^{11}	775
Rural	50–75	1343	25 ± 5	24%	0.648	0.304	3.40×10^{11}	684
Motorway	75–90	2326	45 ± 5	41%	0.693	0.230	8.60×10^{11}	661
Total		5683	100	100%	0.708	0.420	5.41×10^{11}	667

5. Discussion

Based on the results obtained and presented in the article and on the results of other researchers [1,4–7], as well as previous co-authored publications on the measurements of emissions of exhaust compounds using PEMS [17–23], the authors undertook to formulate an indicator that would merge all the results obtained. Such an indicator would characterise the vehicle environmentally in terms of only harmful substances of exhaust emissions NO_x, PN, and CO_2 (since only such a scope of works was ultimately considered as the principal scope in this article). However, it would also be possible to extend it, for example, to energy volumes relating to the energy consumption of hybrid vehicles. In the intention of the authors, it should be an indicator characterised by, among others:

- dimensionless quantity,
- impact of all the exhaust gases concerned on the assessment of the vehicle,
- in the absence of certain components, they may be omitted, and the nature of the indicator will not change,

- independence in application to different types of vehicles (PC, LDV, HDV, NRMM),
- comparability between different types of vehicles,
- proportionality in relation to the environmental performance of vehicles (lower indicator value—higher environmental performance of vehicles).

The authors of the paper propose the use of one universal indicator, however, allowing—through the use of weighting shares—to characterize it with an environmental value or having an impact on human life and health.

With respect to environmental characteristics, based on the analysis of the literature [24–27], it is considered that carbon dioxide has the greatest impact on the greenhouse effect, while nitrogen oxides and particulate matter have a much smaller extent (about 5–10 times smaller). However, these compounds contribute to smog formation, and therefore their ratios of 0.8, 0.15, and 0.05 were assumed for CO_2, NO_x, and PN, respectively.

With respect to the characteristics affecting human health, the weight shares are different, as based on studies presented in [28,29], it appears that nitrogen oxides and particulate matter have the greatest impact on human health (they are carcinogenic), and significantly less—carbon dioxide. Therefore, it is proposed to adopt the following weight shares: $\alpha_{NOx} = 0.45$, $\alpha_{PN} = 0.45$ oraz $\alpha_{CO_2} = 0.1$.

The list of characteristics is open, and other characteristics may be defined in the future. The general form of the emission factor (EF) can be formulated as:

$$\mathrm{EF} = \sum \alpha_i \frac{b_i}{b_{i\ limit}} \tag{1}$$

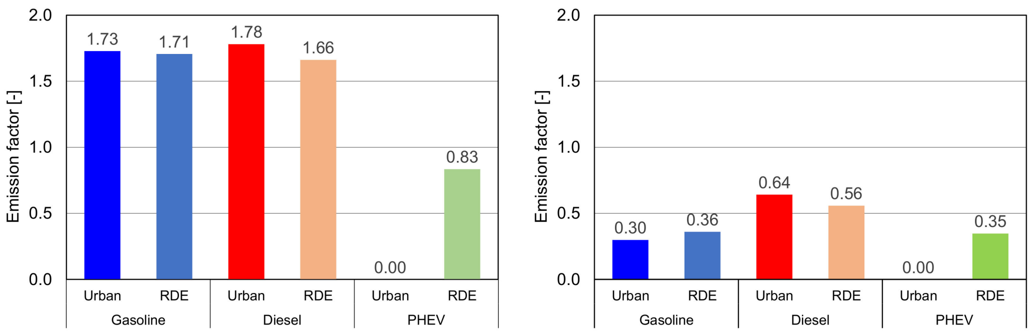
where: EF—emission factor, i—number of harmful compounds included in the factor (e.g., NO_x, PN, CO_2, CO, HC, NH_3, and other), α—weight fraction of the exhaust component [[–], b—road (unit) emission of a particular component of the exhaust emissions (mg/km (1/km for PN) or mg/kWh (1/kWh for PN)), b_{limit}—limit value of the exhaust component concerned (emission limit or target in the case of mileage fuel consumption) (mg/km (1/km for PN) or mg/kWh (1/kWh for PN)).

For the obtained values of exhaust emissions from passenger cars, the emission factor will be calculated as follows:

$$\mathrm{EF} = \alpha_{NOx} \frac{b_{NOx}}{b_{NOx\ limit}} \times \alpha_{PN} \frac{b_{PN}}{b_{PN\ limit}} \times \alpha_{CO_2} \frac{b_{CO_2}}{b_{CO_2\ target}} \tag{2}$$

After considering the type of vehicles, the input values and referring the factor to the urban part of the test and the entire RDE test, the results are presented in Figure 18, and the detailed values used for the calculations are included in Tables A2 and A3 (in the Appendix A). Limit values were adopted as permissible limit values for road emissions of nitrogen oxides and particle number for vehicles of the emission category tested (Euro 6d-Temp), while for road carbon dioxide emission, the target value adopted (95 g/km) was in force in 2020 for the vehicle fleet.

The values of the emission factor in environmental terms (Figure 18a) for the urban part of the test and the entire RDE test are in the range of $\mathrm{EF} \in \langle 0.00; 1.78 \rangle$. However, it should be noted that an index of 0 for hybrid vehicles means no emissions of exhaust components. That is the consequence of the absence of starting the internal combustion engine in the urban part of the test. However, it should be borne in mind that the authors do not assess the energy consumption in the above article. Hence, there is no reference to the energy consumption of such a propulsion. On the other hand, for a vehicle equipped with a gasoline engine, the emission factor (EF = 1.73–1.76) is close to that of a diesel vehicle (EF = 1.66–1.78). The most significant impact on that is the considerable particle number emitted, which in the tests carried out is roughly three times higher than for a gasoline engine.



(**a**) (**b**)

Figure 18. Emission factors (EF) for passenger cars in environmental (**a**) and health (**b**) perspective.

The comparison of this exhaust indicator with respect to human health impacts is more diverse (Figure 18b). For a gasoline vehicle, the value of the index is about two times lower than for a diesel engine. The hybrid vehicle, on the other hand, has an impact on human health throughout the RDE test ($EF_{RDE} = 0.35$) comparable to the coefficient for a gasoline car ($EF_{RDE} = 0.36$).

A similar algorithm of action was proposed for heavy-duty vehicles of categories N2 and N3. In this case, road emission (expressed in g/km) was replaced by unit emission values (expressed in g/kWh), which is in line with the nomenclature used for the exhaust toxicity standards for these vehicles. What needs to be explained is only the approach to applying fuel consumption or carbon dioxide emission standards. Since the adoption of unit fuel consumption (in g/kWh) does not include information on mileage fuel consumption (in dm^3/100 km), this task is difficult. One solution is to refer to literature data through which means to resolve this problem may be found. Rexis et al. [30] and Ragon et al. [31] indicate in the tests of heavy-duty vehicles the possibility of using mileage and unit fuel consumption:

- For typical tractor: 32.6 L/100 km~227 g/kWh (long haul) and 34.3 L/100 km~236 g/kWh (regional delivery),
- For right truck: 31.1 L/100 km~225 g/kWh (long haul) and 34.6 L/100 km~238 g/kWh (regional delivery),

This, expressed as unit emission of carbon dioxide, is equal to 650 g/kWh—and this is the target the authors of the article propose to adopt for use in the emission factor formula, both for vehicles of categories N2 and N3, despite being aware of the differences between these vehicles.

After considering the type of vehicles, the input values and referring the factor to the urban part of the test and the entire RDE test, the results obtained for heavy-duty vehicles are presented in Figure 19, and the detailed values adopted for the calculations are included in Tables A4 and A5 (Appendix A). Limit values were adopted as permissible limit values for NO_x and PN emissions for vehicles of the emission category tested (Euro VI), while for unit emission of carbon dioxide a target of 650 g/kWh was adopted, as previously determined.

The emission factor values for heavy-duty vehicles in environmental perspective in the test fall within the limits of $EF_U \in \langle 1.20; 1.34 \rangle$. The values of the ratios are comparable, however, the vehicle of category N3 shows lower values by about 10% (Figure 19a). Moreover, similar results are obtained when the weighting shares are adjusted for the impact of exhaust gases on human health. In this case (Figure 19b), there is more variation, but consistently lower values are observed for N3 vehicles.

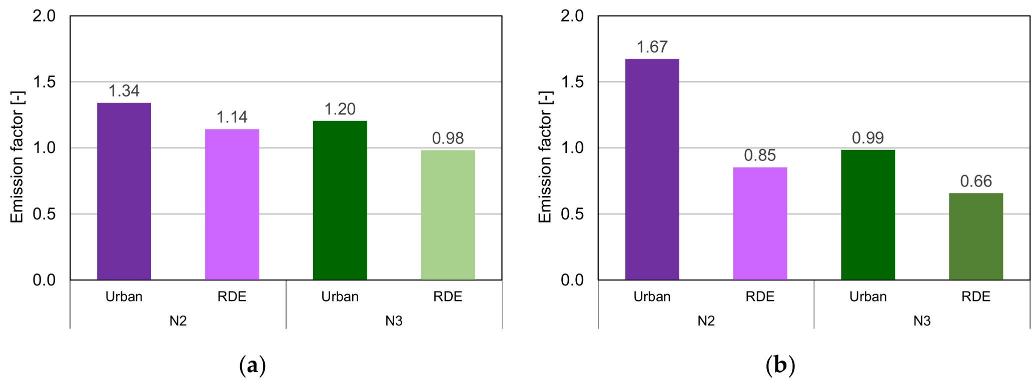


Figure 19. Emission factors (EF) for heavy-duty vehicles in environmental (**a**) and health (**b**) perspective.

6. Conclusions

This article presents the results of comparative tests in real driving conditions of exhaust emissions from passenger vehicles—with a gasoline engine, a diesel engine, and PHEV passenger vehicle (gasoline and electric). The results have been analysed using a moving average window (MAW) analysis method, including cold start conditions.

Based on the results obtained, it has been found that, in the case of the passenger vehicle with a gasoline engine, the conformity factor (CF) for NO_x is 3.1 times greater than CF for PHEV. That vehicle fulfils the requirements to a greater extent than the diesel passenger vehicle (CF 7.4 times smaller). The PHEV fulfilled the requirements in terms of on-road emission of nitrogen oxides to the greatest extent among the tested passenger cars. On the other hand, in the case of the conformity factor for the particle number for the passenger vehicle with a gasoline engine, in relation to that factor for the PHEV passenger car, it is 2.4 times larger in the entire RDE test. The CF of the particle number in the diesel passenger vehicle in the entire RDE test is equal to approximately 0.9 of the PHEV passenger car's factor. Attention should be paid to the relatively high PN road emission in urban traffic from the vehicle with a gasoline engine and the diesel vehicle compared to PHEV.

Using the obtained data on road emissions of NO_x, PN, and CO_2 from the tested passenger vehicles and adopting the mandatory 2020 CO_2 target for fleets of light-duty vehicles, a dimensionless emission factor (EF) was proposed in the RDE test (and in the urban part). The lower value of this factor represents the greater environmental performance of vehicles. Throughout the RDE test, the gasoline and PHEV passenger vehicles are greener (EF_{RDE} = 0.36) than the passenger vehicle with a diesel engine (EF_{RDE} = 0.56), including the health aspect. In terms of environmental index, the environmental performance of gasoline and diesel vehicles is similar, with twice the impact in terms of greenhouse effect as a hybrid vehicle.

For heavy-duty vehicles, comparative tests in real driving conditions at the cold start were conducted for vehicles of N2 and N3 categories with diesel engines. The results of the tests were analysed based on a method using all measurement data. The said algorithm for the light-duty vehicle, with regard to the determination of the dimensionless emission factor and its calculation, was proposed for heavy-duty vehicles, adopting the CO_2 target as 650 g/kWh. In the present case, as regards heavy-duty vehicles, road emissions were replaced by unit emissions applied to such vehicles. The EF values for the entire test are within the range $EF_{RDE} \in \langle 0.98; 1.14 \rangle$ for the environmental indicator and $EF_{RDE} \in \langle 0.66; 0.85 \rangle$ for the health indicator.

The results of the tests of exhaust emissions carried out using PEMS equipment in real driving conditions of light and heavy-duty vehicles made it possible to propose a new universal emission factor (EF). The values of this indicator were considered in the paper in two aspects: environmental and social. The adopted division results only from different values of weight shares of respective harmful compounds of exhaust gases. These shares may be modified, and a uniform approach to toxicity assessment is possible. This, however, requires additional research. The factor is dimensionless, and at the same time allows for characterising the environmental performance of a vehicle in such a way that covers all pollutants. This may be an introduction to further studies on the assessment of exhaust emissions from motor vehicles.

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Abbreviations

a	acceleration vehicle
AMOX	ammonia oxidation catalyst
b	road exhaust emission
CF	conformity factor
CNG	compressed natural gas
COC	certificate of conformity
DOC	Diesel oxidation catalyst
DPF	Diesel particle filter
E	exhaust emission rate
EF	emission factor
EU	European Union
GDI	gasoline direct injection
GPF	gasoline particle filter
HDV	heavy duty vehicle
JRC	Joint Research Centre
LDV	light duty vehicle
M	motorway
MAV	moving average windows
NRMM	non-road mobile machinery
OBFCM	on-board fuel consumption meter
PEMS	portable emission measurement system
PFI	port fuel injection
PHEV	plug-in hybrid electric vehicle
R	rural
RDE	real driving emissions
RPA	relative positive acceleration
SCR	selective catalytic reduction
t	time
u	share
U	urban
v	vehicle speed
WLTC	Worldwide-harmonized Light duty vehicles Test Cycle
WLTP	Worldwide-harmonized Light duty vehicles Test Procedure
ZLEV	zero- and low-emission vehicles

Appendix A

Table A1. Detailed data regarding one of the RDE tests conducted as an example for the tested passenger vehicle with a gasoline engine.

Trip Characteristics	Value	Valid
Urban distance [km]	29.9	>16
Rural distance [km]	28.0	>16
Motorway distance [km]	29.9	>16
Total distance [km]	87.9	>48
Urban distance share [%]	34.1	29–44
Rural distance share [%]	31.9	33 ± 10
Motorway distance share [%]	34.0	33 ± 10
Urban average speed [km/h]	27.6	15–40
Stop share (Urban phase) [%]	19.8	6–30
Motorway speed above 100 km/h [min]	13.4	>5
Motorway max speed [km/h]	127.2	<160
Motorway speed above 145 km/h [%]	0.0	<3
Duration [min]	104.7	90–120
Cold start (t = 300 s)		
Engine coolant temperature [°C]	67.0	<70
Cold start max speed [km/h]	41.9	<60
Cold start stop time [s]	36	<90
Initial idling duration [s]	6	<15
Excess/Absence of Trip Dynamics		
Urban: counts number $a_i > 0.1$ m/s^2	1083	>150
Rural: counts number $a_i > 0.1$ m/s^2	339	>150
Motorway: counts number $a_i > 0.1$ m/s^2	254	>150
Urban: average speed [km/h]	27.6	–
Rural: average speed [km/h]	71.5	–
Motorway: average speed [km/h]	110.9	–
Urban: 95. centile $V \cdot a_{pos}$ [m^2/s^3]	12.9	<18.198
Rural: 95. centile $V \cdot a_{pos}$ [m^2/s^3]	13.8	<24.166
Motorway: 95. centile $V \cdot a_{pos}$ [m^2/s^3]	15.4	<27.194
Urban: RPA [m/s^2]	0.14	>0.131
Rural: RPA [m/s^2]	0.07	>0.061
Motorway: RPA [m/s^2]	0.07	>0.025
Moving Averaging Window Results		
All windows	Number	Share [%]
Urban	1834	40.2
Rural	1663	36.4
Motorway	1067	23.4
Normal windows	Number	Share [%]
Urban	1834	100.0
Rural	1213	72.9
Motorway	874	81.9

Table A2. Emission factors (EF) for passenger cars (environmental option, α_{NOx} = 0.15, α_{PN} = 0.05, α_{CO2} = 0.8).

Vehicle		Urban NOx [mg/km]	Urban PN [1/km]	Urban CO_2 [g/km]	EF_U	RDE NOx [mg/km]	RDE PN [1/km]	RDE CO_2 [g/km]	EF_{RDE}
Gasoline	b	10.87	5.24×10^9	202	1.73	13.29	7.01×10^{11}	198	1.76
	b_{limit}	60	6×10^{11}	95		60	6×10^{11}	95	
Diesel	b	39.48	2.78×10^{11}	200	1.78	31.46	2.44×10^{11}	188	1.66
	b_{limit}	80	6×10^{11}	95		80	6×10^{11}	95	
PHEV	b	0.00	0	0	0.00	4.18	2.88×10^{11}	95	0.83
	b_{limit}	60	6×10^{11}	95		60	6×10^{11}	95	

Table A3. Emission factors (EF) for passenger cars (health option, α_{NOx} = 0.45, α_{PN} = 0.45, α_{CO2} = 0.1).

Vehicle		Urban NOx [mg/km]	Urban PN [1/km]	Urban CO_2 [g/km]	EF_U	RDE NOx [mg/km]	RDE PN [1/km]	RDE CO_2 [g/km]	EF_{RDE}
Gasoline	b	10.87	5.24×10^9	202	0.30	13.29	7.01×10^{11}	198	0.83
	b_{limit}	60	6×10^{11}	95		60	6×10^{11}	95	
Diesel	b	39.48	2.78×10^{11}	200	0.64	31.46	2.44×10^{11}	188	0.356
	b_{limit}	80	6×10^{11}	95		80	6×10^{11}	95	
PHEV	b	0.00	0	0	0.00	4.18	2.88×10^{11}	95	0.35
	b_{limit}	60	6×10^{11}	95		60	6×10^{11}	95	

Table A4. Emission factors (EF) for heavy-duty vehicles (environmental option, α_{NOx} = 0.15, α_{PN} = 0.05, α_{CO2} = 0.8).

Category HDV Vehicle		Urban NOx [g/kWh]	Urban PN [1/kWh]	Urban CO_2 [g/kWh]	EF_U	RDE NOx [g/kWh]	RDE PN [1/kWh]	RDE CO_2 [g/kWh]	EF_{RDE}
N2	b	0.526	1.37×10^{12}	857	1.34	0.460	3.78×10^{11}	780	1.14
	b_{limit}	0.460	6×10^{11}	650		0.460	6×10^{11}	650	
N3	b	0.710	2.29×10^{11}	775	1.20	0.420	1.41×10^{11}	667	0.98
	b_{limit}	0.460	6×10^{11}	650		0.460	6×10^{11}	650	

Table A5. Emission factors (EF) for heavy-duty vehicles (health option, α_{NOx} = 0.45, α_{PN} = 0.45, α_{CO2} = 0.1).

Category HDV Vehicle		Urban NOx [g/kWh]	Urban PN [1/kWh]	Urban CO_2 [g/kWh]	EF_U	RDE NOx [g/kWh]	RDE PN [1/kWh]	RDE CO_2 [g/kWh]	EF_{RDE}
N2	b	0.526	1.37×10^{12}	857	1.67	0.460	3.78×10^{11}	780	0.85
	b_{limit}	0.460	6×10^{11}	650		0.460	6×10^{11}	650	
N3	b	0.710	2.29×10^{11}	775	0.99	0.420	1.41×10^{11}	667	0.66
	b_{limit}	0.460	6×10^{11}	650		0.460	6×10^{11}	650	

References

1. Road Transport: Reducing CO2 Emissions from Vehicles: CO2 Emission Performance Standards for Vehicles and Vans (2020 onwards). Available online: https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en#tab-0-0 (accessed on 28 February 2021).
2. The European Parliament and the Council of the European Union. Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO_2 emission performance standards for new passenger vehicles and for new light commercial vehicles, and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. *Off. J. Eur. Union* **2019**, *111*, 13–534.

3. The European Parliament and the Council of the European Union. Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013. *Off. J. Eur. Union* **2018**, *156*, 26–42.
4. Clairotte, M.; Valverde, V.; Bonnel, P.; Gruering, C.; Pavlovic, J.; Manara, D.; Loos, R.; Giechaskiel, B.; Carriero, M.; Otura, M.; et al. *Light-Duty Vehicles Emissions Testing*; Joint Research Centre, Publications Office of the European Union: Luxemburg, 2019.
5. Suarez-Bertoa, R.; Valverde, V.; Clairotte, M.; Pavlovic, J.; Giechaskiel, B.; Franco, V.; Kregar, Z.; Astorga, C. On-road emissions of passenger vehicles beyond the boundary conditions of the real-driving emissions test. *Environ. Res.* **2019**, *176*, 108572. [CrossRef]
6. Papadopoulos, G.; Ntziachristos, L.; Tziourtzioumis, C.; Keramydas, C.; Lo, T.-S.; Ng, K.-L.; Wong, H.-L.; Wong, C.K.-L. Real-world gaseous and particulate emissions from Euro IV to VI medium duty diesel trucks. *Sci. Total Environ.* **2020**, *731*, 139137. [CrossRef]
7. Mendoza-Villafuerte, P.; Suarez-Bertoa, R.; Giechaskiel, B.; Riccobono, F.; Bulgheroni, C.; Astorga, C.; Perujo, A. NOx, NH_3, N_2O and PN real driving emissions from a Euro VI heavy-duty vehicle. Impact of regulatory on-road test conditions on emissions. *Sci. Total Environ.* **2017**, *609*, 546–555. [CrossRef] [PubMed]
8. Ko, S.; Park, J.; Kim, H.; Kang, G.; Lee, J.; Kim, J.; Lee, J. NOx emissions from Euro 5 and Euro 6 Heavy-Duty Diesel Vehicles under Real Driving Conditions. *Energies* **2020**, *13*, 218. [CrossRef]
9. Grigoratos, T.; Fontaras, G.; Giechaskiel, B.; Zacharof, N. Real world emissions performance of heavy-duty Euro VI diesel vehicles. *Atmos. Environ.* **2019**, *201*, 348–359. [CrossRef]
10. Tansini, A.; Zacharof, N.; Prado Rujas, I.; Fontaras, G. Analysis of VECTO data for Heavy-Duty Vehicles (HDV) CO_2 emission targets. *JRC Sci. Policy Rep.* **2018**. [CrossRef]
11. Vermeulen, R.J.; Vonk, W.A.; van Gijlswijk, R.N.; Buskermolen, E.G. *The Netherlands In Service Emissions Testing Programme for Heavy-Duty Vehicles 2015–2016—Annual Report. TNO 2016 R11270*; Earth, Life & Social Sciences: Delft, The Netherlands, 2016.
12. Leach, F.C.P.; Peckham, M.S.; Hammond, M.J. Identifying NOx Hotspots in Transient Urban Driving of Two Diesel Buses and a Diesel Car. *Atmosphere* **2020**, *11*, 355. [CrossRef]
13. Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as Regards Emissions from Light Passenger and Commercial Vehicles (Euro 6). *Off. J. Eur. Union* **2016**, *82*, 1–98. Available online: http://data.europa.eu/eli/reg/2016/427/oj (accessed on 28 February 2021).
14. Commission Regulation (EU) 2016/646 of 20 April 2016 amending Regulation (EC) No 692/2008 as Regards Emissions from Light Passenger and Commercial Vehicles (Euro 6). *Off. J. Eur. Union* **2016**, *109*, 1–22. Available online: http://data.europa.eu/eli/reg/2016/646/oj (accessed on 28 February 2021).
15. Commission Regulation (EU) 2017/1154 of 7 June 2017 Amending Regulation (EU) 2017/1151 Supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on Type-Approval of Motor Vehicles with Respect to Emissions from Light Passenger and Commercial Vehicles (Euro 5 and Euro 6) and on Access to Vehicle Repair and Maintenance Information, Amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and Repealing Regulation (EC) No 692/2008 and Directive 2007/46/EC of the European Parliament and of the Council as Regards Real-Driving Emissions from Light Passenger and Commercial Vehicles (Euro 6). *Off. J. Eur. Union* **2017**, *175*, 708–732. Available online: http://data.europa.eu/eli/reg/2017/1154/oj (accessed on 28 February 2021).
16. Commission Regulation (EU) 2018/1832 of 5 November 2018 Amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) 2017/1151 for the Purpose of Improving the Emission Type Approval Tests and Procedures for Light Passenger and Commercial Vehicles, Including Those for In-Service Conformity and Real-Driving Emissions and Introducing Devices for Monitoring the Consumption of Fuel and Electric Energy. *Off. J. Eur. Union* **2018**, *301*, 1–314. Available online: http://data.europa.eu/eli/reg/2018/1832/oj (accessed on 28 February 2021).
17. Pielecha, J.; Skobiej, K.; Kurtyka, K. Exhaust emissions and energy consumption analysis of conventional, hybrid, and electric vehicles in real driving cycles. *Energies* **2020**, *13*, 6423. [CrossRef]
18. Gis, W.; Gis, M.; Pielecha, J. Comparative studies of exhaust emissions from three city buses in real traffic conditions, one with LNG, the other with CI engine and a hybrid bus. *SAE Tech. Pap.* **2020**. [CrossRef]
19. Pielecha, J.; Gis, M.; Skobiej, K.; Kurtyka, K. Measurements of particulate emissions from Euro 5/6 passenger vehicles in different drive settings. *IOP Conf. Series: Earth Environ. Sci.* **2021**, *642*, 12018. [CrossRef]
20. Gis, M.; Pielecha, J.; Gis, W. Exhaust emissions of buses LNG and Diesel in RDE tests. *Open Eng.* **2021**, *11*, 356–364. [CrossRef]
21. Pielecha, J.; Gis, M. The use of the mild hybrid system in vehicles with regard to exhaust emissions and their environmental impact. *Arch. Transp.* **2020**, *55*, 41–50. [CrossRef]
22. Gis, W.; Gis, M.; Pielecha, J. Evaluation of Exhaust Emissions in Real Driving Emissions Tests in Different Test Route Configurations. In *Advances in Intelligent Systems and Computing*; Springer Science and Business Media LLC: Berlin/Heidelberg, Germany, 2019; pp. 143–153.
23. Skobiej, K.; Pielecha, J. Plug-in hybrid ecological category in real driving emissions. *Energies* **2021**, *14*, 2340. [CrossRef]
24. Mohamued, E.A.; Ahmed, M.; Pypłacz, P.; Liczmanska-Kopcewicz, K.; Khan, M.A. Global Oil Price and Innovation for Sustainability: The Impact of R&D Spending, Oil Price and Oil Price Volatility on GHG Emissions. *Energies* **2021**, *14*, 1757. [CrossRef]

25. Massar, M.; Reza, I.; Rahman, S.M.; Abdullah, S.M.H.; Jamal, A.; Al-Ismail, F.S. Impacts of Autonomous Vehicles on Greenhouse Gas Emissions—Positive or Negative? *Int. J. Environ. Res. Public Health* **2021**, *18*, 5567. [CrossRef] [PubMed]
26. Tucki, K.; Mruk, R.; Orynycz, O.; Botwińska, K.; Gola, A.; Bączyk, A. Toxicity of Exhaust Fumes (CO, NOx) of the Compression-Ignition (Diesel) Engine with the Use of Simulation. *Sustainability* **2019**, *11*, 2188. [CrossRef]
27. Nerhagen, L.; Janhäll, S. *Exhaust Emissions and Environmental Classification of Cars. What Indicators Are Relevant According to External Cost Calculations? VTI 2015, Notat 3A-2015*; The Swedish National Road and Transport Research Institute: Linköping, Sweden, 2015.
28. McClellan, R.O.; Hesterberg, T.W.; Wall, J.C. Evaluation of carcinogenic hazard of diesel engine exhaust needsto consider revolutionary changes in diesel technology. *Regul. Toxicol. Pharmacol.* **2012**, *63*, 225–258. [CrossRef]
29. Zhang, X.; Wang, Q.; Qin, W.; Guo, L. Sustainable Policy Evaluation of Vehicle Exhaust Control—Empirical Data from China's Air Pollution Control. *Sustainability* **2020**, *12*, 125. [CrossRef]
30. Rexeis, M.; Röck, M.; Hausberger, S. Comparison of Fuel Consumption and Emissions for Representative Heavy-Duty Vehicles in Europe. 2018. Available online: https://www.theicct.org/publications/HDV-EU-fuel-consumption-and-emissions-comparison (accessed on 1 April 2021).
31. Ragon, P.-L.; Rodríguez, F. The EU Heavy-Duty CO2 Standards: Impact of the COVID-19 Crisis and Market Dynamics on Baseline Emissions. 2020, ICCT WORKING PAPER 2020-30. Available online: https://theicct.org/sites/default/files/publications/eu-hdv-emissions-baseline-20201210.pdf (accessed on 1 April 2021).