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The Assessment of PM2.5 and PM10 Immission in Atmospheric Air in a Climate Chamber during Tests of an Electric Car on a Chassis Dynamometer

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Abstract: Electric cars, like internal combustion vehicles, emit particulate pollution from non-exhaust systems, i.e., tires and brakes, which is included in the Euro 7 emission standard planned for implementation. Tests conducted on chassis dynamometers are accompanied by particulate emissions from non-exhaust systems, which are introduced into the ambient air on the test bench. Particulate emissions tests from non-engine systems on chassis dynamometers are mainly aimed at measuring the mass or number of particulates from tires and brakes. In contrast, little attention is paid to the immission of particulate matter from tires and brakes on the dynamometer during tests, which in the case of electric cars include, for example, measurements of energy consumption or range. Therefore, in order to draw attention to the problem of these emissions, the authors carried out measurements of PM2.5 and PM10 immissions into the air in the climatic chamber during tests of an electric car on a chassis dynamometer. The car tests were carried out in accordance with the WLTC (Worldwide harmonized Light duty Test Cycle) and at constant speed. Based on the test results, a model was proposed for the immission of particulate matter in laboratory air from tire and brake abrasion, taking traffic parameters into account. The results and the developed model show that air quality, in terms of particulate content, deteriorates significantly during testing.

Keywords: non-exhaust particle emissions; PEV testing; chassis dyno; air quality

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1. Introduction

Particulate matter is a pollutant that is dangerous to human health and other living organisms. The harmfulness of the particles is determined in particular by their size and chemical composition [1,2]. Due to the possibility of greater penetration into the human organism, particles of a smaller size, i.e., PM2.5, whose diameters are smaller than 2.5 µm, are more dangerous [1,3,4]. Motor vehicles driven by diesel and gasoline direct injection engines are important sources of particulate emissions [5–7]. However, the problem of particulate emissions is not related only to engine exhaust emissions but also affects all wheeled vehicles, taking particulate emissions from tire abrasion, road surfaces and brake mechanisms into account. Particulate matter from tire and brake abrasion contains, among other things, microplastics, heavy metals and a number of organic chemical compounds [8–10]. Air quality is not only affected by particulate matter but also by the emissions of other pollutants, including O_3, NO_X, VOC and SO_2, which are the subjects of numerous studies, including papers [11–14].

Electric cars have been declared emission-free. The gaseous and particulate emissions from these vehicles associated with electricity generation are, in their case, transferred to power plants. However, particulate emissions are not the only ones associated with exhaust gases, a fact that also caught the attention of lawmakers in the development of the Euro 7 standard, which also limits particulate emissions [15]. In the context of future environmental policy and the development of electric vehicles, the issue of non-exhaust emissions is becoming increasingly important.

The problem of dust emissions from tires, brakes and road surfaces has been the subject of many papers [16–26]. In them, the authors focused on the problem of measuring dust emissions from these non-engine sources under laboratory and road conditions [16].

Measuring dust emissions from brake pads is complicated by the fact that the dust spreads in different directions and is not easy to collect or measure. Traditional measurement methods, such as those used for exhaust gases, are not reliable. Potential measurement methods include:

1. Brake dynamometer: This laboratory device allows the simulation of brake operation under controlled conditions. With it, brake pad particle emissions can be measured during various braking scenarios [17].
2. On-road methods: These involve measuring brake pad particulate emissions directly on the road. For this purpose, vehicles are equipped with special devices to collect and analyze dust emitted during driving [18,19].
3. Laboratory analysis: Brake pad dust can also be collected and analyzed in the laboratory, which allows for the accurate determination of its chemical and physical composition [17,20,24].
4. Computer simulations: Modern technologies allow the modeling and simulation of brake pad dust emissions, which can contribute to a better understanding of the process and potential environmental impacts [21].
5. Airborne particle monitoring: Some studies use air quality monitors to measure the concentration of particles in the air near roads, which can provide some idea of brake pad dust emissions [22].

Each of these methods has its advantages and disadvantages, and the choice of the appropriate method depends on the purpose of the study and the resources available. Research in this area is still underway to develop more effective and accurate methods for measuring brake pad dust emissions. When testing the energy consumption and range of an electric passenger car, it is also important to evaluate the immission of particulate pollutants into the ambient air in a test chamber equipped with a chassis dynamometer. According to the authors, the research conducted fills a gap in this area. The authors of this article wish to point out the importance of their work for the health of workers performing tests on laboratory premises.

2. Materials and Methods

The tests were carried out on an AVL-Zöllner (AVL List GmbH, Graz, Austria) chassis dynamometer built in a climate chamber at the Laboratory of the Scientific Center for Automotive Ecology of the Rzeszow University of Technology. The basic technical data of the electric-powered autonomous car under test are summarized in Table 1.

Table 1. Technical data of the tested battery electric vehicle.

Parameter	Data
Year of production	2015
Maximum net power (kW)	107
Total torque (Nm)	250
Odometer (km × 1000)	34.3
Drive	Front
Transmission type	One-speed automatic 44H
Electric motor (traction)	Synchronous with permanent magnet
Maximum power of the electric motor (kW)	45
Maximum torque of the electric motor (Nm)	169
Traction battery	Lithium-ion Nominal Capacity 23.0 kWh
Test weight (kg)	1860

Table 1. *Cont.*

Parameter	Data
Tires: Triangle SporteX TH201 for summer season	215/55 R17 94Y
Tire tread depth (mm)	Front left 6.5 Front right 6.6
Tire pressure (bar)	2.5
Tires date of production	44th week of 2021
Tire mileage (km)	4600
Standard front-ventilated brake discs	287 × 25 mm
Brake pads	FORD standard
Road load force	
F0 (N)	260.365
F1 (N/km/h)	0
F2 (N/(km/h)^2)	0.05064

The tests were carried out for test cycles consisting of the WLTC 3b section, together with the urban section (Low + Medium) and for a driving section at a constant speed of 100 km/h. A view of the test cycle is shown in Figure 1.

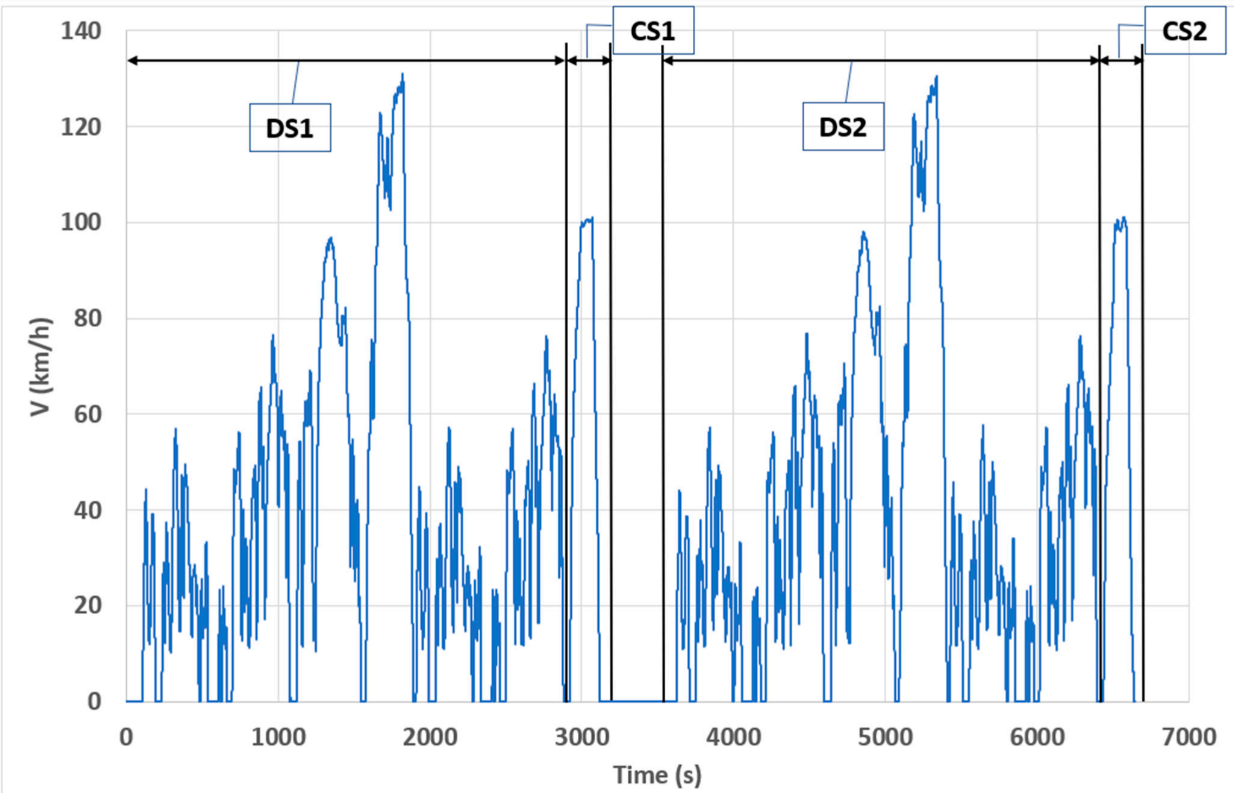

Figure 1. Research driving cycle: DS1—Dynamic speed segment 1, DS2—Dynamic speed segment 2, CS1—Constant speed segment 1, CS2—Constant speed segment 2.

The view of the car on the test stand is shown in Figure 2. Measurements of PM2.5 and PM10 were realized using DT-9881M (CEM Instruments, Kolkata, India) and SOWA (United Systems Ltd., Lublin, Polska) meters. The technical data of these meters are included in Tables 2 and 3. The sampling intake of the SOWA meter was placed at a distance of 0.3 m from the axis of the right front wheel at a height of 0.02 m above the floor. The DT-9881M meter was on a tripod at a distance of 1.5 m from the front axle wheels and at a height of 1.3 m. The particulate sensors used in both devices were subjected to comparative measurements, which showed a difference in PM10 concentration readings of no more than 3 μg/m^3 and 2 μg/m^3 for PM2.5 (average differences for 5 measurements).

Table 2. Technical data of the SOWA pollution meter.

Analyzed Parameter	Value
Type of PM2.5 Sensor	Laser
Resolution	±1 $\mu g/m^3$
Uncertainty	±10 $\mu g/m^3$
Measuring range	1–500 $\mu g/m^3$
Type of PM10 Sensor	Laser
Resolution	±1 $\mu g/m^3$
Uncertainty	±10 $\mu g/m^3$
Measuring range	1–500 $\mu g/m^3$

Table 3. Technical data of the DT-9881M particle meter.

Analyzed Parameter	Value
Type of Particle Sensors	Laser
Channel	0.3, 0.5, 1.0,2.5, 5.0, 10 μm
Flow Rate	0.1ft^3 (2.83 L/min) controlled by internal pump
Mass Concentration Channel	PM2.5: 0~500 $\mu g/m^3$; PM10: 0~500 $\mu g/m^3$
Uncertainty	±10 $\mu g/m^3$
Counting Efficiency	50% @ 0.3 μm; 100% for particles > 0.45 μm
Count Modes	Cumulative, Differential, Concentration

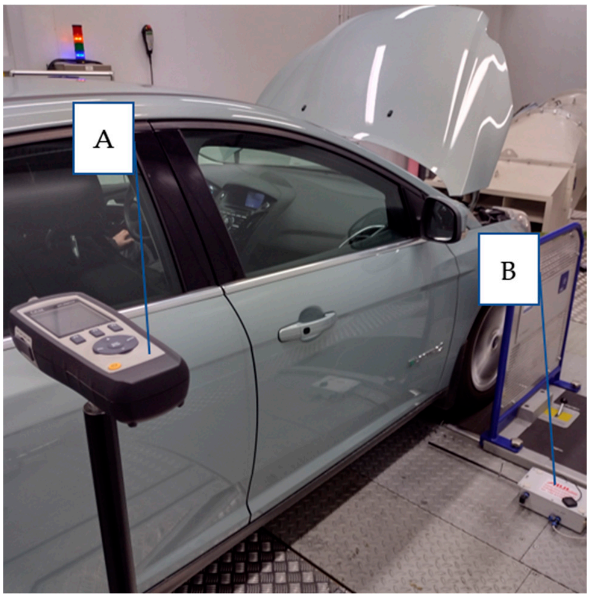

Figure 2. View of the test stand with dust meters marked: A—DT-9881M particle meter, B—SOWA pollution meter.

Measurements with the SOWA analyzer were carried out in a continuous system, with dust values recorded at a resolution of 1 Hz. Their purpose was to determine the relationship between the test parameters and the measured concentrations of PM2.5 and PM10 near the right front wheel of the car. The DT-9881M meter was used to measure the immission of particulate pollutants into the air at the test stand. Measurements with the DT-9881M meter included mass concentration and particle count with particle size in the diameter range of 0.3, 0.5, 1.0, 2.5, 5 and 10 μm. They were carried out before the start of the test and during the post-particle test: DS1, CS1, DS2 and CS2. The ambient temperature during the tests was 23 ± 3 °C. Laser particulate sensors work on the principle of scattering the laser light beam through particulate matter contained in the air forced to flow through the measurement chamber by a turbine pump. The laser beam flux falls on a highly sensitive photodiode. Depending on the diameter of the particle, the laser beam scatters, is reflected in the mirror and enters the detector, which makes it possible to determine the particle diameters. Thus, it is possible to determine the number of particles within a certain measurement range. The output signal of the photodiode is amplified and filtered and then the concentration of dust in the air is calculated on this basis with the help of a mathematical model. The results of the calculation are sent in the form of a digital signal to a microcontroller, which allows the results to be recorded and presented on an LCD display. The circuit diagram is shown in Figure 3.

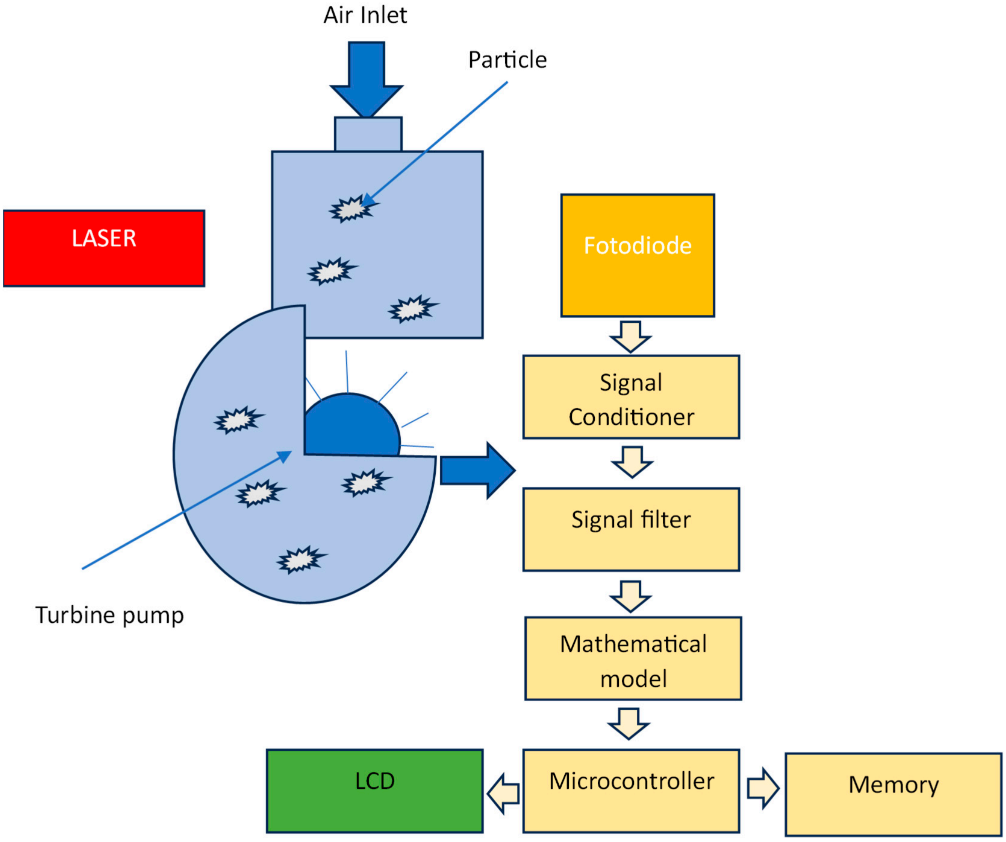

Figure 3. Diagram illustrating the principle of operation of the device for measuring PM concentration in air.

3. Results and Discussion

The results of the study made it possible to assess the change in the immission of particulate pollutants in the air and also to develop an estimated model of the immission of PM10 particulate pollutants associated with tire abrasion, roller surface and brake friction mechanisms. Detailed results are included in Sections 3.1 and 3.2.

3.1. Results of Dust Pollution Immission Measurements

The results of measuring the concentrations and number of particulate matter in the air at the test station in the climate chamber are graphically presented in the diagrams in Figures 4 and 5. Figure 4 shows the values of the average concentrations of dust pollutants in the air before the test (initial concentration), after the completion of the dynamic part of DS1, after the completion of the constant-speed phase of CS1, after the completion of the dynamic part of DS2 and after the completion of the second constant-speed phase of CS2. Each of these measurements was performed twice. Figure 5 shows a comparison of the average number of particles (#/dm^3) in each diameter range recorded with the DT-9881M meter at the same points as the measurements of particle concentrations, i.e., before the test (initial concentration), after completion of the DS1 dynamic part, after completion of the

CS1 constant-speed phase, after completion of the DS2 dynamic part and after completion of the second constant-speed phase.

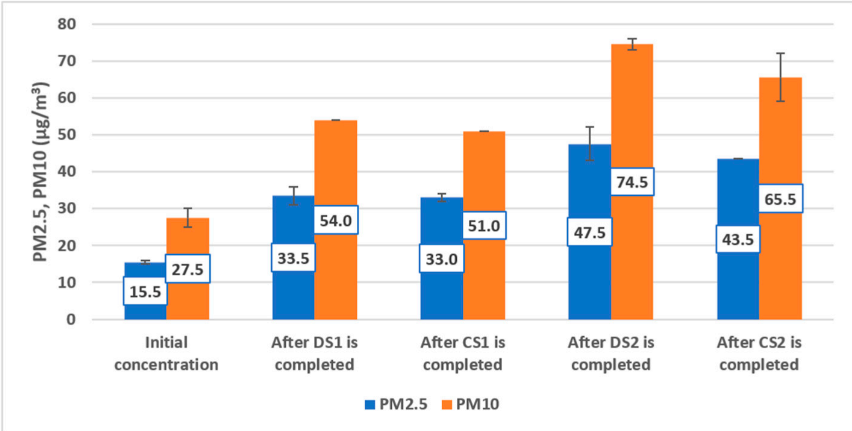

Figure 4. Change in PM2.5 and PM10 concentrations when measured with the CEM DT9881M meter (the values of the error bars in the graph refer to the differences between the maximum and minimum values).

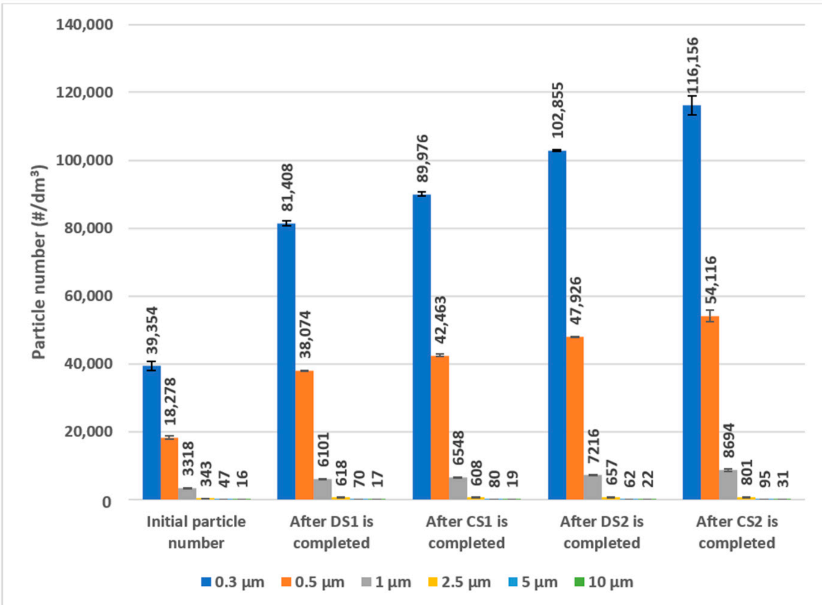

Figure 5. Change in particle number in air of laboratory when measured with CEM DT9881M meter (the values of the error bars in the graph refer to the differences between the maximum and minimum values).

Measuring tire and brake dust emissions is more difficult than measuring exhaust particulate emissions, mainly because the dust from tires and brakes disperses in many different directions and is more difficult to measure. Traditional exhaust measurement methods, such as placing a probe in the exhaust pipe, are not effective for particulate emissions from non-engine systems. Consequently, the results obtained refer to the immission of particulate matter into the air inside the laboratory, which comes not only from direct emissions from the non-motor systems of tires and brakes, but also from the surface of the road roller. In addition, particulate matter is lifted from the wall surfaces and the floor of the test stand due to airflow in the laboratory. The additional test, during which the speed of the car was zero while the speed of the fan corresponded to a maximum wind speed of 65 km/h (this is the highest speed possible at the stand for the selected fan), showed that concentration values due to resuspension increased by an average of about 3 µg/m^3 for PM10 and by about 4 µg/m^3 for PM2.5.

The results of measurements of PM2.5 and PM10 concentrations (Figure 4) showed that during the tests of the energy consumption and range of an electric car, their concentration in the air inside the laboratory increased over a large range. In the case of PM2.5 particles, the values of the initial average concentration at the test point (at a height of 1.3 m) were about 15.5 $\mu g/m^3$, while after the test, the concentration value reached about 43.5 $\mu g/m^3$. It can be seen that initially, after the completion of the DS1 part, the values of PM2.5 concentration (similarly PM10) were characterized by a very large increase. After the first constant-speed phase CS1, the values of PM2.5 and PM10 concentrations decreased slightly, confirming the low emission of dust particles from tire and brake abrasion during constant-speed driving. After the second dynamic phase of DS2, the concentrations increased noticeably and finally, after the entire test was completed, the concentration of PM2.5 particles increased by about 30% in relation to the concentration recorded after the first dynamic phase of DS1. Similarly, the concentration value of PM10 particles increased by about 21%. The large increase in the concentration of pollutants in the air during the first dynamic phase of DS1 may be related to the start of the tests from a cold start. The authors of the paper [23] observed that the increase in the concentration of tire-wear particles is influenced by the initial temperature of the tires, which was manifested by a significant increase in emissions during the first seconds of the driving cycle during tests from a cold start. The authors of this study justify this effect through the different mechanisms of tire-wear particle formation.

It is worth noting that the obtained values of concentration of PM10 particles in the laboratory with a chassis dynamometer correspond to the results presented by Bukowiecki et al. [19], among others. The authors of the aforementioned study carried out measurements in an urbanized area while noting the influence of the resuspension of deposited road dust on the results. In more detail, the issue of non-exhaust emissions is presented in works [27–30].

The concentrations of PM2.5 particles during the electric car tests in the air inside the laboratory reached about 43.5 $\mu g/m^3$ after the entire test, which, according to the European Air Quality Index [31], corresponds to poor air quality. For PM10 particles, the final concentration level was about 65.5 $\mu g/m^3$, which also indicates poor air quality.

In addition, Figure 5 shows the changes in the number of particles with specific sizes in the air during the energy consumption and range tests of the test car. As with the concentrations, there was a clear increase in the number of particles, particularly those with the smallest diameter ranges (0.3, 0.5 and 1 μm). Taking the changes in the quantity of recurring particles and their sizes into account, it should be noted that the particles generated due to tire wear and braking system elements had a significant impact on the obtained concentration results. The significant influence of the contribution of these particles to the measurement results of the analyzed concentration is indicated by the authors of works [18,19], among others.

During real-world driving, additional lateral forces are exerted on the vehicle that put additional stress on the wheels and contribute to increased dust emissions caused by tire abrasion. As a result, the results obtained in laboratory tests are underestimated in relation to actual conditions on the road [32]. Also important during laboratory testing is the value of the adopted motion resistance force, which affects the value of the driving force. In tests on a chassis dynamometer, the motion resistance forces may differ from the actual resistance found on the road [33]. The value of motion resistance force affects not only energy consumption and exhaust emissions [34,35], but also the abrasive wear of tires and dynamometer rollers. Particle emissions from tires and brakes are also affected by the weight of the car under test. As indicated in [36], an approximately twofold increase in the weight of the car entailed an approximate 90% increase in maximum PM2.5 and PM10 concentrations during the braking phases. During bench testing, bearing in mind the effect of lateral forces on the wheels, it is important to position the car correctly on the dynamometer rollers and to correctly set the car's wheel alignment. On the other hand, the roller surface might result in higher emissions due to the rough surface [37].

It should be borne in mind that the test results obtained depend on a great many factors, in particular the design of the brake friction elements and the design and age of the tires, as well as the measurement method used, taking into account the sampling location. In the studies presented in the literature, the results are related to the main objective of the research conducted, i.e., the determination of particulate emissions during tire and brake abrasion. The authors of these studies developed special devices (including wheel housings and brake mechanisms) that collect particles from the abrasion of tires and brake components [23,38].

The research presented in this article was aimed at determining immissions into the air in a laboratory room. Therefore, it is difficult to compare the resulting immission results with those presented in the literature and aimed at determining particulate emissions. The issue of airborne pollutant concentration is also relevant in other partially enclosed spaces, such as road tunnels. This issue is discussed in detail in the article [39], for example. The results showed that PM2.5 and PM10 concentrations in the Lisbon tunnel studied were about 20 and 10 times higher, respectively, than those found in the background atmosphere. The results presented in terms of the trend of changes in concentrations depending on traffic conditions are consistent with the results of other authors [23,38,40].

3.2. Relation of PM10 Concentration to Vehicle Acceleration

This subsection presents a preliminary model for calculating estimates of PM10 concentrations on a chassis dynamometer of a defined area (at a distance of 30 cm from the axis of the right front wheel) during a driving cycle based on the average acceleration of the test vehicle. The model was developed based on measurements made with a SOWA meter positioned behind the right front wheel of the test vehicle (Figure 2). Figure 6 shows the proposed block diagram of the model.

Figure 6. Block diagram of the computational model.

In the first stage, the results of the car acceleration measurements on the chassis dynamometer were subjected to filtering using a low-pass filter, the parameters of which are shown in Table 4. The filter parameters were selected based on an FFT analysis carried out using the Filter Designer tool included in the Toolbox Signal Processing of the MATLAB package. The results of the Fourier analysis for the signal containing the acceleration of the car on the chassis dynamometer are shown in Figure 7.

Table 4. Parameters of the low-pass filter.

Analyzed Parameter	Value
Response Type	Lowpass
Design Method	FIR Equiripple
Frequency Specifications	
Units	Hz
Fs	1
Fpass	0.01
Magnitude Specifications	
Units	Linear
Dpass	0.05
Dstop	0.001

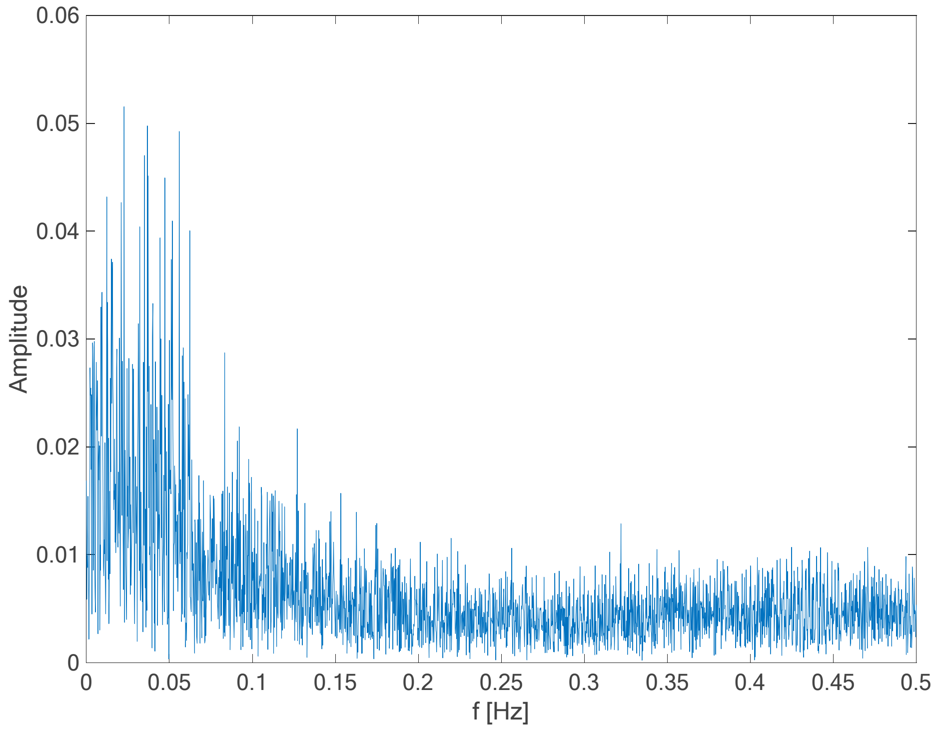

Figure 7. FFT analysis of car acceleration signal on chassis dynamometer.

Then, using the Regression Learner tool, which is part of the MATLAB package, the regression curve with the smallest RMSE error of 7.90505 for the Gaussian Process Regression GPR (Rational Quadratic) was selected. In order to simplify the use of the model, the simulation results were approximated with a third-degree curve. The simulation and approximation results are shown in Figure 8.

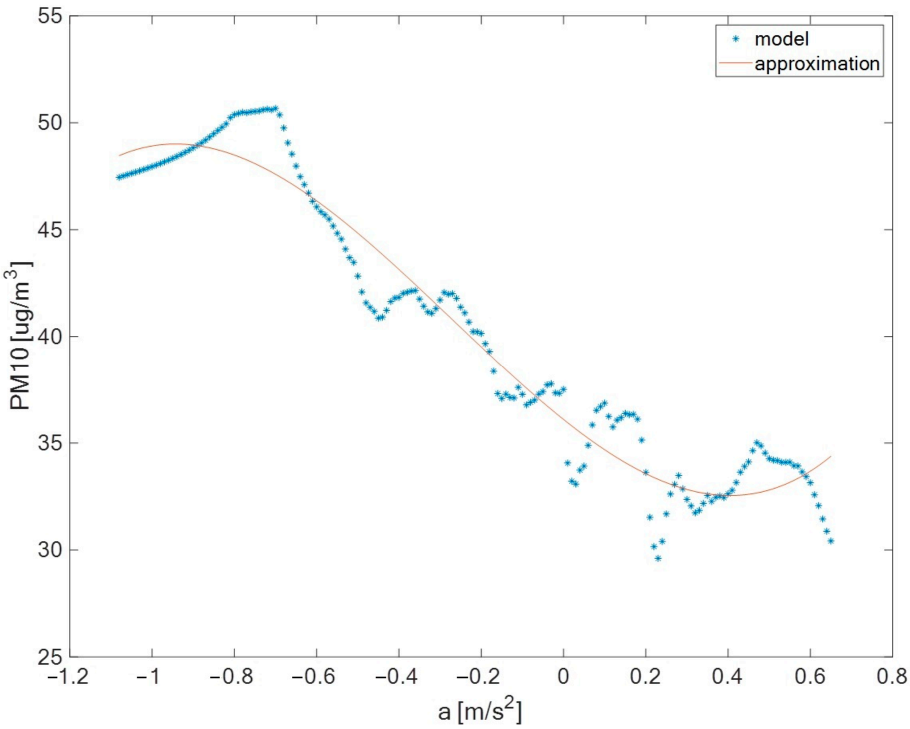

Figure 8. The result of estimating the dependence of PM10 concentration on car acceleration on the chassis dynamometer in the analyzed area behind the wheel of the test vehicle.

As a result of the approximation, a relationship was obtained that allowed the estimation of changes in PM10 particle concentration as a function of the acceleration of a vehicle subjected to tests on a chassis dynamometer, as expressed by Equation (1):

$$PM10 = 13.4485a^3 + 10.8655a^2 - 15.3942a + 36.1087 \quad (1)$$

where:

PM10—PM10 concentration, $\mu g/m^3$

a—acceleration, m/s^2.

4. Conclusions

The results of the study showed that during tests of an electric car on a chassis dynamometer, the air quality in the climate chamber was significantly affected by the emission of dust from the abrasion of tires and brake mechanisms. The concentration values of PM2.5 dust reached maximum values of about 42.5 $\mu g/m^3$ and were higher than the concentration before the start of the test at 15.5 $\mu g/m^3$. Higher concentrations were also evident during the dynamic phases of the driving cycle, which is related to tire abrasion during both braking and acceleration. In particular, as shown in the model, increased dust concentrations occur for braking phases with long delays. Relating the values of the obtained PM2.5 and PM10 concentrations to the air quality index scale, it can be concluded that the air quality deteriorated to poor quality levels during the laboratory tests. Given the increasing concentration of particulate matter in the air, it is important, especially for the driver, to use a dust mask (especially when getting out of the car after a test) and to conduct tests with the car windows closed. An alternative, and preferably an additional solution, is to improve the ventilation system in the laboratory room. Additional factors influencing airborne dust immission are the specific conditions of the laboratory room, particularly the movement of air lifting particulate matter deposited on the room's surfaces and equipment. The study showed that concentration values due to resuspension increased, on average, by about 3 $\mu g/m^3$ for PM10 and by about 4 $\mu g/m^3$ for PM2.5. Bearing in mind the requirements for air quality indices, the initiated analysis of the problem of the immission of pollutants from non-engine systems in the air in the laboratory prompts further research in this area and the development of wards for conducting such tests.

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Abbreviations

AVL	Anstalt für Verbrennungskraftmaschinen List
BEV	Battery electric vehicle
CS1	Constant speed segment 1
CS2	Constant speed segment 2

DS1	Dynamic speed segment 1
DS2	Dynamic speed segment 2
PM2.5	Atmospheric particles with aerodynamic diameter below 2.5 µm
PM10	Atmospheric particles with aerodynamic diameter below 10 µm
TRWP	Tire road wear particle
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
WLTC	Worldwide harmonized Light duty Test Cycle

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