atmosphere

MDPI

Article

Analysis of Parameters Influencing the Formation of Particles during the Braking Process: Experimental Approach

Saša Vasiljević [1], Jasna Glišović [2,*], Jovanka Lukić [2], Danijela Miloradović [2], Milan Stanojević [1] and Milan Đorđević [1]

[1] Department in Kragujevac, Academy of Professional Studies Šumadija, Kosovska 8, 34000 Kragujevac, Serbia; svasiljevic@asss.edu.rs (S.V.); mstanojevic@asss.edu.rs (M.S.); mdjordjevic@asss.edu.rs (M.Đ.)
[2] Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia; lukicj@kg.ac.rs (J.L.); neja@kg.ac.rs (D.M.)
* Correspondence: jaca@kg.ac.rs

Abstract: Knowing and understanding the parameters influencing the concentration of particles created by brake wear, as one of the main contributors to non-exhaust emissions from vehicles, is important for the further development of systems on vehicles to reduce the concentration of particles, and also for further research in the field of developing new friction pairs. In this research, a brake inertial dynamometer was used to measure brake particles, and four different brake pads were examined. Based on a previous review of the applied tests and driving cycles, the braking parameters were determined, i.e., the initial simulated speed of the vehicle, the load of one-quarter of the vehicle, and the brake pressure. The ambient temperature, air humidity, coefficient of friction between friction pairs, deceleration, and braking time can have an influence depending on the brake pad. Further, during the measurement, the temperatures of the brake pads were also measured, where the initial temperature of the brake pads was always the same. In order to process the data, several methods were used, including the presentation of the obtained results in a time domain, the application of the Taguchi design of the experiment with the analysis of the parameters, and a correlation analysis using the Pearson and Spearman correlation coefficients. In this research, the authors concluded that the influences of the parameters primarily depend on the applied brake pads. The vehicle speed turned out to have a large influence in all cases, as did the load, i.e., the influence of the vehicle weight (indirectly through the kinetic energy of the vehicle). In this case, the pressure showed less influence on the particle concentration. An important braking parameter that has a significant impact on the concentrations of $PM_{2.5}$ and PM_{10} particles is the final temperature of the brake pads.

Keywords: brake wear; non-exhaust; emission; particles; parameters

check for updates

Citation: Vasiljević, S.; Glišović, J.; Lukić, J.; Miloradović, D.; Stanojević, M.; Đorđević, M. Analysis of Parameters Influencing the Formation of Particles during the Braking Process: Experimental Approach. *Atmosphere* **2023**, *14*, 1618. https://doi.org/10.3390/atmos14111618

Academic Editor: Long WEI

Received: 11 September 2023
Revised: 14 October 2023
Accepted: 18 October 2023
Published: 28 October 2023

1. Introduction

Based on [1], environmental pollution is the cause of the premature death of 9 million people per year, i.e., every sixth death worldwide. This makes pollution one of the risk factors for human health. Today, there are a number of environmental and air pollutants encountered by modern society, and one of the air and environmental pollutants is particles (PM, particulate matter). Particulate matter is a mixture of solid particles and droplets in the air consisting of various components, such as organic compounds, metals, acids, soil, and dust [2]. According to NIST (National Institute of Standards and Technology) [3], they can be defined as a three-dimensional discontinuity of the condensed phase in a dispersed system. Also, according to [2], particles represent solid, liquid, or combined substances that are released into the air or the environment, and which are of different sizes, composition, and origin.

According to their size, particles can usually be divided into three groups: coarse particles with a size of 10–2.5 μm (PM_{10}), fine particles 2.5–1 μm ($PM_{2.5}$), and ultra-fine particles with a size of less than 0.1 µm ($PM_{0.1}$) [4]. Based on [5], it can be concluded that particles with a smaller diameter are much more dangerous than particles with a larger diameter because particles with a smaller diameter can reach deeper into the body, even into the bloodstream.

The consequences of exposure to particles can be different and can have short-term and long-term effects. A study [6] in which the influence of particles in a closed space was examined came to the conclusion that particles can lead to short-term health effects such as eye irritation, coughing, difficulty concentrating, headaches, and dizziness. Exposure to particles can also lead to serious consequences for human health, as they can have an impact and lead to diseases of the cardiovascular system, nervous system, and respiratory system [7,8]. It has also been determined, according to reference [9], that particles can affect the renewal, repair, and mutations in DNA, and the greatest impact is exerted by $PM_{2.5}$ particles, as well as those with a smaller diameter.

In addition to the effect of particle size on the degree of harm to human health, the composition of the particles also has an important influence, as the composition affects the toxicity of the particles [10]. Particles that are smaller in diameter and have greater toxicity according to their composition are more dangerous for human health and also to the environment. The composition of particles [11] largely depends on the source from which they originate, so some particle sources may contain materials that are very harmful to human health and the environment. Thus, smaller particles and those with a more toxic composition have the greatest impact on human health and can lead to various diseases and even death.

The global trend of particle pollution today differs depending on the region of the world where $PM_{2.5}$ and PM_{10} particle pollution is observed, and also on the development of a region, both in terms of pollutants and environmental standards [12,13]. Based on data from the World Health Organization for 2022, in countries with higher incomes, a smaller trend of particle growth is observed [14]. Also in [14], it is stated that air quality monitoring is carried out in 117 countries, and that in countries with high incomes, 17% of cities have particle pollution lower than what is recommended as the limit of pollution by particles $PM_{2.5}$ and PM_{10}, while in countries with medium and low incomes, that percentage is less than 1% of cities.

Today, there are a number of different sources of particles that are released into the environment [15], among which factories, combustion in households, fires, construction sites, traffic, etc. can be singled out. These particles, depending on their source, have different effects on increasing the risk to human health. If we look at the whole world, pollution by $PM_{2.5}$ and PM_{10} particles differs in different regions of the world, and it also varies according to the sources that dominate in different regions of the world [16,17]. This difference can also be observed in the different regions of different countries.

Based on research [18] in which 16 European and Asian cities were analyzed, that is, the sources of $PM_{2.5}$ particles were analyzed by month, it was determined that some sources are more dominant in certain months, while other sources are more dominant in others. Certainly, the dominance differs according to cities, but it was certainly concluded that the most dominant sources are biomass burning, industry, and traffic.

The research [19] analyzed the sources of $PM_{2.5}$ and PM_{10} particles in different regions of the world, where several sources of particles were taken into account. It is noticeable that the emission of particles differs in different regions of the world, as well as the dominant sources of them depending on the region of the world. Similar results were obtained in the research [20], where the sources of $PM_{2.5}$ particles and their impact on mortality were analyzed. It was established that the sources of particles differ according to the regions of the world, as well as the composition of those particles, and also that they have different effects on the health of people in different regions of the world. Also in this paper, it was determined that, in addition to industry, traffic, and biomass, the concentration of particles was significantly influenced by other human activities. As previously emphasized, the impact of particles on humans is significantly influenced by their composition, e.g., in a study [21] conducted in Hong Kong, it was determined that the composition of particles differs depending on the source of the particles, and the composition also differs in relation to the size of the particles.

Sources of PM_{10} and $PM_{2.5}$ particles in traffic can generally be divided into two groups of emissions: those that are the product of combustion in the vehicle's engine (so-called exhaust emissions) and those that are produced by wear and tear, i.e., the mutual contact of two or more elements on the vehicle or the road, or by the resuspension of particles from the road (so-called non-exhaust emission) [22,23].

Non-exhaust emission sources include brakes, tires, roads, re-raising of dust from roads, wear of engine elements, clutches, etc. [23,24]. Previous regulations did not take into account non-exhaust emissions in the reduction of exhaust gas emissions, so they represent the emission of particles that were not taken into account as an emission that is important as a source of pollution [25].

However, predictions show that in the future, the non-exhaust emissions will be higher than the exhaust emissions [23]. Based on [26], the concern about the increase of non-exhaust particles comes from the use of electric vehicles, which may have an increased mass of the vehicle due to the battery, which would lead to the creation of higher non-exhaust emissions. This is supported by a study [27] in which it was determined that with each increase in vehicle mass, the emission of particles increases linearly, i.e., that the emission can increase by up to 25%.

Particle emission is also influenced by the vehicle category [28]. Based on research [29], it was concluded that resuspended road dust (43%), non-exhaust emissions (37%), diesel exhaust emissions (13%), and gasoline exhaust emissions (7%) participate in the total emission of particles. In a study [28] conducted on the M25 motorway in Great Britain during the lockdown due to the outbreak of the COVID-19 pandemic, it was found that there was a much lower flow of vehicles of different categories, and there was a reduction in non-exhaust emissions of $PM_{2.5}$ and PM_{10} particles for all vehicle categories. It was also concluded that heavy-duty vehicles emit particles much more than other vehicles and that the most dominant source of particles on the highway is resuspension from the road, followed by road wear, tire wear, and brake wear.

In a study [30] conducted in Rome, where the concentrations and volumetric masses of PM_{10} particles were measured, it was concluded that after the end of the lockdown, the concentrations and volume masses of PM_{10} particles doubled near city roads. An important conclusion is that the non-exhaust emissions attributed to the brakes have increased and that special attention should be paid to the reduction of these emissions because they exceed the exhaust emissions of traffic.

The impact of the lockdown on the emission of PM_{10} particles generated in traffic and on the Marylebone Road (roadside) and Honor Oak Park (background) in London was also investigated by monitoring characteristic materials in the particles, and it was determined that brake wear is the largest source of non-exhaust particles [31].

Calculation of the emission factors (hereinafter EFs) of PM_{10} particles, i.e., their determination at the source [32], led to the conclusion that by combining the EFs of different sources, the emission of non-exhaust particles is greater than the EFs of exhaust emissions. Emission factors were determined for different sources of particles based on [32] and the importance of each source in the total mass can be observed, namely brake wear (3.8–4.4 mg/vkm), petrol exhaust (3.9–4.5 mg/vkm), diesel exhaust (7.2–8.3 mg/vkm), resuspension (9–10.4 mg/vkm), road surface wear (3.9–4.5 mg/vkm), and unexplained (7.2 mg/vkm).

In the research [33], the non-exhaust emissions of vehicles were analyzed and it was determined that PM_{10} particles have different substances in their composition: 51–64% soil and cement dust, 26–40% tailpipe exhaust, 7–9% tire wear, and 1–3% brake wear, while $PM_{2.5}$ emissions are mainly composed of 59–80% tailpipe exhaust, 11–31% soil and cement dust, 4–10% tire wear, and 1–5% brake wear. Also, based on the source [33], it was determined that $PM_{2.5}$ particles in China originate from road dust (8.1 Gg year^{-1}), tire wear (2.5 Gg year^{-1}), and brake wear (0.8 Gg year^{-1}).

A study [34] conducted in Delhi, where the sources of PM_{10} particles were identified, found that non-exhaust emissions contributed 86%, while exhaust emissions contributed 14% of the total particulate emissions. When it comes to non-exhaust emissions in the total emissions of PM_{10}, the biggest influences are the resuspension of particles from the road, followed by brake wear, then tire wear and road wear.

A study [35] investigating non-exhaust sources of particulate matter on Marylebone Road estimated that different sources contribute to the total emissions, with re-suspended dust 38.1 $\pm$ 9.7%, brake dust 55.3 $\pm$ 7.0%, and tire dust 10.7 $\pm$ 2.3%.

Based on [36], brakes can participate in the total non-exhaust emissions of PM_{10} and up to 55%, i.e., up to 21% of the total mass of PM_{10} particles that arise from traffic. On the other hand, according to [37], the braking system participates in the total non-exhaust emissions of PM_{10} particles from 16% to 55% in urban areas. In addition, according to [37], brakes contribute 39% and 63% of the total concentration of non-exhaust $PM_{2.5}$ particles in urban areas.

The problem of pollution can be reflected in the fact that, due to air flow, non-exhaust particles can be carried kilometers away from the place of origin. During the movement of the vehicle, due to the air flow near the wheels, as shown by the application of CFD (computational fluid dynamics) in [38], the particles can be further dispersed in urban areas or can be lifted (re-suspended) again from the road surface. It was also shown in [39] that when the vehicle is moving, cooling air flow around the brakes additionally leads to the release of particles produced during braking from the brake surfaces.

Based on [40], it is estimated that every year a motor vehicle wears out 0.5 kg of brake friction material, while based on [41], 35% of the lost mass of brake pad friction material is released in the form of particles into the air (airborne), while according to [42], the percentage ranges from 35% to 58.5%.

The problems caused by particle emissions are primarily related to their specific compositions. Due to the specific composition of friction materials, which increases their potential danger to human health, they can have a potentially negative effect on human health and environmental pollution [43]. The reason for this is the composition of the friction pairs of the brakes, so the particles produced by brake wear have a composition related to the composition of the friction pairs. Based on [44], it can be concluded that there is a connection and influence between the composition of particles caused by brake wear and their impact on health.

Thus, materials such as Fe, Ca, Cu, Pb, Sb, Sn Ba, Si, Ca, Zn, etc. can be found in the composition of brake particles [45,46]. Based on [45], the composition of brake friction pairs plays a significant role in the size distribution of the resulting particles and the concentration of the particles. In order to reduce the harmfulness of particles in terms of their composition, natural materials are being used more and more in friction pads, which is shown in the source [47], or legal regulations are being applied that limit the use of some harmful materials [48].

The application of such regulations in some countries has led to the application of labels indicating how much metal and certain materials are used in the composition of the brake pads. Thus, according to the composition, the brake pads would bear the marks A, B, or N, where N would have the lowest percentage of harmful metals, depending on the area where it was registered. Although N-marked pads should be applied from January 2025, some manufacturers have already adapted to these regulations and are producing such brake pads. The wear of friction pairs and brakes can be affected by various factors, which is shown in the following chapter.

The goal of this paper was to determine the most influential parameters that affect the generation of non-exhaust emissions of $PM_{2.5}$ and PM_{10} particles. The focus in this case is on operating parameters controlled by the driver (vehicle speed, brake pressure, and vehicle load), ambient conditions (ambient temperature and air humidity), and also secondary factors, such as output factors (temperature of the brake pads on at the end of the braking process, braking torque, and braking time) and the analysis of their relationships with the formation of particles. Different brake pads were used in this research, so the goal was also to determine whether different parameters that act on the formation of $PM_{2.5}$ and PM_{10} particles act identically and to the same extent when using different friction pads. In this case, the experimental measurements and research were carried out using an inertial brake dynamometer, while the data analysis was carried out using statistical methods in order to reach the appropriate conclusions.

In relation to previous research, which was carried out by other authors, this paper analyzed the influence of a lot more parameters that can change the concentration of the resulting particles. Likewise, these braking parameters were analyzed on several brake pads that differed by the material used and also by smaller design elements. In order to reach a conclusion about their influence, several different statistical analyses were applied in this paper, where they were compared for each brake pad in order to analyze whether the parameters have a different effect in relation to the applied brake pad.

2. Review of Previous Research

In a previous study, Vasiljević et al. [49] analyzed numerous studies and the conclusions of other authors regarding the parameters influencing the process of the formation of brake wear particles. Compared to previous research, this paper analyzed a larger number of factors that can be controlled by the driver and those that cannot be directly controlled during braking. Taking into account the study [50], it can be seen that there are several ways of researching the emission of brake particles, such as road tests, the application of different dynamometers, and pin-on-disc tribometers, as well as simulations.

During the measurements, different parameters are taken into account, but measurement uncertainty and repeatability due to the application of different methods must also be taken into account. By using a dynamometer, results can be obtained that are the closest to the results of real tests, bearing in mind that real parts of the brake system are used, as well as being on a motor vehicle [50,51]. The application of an inertial brake dynamometer is a laboratory method where real brake parts are applied, and an advantage is reflected in the fact that it is easy to manage the braking conditions and parameters in laboratory conditions [52]. Using a dynamometer, in the case of brake testing, it is also possible to determine the exact brake emissions, bearing in mind that during road tests, it is difficult to separate the emissions of brake wear from other particle emissions.

Considering the number of different methods, it is necessary to take into account measurement uncertainties, as shown in the case of CFD method application [53], as well as in the case of exhaust gas emissions [54]. In relation to computer simulations, where parameters are defined, in the case of laboratory research, the measurement uncertainty is smaller, bearing in mind that real factors are monitored that would be similar to those in the real conditions of a braking process on the road.

Augsburg et al. [55] showed in their research that the emission of particles can be influenced by various factors, namely the temperature of the contact zone of the brake pairs, the composition of the friction pairs, atmospheric conditions such as air humidity, wheel angular velocity, vehicle weight, deceleration, brake geometry, the possibility of particles leaving the housing, etc. The factors influencing particle emissions can be divided into three groups, namely, the friction materials from which the friction pairs are made, the type and brake assembly (size, disc brakes, the quality of the brakes, etc.), and driving conditions (initial speed, hydraulic pressure in the braking system, temperature, etc.). According to reference [56], the most influential factors for the emission of PM_{10} particles are energy dispersion, initial temperature, braking energy, final rotor temperature, braking energy, and deceleration.

The load has been shown to be one of the significant factors that has an impact on the concentration of particles that occur during brake wear. Thus, researchers [27,57] came to the conclusion that with an increase in the load on the vehicle during braking, there is an increase in the resulting concentration of particles. It was determined that with an increase in the load by 60–70 kg, the amount of generated particles increases by 25%. It was concluded that the intensity of braking is also one of the strong predictors that affect the concentration of particles $PM_{2.5}$ and PM_{10}, whose source is the braking system.

In research [58–60], an inertial brake dynamometer was applied and low-metal and NAO brake pads were used, and the influences of deceleration, initial braking speed, and pressure were investigated. It was established that the inertial braking speed has an influence on the resulting concentration of particles and that at higher initial speeds, a higher concentration of particles occurs. Deceleration also has an effect on the resulting particle concentration, while braking pressure has been shown to have the least effect on the particle emissions. It was also determined that in the case of untrodden brake pads, where a stable coefficient of friction has not been created, a higher concentration of particles is emitted.

In research [61], it was concluded that more particles are released with a change in braking speed. Specifically, in this case, braking at 50 km/h leads to an increase in the particle concentration by 40% to 90% compared to a speed of 30 km/h. The percentage increase depends generally on the deceleration, where a greater deceleration leads to the emission of a greater concentration of particles. On the other hand, in study [62], where different braking pressures were applied, it was determined that at higher braking pressures, there is also an increase in the emission of particles. It was also established that an increase in temperature leads to an increase in the emission of particles.

In the research [63], six different vehicles were used, on which the tests were carried out, and the resulting emission of particles was compared. Furthermore, in this test, there were three braking modes, i.e., full stop (strong braking), normal deceleration, and a non-braking mode. It was concluded that there was a significant difference in the concentration of particles that were created, which the authors attributed to the type of vehicle and the braking force. It was concluded that a significantly large concentration of particles that contain metals is released during strong braking.

Research [64–67] has pointed out the importance of the influence of the temperature of the brake friction pairs. An increase in the temperature between the friction pairs leads to an increase in the resulting concentration of particles. It was found that in the temperature range from 170 °C to 270 °C, there is a drastic increase in nanoparticles. The critical temperature for the formation of ultrafine particles in the case of organic binding material is about 180 °C, while in the case of friction pads with inorganic binding material, it is about 240 °C. In the research [68], it was found that ultrafine particle emission increases when the disk temperature exceeds 170 °C. However, under normal driving conditions, the reference temperature does not exceed 153 °C, so in such conditions, ultrafine particle emission is not expected.

In the study [69], the particle emission was investigated under conditions of complete humidity, partial humidity, and dry. It was found that in cases of complete and partial humidity, there is a lower wear rate compared to completely dry conditions for both brake pads. Based on the above, Djafri et al. [70] examined different materials used as disc rotors and at different values of air humidity, where they concluded that a water film can act as a lubricant in the contact area of friction pairs. Thus, the wear rate in this case varied inversely with the relative humidity.

Table 1 shows the analyzed parameters and conclusions reached by different authors regarding the influence of these parameters on the generation of brake wear particles.

Table 1. Conclusions of the influence of braking parameters on the resulting concentration of particles by other authors.

Reference	Analyzed Parameters	Conclusion about the Influence of the Parameter
Songkitti et al. [27] Oroumiyeh and Zhu [57]	Load	With an increase in the vertical load of the vehicle during braking, there is also an increase in the concentration of the resulting particles.
Candeo et al. [58]	Inertial braking speed and brake pressure	The initial speed has a more significant influence on the concentration of particles in relation to the braking pressure. The effect of braking pressure is negligible in some cases.
Hagino et al. [59]	Inertial braking speed and deceleration	At higher initial speeds and decelerations, the highest concentration of particles occurs.
Chasapidis et al. [61]	Inertial braking speed and deceleration	Increasing the speed also increases the concentration of particles. The percentage increase depends on the deceleration. Greater deceleration leads to higher concentrations of particles.
Mamakos et al. [62]	Braking pressures	Increasing the brake pressure leads to an increase in the concentration of the resulting particles.
Perrenoud et al. [63]	Braking intensity	Heavy braking leads to a higher concentration of particles compared to normal braking.
Men et al. [64] Niemann et al. [65] Matějka et al. [66] Paulus and Kloda [67]	Temperature of brake pairs	The temperature of the brake pairs has a significant influence on the resulting concentration of particles. Ultrafine particle emission increases at higher temperatures.
Farwick zum Hagen [68]	Temperature of brake pairs	Ultrafine particle emission increases at a temperature of 170 °C; the operating temperature of the brakes does not exceed 153 °C.
Abdul Mokti et al. [69] Djafri et al. [70]	Air humidity	An increase in humidity leads to a decrease in the brake wear rate because the water film acts as a lubricant.

3. Research Methodology

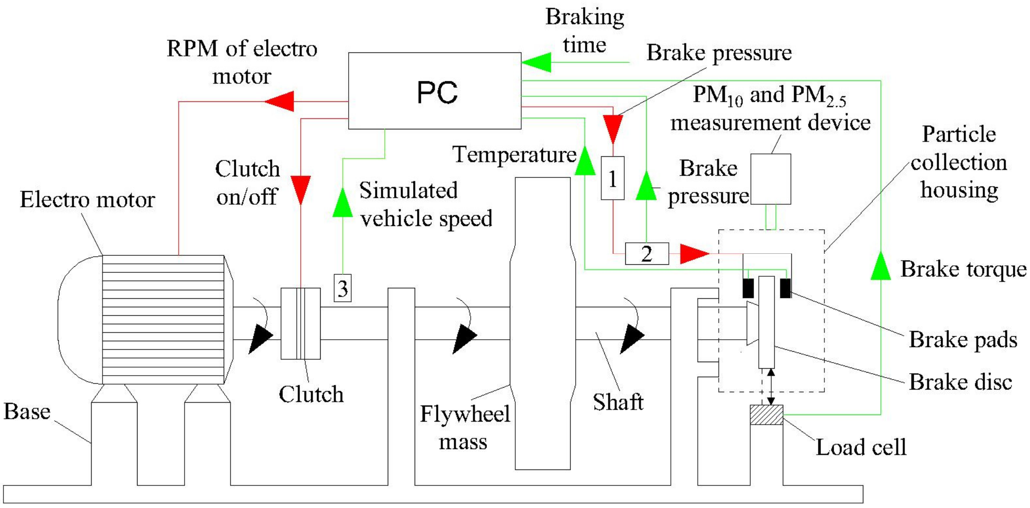
It is necessary to bear in mind the fact that there are a number of different methodologies that can be used in the investigation of particle emissions resulting from the wear of the braking system.

3.1. Inertia Brake Dynamometer and Influential Parameters in the Research

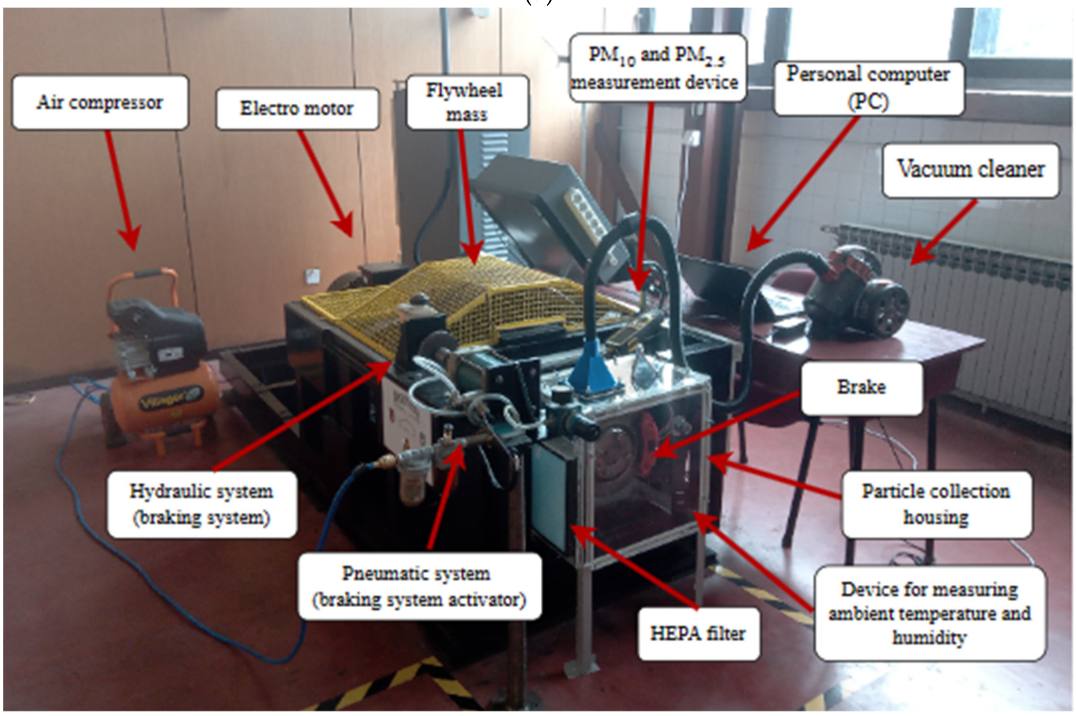
In this case, the inertial brake dynamometer BrakeDyno2020, which is located at the Faculty of Engineering at the University of Kragujevac, Serbia, was used to test the emission of particles. A schematic view of the inertial brake dynamometer is given in Figure 1a, while Figure 1b shows the layout of the brake dynamometer that was used in this case. The control of the drive of the inertial brake dynamometer and the activation of the brake system were realized by using a computer and the LabView 2021 software package.

Using an inertial brake dynamometer, the kinetic energy of one-quarter of the vehicle was simulated. The desired value of the kinetic energy was achieved in such a way that the electric motor reached a certain number of revolutions, and the engine drove the inertial mass, which was further connected to the brake disc, which rotated at the same number of revolutions. The required number of revolutions of the electric motor was given based on the calculation presented in [71].

The activation and deactivation of the braking system was also controlled using the software. Applying a certain pressure to the brake installation was achieved mechanically, while activation was conducted electronically. The brake installation consists of two parts, hydraulic and pneumatic. Thus, the brake was activated by the hydraulic part of the installation, while the pneumatic part was activated by the software, which can be equated with the activation of the brake on a real vehicle.



(**a**)



(**b**)

Figure 1. Inertial brake dynamometer used in this research, (**a**) Schematic diagram of the inertial brake dynamometer (Green line—Output parameters (data), Red line—Input parameters (data)-control, 1—Pneumatic system (braking system activator), 2—Hydraulic system (braking system (master cylinder)), and 3—Speed sensor); (**b**) Design of the inertial brake dynamometer.

In this research, an OMRON E2A series inductive sensor was used to measure the speed of the flywheel mass. Through this sensor, the number of revolutions was measured by the computer in real time. The number of revolutions of the inertial mass was changed by the electric motor, whose number of revolutions was regulated by a computer. By knowing the characteristics of the inertial mass and setting the speed, the appropriate value of kinetic energy was achieved, which corresponds to the movement of a vehicle of a given weight, i.e., 1/4 of the vehicle (the assumption of an equal distribution of weight on the wheels was adopted to simplify the analysis). The computer records and displays the speed that would correspond to the vehicle under driving conditions, as well as the vehicle's load. In this case, there is no possibility of changing the flywheel mass, so by changing the number of revolutions of the same, the kinetic energy values that the vehicle would have at the beginning of braking are realized, and by calculating the number of revolutions of the flywheel mass, the speed that the vehicle would have is simulated. These values are recorded directly in the computer for later data analysis.

The WPM-131D sensor was used to measure the pressure in the hydraulic part of the brake installation. With the force sensor CZL312, the braking moment is indirectly measured with the knowledge of the force arm. All of the mentioned sensors are connected to the computer via an online connection, and the obtained data are displayed and recorded so that data analysis can be performed later.

When it comes to data collection, the inertial brake dynamometer used in this case had two segments. The first segment had online segments, i.e., elements that collect data directly, which are recorded on the computer and through which the dynamometer was controlled. In this way, data such as the brake pressure in the hydraulic installation (the braking pressure), brake pad temperature, braking time, and the speed of the electric motor, i.e., the number of revolutions of the electric motor, are measured and recorded, while braking torque is obtained by calculation. Offline data that were measured were the concentration of $PM_{2.5}$ and PM_{10} particles, ambient temperature, and air humidity.

3.1.1. Brake Pad Temperature Measurements

The temperatures of the brake pads were measured using sensors inserted into the brake pads. Specifically, four temperature sensors were used, i.e., two sensors for each pad. In this way, the heating of the brake pad was measured. Figure 2 shows the method of placing the sensors inside the brake pads. In this case, high-precision temperature sensors WZP-PT100 were used. At all times, they displayed the temperature of the brake pads on the computer, and when measuring the concentration of the generated particles, the temperature was recorded directly on the computer so that the data could be analyzed.

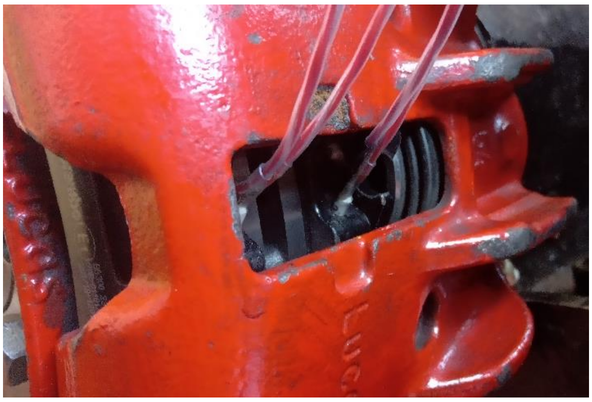


Figure 2. Temperature sensors for measuring the brake pad temperature.

3.1.2. Particle Concentration Measurements

In order to enable the measurement of only the emissions of particles that occurred during braking, a closed housing was constructed in which only the braking system was located, and the housing was closed from all sides. The housing was constructed in such a way after the authors analyzed the solutions of the housing of other researchers [72], and a detailed explanation of the housing construction is presented in [73]. The role of the housing is to ensure the measurement of only particles that are generated during braking, and that is why the housing is hermetically sealed to prevent the entry of particles from the environment during braking. If the case is opened, particles from the environment enter, so the air in the housing must be purified. For this purpose, there is a HEPA filter in that tube on the housing, while a vacuum cleaner is connected on the other side, which pulls air from the outside into the housing, and which is then purified through the filter, removing particles that are not a product of brake wear. Thus, only clean air enters the housing, and dirty air is expelled from the housing.

The housing is ventilated each time after the measurement until the concentration of $PM_{2.5}$ and PM_{10} particles is reached from a minimum of 0 μg/m^3 to a maximum of 2 μg/m^3. It is important to note that the vacuum cleaner was turned off during the measurement of the concentration of particles, i.e., it was turned off during braking. The role of the vacuum cleaner was to draw in clean air through the HEPA filter after every braking test and cleaning of the housing, and to extract the air from the housing with the particles. In this way, it was achieved that there was clean air in the housing with a minimum concentration of particles that was within the previously mentioned limits.

The device used to measure the concentration of particles has its own pump that extracts air, and on that occasion, it measures the concentration of the formed particles. In order to increase the reliability of the obtained data, each measurement with the same parameters was repeated three times, and the dispersion of the measured concentration values was within the permitted limits.

In this case, the device Trotec PC220 was used to measure the concentration of particles. It has the ability to measure the concentration of $PM_{2.5}$ and PM_{10} particles. This device has a calibration certificate, i.e., it is calibrated and complies with the manufacturer's specifications. Its efficiency for particle counting is 50% for particles up to 0.3 μm and 100% for particles larger than 0.45 μm. These data can be confirmed to be within acceptable limits considering that the particle measuring device is near the source of the particles, i.e., in this case, the brake, which is in this housing. The device is placed directly on the housing made of Plexiglas, and it is placed near the brake, which allows it to draw in particles. This device has its own particle suction pump, so when extracting air with particles, it additionally draws air into the housing, which is purified through a HEPA filter. The device installed on the housing is shown in Figure 3.

Figure 3. Device for measuring the concentration of particles mounted on the housing.

This device uses an optical measurement method; thus, using a laser it measures the size and number of particles and calculates the particle concentration of the entrapped particles. The device itself is not directly connected to the computer (an off-line device), but it has its own memory, i.e., a data logger, in which it stores the data it measures, and the data are then transferred to the computer.

The device can measure several different parameters, but in this case, the concentrations of $PM_{2.5}$ and PM_{10} particles were measured because they are the most often measured when it comes to air quality analysis.

3.1.3. Applied Braking Parameters—Brake Test

As there is currently no standardized brake cycle for testing brake pads and particulate emissions generated during braking, the authors developed their own test for testing and data analysis. The authors of this paper previously performed an analysis of braking cycles and tests that were developed earlier by other authors, and the conclusions are presented in [74]. Based on the monitored parameters in previous research, the authors developed their test with influential parameters based on previously applied cycles in the research of particulate emissions from brakes. Thus, in this case, the authors varied three parameters that are crucial in real driving conditions, which can also be directly controlled by vehicle drivers.

The input data in the braking process were varied: the load corresponding to one-quarter of the vehicle's mass, the initial braking speed, and the pressure in the brake system. Table 2 shows the varied values of the previously mentioned parameters, and the tests were performed for all possible combinations. All measurements were performed three times with the same parameters for all brake pads.

Table 2. Values of braking parameters in the applied test.

Parameter	Parameter Values That Are Varied in the Test
Load corresponding to 1/4 of the vehicle's mass [kg]	150, 250
Initial braking speed [km/h]	20, 40, 60, 80
Brake pressure in the braking system [MPa]	1, 2, 3, 4

Later in the analysis, other parameters that can be called secondary input parameters were also taken into account, and it was investigated whether they have an impact on the resulting concentrations of $PM_{2.5}$ and PM_{10} particles. The secondary parameters include: brake pads' temperature at the end of braking, braking torque, braking time, ambient temperature, and air humidity. Bearing in mind that the measurements were made in the summer period, the initial temperature of the brake pads was about 28 $\pm$ 0.5 °C. After each measurement, the brakes were then allowed to cool to that temperature.

3.2. Applied Materials

In this research, four different brake pads that are available for sale on the market in the territory of the Republic of Serbia were used. As a brake rotor disc, a cast iron disc was used, which, according to its construction, belongs to the class of ventilated discs. All applied pairs are available on the market. The brake pads were made by different manufacturers; they differ according to their composition and also according to their design. These commercial brake pads are code named A, B, C, and D. Figure 4 shows pictures of the brake pairs that were used in this research.

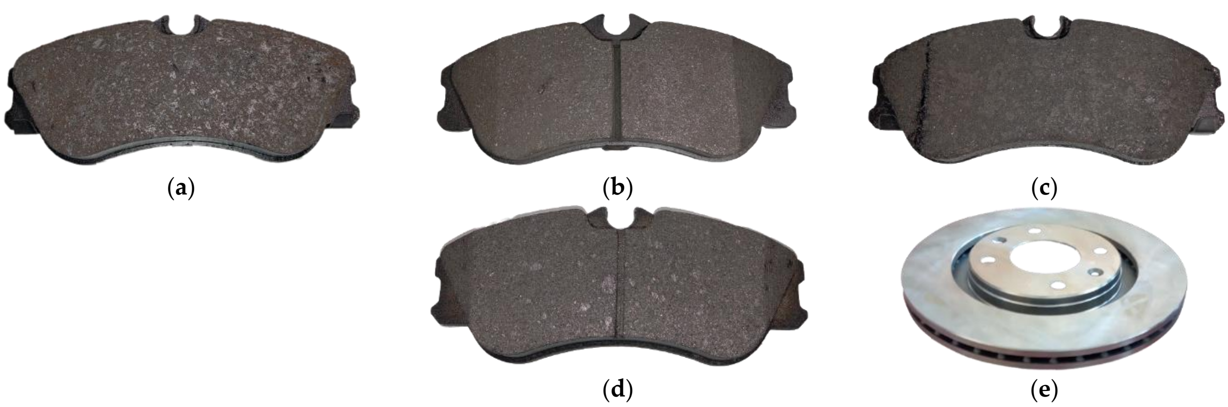


Figure 4. Applied brake pads and brake rotor, where: (**a**) brake pad A, (**b**) brake pad B, (**c**) brake pad C, (**d**) brake pad D, and (**e**) rotor used in this research.

In order to understand and describe the brake pads, Table 3 was created. The table presents data on the brake pads and their characteristics based on the available data, cost price, and geometry. The brake pads differ according to the price range and according to their composition, because some of them are presented as environmentally acceptable, with the label that they were produced according to the standard with N components, unlike those that do not have such labels. The geometric features refer to the design itself, although they are intended for the same vehicle model; however, the design itself differs in terms of whether the friction surface is completely flat to those that have a slot in the middle of the pad or have beveled side edges of the friction surface.

Table 3. Characteristics of the used brake pads.

Brake Pad Code	Brake Pad Type	Brake Pad Geometry	Price Range
A	Semi-metallic	No lots or chamfer	1
B	Low-metallic, eco-friendly formulation	Parallel single slot, parallel single chamfer	3
C	N category of formulation	Parallel single chamfer	2
D	Semi-metallic	Parallel single slot, parallel single chamfer	4

3.3. Applied Statistical Analyses and Data

Two statistical analyses are presented in this paper. The basic presentation of the obtained results in this case is given by diagrams of the obtained values based on some braking parameters that were input to the entire system. All analyses were performed for four brake pads to determine whether there is the same influence of the parameters regardless of the type of brake pads.

The first statistical analysis refers to the analysis of the results obtained using the Taguchi methodology, where an analysis of the influence of brake parameters was performed, which are input data in every brake system and on which the driver can have an influence when activating the brake or driving the vehicle. These factors include the brake pressure in the hydraulic part of the brake system, the load on one-quarter of the vehicle, and the speed of the vehicle.

In this case, the Taguchi design of the experiment was applied at the level of L32 (2^1 4^2), where all measurements were included. After the design of the experiment, data processing was performed using Taguchi analysis, where the general influence on the resulting concentration of particles with average values, and according to the brake pads, was shown. In this case, in addition to the influencing factors, the best combination of parameters for the lowest concentration of particles was performed and shown.

An application of Taguchi analysis is shown in the paper [75], where the influence of parameters is also analyzed. As explained in [76], by applying the Taguchi method, it is possible to determine the influence of certain factors on some output parameters and to optimize the way of influence. This method can be applied to analyze the impact of making the output parameter have a higher or lower value. In the case of an application for the emission of particles resulting from brake wear, the influence of parameters is analyzed in order to achieve the lowest emission value. The influence of individual factors, in this case on the emission of particles, is shown in individual diagrams. Thus, each input parameter, using this method, is shown with an individual diagram in order to reach the correct conclusion about the influence of the parameters on the output value. Based on the above, as many diagrams are obtained for one analysis as there are input parameters whose influence is analyzed.

Another statistical method that was applied is an analysis of the correlation between the concentrations of the PM_{10} and $PM_{2.5}$ particles and the braking parameters. In this case, in addition to the direct braking parameters that are influenced by the driver, which were previously mentioned, a correlation was made between the obtained particle concentrations and indirect braking parameters. The final temperature of the brake pads, braking torque, kinetic energy of the vehicle, braking time, deceleration, air humidity, ambient temperature, and friction coefficient between the friction pairs were taken as indirect parameters. All analyses were carried out for all brake pads according to the data obtained by measuring the concentrations of the PM_{10} and $PM_{2.5}$ particles.

As values for assessing the strength of the correlations between the parameters in this case, the values according to [77] were applied, i.e., the values shown in Table 4. Only parameter values that had a statistically significant correlation at the levels of 0.01 and 0.05 were taken into account. A total of 385 data points were used, i.e., 96 data points for each brake pad.

Table 4. Correlation values and their strength of association [77].

The Value of the Correlation Coefficient	Interpretation of the Correlation Relationship
0.00–0.30	Very weak correlation relationship
0.31–0.50	Weak correlation relationship
0.51–0.70	Moderate correlation relationship
0.71–0.90	Strong correlational relationship
0.91–1.00	Very strong correlation relationship

A general analysis was also performed, where the average value was calculated based on the basic input data, i.e., the direct data, and correlations with the values and input parameters were calculated.

Data correlation analysis was performed using the IBM SPSS 23 software package. In this case, two methods were used for analysis, i.e., two coefficients and methods for determining the correlation, namely Pearson's correlation coefficient and non-parametric analysis using Spearman's correlation coefficient.

4. Results

In this chapter, the obtained measurement results are presented. It should be noted that the particle concentrations were measured inside the housing where the measurement was performed and in which the brake caliper and disc were located.

4.1. Analysis of Measured Data

4.1.1. Analysis of Obtained Particle Concentrations According to the Influence of Input Braking Parameters

The measured concentrations of the particles refer to the currently observed values, while during the movement of the vehicle, they would decrease under the atmospheric influence and the influence of the aerodynamic forces acting on the vehicle. Figure 5 shows the average concentration of PM_{10} and $PM_{2.5}$ particles for each brake pad. The displayed values represent the average value in relation to all measurements carried out in this case. It is noticeable in this case that the highest concentration of particles was obtained for brake pad B, while the lowest concentration of particles was for brake pad D. It is interesting that brake pads A and C emitted a similar concentration of particles for both PM_{10} and $PM_{2.5}$, with the fact that brake pad A gave a 5.58% lower concentration of PM_{10} particles, while its concentration of $PM_{2.5}$ particles was 4.49% lower.

Comparing the lowest value of the concentration of PM_{10} particles (brake pad D) with the highest concentration (brake pad B), it is noticeable that the highest value is higher by 49.02%. On the other hand, comparing the highest (brake pad B) and the lowest (brake pad D) concentration values of $PM_{2.5}$ particles, it can be noted that the concentration is higher by 51.24%.

By observing the load as a factor that can affect the concentration of the resulting particles, Figure 6 shows the average concentration of particles according to the load based on all measurements and according to the type of brake pad.

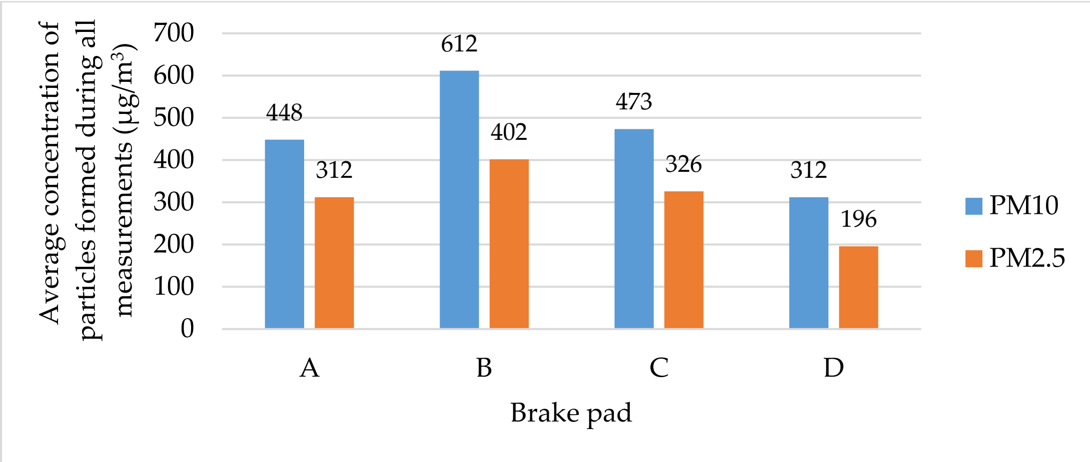
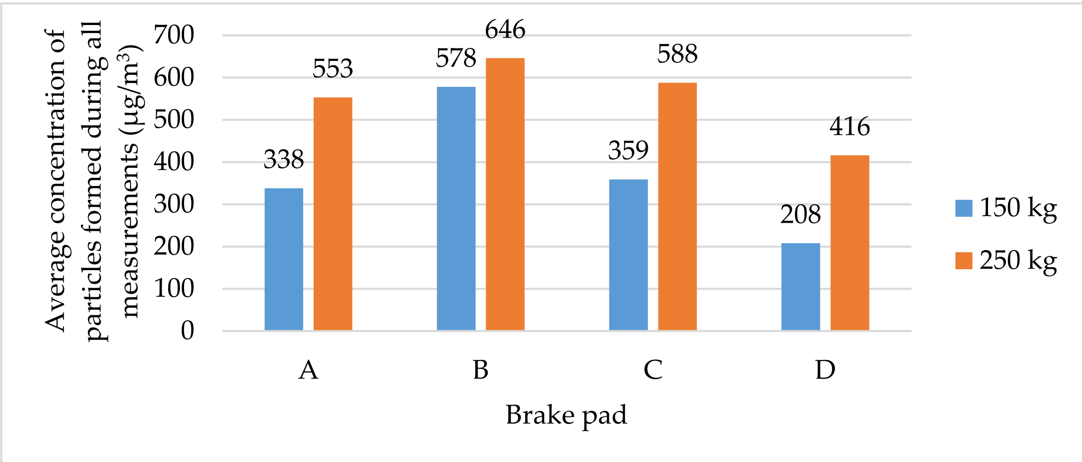
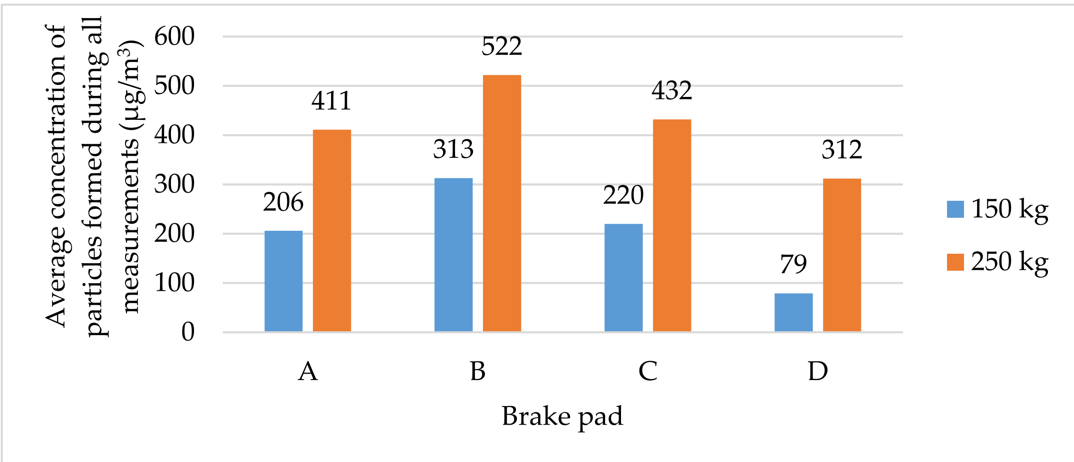


Figure 5. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the type of brake pad.



(**a**)

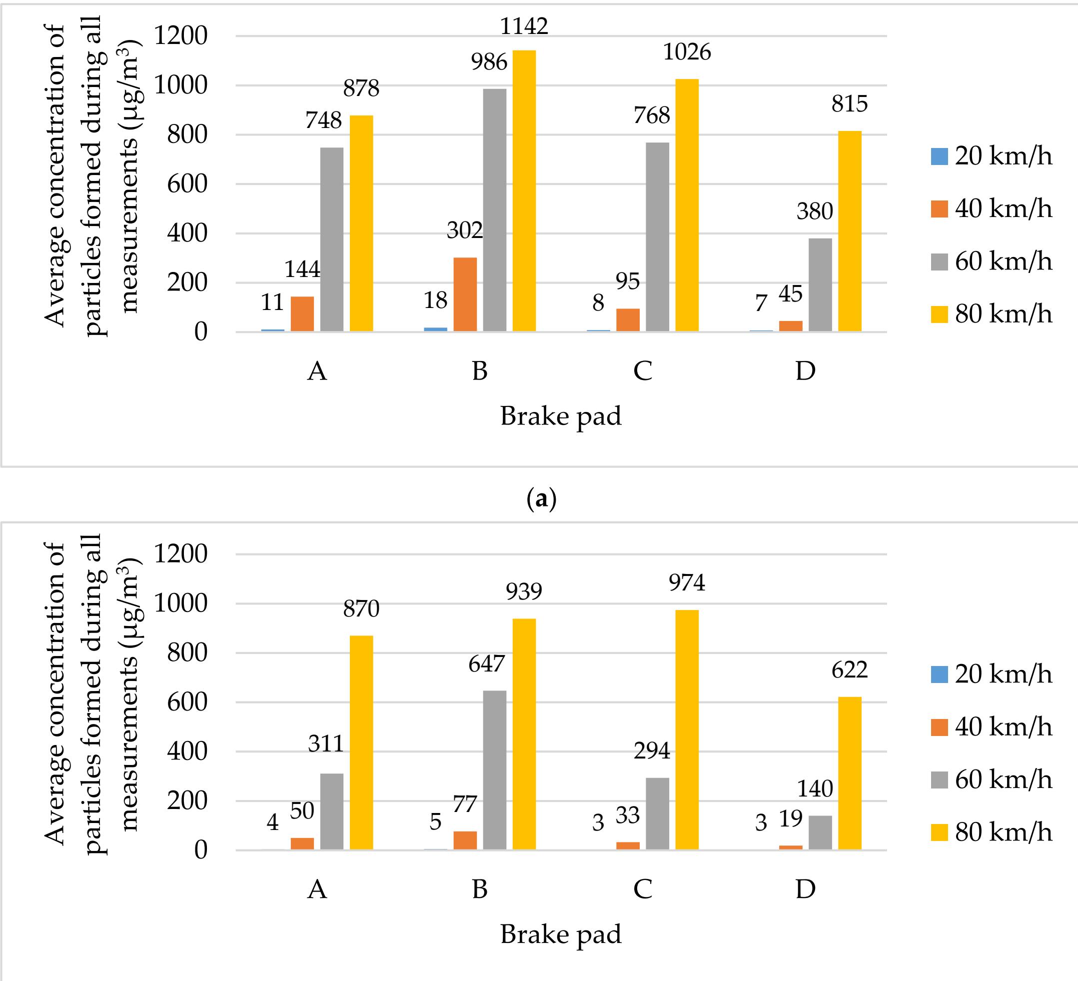


(**b**)

Figure 6. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the type of brake pad and load, where: (**a**) PM_{10}, (**b**) $PM_{2.5}$.

Looking at the PM_{10} and load results, it is noticeable that there was some variation between different brake pads. Thus, brake pads A and C had a similar difference when the load changed, i.e., at a lower load, brake pad A had a lower concentration by 38.88%, while brake pad C at a lower load had a lower concentration by 38.95%. The smallest difference with the change of load, and when it comes to the concentration of PM_{10} particles, in this case was for brake pad B, where the difference was 10% at a lower load. The biggest difference in this case was measured for brake pad D, where at a lower load, it had a 50% lower concentration of PM_{10} particles. In the case of the concentration of $PM_{2.5}$ particles, the biggest difference when the load changed occurred with brake pad D, which at a lower load had a 74.68% lower concentration of particles compared to the concentration at a higher load. The smallest changes in the emitted concentration of particles were for brake pads B and C, where at a lower load they emitted 40.04% and 40.07% lower concentrations than at a higher load. In this case, brake pad B emitted the highest concentration of particles at both lower and higher loads. The impact of the vehicle's load is similar to the results of some previous research. In this research, it was observed that the load does not have an identical effect on all brake pads.

The influence of the vehicle's speed at the start of braking on the particle concentration was identified in the previous subsection, and Figure 7 shows the average particle concentration according to the measurements for all types of brake pads.



(**b**)

Figure 7. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the speed and type of brake pad, where: (**a**) PM_{10}, (**b**) $PM_{2.5}$.

A change in speed certainly had an effect on the concentration of particles that were generated during braking, and this applied to all brake pads, but the effect was different.

The speed noticeably caused the greatest changes in the case of the concentration of $PM_{2.5}$ particles. Of course, there was also a difference in the concentration of PM_{10} particles, but depending on the brake pad, the percentage of reduction or increase in concentration differed. It is noticeable that the highest concentration of PM_{10} particles at all speeds was obtained for brake pad B, while the lowest concentration of particles at all speeds was measured for brake pad D. The concentration of particles in the case of $PM_{2.5}$ was the highest in the case of a speed of 80 km/h, and the value was the highest for brake pad C, while in the case of other speeds, the highest concentration of particles was in the case of brake pads B. Brake pad D had the lowest concentration of particles, except when the speed was 20 km/h, in which case brake pads C and D had identical $PM_{2.5}$ particle concentration values. It can be determined that brake pads A and C had similar particle concentrations, and they had the closest values.

In this case, it can also be concluded that speed has a significant influence on the resulting concentrations of particles and the values of the resulting emissions, i.e., the concentrations of particles largely depend on the brake pad used on the vehicle. The influence of speed on the particle concentration has been confirmed in this case, and it agrees with the results of other authors. The only difference in this research is that the particle concentration depends on the applied brake pad, and the percentage increase depends on the applied brake pad.

The influence of the pressure in the hydraulic brake system on the concentrations of $PM_{2.5}$ and PM_{10} particles was also analyzed, and the results are shown in Figure 8.

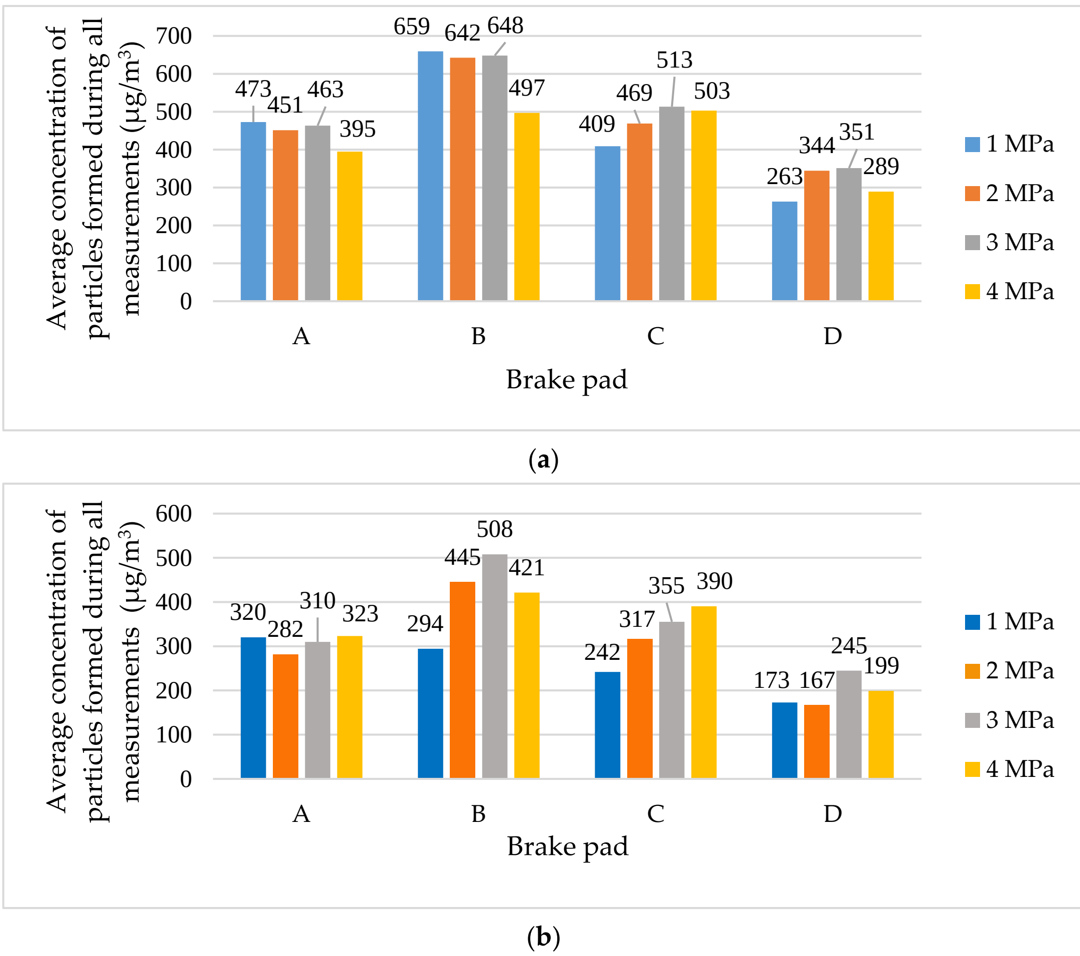


Figure 8. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the brake pressure and type of brake pad, where: (**a**) PM_{10}, (**b**) $PM_{2.5}$.

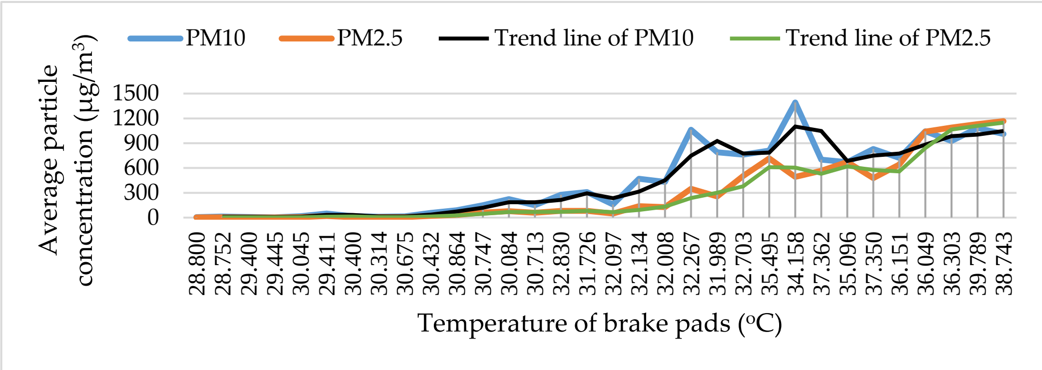
It is noticeable that the pressure had the least impact on the concentration of particles compared to the previous influential variables. If the concentrations of $PM_{2.5}$ and PM_{10} particles are observed for different types of brake pads, it can be noted that the change in pressure had a different effect on different brake pads and the concentrations of particles they generate. In the case of brake pad A, the concentrations of $PM_{2.5}$ and PM_{10} particles varied in relation to the brake pressure applied, with the fact that at a brake pressure of 4 MPa, the concentration of PM_{10} particles was the lowest, while at the same pressure, $PM_{2.5}$ was the highest, but there was no significant increase in relation to the other pressures. In the case of brake pad B with a change in brake pressure, there was no significant change in the concentrations of PM_{10} particles, except in the case of a pressure of 4 MPa where there was a drop in concentration, which was also the case for the concentration of $PM_{2.5}$ particles, while at other pressures, this concentration was increasing. In the case of brake pad C, with increasing pressure, the concentration of PM_{10} particles increased, and at a pressure of 4 MPa, it decreased, while the concentration of $PM_{2.5}$ particles increased with increasing pressure. Brake pad D generated the lowest particle concentration at all pressures. The concentration of PM_{10} particles was the lowest at a pressure of 1 MPa, then there was an increase in concentration, and then there was a decrease at a pressure of 4 MPa. The concentration of $PM_{2.5}$ particles had no significant differences, but the concentration was the highest at a pressure of 3 MPa for brake pad B.

In relation to other researchers, it can be said that the pressure does not have a significant effect on the resulting concentrations of particles, but it leads to variations in the concentrations of particles. Generally, lower concentrations occur at lower pressures, but the exact impact depends directly on the brake pad used.

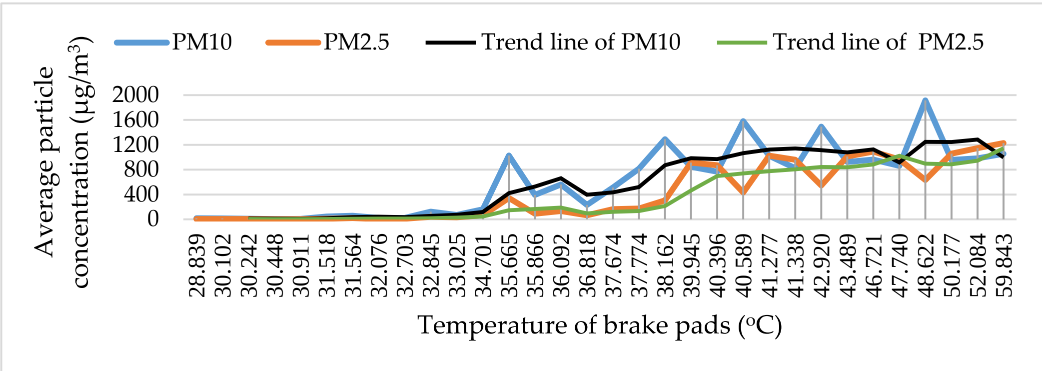
4.1.2. Analysis of Obtained Data According to Indirect (Secondary Input) Brake Parameters

As one of the indirect factors that can have an influence on the concentration of particles, the final temperature of the brake pads and the concentrations of particles were analyzed (Figure 9). By analyzing different brake pads, it is noticeable that the final temperature of the brake pads had a different effect on the concentrations of particles, as well as that there were differences between $PM_{2.5}$ and PM_{10}. As the temperature of the brake pads increased, the concentration of particles also increased. By analyzing trends in particle concentration growth, it can be seen that in the case of brake pads A and C, after a certain value of brake pad temperature, the concentration of $PM_{2.5}$ particles was higher compared to the concentration of PM_{10} particles. It is important to note that in the case of these two brake pads, due to this phenomenon, brake pad A started emitting particles earlier, i.e., at a lower temperature compared to brake pad C. As a result of all of the measurements, there was a certain variation in the concentration of particles, where the increases in the concentrations of $PM_{2.5}$ and PM_{10} particles were monitored. In the case of brake pad D, the difference between the resulting concentrations was the largest compared to the other brake pads. In the case of the brake pad B, the difference between the concentrations of particles was the smallest and reached the highest temperature. At those temperatures, there was a change, so that the concentration of $PM_{2.5}$ was greater than the concentration of PM_{10} particles.

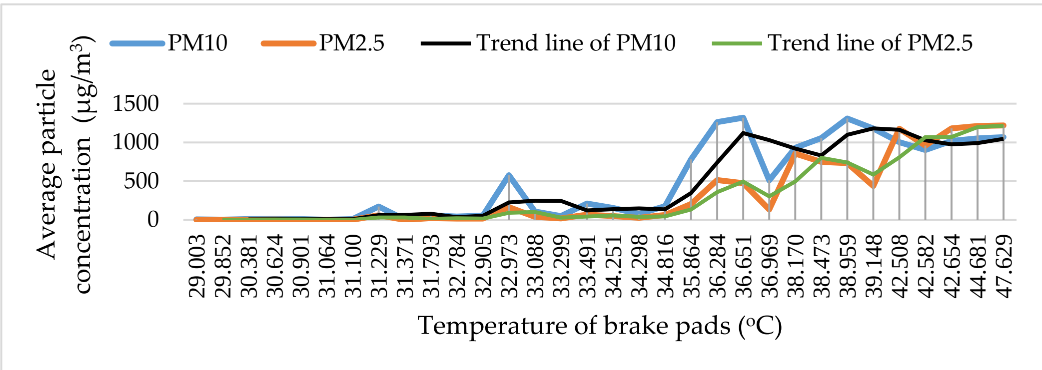
Such results can generally be compared with the results of other authors. As shown in the literature review, the influence of brake pad temperature on the final concentration of particles is evident. It is noticeable that the temperature can have an effect on the concentration of particles, but it differs depending on the applied brake pad. In the case of some of the brake pads, the influence of temperature is such that there is a limit where there is an increase in the concentration of $PM_{2.5}$ compared to the concentration of PM_{10} particles. Likewise, particle concentrations differ from brake pad to brake pad while the temperature is identical.



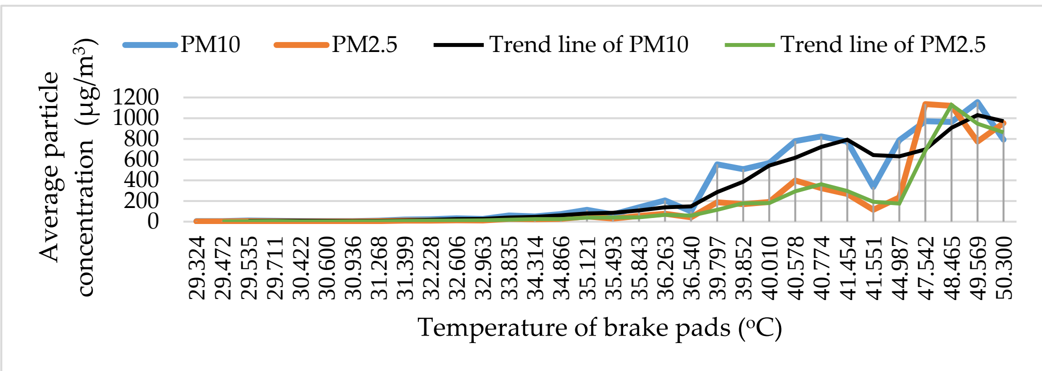
(**a**)



(**b**)



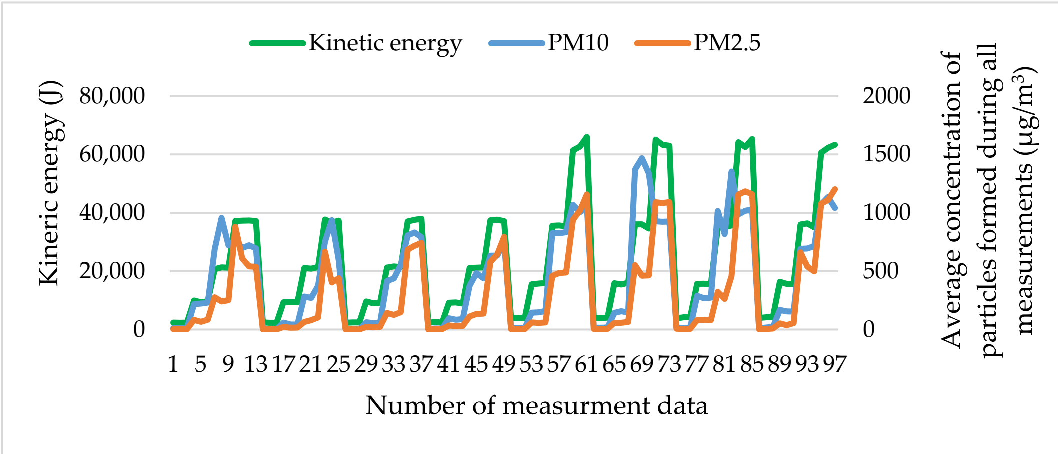
(**c**)



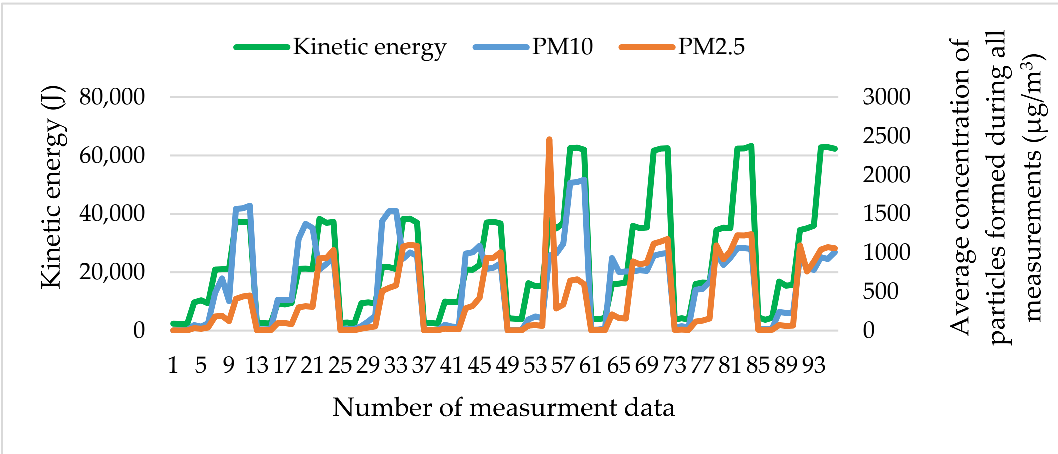
(**d**)

Figure 9. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the final temperature of the brake pad, where: (**a**) brake pad A, (**b**) brake pad B, (**c**) brake pad C, and (**d**) brake pad D.

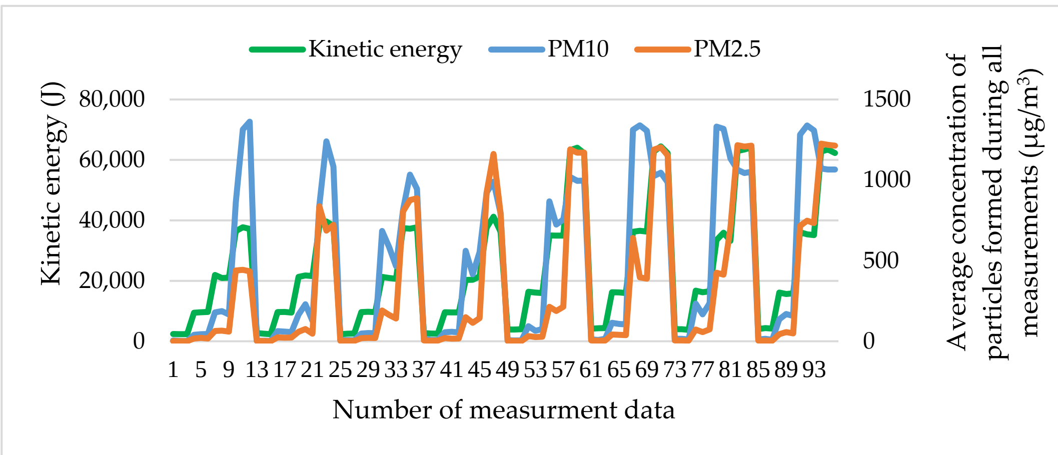
The influence of kinetic energy on the concentrations of $PM_{2.5}$ and PM_{10} particles is shown in Figure 10. It can be seen from the diagram that kinetic energy, as one of the derived influencing factors, had a significant influence on the concentrations of particles. The figure shows trends of changes in particle concentrations in relation to the kinetic energy. It is noticeable that the concentrations of particles follows the trend of kinetic energy.



(**a**)

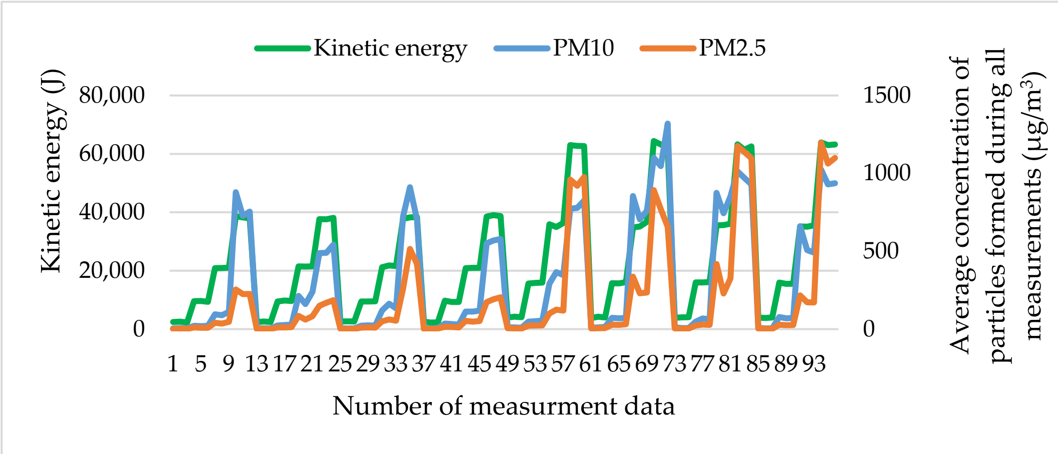


(**b**)



(**c**)

Figure 10. *Cont.*



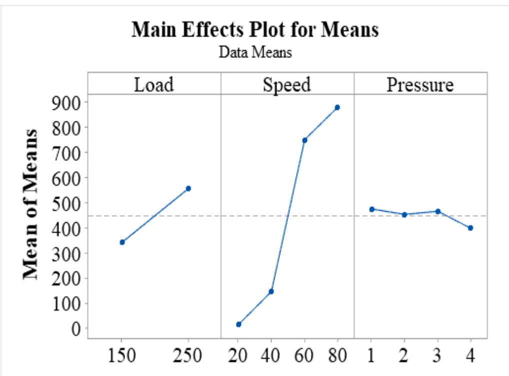
(**d**)

Figure 10. Average concentrations of $PM_{2.5}$ and PM_{10} particles of all measurements related to the kinetic energy, where: (**a**) brake pad A, (**b**) brake pad B, (**c**) brake pad C, and (**d**) brake pad D.

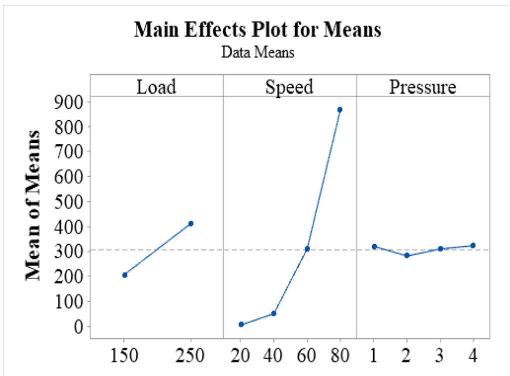
4.2. Analysis of the Influence of Braking Parameters According to Taguchi Analysis

By applying the Taguchi design of the experiment, the analysis of the obtained results of the different parameters' influence on the concentrations of $PM_{2.5}$ and PM_{10} particles for different types of brake pads was achieved. The obtained results are shown in Figure 11. The analysis of the obtained results led to the conclusion that the simulated speed of the vehicle had the dominant influence in all cases, but the intensity of the influence depended on the applied brake pad. With most brake pads, i.e., in three out of four cases, it was concluded that the load showed a strong influence after the vehicle speed, while the pressure showed the least influence. The applied pressure values in this case showed variability in the obtained concentrations of $PM_{2.5}$ and PM_{10} particles. In the case of brake pad B, it was shown that pressure was an influencing factor on the resulting concentrations of particles.

By analyzing the previous data, it can be concluded that when the load increases, there is a higher concentration of particles, but it is certainly necessary to take into account their variability in this case. The previous conclusions can be reached by analyzing each of the diagrams showing the influence of an individual parameter on a certain concentration of $PM_{2.5}$ or PM_{10} particles. This kind of diagram analysis achieves the ranking of factors according to the influence on the resulting concentration of PM_{10} and $PM_{2.5}$ particles.



(**a**)



(**b**)

Figure 11. *Cont.*

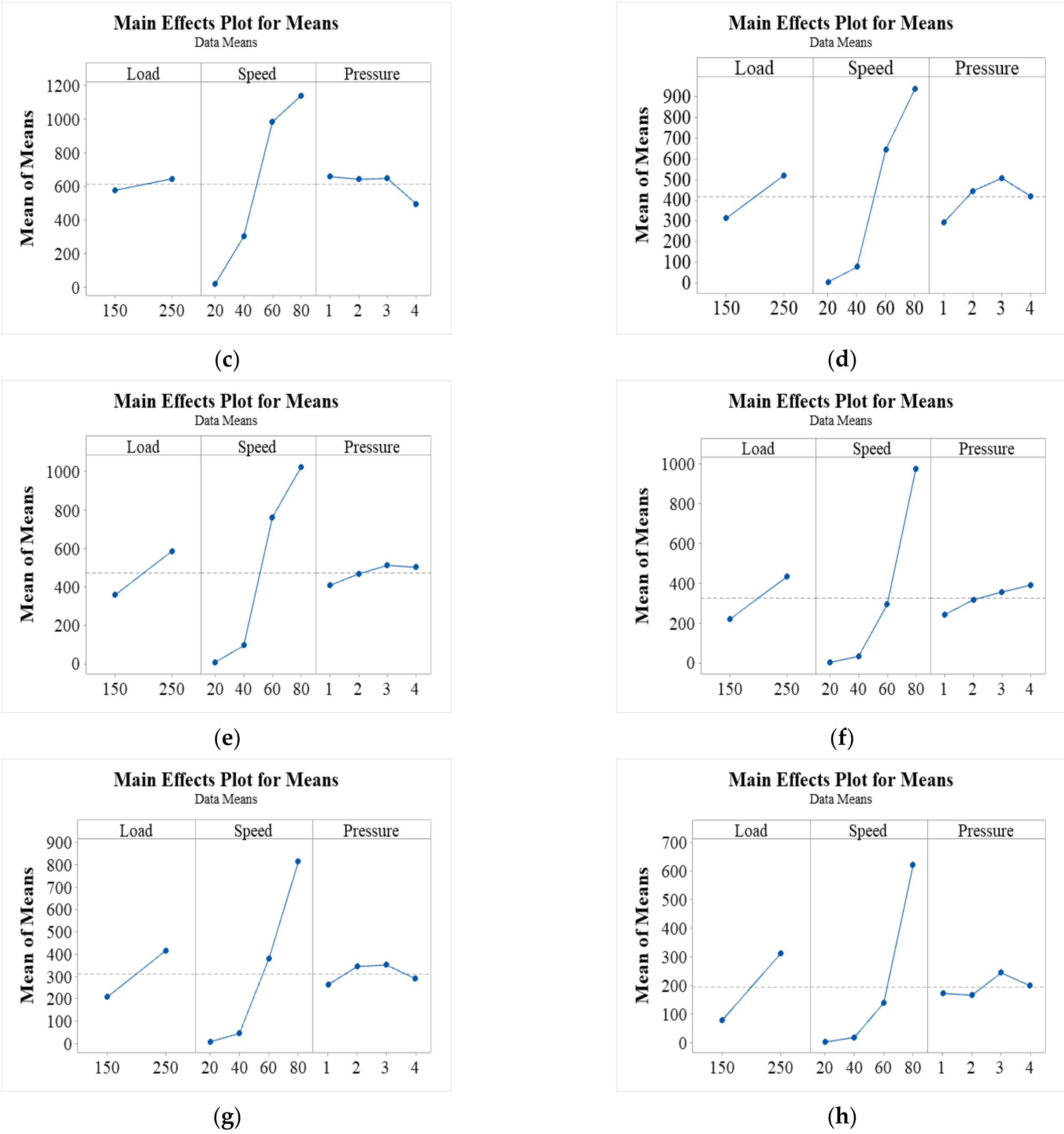


Figure 11. Analysis of the influence of observed factors according to the Taguchi method, where: (**a**) brake pad A—PM_{10}, (**b**) brake pad A—$PM_{2.5}$ (**c**) brake pad B—PM_{10}, (**d**) brake pad B—$PM_{2.5}$, (**e**) brake pad C—PM_{10}, (**f**) brake pad C—$PM_{2.5}$, (**g**) brake pad D—PM_{10}, and (**h**) brake pad D—$PM_{2.5}$.

Analyzing each individual factor for each of the brake pads, it is noticeable that speed has the largest range of influence, followed by load, while mostly pressure has the smallest range of influence. It is noticeable only on the diagram for the brake pad B that there is a slightly larger range of influence of the pressure in relation to the load.

Observing the obtained results for the influence of brake parameters on the concentrations of PM_{10} and $PM_{2.5}$ particles and applying the data obtained by the Taguchi method, the data shown in Table 5 can be obtained. Such data correspond mainly to the previous analysis of the obtained data, and at the same time, in comparison with other researchers, it leads to the conclusion that the results coincide with the obtained data of other authors, where the initial braking speed and load are more influential than the braking pressure. But certainly, as shown in the table, the applied brake pad has an influence again, because it was shown that in the case of brake pad B, the brake pressure in relation to the load has a greater influence.

Table 5. Analysis of the significance of the influence of different brake parameters on the concentrations of PM_{10} and $PM_{2.5}$ particles according to Taguchi analysis.

	Load 1/4 Vehicle		**Initial Braking Speed**		**Brake Pressure in the Braking System**	
	PM_{10}	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
Average value of all measurements	2	2	1	1	3	3
Brake pad A	2	2	1	1	3	3
Brake pad B	3	3	1	1	2	2
Brake pad C	2	2	1	1	3	3
Brake pad D	2	2	1	1	3	3

In this case, a summary table of the obtained data is provided, where the data are displayed based on all average concentration values for different brake pads. Based on Table 4, it can be seen that, in general, the greatest influence on concentration is speed, followed by load, and finally, pressure in the hydraulic braking system. On the other hand, if you look at the influence of brake parameters according to the brake pads, it is noticeable that for brake pads A, C, and D, the most significant parameters are the speed, then the load, and finally, the pressure in the hydraulic brake system. In the case of brake pad B, the greatest influence on the concentrations of both types of particles is speed, followed by pressure, and finally, load. Based on that, by applying the Taguchi method, it is possible to determine that braking parameters can affect the concentrations of generated particles differently when looking at different types of brake pads, so brake pads also have an impact on the resulting concentrations of PM_{10} and $PM_{2.5}$ particles.

4.3. Correlational Analysis of Measurement Data

4.3.1. Correlation Analysis Using the Pearson Coefficient

Based on all of the presented data related to the correlations, a comparative analysis of correlations of different parameters and concentrations of PM_{10} and $PM_{2.5}$, depending on the brake pad using the Pearson coefficient, is shown in Table 6. From this table, where the correlations with the particle emissions according to the type of brake pads are shown, the importance of each parameter can be determined, and its impact on the emissions can be determined.

It can be seen that different parameters affect the concentrations of PM_{10} and $PM_{2.5}$ particles differently. In some cases, the same parameters act identically on the concentrations of particles, but sometimes they act differently in relation to the type of particles. Therefore, the type of brake pad is equally important for the concentrations of particles that occur during brake wear.

Correlation analysis using the Pearson coefficient showed that the parameters can influence the concentrations of particles with different intensities. The concentrations of PM_{10} and $PM_{2.5}$ particles were shown to be in a strong correlation, except in the case of brake pad B, where it was determined that there was a moderate correlation between these two concentrations. The analysis showed that for all brake pads, the speed was strongly correlated with the concentrations of both types of particles. Brake pad temperature was also strongly correlated with particle concentrations. The final temperature was very strongly correlated with the concentration of $PM_{2.5}$ particles in the case of brake pads A and C. The load was shown to have a very weak or weak correlation with the concentration of particles, and in the case of brake pad B, it was even shown to have no correlation with the concentration of PM_{10} particles. Braking time was shown to be a factor that also had a correlation that was weak or moderate with the concentration of both types of particles, but again, depending on the brake pad. Deceleration was shown to be one of the factors that was very weakly correlated with the concentration of PM_{10} particles in the case of brake pad D, and the concentration of $PM_{2.5}$ particles in the case of brake pad B and C. The ambient temperature had a very weak and weak correlation with the concentrations of PM_{10} and $PM_{2.5}$ particles in the case of brake pad A, while in the case of brake pad B, it had a weak correlation with the concentration of PM_{10} particles. The coefficient of friction between the friction pairs was shown to be in a weak and moderate correlation with both types of particles in the case of brake pads C and D. The braking torque was only weakly correlated with the concentration of both types of particles when it comes to brake pad D. Kinetic energy, as a derived parameter, proved to be a very significant parameter for all brake pads. The correlation with particle concentrations depended on the brake pad used, but generally, it was a strong or very strong correlation between kinetic energy and particle concentrations.

Using the Pearson coefficient, it was shown that brake pressure and air humidity were not correlated with the concentrations of PM_{10} and $PM_{2.5}$ particles for any type of brake pad.

Table 6. Comparative analysis of correlations of different parameters and concentrations of PM_{10} and $PM_{2.5}$ depending on the brake pad using the Pearson coefficient, where: (green) very weak correlation, (yellow) weak correlation, (blue) moderate correlation, (pink) strong correlation, and (red) very strong correlation.

	Brake Pad A		Brake Pad B		Brake Pad C		Brake Pad D	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Load of 1/4 of vehicle	0.246 *	0.259 *	0.063	0.218 *	0.232 *	0.247 *	0.282 **	0.359 **
Initial brake speed on brake dyno	0.852 **	0.848 **	0.844 **	0.790 **	0.302 **	0.339 **	0.835 **	0.679 **
Initial brake speed	0.850 **	0.844 **	0.844 **	0.787 **	0.841 **	0.824 **	0.835 **	0.680 **
Brake pressure on brake dyno	−0.067	−0.001	−0.1	0.104	0.074	0.126	0.026	0.054
Brake pressure	−0.064	0.001	−0.09	0.114	0.083	0.134	0.03	0.058
Final brake pad temperature	0.863 **	0.934 **	0.740 **	0.819 **	0.799 **	0.919 **	0.868 **	0.782 **
Brake moment	−0.039	0.024	−0.06	0.127	0.106	0.153	0.203 *	0.204 *
Braking time	0.582 **	0.543 **	0.631 **	0.404 **	0.451 **	0.396 **	0.467 **	0.406 **
Deceleration	0.071	0.118	0.124	0.248 *	0.178	0.204 *	0.207 *	0.158
Ambient air humidity	0.002	−0.016	0.15	0.14	0.154	0.043	−0.032	−0.01
Ambient temperature	0.261 **	0.322 **	0.334 **	0.191	0.146	0.175	0.105	0.074
Coefficient of friction between friction pairs	0.151	0.109	0.16	0.046	0.382 **	0.336 **	0.674 **	0.550 **
Kinetic energy	0.883 **	0.964 **	0.779 **	0.827 **	0.859 **	0.938 **	0.934 **	0.887 **
PM_{10}	-	0.834 **	-	0.629 **	-	0.821 **	-	0.842 **
$PM_{2.5}$	0.834 **	-	0.629 **	-	0.821 **	-	0.842 **	-

* Correlation significant at the level 0.05. ** Correlation significant at the level 0.01.

4.3.2. Correlation Analysis Using the Spearman Coefficient

Based on all of the data obtained by analyzing the correlations between various factors of the vehicle braking process and the concentrations of PM_{10} and $PM_{2.5}$ particles, and taking into account several tested types of brake pads and the application of the Spearman coefficient, the results shown in Table 7 were obtained. In this case, the load proved to be a factor with a very weak correlation with the concentrations of PM_{10} and $PM_{2.5}$ particles in the case of brake pads A, C, and D, while in the case of brake pad B, it did not show a significant correlation. Speed, as one of the factors in the case of brake pads A, B and C, can be concluded to be strongly correlated with the concentration of PM_{10} particles, while in the case of brake pad D, it was highly correlated. Also, speed, as one of the factors, had a very strong correlation with the concentration of $PM_{2.5}$ particles for all four brake pads. The pressure was shown to be weakly correlated only with the concentration of $PM_{2.5}$ particles only for the case of brake pad C. The final temperature of the brake pads turned out to be, like the speed, one of the factors that had a very strong or strong correlation with concentrations for both particles, and the strength of the correlation depended only on the brake pads. The final temperature of the brake pads, in the case of all brake pads and when it comes to the concentration of $PM_{2.5}$ particles, was in a very strongly correlated relationship. In the case of brake pads C and D, it was shown that the braking torque had a very weak correlation with the concentrations of PM_{10} and $PM_{2.5}$ particles, but they were certainly of new significance. Braking time is a factor that, in the case of the concentrations of both types of particles, was in a strong correlation for the case of brake pad A, while in the case of the other three brake pads, this factor was in a moderate correlation with the concentrations of PM_{10} and $PM_{2.5}$ particles. Deceleration, as a factor for the case of brake pad A, was not correlated with the concentrations of PM_{10} and $PM_{2.5}$ particles. In the case of brake pad B, it was weakly correlated with the concentration of $PM_{2.5}$ particles, while in the case of brake pads C and D, it was weakly correlated. The deceleration and concentration of PM_{10} particles were found to be very weakly correlated in the case of brake pads B, C, and D. Air humidity was shown, according to this analysis, to be very weakly correlated with both particle concentrations only in the case of brake pad C. The ambient temperature had an effect only on the concentrations of particles in the case of brake pads A and B, and that in a weak or very weak correlation, depending on the brake pad and the concentration of particles. On the other hand, the coefficient of friction between the friction pairs was shown to have an effect only on particle concentrations in the case of brake pads C and D. In the case of brake pad C, the correlation between the concentrations of PM_{10} and $PM_{2.5}$ particles was very weak, while in the case of brake pad D, it was determined that there was a strong correlation between the concentration of particles and the coefficient of friction between friction pairs. If the correlations between the obtained data on the concentrations of PM_{10} and $PM_{2.5}$ particles were analyzed, it can be determined that there was a certain correlation between the concentrations. Thus, only in the case of brake pad B, the correlation between both particle concentrations was found to have a strong correlation, while the correlation between the concentrations of PM_{10} and $PM_{2.5}$ particles was very strong in the case of brake pads A, C and D. The correlation between kinetic energy and particle concentrations of PM_{10} and $PM_{2.5}$ was shown to be very strong in all cases, except in the case of brake pad B, where the correlation relationship with the concentration of PM_{10} particles was shown to be in a strong correlation relationship.

Table 7. Comparative analysis of correlations of different parameters and concentrations of PM_{10} and $PM_{2.5}$ depending on the brake pad using the Spearman coefficient, where: (green) very weak correlation, (yellow) weak correlation, (blue) moderate correlation, (pink) strong correlation, and (red) very strong correlation.

	Brake Pad A		**Brake Pad B**		**Brake Pad C**		**Brake Pad D**	
	PM_{10}	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
Load of 1/4 of vehicle	0.254 *	0.200 *	0.066	0.188	0.241 *	0.217 *	0.246 *	0.249 *
Initial brake speed on brake dyno	0.895 **	0.956 **	0.867 **	0.909 **	0.880 **	0.940 **	0.912 **	0.915 **
Initial brake speed	0.901 **	0.955 **	0.879 **	0.927 **	0.893 **	0.957 **	0.943 **	0.947 **
Brake pressure on brake dyno	−0.065	−0.028	−0.017	0.12	0.109	0.123	0.012	0.02
Brake pressure	−0.031	−0.002	0.035	0.192	0.181	0.202 *	0.028	0.035
Final brake pad temperature	0.920 **	0.954 **	0.861 **	0.942 **	0.873 **	0.929 **	0.938 **	0.935 **
Brake moment	−0.001	0.027	0.042	0.167	0.225 *	0.233 *	0.263 **	0.274 **
Braking time	0.703 **	0.689 **	0.616 **	0.601 **	0.556 **	0.575 **	0.637 **	0.634 **
Deceleration	0.095	0.152	0.211 *	0.319 **	0.238 *	0.264 **	0.266 **	0.274 **
Ambient air humidity	−0.015	0.029	0.08	0.072	0.250 *	0.227 *	−0.056	−0.088
Ambient temperature	0.310 **	0.288 **	0.479 **	0.462 **	0.082	0.08	0.197	0.168
Coefficient of friction between friction pairs	0.174	0.177	0.14	0.011	0.395 **	0.373 **	0.824 **	0.834 **
Kinetic energy	0.930 **	0.978 **	0.873 **	0.944 **	0.926 **	0.977 **	0.971 **	0.975 **
PM_{10}	-	0.947 **	-	0.853 **	-	0.937 **	-	0.993 **
$PM_{2.5}$	0.947 **	-	0.853 **	-	0.937 **	-	0.993 **	-

* Correlation significant at the level 0.05. ** Correlation significant at the level 0.01.

5. Conclusions

The problem of pollution with PM_{10} and $PM_{2.5}$ particles in traffic will represent a significant problem in the future, especially when it comes to non-exhaust emissions and brake wear. As expected, the harmful impact will intensify with an increase in the mass of vehicles due to the increase in the use of electric vehicles. Particle pollution caused by the wear of brake friction pairs is very harmful to humans and the environment. The composition of the brake pads and the materials from which the rotors are made are different, and the composition of the brake pads is heterogeneous, where there are a number of different materials that can be harmful. In the future, various devices on vehicles will be intensively developed that would lead to a reduction in the release of particles into the atmosphere, and also systems that would reduce the concentrations of the resulting particles. For this reason, understanding the factors influencing particle concentrations is of great importance.

Several direct parameters that the driver has an influence on and indirect factors that define vehicle braking but that the driver cannot directly influence were analyzed in this paper. Several different statistical analysis methods were used for this analysis. The aforementioned leads to the fact that this study differs from previous studies, bearing in mind that a detailed analysis of the parameters was carried out using different statistical methods, comparing their influence on the emissions of brake wear particles depending on the application of different brake pads. Some of the most important conclusions reached after analyzing the data for the case of applying different brake pad materials are:

- The material and geometric features of the applied brake pads on a motor vehicle have an impact on the concentrations of PM_{10} and $PM_{2.5}$ particles. The influence of brake pads has a direct impact on the resulting concentrations, where it was shown that their composition, i.e., applied materials, significantly affects the concentration of particles. Brake pads that are more environmentally acceptable give a higher concentration of particles, but such particles are less harmful considering the materials used. The price of brake pads is certainly dictated by their composition and brand, so a clear conclusion cannot be given from the aspect of that parameter, but it turned out that the brake pads with the lowest price created the lowest amount of particles. It can certainly be concluded that the composition of the brake pads and their design are directly related to the concentrations of PM_{10} and $PM_{2.5}$ particles.
- Using several statistical analyses for data processing and diagram analysis, the direct braking parameters were observed, and it was concluded that they have different effects on the resulting concentrations of particles. In the case of the vehicle's speed, which was simulated using an inertial brake dynamometer, it has the greatest influence on the resulting concentration of particles in relation to load and pressure. The load is a significant parameter for the resulting concentration of particles, where with increasing speed and load, the resulting concentration of particles also increases. Therefore, it can be concluded, which was confirmed by further analysis, that a significant parameter is the vehicle's kinetic energy. Pressure, on the other hand, and its influence depends on the brake pad that is applied and on other parameters, but its influence is generally the smallest on the resulting concentrations of PM_{10} and $PM_{2.5}$ particles, at least in the case of this research.
- When it comes to the indirect braking parameters presented in this case, it has been shown that the concentrations of PM_{10} and $PM_{2.5}$ particles are affected by different braking parameters that generally depend on the brake pad. The final temperature of the brake pads, as well as the temperature between the friction pairs, has a significant influence on the particle concentration. Braking torque, braking time, and deceleration are also important parameters related to particle concentration. Depending on the brake pads, the coefficient of friction between the friction pairs, ambient temperature, and air humidity are also parameters that have an impact.
- Also in this paper, it was shown that the concentration of $PM_{2.5}$ particles in some cases at higher loads and speeds can have a higher value compared to the concentration of PM_{10} particles.
- Vehicle speed has a direct impact on the concentrations of PM_{10} and $PM_{2.5}$ particles. An increase in vehicle speed leads to an increase in the concentration of particles. A change in speed of 20 km/h can significantly increase the concentration of particles by several tens of percent. The change and increase in the concentrations of PM_{10} and $PM_{2.5}$ particles with increasing speed has been confirmed, but the percentage increase depends specifically on the brake pads used. By applying correlation analysis and

Taguchi analysis, it was also concluded that the speed has a very strong correlation with the concentrations of PM_{10} and $PM_{2.5}$ particles.
- Load also affects the concentrations of PM_{10} and $PM_{2.5}$ particles. Due to the increase in the load, as shown in this paper, by 100 kg, there is an increase in the concentration of particles by over 50%, but again, the increase in the concentration of particles depends on the applied brake pads. The load, both by applying correlation analysis and Taguchi analysis, was shown to be a factor that has an influence on the emission of particles.
- It was shown that the kinetic energy of the vehicle is a very important factor for the resulting concentration of particles, which is highly correlated with the formation of particles, so that an increase in kinetic energy directly leads to an increase in the concentration of particles. The relationship between kinetic energy and the resulting concentration of particles was confirmed by correlation analysis.
- The pressure in the hydraulic part of the brake installation proved to be a parameter that has very little influence on the concentration of particles. Pressure changes in the brake system mainly lead to small variations in the concentration of particles. Such conclusions were also reached by correlation analysis.
- The influence of the temperature of the brake pads proved to be one of the dominant factors, which certainly leads to an increase in the concentrations of PM_{10} and $PM_{2.5}$ particles. Depending on the applied brake pad, when the temperature of the brake pad increases, the concentration of $PM_{2.5}$ particles has a higher value than the concentration of PM_{10} particles. Such conclusions were also reached by correlation analysis, where it was determined that the temperature of the brake pads has a strong correlation with the emission of particles.
- Correlation analysis also found that some parameters are directly related to the concentrations of PM_{10} and $PM_{2.5}$ particles, and depending on the brake pad, their strength of connection varies. In the case of braking time, it was shown that braking time has a direct positive relationship with the concentrations of PM_{10} and $PM_{2.5}$ particles for all brake pads. Ambient temperatures, coefficient of friction between friction pairs, and deceleration have an impact in the case of some of the applied brake pads, but they are more dominant than some other parameters such as braking torque and air humidity.
- Further research will be focused on the brake rotor and the applications of the various rotors that are most commonly used and available on the market. A detailed analysis of the influence of various parameters will also be focused on the exact composition of the brake pads in subsequent research, i.e., an analysis of the individual materials in the composition of the brake pads will be conducted.
- At the time of the experimental measurements, there were no regulations that would prescribe the methodology of the test. Bearing in mind the proposal of the laboratory method of testing the emissions of brake wear particles [78], future research could be carried out in accordance with this proposal, taking into account the methodology and the driving cycle that was proposed.

Author Contributions: The following author contributions are acknowledged: Conceptualization, M.Đ.; Formal analysis, S.V.; Funding acquisition, J.L.; Investigation, J.G. and M.S.; Methodology, S.V. and D.M.; Validation, J.L., D.M. and M.Đ.; Visualization, M.S.; Writing—original draft, S.V.; Writing—review and editing, J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be provided via the SCIDAR—A Digital Archive of the University of Kragujevac: https://scidar.kg.ac.rs/ (accessed on 10 October 2023).

Acknowledgments: J.G. acknowledges funding from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Fuller, R.; Landrigan, P.J.; Balakrishnan, K.; Bathan, G.; Bose-O'Reilly, S.; Brauer, M.; Caravanos, J.; Chiles, T.; Cohen, A.; Corra, L.; et al. Pollution and health: A progress update. *Lancet Planet. Health* **2022**, *6*, e535–e547. [CrossRef]
2. Rai, P.K. Particulate Matter and Its Size Fractionation. In *Biomagnetic Monitoring of Particulate Matter*; Rai, P.K., Ed.; Elsevier: Amsterdam, The Netherlands, 2015; Volume 1, pp. 1–13.
3. Mangipudy, R.M. Aerosols. In *Encyclopedia of Toxicology*, 2nd ed.; Wexler, P., Ed.; Elsevier: Amsterdam, The Netherlands, 2005; p. 51.
4. Dimopoulos Eggenschwiler, P.; Schreiber, D.; Papetti, V.; Gramstat, S.; Lugovyy, D. Electron Microscopic Characterization of the Brake Assembly Components (Disc and Pads) from Passenger Vehicles. *Atmosphere* **2022**, *13*, 523. [CrossRef]
5. Schraufnagel, D.E. The health effects of ultrafine particles. *Exp. Mol. Med.* **2020**, *52*, 311–317. [CrossRef]
6. Nezis, I.; Biskos, G.; Eleftheriadis, K.; Kalantzi, O.I. Particulate matter and health effects in offices—A review. *Build Environ.* **2019**, *156*, 62–73. [CrossRef]
7. Saini, M.; Joon, M.; Saini, S.K. Human Health Effects of Particulate Matter. In *Airborne Particulate Matter*, 1st ed.; Sonwani, S., Shukla, A., Eds.; Springer: Singapore, 2022; pp. 195–228.
8. Burns, J.; Boogaard, H.; Polus, S.; Pfadenhauer, L.M.; Rohwer, A.C.; van Erp, A.M.; Turley, R.; Rehfuess, E. Interventions to reduce ambient particulate matter air pollution and their effect on health. *Cochrane Database Syst. Rev.* **2019**, *5*, CD010919. [CrossRef] [PubMed]
9. Quezada-Maldonado, E.M.; Sánchez-Pérez, Y.; Chirino, Y.I.; García-Cuellar, C.M. Airborne particulate matter induces oxidative damage, DNA adduct formation and alterations in DNA repair pathways. *Environ. Pollut.* **2021**, *287*, 117313. [CrossRef] [PubMed]
10. Kelly, F.J.; Fussell, J.C. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmos. Environ.* **2012**, *60*, 504–526. [CrossRef]
11. Hien, P.D.; Bac, V.T.; Thinh, N.T.H.; Anh, H.L.; Thang, D.D.; Nghia, N.T. A Comparison Study of Chemical Compositions and Sources of PM1.0 and PM2.5 in Hanoi. *Aerosol Air Qual. Res.* **2021**, *21*, 210056. [CrossRef]
12. Jbaily, A.; Zhou, X.; Liu, J.; Lee, T.H.; Kamareddine, L.; Verguet, S.; Dominici, F. Air pollution exposure disparities across US population and income groups. *Nature* **2022**, *601*, 228–233. [CrossRef]
13. Hammer, M.S.; van Donkelaar, A.; Li, C.; Lyapustin, A.; Sayer, A.M.; Hsu, N.C.; Levy, R.C.; Garay, M.J.; Kalashnikova, O.V.; Kahn, R.A.; et al. Global Estimates and Long-Term Trends of Fine Particulate Matter Concentrations (1998–2018). *Environ. Sci. Technol.* **2020**, *54*, 7879–7890. [CrossRef]
14. Billions of People Still Breathe Unhealthy Air: New WHO Data. Available online: https://www.who.int/news/item/04-04-2022-billions-of-people-still-breathe-unhealthy-air-new-who-data (accessed on 3 December 2022).
15. Hopke, P.K.; Dai, Q.; Li, L.; Feng, Y. Global review of recent source apportionments for airborne particulate matter. *Sci. Total Environ.* **2020**, *740*, 140091. [CrossRef] [PubMed]
16. Mukherjee, A.; Agrawal, M. World air particulate matter: Sources, distribution and health effects. *Environ. Chem. Lett.* **2017**, *15*, 283–309. [CrossRef]
17. Sokhi, S.R.; Moussiopoulos, N.; Baklanov, A.; Bartzis, J.; Coll, I.; Finardi, S.; Friedrich, R.; Geels, C.; Grönholm, T.; Halenka, T.; et al. Advances in air quality research—Current and emerging challenges. *Atmos. Chem. Phys.* **2022**, *22*, 4615–4703. [CrossRef]
18. Almeida, S.M.; Manousakas, M.; Diapouli, E.; Kertesz, Z.; Samek, L.; Hristova, E.; Šega, K.; Padilla Alvarez, R.; Belis, C.A.; Eleftheriadis, K. Ambient particulate matter source apportionment using receptor modelling in European and Central Asia urban areas. *Environ. Pollut.* **2020**, *266*, 115199. [CrossRef]
19. Karagulian, F.; Belis, C.A.; Dora, C.F.C.; Prüss-Ustün, A.M.; Bonjour, S.; Adair-Rohani, H.; Amann, M. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmos. Environ.* **2015**, *120*, 475–483. [CrossRef]
20. McDuffie, E.E.; Martin, R.V.; Spadaro, J.V.; Burnett, R.; Smith, S.J.; O'Rourke, P.; Hammer, M.S.; van Donkelaar, A.; Bindle, L.; Shah, V.; et al. Source sector and fuel contributions to ambient PM2.5 and attributable mortality across multiple spatial scales. *Nat. Commun.* **2021**, *12*, 3594. [CrossRef] [PubMed]
21. Cheng, Y.; Lee, S.; Gu, Z.; Ho, K.; Zhang, Y.; Huang, Y.; Chow, J.C.; Watson, J.G.; Cao, J.; Zhang, R. PM2.5 and PM10-2.5 chemical composition and source apportionment near a Hong Kong roadway. *Particuology* **2015**, *18*, 96–104. [CrossRef]
22. Nagpure, A.S.; Gurjar, B.R.; Kumar, V.; Kumar, P. Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi. *Atmos. Environ.* **2016**, *127*, 118–124. [CrossRef]

23. OECD. *Non-Exhaust Particulate Emissions from Road Transport: An Ignored Environmental Policy Challenge*; OECD Publishing: Paris, France, 2020.
24. Thorpe, A.; Harrison, R.M. Sources and properties of non-exhaust particulate matter from road traffic: A review. *Sci. Total Environ.* **2008**, *400*, 270–282. [CrossRef]
25. Harrison, R.M. Airborne particulate matter. *Philos. Trans. R. Soc. A* **2020**, *378*, 20190319. [CrossRef]
26. Timmers, V.R.J.H.; Achten, P.A.J. Non-exhaust PM emissions from electric vehicles. *Atmos. Environ.* **2016**, *134*, 10–17. [CrossRef]
27. Songkitti, W.; Sa-ard-iam, S.; Plengsa-Ard, C.; Wirojaskunchai, E. Effects of Payloads on Non-exhaust PM Emissions from A Hybrid Electric Vehicle during A Braking Sequence. *Aerosol Air Qual. Res.* **2022**, *22*, 220150. [CrossRef]
28. Lin, S.; Liu, Y.; Chen, H.; Wu, S.; Michalaki, V.; Proctor, P.; Rowley, G. Impact of change in traffic flow on vehicle non-exhaust PM2.5 and PM10 emissions: A case study of the M25 motorway, UK. *Chemosphere* **2022**, *303*, 135069. [CrossRef] [PubMed]
29. Demir, T.; Karakaş, D.; Yenisoy-Karakaş, S. Source identification of exhaust and non-exhaust traffic emissions through the elemental carbon fractions and Positive Matrix Factorization method. *Environ. Res.* **2022**, *204*, 112399. [CrossRef] [PubMed]
30. Winkler, A.; Amoroso, A.; Di Giosa, A.; Marchegiani, G. The effect of Covid-19 lockdown on airborne particulate matter in Rome, Italy: A magnetic point of view. *Environ. Pollut.* **2021**, *291*, 118191. [CrossRef] [PubMed]
31. Hicks, W.; Beevers, S.; Tremper, A.H.; Stewart, G.; Priestman, M.; Kelly, F.J.; Lanoisellé, M.; Lowry, D.; Green, D.C. Quantification of Non-Exhaust Particulate Matter Traffic Emissions and the Impact of COVID-19 Lockdown at London Marylebone Road. *Atmosphere* **2021**, *12*, 190. [CrossRef]
32. Lawrence, S.; Sokhi, R.; Ravindra, K. Quantification of vehicle fleet PM 10 particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques. *Environ. Pollut.* **2016**, *210*, 419–428. [CrossRef]
33. Zhang, J.; Peng, J.; Song, C.; Ma, C.; Men, Z.; Wu, J.; Wu, L.; Wang, T.; Zhang, X.; Tao, S.; et al. Vehicular non-exhaust particulate emissions in Chinese megacities: Source profiles, real-world emission factors, and inventories. *Environ. Pollut.* **2020**, *266*, 115268. [CrossRef]
34. Singh, V.; Biswal, A.; Kesarkar, A.P.; Mor, S.; Ravindra, K. High resolution vehicular PM10 emissions over megacity Delhi: Relative contributions of exhaust and non-exhaust sources. *Sci. Total Environ.* **2019**, *699*, 134273. [CrossRef]
35. Harrison, R.M.; Jones, A.M.; Gietl, J.; Yin, J.; Green, D.C. Estimation of the Contributions of Brake Dust, Tire Wear, and Resuspension to Nonexhaust Traffic Particles Derived from Atmospheric Measurements. *Environ. Sci. Technol.* **2012**, *46*, 6523–6529. [CrossRef]
36. Grigoratos, T.; Martini, G. Brake wear particle emissions: A review. *Environ. Sci. Pollut. Res. Int.* **2015**, *22*, 2491–2504. [CrossRef] [PubMed]
37. Philippe, F.; Morgeneyer, M.; Xiang, M.; Manokaran, M.; Berthelot, B.; Chen, Y.; Charles, P.; Guingand, F.; Bressot, C. Representativeness of airborne brake wear emission for the automotive industry: A review. *Proc. Inst. Mech. Eng. Part. D J. Automob. Eng.* **2021**, *235*, 2651–2666. [CrossRef]
38. Broniszewski, J.; Piechna, J.R. Fluid-Structure Interaction Analysis of a Competitive Car during Brake-in-Turn Manoeuvre. *Energies* **2022**, *15*, 2917. [CrossRef]
39. Cravero, C.; Marsano, D. Flow and Thermal Analysis of a Racing Car Braking System. *Energies* **2022**, *15*, 2934. [CrossRef]
40. Chłopek, Z.; Jakubowski, A. A study of the particulate matter emission from the braking systems of motor vehicles. *Eksploat. I Niezawodn.* **2009**, *4*, 45–52.
41. Garg, B.D.; Cadle, S.H.; Mulawa, P.A.; Groblicki, P.J.; Laroo, C.; Parr, G.A. Brake Wear Particulate Matter Emissions. *Environ. Sci. Technol.* **2000**, *34*, 4463–4469. [CrossRef]
42. Perricone, G.; Alemani, M.; Metinöz, I.; Matějka, V.; Wahlström, J.; Olofsson, U. Towards the ranking of airborne particle emissions from car brakes—A system approach. *Proc. Inst. Mech. Eng. Part. D J. Automob. Eng.* **2017**, *231*, 781–797. [CrossRef]
43. Glišović, J.; Pešić, R.; Lukić, J.; Miloradović, D. Airborne Wear Particles from Automotive Brake Systems: Environmental and Health Issues. In Proceedings of the 1st International Conference on Quality of Life Center for Quality, Kragujevac, Republic of Serbia, 9–10 June 2016; Arsovski, S., Ed.; Faculty of Engineering: Kragujevac, Republic of Serbia, 2016.
44. Gerlofs-Nijland, M.E.; Bokkers, B.G.H.; Sachse, H.; Reijnders, J.J.E.; Gustafsson, M.; Boere, A.J.F.; Fokkens, P.F.H.; Lesemana, D.L.A.C.; Augsburg, K.; Cassee, F.R. Inhalation toxicity profiles of particulate matter: A comparison between brake wear with other sources of emission. *Inhal. Toxicol.* **2019**, *31*, 89–98. [CrossRef]
45. Sanders, P.G.; Xu, N.; Dalka, T.M.; Maricq, M.M. Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests. *Environ. Sci. Technol.* **2003**, *37*, 4060–4069. [CrossRef]
46. van Laaten, N.; Merten, D.; von Tümpling, W.; Schäfer, T.; Pirrung, M. Comparison of Spider Web and Moss Bag Biomonitoring to Detect Sources of Airborne Trace Elements. *Water Air Soil. Pollut.* **2020**, *231*, 512. [CrossRef]
47. Vasiljević, S.; Glišović, J.; Stojanović, B.; Stojanović, N.; Grujić, I. Analysis of influencing factors on brake wear and non-exhaust emission with reference to applied materials in brake pads. *Mobil. Veh. Mech.* **2021**, *47*, 45–59.
48. Copper Free Brake Initiative. Available online: https://www.epa.gov/npdes/copper-free-brake-initiative (accessed on 20 December 2022).
49. Vasiljevic, S.; Glišović, J.; Stojanovic, B.; Stojanovic, N.; Grujic, I. The analysis of the influential parameters that cause particles formation during the braking process: A review. *Proc. Inst. Mech. Eng. J J. Eng. Tribol.* **2022**, *236*, 31–48. [CrossRef]

50. Rahimi, M.; Bortoluzzi, D.; Wahlström, J. Input Parameters for Airborne Brake Wear Emission Simulations: A Comprehensive Review. *Atmosphere* **2021**, *12*, 871. [CrossRef]
51. Federici, M.; Alemani, M.; Menapace, C.; Gialanella, S.; Perricone, G.; Straffelini, G. A critical comparison of dynamometer data with pin-on-disc data for the same two friction material pairs—A case study. *Wear* **2019**, *424–425*, 40–47. [CrossRef]
52. Miloradović, D. *Ispitivanje Motornih Vozila*, 1st ed.; Faculty of Engineering: Kragujevac, Republic of Serbia, 2021.
53. Xia, L.; Zou, Z.J.; Wang, Z.H.; Zou, L.; Gao, H. Surrogate model based uncertainty quantification of CFD simulations of the viscous flow around a ship advancing in shallow water. *Ocean. Eng.* **2021**, *234*, 109206. [CrossRef]
54. Cravero, C.; De Domenico, D.; Marsano, D. Uncertainty Quantification Analysis of Exhaust Gas Plume in a Crosswind. *Energies* **2023**, *16*, 3549. [CrossRef]
55. Augsburg, K.; Gramstat, S.; Horn, R.; Sachse, H. Measures Development for Brake Dust Emissions with Computational Fluid Dynamics and Particle Imaging Velocimetry. *SAE Tech. Pap.* **2011**, *1*, 2345.
56. Liu, Y.; Wu, S.; Chen, H.; Federici, M.; Perricone, G.; Li, Y.; Lv, G.; Munir, S.; Luo, Z.; Mao, B. Brake wear induced PM10 emissions during the world harmonised light-duty vehicle test procedure-brake cycle. *J. Clean. Prod.* **2022**, *361*, 132278. [CrossRef]
57. Oroumiyeh, F.; Zhu, Y. Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity. *Atmos. Environ. X* **2021**, *12*, 100121. [CrossRef]
58. Candeo, S.; Leonardi, M.; Gialanella, S.; Straffelini, S. Influence of contact pressure and velocity on the brake behaviour and particulate matter emissions. *Wear* **2023**, *514–515*, 204579. [CrossRef]
59. Hagino, H.; Oyama, M.; Sasaki, S. Airborne brake wear particle emission due to braking and accelerating. *Wear* **2015**, *334–335*, 44–48. [CrossRef]
60. Gramstat, S.; Mertens, T.; Waninger, R.; Lugovyy, D. Impacts on Brake Particle Emission Testing. *Atmosphere* **2020**, *11*, 1132. [CrossRef]
61. Chasapidis, L.; Grigoratos, T.; Zygogianni, A.; Tsakis, A.; Konstandopoulos, A.G. Study of Brake Wear Particle Emissions of a Minivan on a Chassis Dynamometer. *Emiss. Control Sci. Technol.* **2018**, *4*, 271–278. [CrossRef]
62. Mamakos, A.; Arndt, M.; Hesse, D.; Augsburg, K. Physical Characterization of Brake-Wear Particles in a PM10 Dilution Tunnel. *Atmosphere* **2019**, *10*, 639. [CrossRef]
63. Perrenoud, A.; Gasser, M.; Rutishauser, B.R.; Gehr, P.; Riediker, M. Characterisation of nanoparticles resulting from different braking behaviours. *Int. J. Biomed. Nanosci. Nanotechnol.* **2010**, *1*, 17–33. [CrossRef]
64. Men, Z.; Zhang, X.; Peng, J.; Zhang, J.; Fang, T.; Guo, Q.; Wei, N.; Zhang, Q.; Wang, T.; Wu, L.; et al. Determining factors and parameterization of brake wear particle emission. *J. Hazard. Mater.* **2022**, *434*, 128856. [CrossRef]
65. Niemann, H.; Winner, H.; Asbach, C.; Kaminski, H.; Frentz, G.; Milczarek, R. Influence of Disc Temperature on Ultrafine, Fine, and Coarse Particle Emissions of Passenger Car Disc Brakes with Organic and Inorganic Pad Binder Materials. *Atmosphere* **2020**, *11*, 1060. [CrossRef]
66. Matějka, V.; Perricone, G.; Vlček, J.; Olofsson, U.; Wahlström, J. Airborne Wear Particle Emissions Produced during the Dyno Bench Tests with a Slag Containing Semi-Metallic Brake Pads. *Atmosphere* **2020**, *11*, 1220. [CrossRef]
67. Paulus, A.; Kloda, M. Influence of Test Cycle and Energy Input on Brake Emissions. In Proceedings of the EuroBrake2020, Conference, Barcelona, Spain, 2–4 June 2020. EB2020-EBS-019.
68. Farwick zum Hagen, F.H.; Mathissen, M.; Grabiec, T.; Hennicke, T.; Rettig, M.; Grochowicz, J.; Vogt, R.; Benter, T. On-road vehicle measurements of brake wear particle emissions. *Atmos. Environ.* **2019**, *217*, 116943. [CrossRef]
69. Abdul Mokti, M.F.F.; Abdul Hamid, M.K.; Abu Bakar, A.R. Humidity and Water Effect on Wear Characteristics of Disc Braking System. *Appl. Mech. Mater.* **2016**, *819*, 612–617. [CrossRef]
70. Djafri, M.; Bouchetara, M.; Busch, C.; Weber, S. Effects of humidity and corrosion on the tribological behaviour of the brake disc materials. *Wear* **2014**, *321*, 8–15. [CrossRef]
71. Grujic, I.; Vasiljevic, S.; Glisovic, J.; Stojanovic, N. Simulation of vehicle's inertia using a flywheel mass to test disc brake system. In *New Technologies, Development and Application III*, 1st ed.; Karabegović, I., Ed.; Springer: Cham, Switzerland, 2020; pp. 360–367.
72. Vasiljević, S.; Glišović, J.; Stojanović, J.; Grujić, I. An overview of non-exhaust brake emission measuring methods. In Proceedings of the 15th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI 2021, Banja Luka, Republic of Srpska, 28–29 May 2021.
73. Vasiljević, S.; Glišović, J.; Stojanović, N.; Grujić, I. Design of chamber for collection and measurement of particles formed by brake wear on an inertial brake dynamometer. *Trakt. I Pogon. Mašine* **2021**, *26*, 36–42.
74. Vasiljević, S.; Glišović, J.; Lukić, J.; Stojanović, N.; Grujić, I. Overview of tests and driving cycles conducted on an inertial brake dynamometer in the testing of particles formed during brake wear. In Proceedings of the EuroBrake, Mainz, Germany, 17–19 May 2022. EB2022-TSD-012.
75. Vasiljević, S.; Lukić, J.; Miloradović, D.; Glišović, J. Driving cycles for studying brake wear particle emissions on an inertial brake dynamometer. *Tribol. Mater.* **2023**, *2*, 8–19. [CrossRef]
76. Vasiljević, S.; Taranović, D.; Lukić, J.; Miloradović, D.; Glišović, J. Design of experimental research on influencing factors on the particle emission caused by brake wear. In Proceedings of the 16th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI 2023, Banja Luka, Republic of Srpska, 1–2 June 2023.

77. Hinkle, D.E.; Wiersma, W.; Jurs, S.G. *Statistics for the Behavioral Sciences: Applying Statistical Concepts Workbook*, 5th ed.; Houghton Mifflin: Boston, NY, USA, 2003; pp. 154–196.
78. Economic Commission for Europe. Proposal for a New UN GTR on Laboratory Measurement of Brake Emissions for Light-Duty Vehicles, ECE/TRANS/WP.29/GRPE/2023/4. Available online: https://wiki.unece.org/display/trans/PMP+Web+Conference+23.11.2022 (accessed on 11 October 2023).