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Particle Number Emission from Vehicles of Various Drives in the RDE Tests

Jacek Pielecha [1,*], Kinga Skobiej [1], Maciej Gis [2] and Wojciech Gis [2]

[1] Faculty of Civil and Transport Engineering, Poznan University of Technology, pl. M. Sklodowskiej-Curie 5, 60-965 Poznan, Poland
[2] Motor Transport Institute, Jagiellonska Street 80, 03-301 Warsaw, Poland
* Correspondence: jacek.pielecha@put.poznan.pl; Tel.: +48-61-665-2118

Abstract: In this study, the authors assessed the road emissions of several passenger cars using specialised instrumentation, of the PEMS type, to measure particle number emissions in real traffic conditions. The tests were performed on a RDE test route developed and compliant with EU guidelines. The results of the tests were discussed in terms of the direct (created in the internal combustion engine) emission of particulate matter in various road conditions. Additionally, an index was determined that characterizes the number of particles according to their diameter in relation to the content of particles in the air. A characteristic of combustion engines (gasoline, diesel) is that during a cold start of the engine, the concentration of the number of particles with diameters around 100 nm increases more than 200 times (for hybrids—300 times). On this basis, it can be concluded that particle emissions with diameters smaller than 23 nm are significant in motor vehicles powered by combustion engines, regardless of whether they are conventional or hybrid vehicles. The share of particles with diameters less than 5 nm is 66% (for diesel engines) and 40% (for gasoline engines) of all the particles.

Keywords: passenger vehicle; environment; particle numbers; RDE tests

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1. Introduction

European passenger car emissions standards are one of the strictest in the world. Until the end of 2020, the Euro 6d-Temp emission standard was in force, and from 1 January 2021—Euro 6d. With its introduction, a comprehensive requirement for type-approval testing came into effect, taking into account road emission testing of vehicles in real traffic conditions. It is not without reason that the European Union has become the determinant of such emission rigor. Year after year, air quality in large European urban areas is deteriorating, and the number of people that falls ill as a result is rising. Various factors contribute to this, including motor transport, which is responsible (depending on the lie of the land) for as much as 70% of air pollution. Taking into account the increasing "restrictions" imposed by the European Commission, the authors of this article decided to refer to the emission of exhaust pollutants in terms of particulate matter. Particulate matter with a diameter of less than 1 µm penetrates directly into the bloodstream, even leading to death. The parameters of particulate matter emitted from internal combustion engines determine their limitation. For a dozen or so years, the number of particulates emitted in vehicle exhaust has been a major problem. Unfortunately, only internal combustion vehicles fuelled with hydrogen will not—in the future—emit particles of nanometric size.

Transportation is an important part of the modern economy. The impact of the COVID-19 pandemic and the resulting restrictions have significantly affected passenger transportation. In order to prevent the spread of the virus, people have significantly changed their transportation habits, reducing the use of public transportation in favour of personal vehicles. According to mobility analyses, due to restrictions and fear of infection, the number of public transportation passengers has decreased (by about 30%) [1,2], while the number of people using a personal vehicle regularly has increased (by about 25%) [3,4], both as drivers and passengers. This indicates a problem with public transportation and the inability to replace private vehicles, especially in times of crisis.

Boldizsár et al. [5] examined the trends in changes in the vehicle population in the European Union countries, and the relationship between road freight transport and population development in the studied countries was analysed from an economic point of view. The study found no correlation between social and freight transport indicators in the European Union Member States. On the other hand, there is a correlation in the economic dimension.

According to the European Parliament, almost 30% of total carbon dioxide emissions within the European Union come from the transport sector; 72% come from road transport, of which the share of passenger vehicles is as high as 60.7%. For this reason, it is important to reduce exhaust emissions from car exhaust systems [6], especially in diesel engines [7]

There are many solutions to reduce exhaust emissions. According to [8], by 2020, start–stop functional systems (micro hybrid) will almost completely replace traditional purely ICE (internal combustion engine) systems (Figure 1). The development of more electrified topologies is growing rapidly, relative to today's very low sales volumes, but remains at a low level. Therefore, the sum of the market share of mild hybrids (electric installation 48 V), full hybrids, plug-in hybrids, and battery electric vehicles will be just over 10%. In the subsequent 5 years, a distinctive growth in mild hybrids (2025: 33% market share), plug-in hybrids (2025: 13% market share), and battery electric vehicles (2025: 8% market share) is expected.

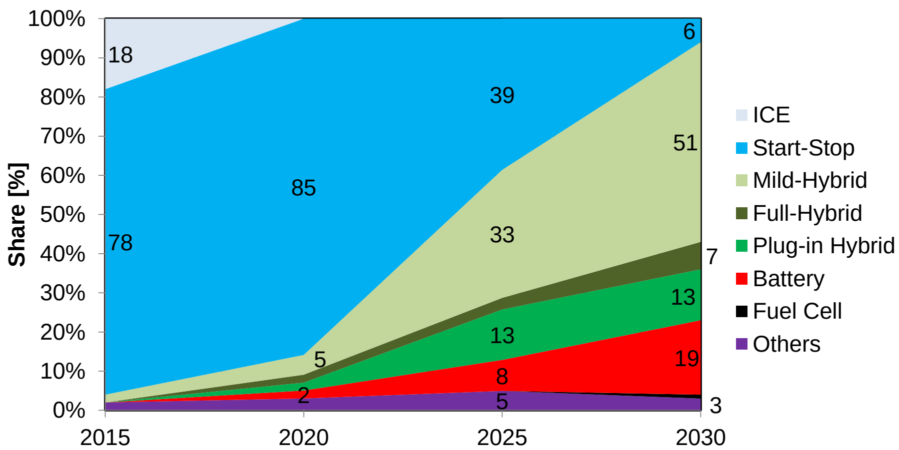

Figure 1. Prediction of change in share of powertrains used in vehicles by 2030 [8]; CO_2 fleet emissions: 95 g/km (2020), 75 g/km (2025), and 65 g/km (2030).

Due to increasingly stringent standards, manufacturers are using various solutions to reduce not only the gaseous components of exhaust gases but also, most importantly, particulate matter. Particulate matter also includes nanoparticles that cannot be seen, which are the most dangerous to human health and life. One approach is the use of alternative fuels [9] such as bioethanol, butanol, or oxymethylen ether [10], for example, which is not valid for biodiesels [11]. The next step is the electrification of powertrains. FEV assumes a significant future share of electrified vehicles. However, looking ahead to 2030, 80% of vehicles will still be powered by hybrids using internal combustion engines [12].

The authors, in their previous work, undertook the possibility of the emission evaluation of conventional, hybrid, and electric vehicles under real traffic conditions, pointing out the required further research on this topic. In [13], a comparative assessment was made of the energy consumption under different traffic conditions of passenger vehicles with different propulsion systems. The lowest total energy consumption under real traffic conditions is that of an electric vehicle, which is about 10% higher for a plug-in hybrid gasoline vehicle, and it is the highest for an internal combustion vehicle (30% higher than an electric vehicle). Another article [14] also made an ecological environmental assessment of N_2-and N_3-category trucks, showing that trucks in the latter category significantly exceed particulate emission standards. Articles [15,16] present the authors' categorization of vehicles in terms of environmental performance, determining their aspects under real traffic conditions. A four-stage environmental categorization was used, and the division was made using the fulfilment of requirements in RDE (real driving emissions) tests.

This means that the problem of exhaust emissions from automobile transport will continue to be significant. In urban areas, excessive emissions of exhaust pollutants (especially nitrogen oxides and particulate matter) may contribute not only to poorer air quality but also to increased morbidity among residents. According to [17], atmospheric pollution by nanoparticles negatively affects human health and the environment. Particles with a diameter of 10 μm or smaller can cause various diseases, primarily heart and lung diseases and associated deaths. In accordance with [18], published by the National Institute of Public Health—National Institute of Hygiene, it appears that, between 2005 and 2017, the phenomenon of smog (mainly contains suspended dust) was responsible for an average of about 3800 deaths per year. Air pollution is a significant problem, especially during the autumn and winter. The main reason for this is considered to be heating systems, which require the burning of fuels including coal. However, this is not the only problem. Automobile transportation is also responsible for air pollution. This problem is increasingly recognized, especially in large cities. For this reason, the EU is trying to legally regulate the maximum emissions of passenger cars, among others, through strict limits on individual exhaust pollutants.

The more distant view towards 2030 is, today, still uncertain. The interaction of the development of the plug-in hybrid market share and the sales volumes for battery-powered vehicles is not yet predictable and is primarily linked to the development progress of battery technology (energy density and price), the development of the charging infrastructure, and the development of oil prices.

2. Emission of Particulate Matters in Poland

The Chief Inspectorate for Environmental Protection surveyed the country (Poland) and then published a report on the annual assessment of air quality, in accordance with the principles set forth in Article 89 of the Law—Environmental Protection Law [19]. The air quality assessment was performed by zone, and the result was the assignment of a class to each zone for each of the assessed pollutants. According to the adopted methodology, for example, assigning class A to a zone means that no exceedances of the normative concentration values of a given pollutant in force in Poland were found in its territory in a specific year.

According to the annual assessment, in the case of concentrations of particulate matter (PM_{10}), the classification of zones was adopted according to the parameters: the permissible level for 24 h concentrations and the permissible level for annual average concentrations.

In the 2019 assessment of PM_{10} particulate matter, 7 of the 12 agglomerations were classified as class C. In the previous year, 10 agglomerations received class C. In the area of 5 of the 18 zones—cities with more than 100,000 inhabitants—exceedances were found, resulting in their assignment to class C [20]. This means a significant deterioration of air quality (Figures 2 and 3).

The study also identified the main reasons for PM exceedances. In the case of 24 h PM_{10} (PM was above 50 $\mu g/m^3$), the main cause was the impact of emissions related to individual building heating. However, the contribution of emissions related to vehicle traffic was also marked (for 29% of the zones with exceedances). This is no different for $PM_{2.5}$ emissions, with the main source being the combustion of fossil fuels for building heating. Road transport, in this case, is responsible for about 10% of national $PM_{2.5}$ emissions. Taking into account the place and height of the introduction of traffic pollutants into the atmosphere, it can be concluded that in the central parts of agglomerations (with a dense grid of streets with heavy vehicle traffic), road emissions from cars can be the determining factor in the occurrence of the exceedances of limit values [20].

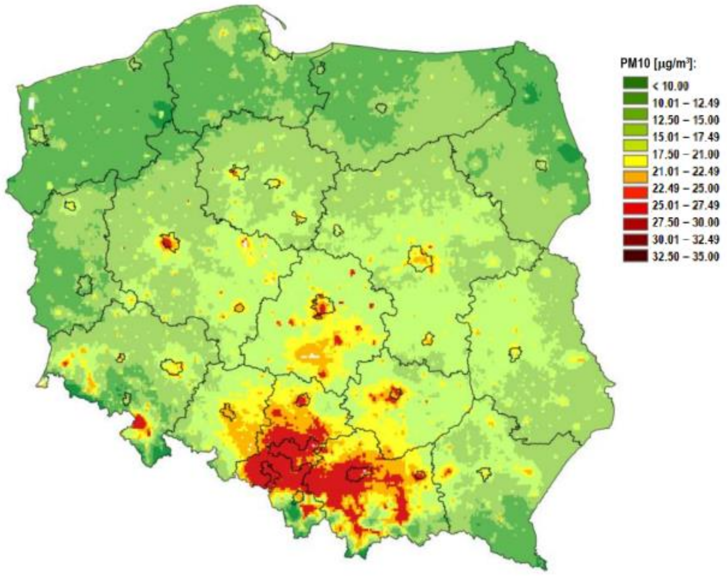

Figure 2. Spatial distribution of PM_{10} concentrations across Poland in 2019 [20]. Reprinted with permission from [20]. Copyright 2019, State Environmental Monitoring.

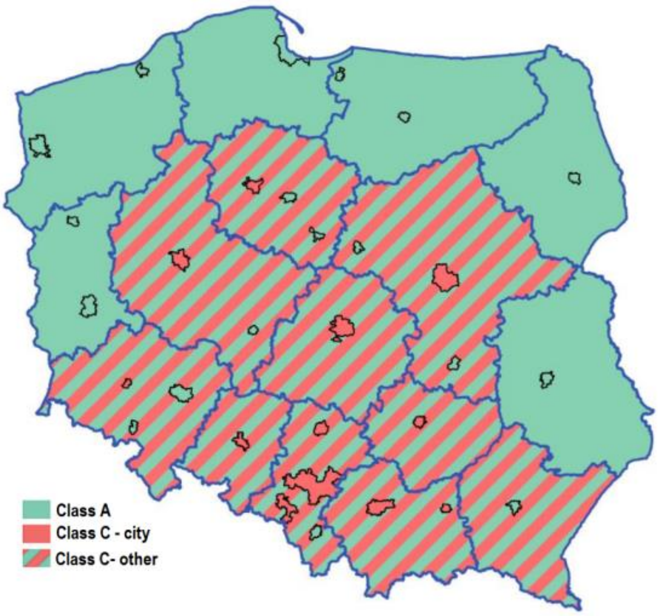

Figure 3. Classification of zones in Poland for PM_{10} dust, based on air quality assessment for 2019 [20]. Reprinted with permission from [20]. Copyright 2019, State Environmental Monitoring.

The situation with particulate emissions from both automobile transport and heating could be solved by increasing the share of renewable energy sources (RES). Unfortunately, the development of this sector in the country is quite slow. According to [21], in 2030, Poland will have a share of RES of about 19%. The leader in this regard will be the Netherlands (59%). The European average is expected to be 27% (Figure 4).

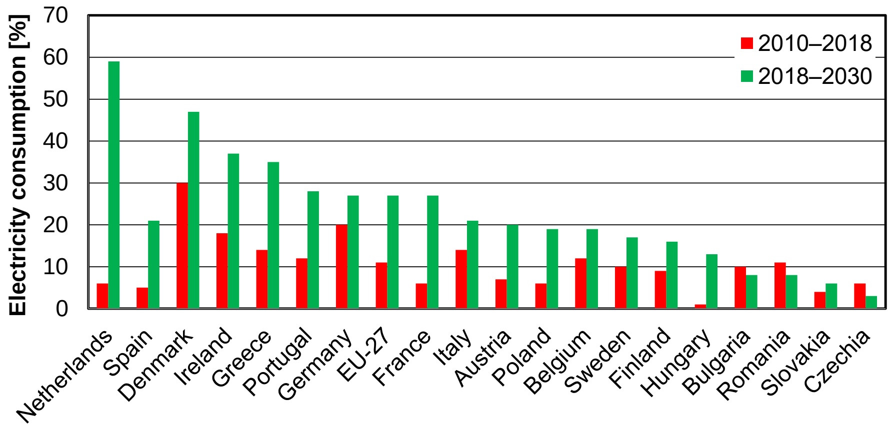

Figure 4. Renewables growth in Europe 2010–2018 and 2018–2030 [21]. Reprinted with permission from [21]. Copyright 2020, Ember.

3. Number of Particle Matters

The particle number (PN) problem has been recognized in the European Union for a long time. For this reason, the PN emissions of particles > 23 nm have been controlled, since 2011 for diesel vehicles and since 2014 for gasoline direct-injection vehicles [22]. Studies related to PN emissions are carried out all over the world. Korea is a case in point. In this case, to monitor the greenhouse gases and vehicle exhaust emissions from and establish emission factors for the transportation sector, National Institute of Environmental Research (NIER) test modes have been used for experimental test modes, because NIER test modes reflect driving patterns in Seoul. The test modes consist of 15 test cycles numbered from 0 to 15, and every single one takes into account diverse traffic conditions. According to the results, a significant impact on CO_2 and PN emissions was determined. In conclusion, it is highlighted that the most influential test condition over the whole range of test modes is the use of the air conditioner, in which both the CO_2 and PN emission levels increased. One of the test modes tested the impact of the starting temperature parameter. A cold engine start requires sufficient time for the warming-up process of the engine and aftertreatment systems that reduce harmful exhaust gases. Because the air–fuel ratio becomes richer, and the spark timing is delayed, the PN emission level increased by approximately three times and the CO_2 emission level increased by 6.1%, compared with those under a warmed-up engine start. The PN emission results also increased from 6.65×10^{11} #/km to 2.86×10^{12} #/km, and most of the increase occurred in phase, which included the engine start and warming-up processes.

The laboratory-type approval of vehicles was augmented by on-road real-driving emissions testing with portable emissions measurement systems (PEMS) [23]. PEMS, due to their small size and simpler design, may have higher measurement uncertainty compared to laboratory-grade equipment [24]. PEMS measure undiluted exhaust gas with all the associated challenges [25].

In contrast to studies assessing instruments for ambient air or personal exposure, the assessment of PN PEMS is limited [26]. The studies gave maximum differences of 50% (light-duty) [27] to 65% (heavy-duty) [28] to the laboratory systems, for the majority of cases. This measurement uncertainty is taken into account when the vehicles are assessed on the road.

The authors of [29] focused their research on measuring PN below 23 nm, emitted from a spark-ignition DI/PFI engine using an EEPS system connected to a sample conditioning device. The engine was fuelled with ethanol, both pure and a 30% blend. The bulk of the emissions were shown to consist of PN smaller than 23 nm, and the number of particles varied with fuel, injection strategy, and operating conditions. The authors note that a cold start does not increase the emissions of small-sized nanoparticles.

Another paper [30] studied the emissions of PN larger than 10 nm and 23 nm in a WLTC test and in real traffic conditions, using two particle counters (PNCs). They showed that PN_{10} emissions were 32% and 15% higher than PN_{23} in Worldwide harmonized Light duty vehicles Test Cycle (WLTC) and laboratory RDE cycles, respectively.

In [31], the researchers studied a gasoline direct-injection vehicle using two reference particle-count-measurement systems. The tests were conducted at several certified laboratories, which conducted measurements using their own nanoparticle-emission-measurement systems. They found that the vehicle's emissions (from cold and hot starts) ranged from 1 to 15 $\times$ 10^{12} #/km, with a 10%–50% ratio of particles smaller than 23 nm in diameter compared to those larger than 23 nm.

At the same time, in recent studies of hybrid vehicles, for example, the authors of [32] point out that a cold start is important for testing particles with diameters smaller than 23 nm. A plug-in hybrid diesel vehicle meeting the Euro 6d standard was tested. The gaseous emissions in the laboratory and on various test routes were less than the requirements of the standard; however, emissions of N_2O and PN smaller than 23 nm were higher during a cold start in road tests.

The cited data from various studies demonstrate the significant problem of testing particulates in the range of less than 23 nm, but insufficient consideration has been given to the issue holistically. What would be required would be a comparison of several vehicles with different power systems in terms of particulate emissions, primarily under actual traffic conditions. This approach also means that comparisons have been made for vehicles that are currently in use, and their usefulness is confirmed by public interest.

4. Purpose of the Article

The purpose of this article is to evaluate the comparative amount of particulate matter in all parts of the RDE test (cold start, urban driving, rural driving, motorway driving) of vehicles characterized by different types of propulsion units that are currently used on the market. Among the cars tested, the main focus was on the variety of drive units: gasoline, diesel, mild hybrid, and plug-in hybrid. The tests were carried out under real traffic conditions, using a PEMS-PN type measuring apparatus to measure the number of particulate matter and, in addition, to determine the concentration of selected exhaust pollutants (carbon dioxide) and exhaust flow rate.

An additional objective was to determine an index that would characterize the number of particulates, according to their diameter, produced by vehicles, in relation to the content of particulates in the air. This is a new issue that has not been previously considered in publications by other authors.

5. Methodology

5.1. Test Objects

Four passenger cars were used for the study. Each was characterized by a different powertrain; however, the cars had relatively similar engine displacements and power indicator. Selected technical data of the test objects are listed in Table 1.

5.2. Road Test–Description

The test subjects have been tested in real traffic conditions. The research route was in Poznan and its vicinities. It was determined according to the EU-wide directive, which contains all the guidelines [33,34]. Thus, the road was planned in such way that it included a cold-start procedure, as well as urban, rural, and motorway sections. What is worth emphasizing is that the tests were performed on the same day (in respective driving modes). One driver drove the vehicles, with the same load (driver, passenger, and measurement equipment). The test subjects have been tested in real traffic conditions.

The RDE test route was selected in accordance with the requirements of the standard (Package 4), in which the basic requirements for the different parts of the test are as follows:

- urban: a maximum driving speed of up to 60 km/h, a minimum distance of 16 km, and a share of about 34% of the total (±10%);
- rural: speed range 60–90 km/h, minimum distance of 16 km, and a share of about 33% of the total (±10%);
- motorway: speed range above 90 km/h, minimum distance of 16 km, and a share of about 33% of the total (±10%).

Table 1. Selected technical data of research objects.

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Powertrain	Conventional	Conventional	Mild hybrid	Plug-in hybrid
Fuel type	Gasoline	Diesel	Gasoline	Gasoline and electric
Engine capacity	1591 cm^3	1685 cm^3	1497 cm^3	1999 cm^3
Cylinders/valves	4/16	4/16	4/16	4/16
Injection system	Direct	Direct	Direct	Direct
Maximum power	132 kW 5500 rpm	104 kW 4000 rpm	135 kW 5800 rpm	151 kW 6000 rpm
Maximum torque	265 Nm 1500–4500 rpm	340 Nm 1750–2500 rpm	280 Nm 1200–4000 rpm	375 Nm 2330 rpm
Maximum power of electric motor	–	–	–	49 kW 2330–3300 rpm
Maximum torque of electric motor	–	–	–	205 Nm 0–2330 rpm
Power indicator (power/displacement)	83 kW/dm^3	62 kW/dm^3	90 kW/dm^3	76 kW/dm^3
Battery capacity	–	–	1.2 Ah	31.3 Ah
Empty vehicle weight	1465 kg	1515 kg	1430 kg	1740 kg
Exhaust emission standard	Euro 6d, GPF	Euro 6d, DPF, SCR	Euro 6d	Euro 6d

The tests were repeated 3 times on the same measuring route (without changing the direction). The final values of emissions did not differ by more than 10%. The values shown in the article are representative values for the given parameter category.

5.3. Measurement Equipment

The exhaust emission levels from the tested vehicles were analysed with the use of SEMTECH DS portable system by Sensors Inc. The device was placed in the vehicle, and a flowmeter was connected to the exhaust unit to measure the exhaust flow levels (selected depending on the engine displacement).

The device is equipped with analysers, through which it is possible to measure the concentration of such substances as carbon dioxide, carbon monoxide, hydrocarbon, nitrogen oxides (including nitric oxide and nitrogen dioxide), oxygen, and exhaust mass intensity. Each analyser has a different range and accuracy. A nondispersive infrared analyser is used to measure carbon dioxide concentration, which has a measurement range of 0% to 20% and a measurement accuracy of 2.5%. Other analysers of the system not used during the tests are a flame ionization detector to measure hydrocarbon concentration, a non-dispersive ultraviolet detector to measure nitrogen oxides, and an electrochemical analyser to measure oxygen concentration. The flue gas flow rate is measured from 0 kg/h to 500 kg/h, with an accuracy of ±1% [35].

Data from the vehicle's diagnostic system, GPS, ambient temperature, and pressure measurement system were also recorded. Those values are recorded with 1 Hz frequency; thus, it is possible to observe dynamic changes in the concentration of harmful substances in exhaust gases [35].

EEPS spectrometer was second used device. Particles enter the instrument as part of the aerosol inlet flow through a cyclone with a 1 µm cut. Next, the particles pass through an electrical diffusion charger, in which ions are generated. These mix with the particles and electrically charge them, to provide a predictable charge level based on particle size.

The charger is mounted in-line with the analyser column and is located at the top of the instrument. Particles then enter the sizing region through an annular gap, where they meet a stream of particle-free sheath air. The sizing region is formed by the space between two concentric cylinders. The outer cylinder is built from a stack of sensing electrode rings that are electrically insulated from each other. The electrodes are connected to a very sensitive charge amplifier, also called an electrometer, with an input near ground potential. The inner cylinder is connected to a positive high voltage supply, which forms the high voltage electrode. This creates an electric field between the two cylinders. While the positive-charged particles stream with the sheath air from the top to the bottom of the sizing region, they are also repelled from the high voltage electrode and travel towards the sensing electrodes. Particles that land on the sensing electrodes transfer their charge. The generated current is amplified by the electrometers, digitized, and read by a microcontroller. The data are processed in real time to obtain 10 particle size distributions per second [36].

6. Results

6.1. Test Requirements

The tests of the described vehicles were performed under real traffic conditions (RDE). All of them were conducted at a similar time and in similar weather conditions. During the tests, the driver was the same, which excluded the influence of different driving styles on the realization of the tests and their results. The realization of the sample tests, i.e., the waveforms of driving speed as a function of road, is shown in Figure 5. The figures show differences in the speed waveforms for the individual tests; however, the analysis performed after the test was fully executed, so did not disqualify any of them—the parameters for the tests were within acceptable limits (according to the standards).

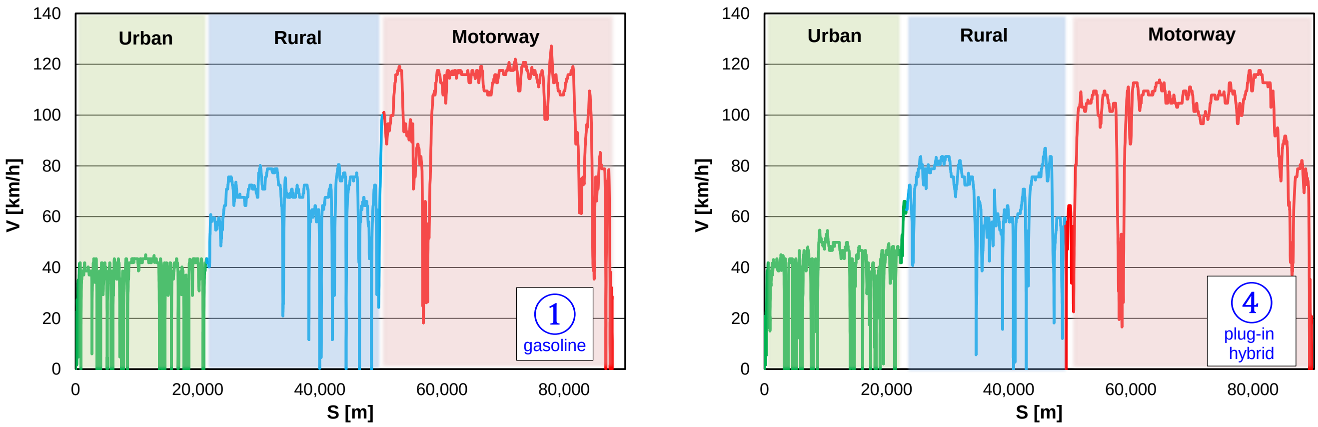

Figure 5. Implementation of the RDE test for vehicles 1 and 4—the course of speed as a function of distance; 1—gasoline, 4—plug-in hybrid.

Moreover, a comparison of the shares of driving speed and acceleration (made for a broader presentation of the similarity of the test results) made it possible to conclude that they were in good agreement. This was additional evidence for the possibility of comparing the results, that is, for further analysis of the obtained test results (Figure 6). The characteristics shown in the figures make it clear that the largest share of vehicle work is in stopping the vehicle (a share of 13%–16% of the total test time) and vehicle speed in the range from 12 m/s to 15 m/s (43–54 km/h). The speed ranges for the other acceleration values were also characterized by considerable similarity.

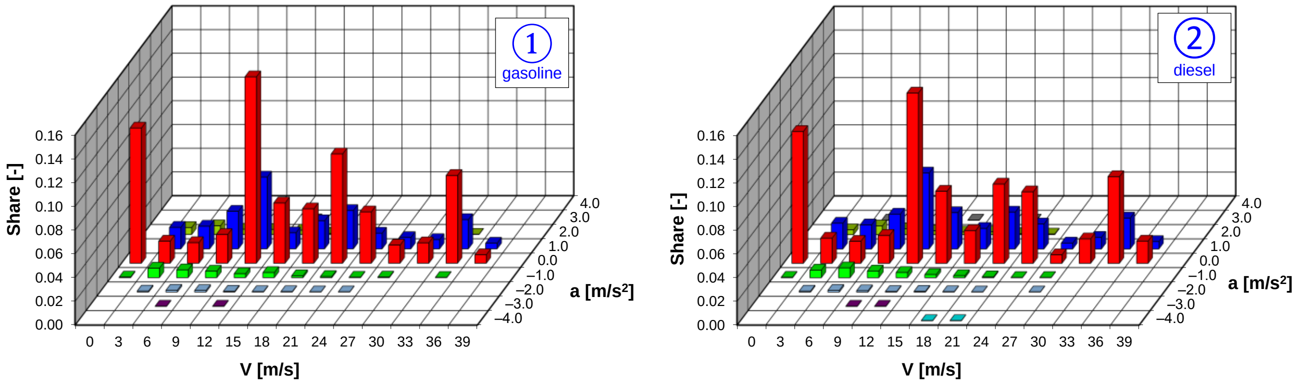

Figure 6. Comparison of the share of the vehicle's operation in the velocity–acceleration coordinates for vehicles 1 and 2; 1—gasoline, 2—diesel.

6.2. Dynamic Parameters of Tests

To be valid, an RDE test must be carried out within specified boundary conditions, with respect to overall test characteristics as well as traffic dynamics. To assess traffic dynamics, two requirements have been introduced in the RDE legislation: the 95th percentile (P95) of $v \cdot a_{pos}$ (for $a_{pos} \geq 0.1$ m/s^2) and the average RPA. The parameter $v \cdot a_{pos}$, the product of vehicle speed and positive acceleration, is commonly used as an indicator for high(er) dynamics of a trip, and RPA, the relative positive acceleration, is used an indicator for the lack of dynamics in a trip. These two RDE trip dynamics parameters are determined in three speed bins, i.e., the 'urban' (below 60 km/h), the 'rural' (60 to 90 km/h), and the 'motorway' speed bins (above 90 km/h). With the average speed per speed bin, the result is three pairs of an average speed and a dynamics parameter [37] (Figures 7 and 8).

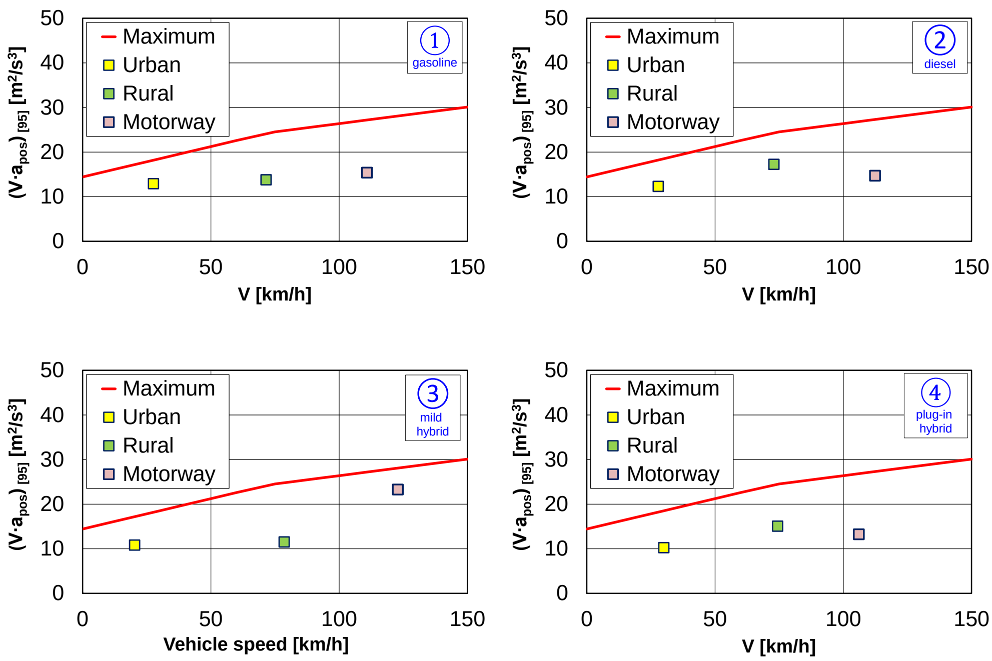

Figure 7. Values of driving dynamics parameters P95 of $v \cdot a_{pos}$ compared to the RDE limits for P95 of $v \cdot a_{pos}$ for vehicle 1–4; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

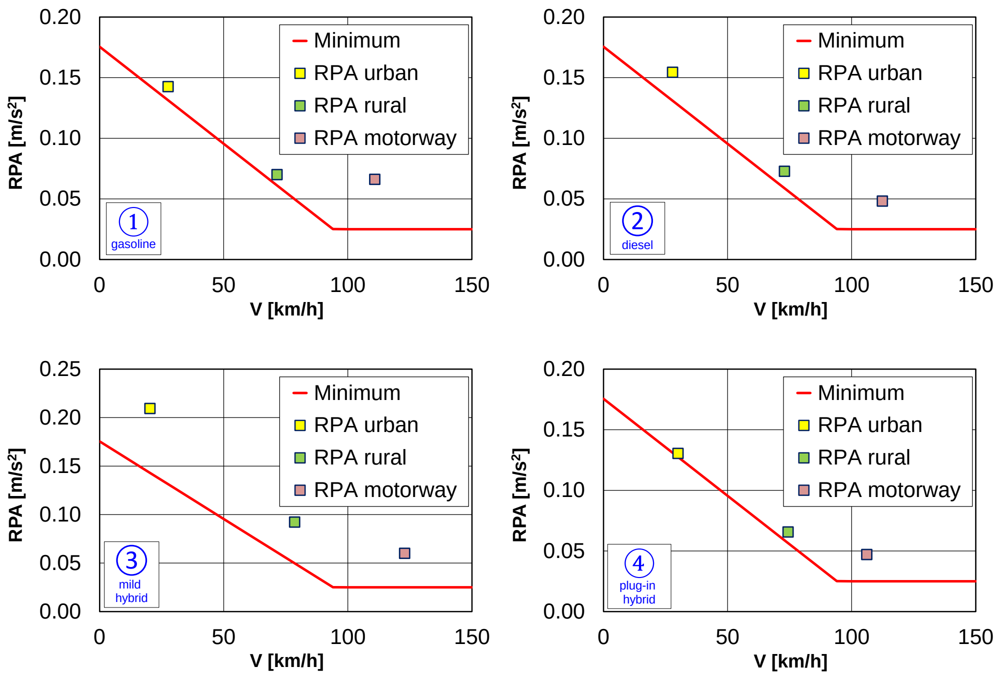

Figure 8. Values of relative positive acceleration compared to the RDE limits for average RPA for vehicle 1–4; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

For the vehicles tested, their driving dynamics were similar. None of them exceeded the permissible values, falling within the allowed range. Among the differences, slightly higher driving dynamics can be noted for vehicle 1 compared to the other vehicles. Vehicle 4, on the other hand, had the lowest value of the RPA parameter in the urban part. Moreover, in the rural and motorway parts, vehicle 4 had slightly lower driving dynamics compared to the other vehicles tested. The differences, which are normal for RDE tests, were not so large that they were considered similar to each other.

6.3. Comparison of Particle Number Distribution for Each Part of the RDE Test

In tests of vehicles under real-driving conditions, the dependence of the number of particulates and their aerodynamic diameters were recorded. Depending on the type of propulsion system used in the vehicles, the particles were of different sizes, and their numbers depended on the parts of the RDE test. The following parts of the RDE test were analysed:

- cold start—the period of the first 300 s after the engine is started (for a plug-in hybrid vehicle—the engine was started in the middle of the test);
- urban part of the RDE test (including the start-up period);
- motorway part of the RDE test;
- the whole RDE test.

Analysis of the data obtained showed that the highest concentration of the number of particles occurs during cold start—regardless of the type of vehicle tested. However, there are differences in their number of particles (#) and in their size (diameter size). For vehicle 1 (gasoline) (Figure 9, ①), during cold start, the highest number of particles was located in the 80–100 nm range. For vehicle 2 (diesel) (Figure 9, ②), the highest concentrations occurred for particles between 40 nm and 60 nm in diameter. Hybrid vehicles were characterized differently: for the mild hybrid (Figure 9, ③), the values were from 40 nm to 60 nm, with a concentration of about 20,000 #/cm^3. In contrast, for the plug-in vehicle, the particle concentration was about 28,000 #/cm^3, which was due to the internal combustion engine being turned on during high-speed operation (Figure 9, ④). This was the first engine start-up, so the particle concentration due to significant engine load was about 50% higher than for other vehicles, where engine start-up occurred at idle—without significant engine load.

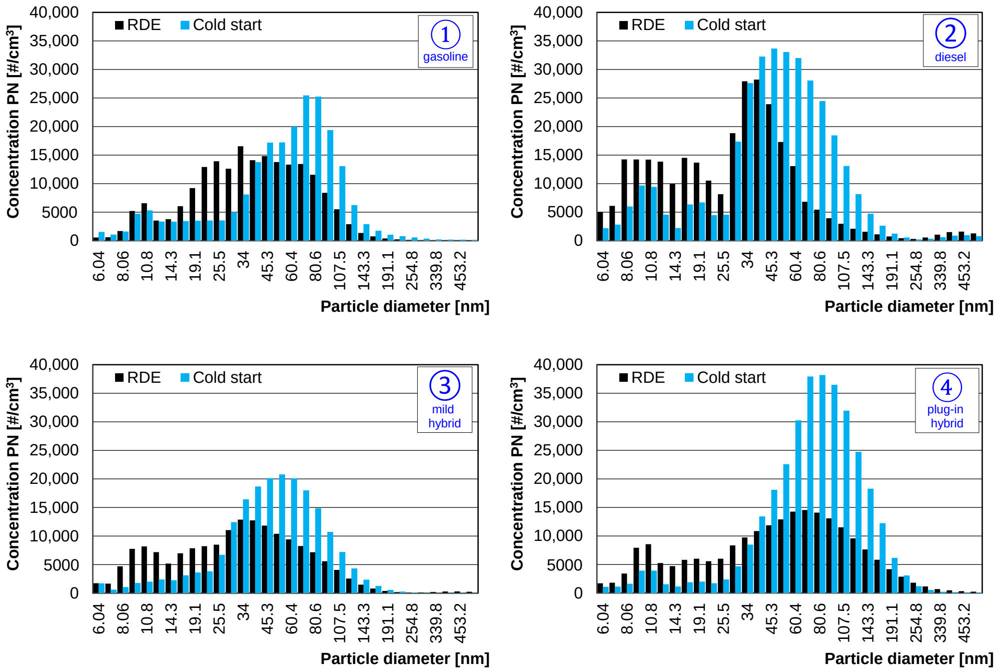

Figure 9. Number distribution of particulate matter for vehicles 1–4 in the cold start phase of the engine against the values obtained during the whole test; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

The analysis of the concentration of the number of particles in the different parts of the RDE test is also not insignificant. Examination of individual parts showed significant differences in their concentration and characteristic diameter (found in the highest concentration) depending on the powertrain. In the case of vehicle 1 (gasoline) (Figure 10, ①), a significant increase in the number of particles ranging from 19 nm to 34 nm is evident for motorway driving. A smaller number of particles was recorded in the urban and rural parts (with dominant diameters in the 60–100 nm range).

A different distribution of the number of particles occurred for vehicle 2 (diesel) (Figure 10, ②), for which a lower concentration of particles and a shift of their characteristic diameter to the left, towards smaller diameter values, were observed (mainly by the effective operation of the particle filter).

Other characteristics were observed for hybrid vehicles. For the mild hybrid vehicle (Figure 10, ③), in which the internal combustion engine shut down very often during the urban phase, particulate concentrations were significant mainly due to engine cooling at standstill. Such cooling of the engine and, with it, the exhaust aftertreatment systems has a major impact on the particulate matter emitted, obviously at the expense of reduced fuel consumption.

The plug-in hybrid vehicle in the RDE test started driving using its electric motor, and its internal combustion engine was only switched on during the off-road portion (Figure 10, ④). This condition caused the internal combustion engine to start during high speed, so there was no time for the low-load warm-up phase of the engine. The increased load caused the average concentration of particulate matter in the rural section to be the highest of all vehicles, at around 10,000 #/cm^3. A consequence of the increased load was also the large diameter of the emitted particles, which were in the range of 80 nm to 100 nm.

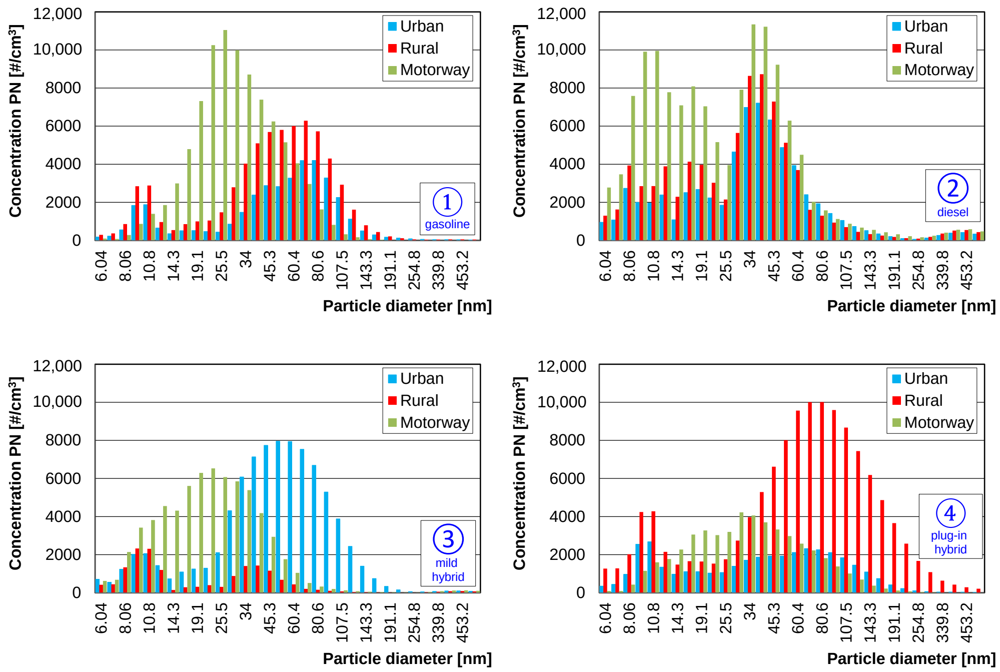

Figure 10. Dependence of particle number concentration on particle diameter for vehicles 1–4 in different parts of the RDE test (urban, rural, motorway); 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

7. Discussion

In order to compare the obtained results of particle number concentration in different phases of the test to the value of their concentration in the surrounding air (in particular diameter ranges), the authors proposed a dimensionless index. It denotes the multiplicity of the increase in the particle number concentration, under the given measurement conditions, to the value of the particle number concentration in the ambient air, for a particular particle diameter. Since one is comparing quantities that change linearly over a very wide range, and relative changes are of most interest, this ratio is described by the formula:

$$L = 10 \log (PN_{E,D}/PN_{A,D}) \text{ [dB]}, \quad (1)$$

L—particle number change indicator [dB];
$PN_{E,D}$—concentration of the number of D-diameter particles in the exhaust gas [#/cm^3];
$PN_{A,D}$—concentration of the number of particles of diameter D in the air [#/cm^3].

On the basis of the comparison, it was found that the characteristic of gasoline and diesel engines is that, during a cold start of the engine, the concentration of the number of particles with diameters around 100 nm increases more than 300 times (L = 25 dB), in relation to the content in the air. In contrast, during the entire RDE test, the concentration of the number of particles with diameters between 25 nm and 100 nm increases 30 to 100 times (L = 15 dB and 20 dB, respectively) (Figure 11, ①, ②). For the mild hybrid vehicle, the increase in the number of particles was the smallest amounting to 2–3 dB, which translates into the fact that during a cold start-up of the engine, the number of particles of given diameters increases by 100% (Figure 11, ③). Such a relationship is mainly dictated by the fact that the cold start of the engine occurs (as in conventional engines) during the initial period of driving the vehicle. Therefore, the nature of changes in the number of particles as a dependence on their diameter is very similar to a conventional vehicle powered only by an internal combustion engine. The comparison of the particle spectrum is different for a plug-in hybrid vehicle, in which the cold start occurred during the rural phase of the RDE test. Such a start-up at a very low SOC (state of charge), during an increased driving speed, forced a high load on the engine, resulting in an increased particulate number. This increased particle count (for diameters of 30–150 nm) was characteristic throughout the test, which was a consequence of the engine starting in the rural phase (Figure 11, ④).

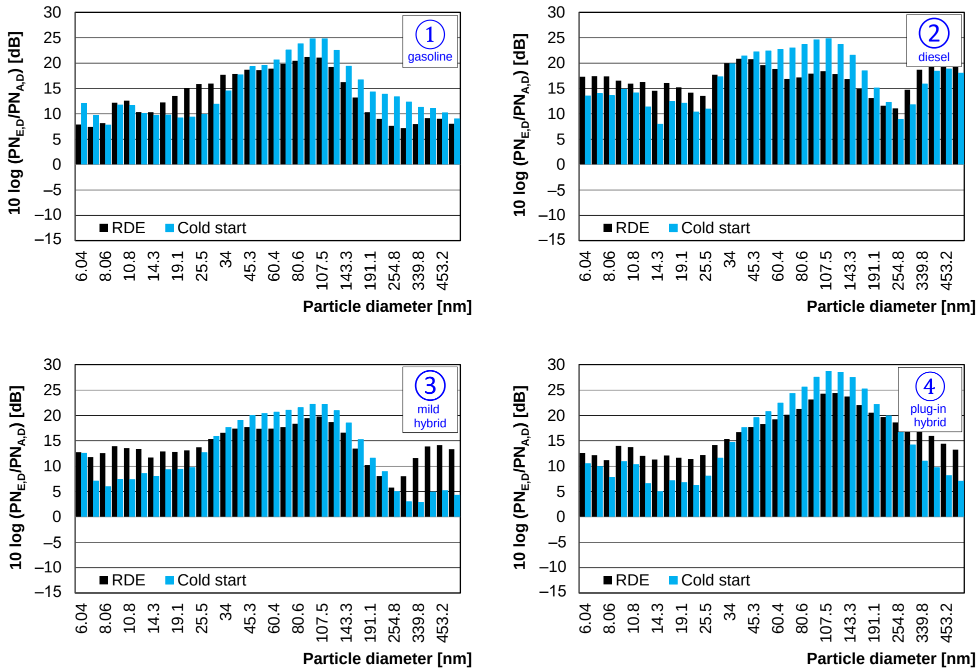

Figure 11. Particle number increase rate for vehicles 1–4 in the cold start phase of the engine and throughout the RDE test; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

This indicator was used to determine the increase/decrease characteristics of the number of particulates in the different phases of vehicle testing: during the cold start of the internal combustion engine in the urban, rural, and motorway parts of the RDE test. A very important informative factor of the indicator is that its negative values show the cleaning function of the vehicle—the number of particles of given diameters emitted from the vehicle is less than the number of particles in the air. This effect is very evident for a gasoline-powered vehicle during the motorway phase (Figure 12, ①), where the concentration of particles from the vehicle is 30 times smaller than in the air. For the other vehicles, such a large effect was not recorded, with only a very small similar correlation for the plug-in hybrid vehicle. For the conventional diesel-powered vehicle (Figure 12, ②), similar particle increase rates were recorded for all phases of the test for the entire range of their diameters. Only the urban phase is notable here, in which this increase was about 15 dB for particles in the 6–20 nm range, confirming the attention paid to this fact by other authors. At the same time, this phase has a very large impact on particle emissions throughout the test, which is also taken into account in the RDE regulations, which now mandate compliance with the requirements for emission factors in the urban part of the RDE test and throughout the test.

Particle increase rates for hybrid vehicles were of a different nature. For the mild hybrid vehicle, the urban phase was characteristic, with large indicator values (about 15–20 dB for particles with diameters of 30–150 nm) (Figure 12, ③). This was the effect of the urban phase, in which the frequency of engine starting was the highest, and, at the same time, the acceleration value was the highest. This resulted in the formation of large-diameter particles as a result of short-term increased engine load. The effect of running the plug-in hybrid vehicle's engine in the extra-urban part is very evident from the particle-count-increase graph (Figure 12, ④). Starting the internal combustion engine at speeds in excess of 60 km/h with a significant engine load resulted in the formation of particles with very large diameters, the number of which is several times greater than in the other phases. This results in the fact that, despite the reduction in particulate matter in plug-in hybrid vehicles in the urban part, unfortunately, during trips on longer routes, the environmental aspects are not satisfactory. During high-speed driving, when the internal combustion engine turns on when the SOC is approaching its minimum value, the particulate emissions are significantly higher than the other types of vehicles.

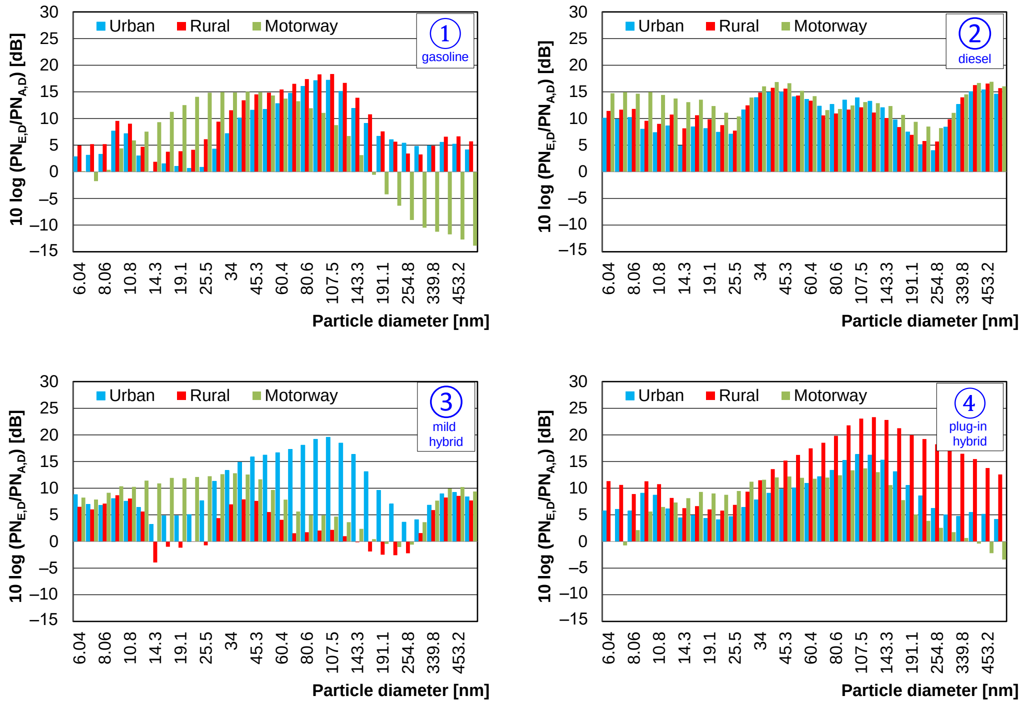

Figure 12. Particle number increase rate for vehicles 1–4 in each part of the RDE test (urban, rural, motorway); 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

When considering the total number of particulates from the studied vehicles, it should be noted that the vehicles were characterized by similar levels of values, which makes it possible to conclude that they have similar environmental values. However, a detailed analysis shows that the number of particulates emitted in each phase is significantly different for the vehicles studied. For a conventional gasoline-powered vehicle (Figure 13, ①), the proportion of particulate matter (D > 23 nm) in the test phases was as follows: urban—2%, rural—4%, and motorway—94%. This means that by far the largest share of particulates is emitted in the motorway phase, where the exhaust gas flow rate is the highest; though, at the same time, based on Figure 12, ①, it should be kept in mind that the particulate filter used reduces the largest particulates produced in this test phase. A similar proportion of particles was observed in other measurement ranges, with an increase in the number of particles for the larger measurement range. For particle diameters D > 19 nm, the increase was 10%; for D > 10 nm, the value was 25% greater; and for particles with a diameter of D > 5 nm, the number of particles was 27% greater than the reference measurement (D > 23 nm).

The total number of particulates for a conventional diesel-powered vehicle was lower compared to a gasoline-powered engine, at $1.25{\cdot}10^{13}$ units. Moreover, the proportion of particulates in the different phases of the test was different, which may be due to the effectiveness of the particulate filter for such an engine and the entire exhaust aftertreatment system. In the urban phase, the share was 40%; in the rural phase, the share was25%; and in the motorway phase, the share was 35%. Similar proportions of shares were also maintained when considering the number of particulates for other diameter measurement ranges (Figure 13, ②). For diesel-powered vehicles, it is very important for the initial range of particle diameters to be considered; for particle diameters D > 19 nm, the increase was 9%; however, already for D > 10 nm, the value was 97% higher, and for particles with a diameter of D > 5 nm, the number of particles was 183% higher compared to the reference measurement (D > 23 nm). This means that for diesel-powered vehicles, the proportion of particles with very small diameters (D < 10 nm) is significant, while at the same time the filtration efficiency of such particles is very low.

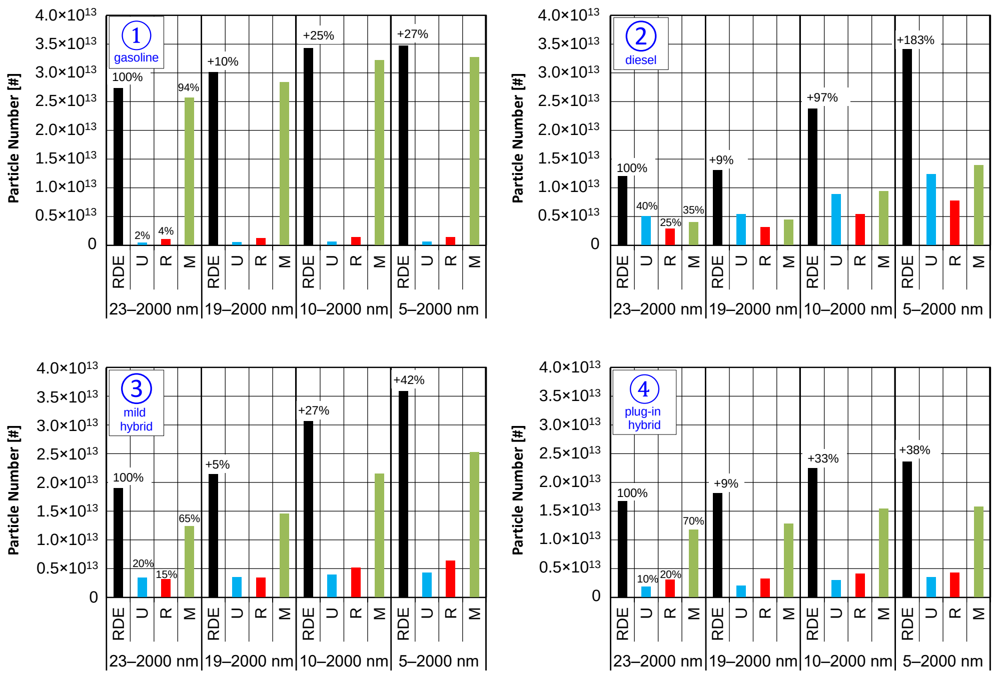

Figure 13. Total number of particles for vehicles 1–4 in the RDE test and its individual parts (urban, rural, motorway), along with a division of the diameters considered; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

For the mild hybrid vehicle (Figure 13, ③), particle number values were obtained that were consistent with the type of engine used. The overall nature of the changes in the evaluated parameters was similar to the gasoline-powered engine. However, the use of an electric motor in this vehicle reduced the total number of particles (1.8×10^{13} units), compared to vehicle ①. The proportion of particulate matter by phase was more similar to the gasoline-powered vehicle (urban—20%, rural—15%, motorway—65%). Moreover, the number of particles similarly increased when the initial particle diameter was taken into account. For particle diameters D > 19 nm, the increase in the number of particles was 5%; for D > 10 nm, the number of particles was 27% higher; and, for particles with a diameter of D > 5 nm, the number of particles was 42% higher, compared to the reference measurement (D > 23 nm).

The particle count values for the plug-in hybrid vehicle (Figure 13, ④) were similar to the previous hybrid vehicle (with a similar internal combustion engine used). However, the reduced proportion of internal combustion engine operation throughout the test reduced the overall particle count ($1.6 \cdot 10^{13}$ units), compared to the ③ vehicle. The proportion of the number of particulates in each phase was similar to the mild hybrid vehicle and was 10% in the urban phase, 20% in the rural phase, and 70% in the motorway phase. The number of particles was higher when the initial particle diameter value was smaller. For particle diameters D > 19 nm, their number was 9% higher; for D > 10 nm, the value was 33% higher; and, for particles with a diameter of D > 5 nm, the number of particles was 38% higher compared to the reference measurement (D > 23 nm).

On this basis, it can be concluded that the particle emissions with diameters smaller than 23 nm are significant in motor vehicles powered by internal combustion engines, regardless of whether they are conventional or hybrid vehicles. The share of particles with diameters of less than 5 nm is:

- For diesel engines: about 200% of the number of particles with D > 23 nm;
- For gasoline engines: about 30%–40% of the number of particles with D > 23 nm.

The research carried out allowed for estimating the particle count contribution to RDE tests of conventional and hybrid vehicles depending on the test phase, the cold start phase, and the initial diameter of the particles considered. Consideration of the initial diameter of particulate matter is important in terms of the introduction of future regulations for exhaust gas toxicity tests. A reduction in this diameter will result in a significant increase in the number of particles, which may cause the conformity factor (CF) values for the number of particles to be exceeded. Such a comparison against the tests performed is shown in Figure 14, which shows that a conventional gasoline-powered vehicle exceeds (CF_{PN} = 1.5) only in the motorway phase, when considering particles with initial diameter D < 19 nm (Figure 14, ①). The provision of CF_{PN} = 1, which should be in effect from Euro 7 onward, is also met under all conditions.

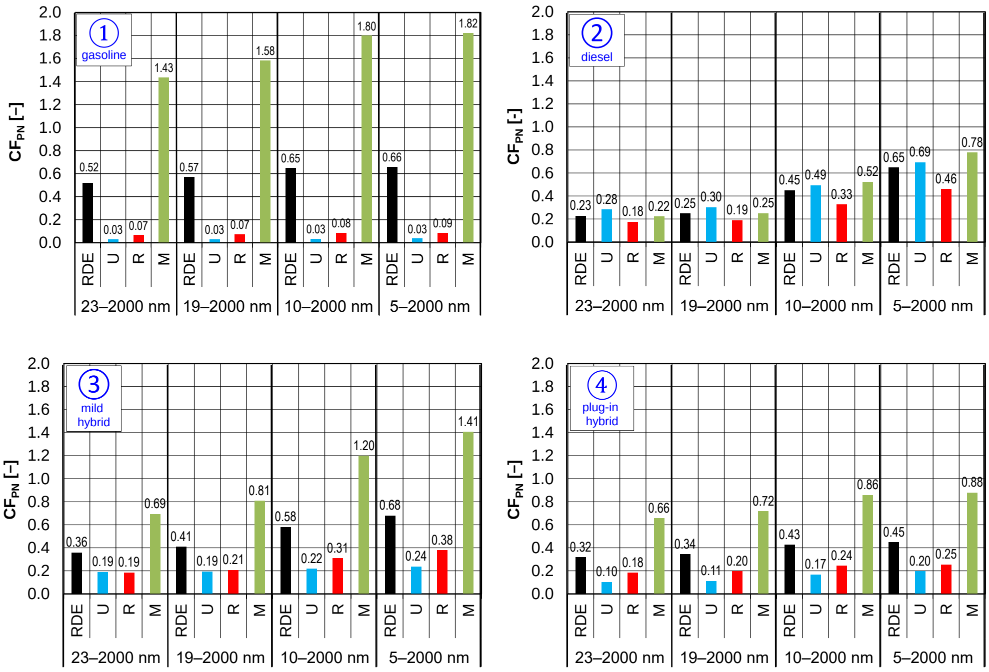

Figure 14. Conformity factor for the number of particles for vehicles 1–4 in the RDE test and its individual parts (urban, rural, motorway), along with a division of the diameters considered; 1—gasoline, 2—diesel, 3—mild hybrid, 4—plug-in hybrid.

For a vehicle equipped with a diesel-powered engine, the CF_{PN} values are always less than 1 (Figure 14, ②). This means that the exhaust after-treatment systems on such vehicles do their job regardless of the test phase and allow them to meet the requirements for small particles. Although the increase in the number of particles with diameters below 23 nm is significant (almost three times the number), the very small value of particles with diameters over 23 nm results in them not exceeding their emission limits (CF_{PN} = 0.78—in the worst case).

As for the mild hybrid vehicle (Figure 14, ③) a similar relationship is observed as for the gasoline-powered vehicle, which is as expected. The CF index is met in each case for the entire RDE test (CF_{PN} = 0.36–0.68) and for the urban phase (CF_{PN} = 0.19–0.24), regardless of the consideration of the initial particulate measurement diameter. Only in the rural phase were two cases of exceeding the value equal to 1 (CF_{PN} = 1.2 and 1.42) observed, when testing for particles with a diameter of D > 10 nm and D > 5 nm, respectively.

Conformity factor values for the plug-in hybrid vehicle (Figure 14, ④) represent a compromise between the mild hybrid vehicle and the conventional gasoline-powered vehicle. The CF index takes values less than 1, for all cases considered—for the entire RDE test (CF_{PN} = 0.32–0.45) and for the urban phase (CF_{PN} = 0.10–0.20). This means that despite running the engine under the conditions of significant internal combustion engine load and speed, emission factors with regard to particulate matter are not exceeded.

8. Conclusions

The major conclusions of the paper can be summarized in the following points:

1. The highest concentration of the number of particles (for D = 30–100 nm) occurs during cold start—regardless of the type of vehicle tested.
2. The article determines an index that characterizes the number of particulates according to their diameter produced by vehicles, in relation to the content of particulates in the air. The value of the index is:
    - for a gasoline engine: L = 20 dB (for RDE test) and L = 25 dB (for cold start); it is for the diameter of particles D = 60–120 nm;
    - for a diesel engine: L = 20 dB (for RDE test, D = 30–60 nm) and L = 25 dB (for cold start, D = 100–120 nm);
    - for a mild hybrid: L = 15–20 dB (for RDE test, D = 30–120 nm) and L = 20–22 dB (for cold start, D = 60–140 nm);
    - for a plug-in hybrid: L = 20–25 dB (for RDE test, D = 70–150 nm) and L = 25–30 dB (for cold start, D = 80–150 nm).
3. Particle emissions with diameters smaller than 23 nm are significant in motor vehicles powered by combustion engines, regardless of whether they are conventional or hybrid vehicles. The share of particles with diameters of less than 5 nm is 66% (for diesel engines) and 40% (for gasoline engines) of all the particles.
4. The conformity factor for the number of particles for a vehicle equipped with:
    - a gasoline-powered engine is three times higher in the motorway phase than in the overall RDE test;
    - a diesel-powered engine is similar in each phase of the RDE test;
    - a hybrid (mild and plug-in) powered engine is two times higher in the motorway phase than in the overall RDE test.

The studies carried out do not exhaust the issue under consideration but are only an indication of the possibility of assessing the number of particles as well as the dissonance between the parameters determined. Reducing the initial diameter of particulate matter in both type-approval and on-road tests will again involve changing the equipment and its approval for use; at the same time—which is the most negative effect—this will not reduce particulate matter emissions in cars already in use. All the achievements presented in the article concern vehicles approved according to the Euro 6d emission standard, while (using Poland as an example) 80% of vehicles (or more) are equipped with older engines, in which particulate emissions are many times higher than the considered measurement ranges. Therefore, the next aspect to be resolved is to assess the number of particulates from vehicles already in operation and take measures to increase the environmental requirements of vehicles at the stage of, for example, annual maintenance.

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Abbreviations

a	acceleration vehicle
A	air
b	road exhaust emission
CF	conformity factor
E	exhaust
FC	fuel consumption
FEV	Forschungsgesselschaft für Energietechnik und Verbrennungsmotoren
HEV	hybrid electric vehicle
ICE	internal combustion engines
L	particle number change indicator
M	motorway
NEDC	New European Driving Cycle
NIER	National Institute of Environmental Research
PEMS	portable emission measurement system
PHEV	plug-in hybrid electric vehicle
PN	particle number
PNC	particle counter
R	rural
RDE	real driving emissions
RES	renewable energy sources
RPA	relative positive acceleration
S	distance
SOC	state of charge
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

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