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Driving cycles for studying brake wear particle emissions on an inertial brake dynamometer

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Abstract

With the development of contemporary drive systems that have a lower or zero emission of exhaust products, a significant reduction in the harmful influence of traffic on the environment has been achieved, but today new pollutants have been identified on the vehicle. One of such non-exhaust pollutant are brakes whose wear can be a significant particulate matter (PM) contributor. Examining the mechanisms of the formation of particles during braking, and therefore, brake wear is becoming one of the important areas of research today. There are several tests and driving cycles that are applied during the research of the brakes, but they are not primarily defined for testing particle emissions during braking. UNECE (United Nations Economic Commission for Europe) has included in its plan the introduction of standardised cycles that will prescribe a brake cycle whose purpose will be to examine the formation of particles. The brake pads are made of a mixture of different materials that ensure the longevity and efficiency of the brake system and the applied materials have different wear intensities in certain operating conditions. The most common laboratory tests in this area are performed using inertial brake dynamometers. This paper presents an experimental planning method of quantifying the influence of some of the operating parameters (initial speed of the vehicle, braking pressure and vehicle's load per one brake disc-pads friction pair) on the airborne particulate matter for four different brake pads materials during testing on an inertial brake dynamometer.

1. Introduction

The emission of harmful materials has been identified as one of the major environmental problems facing humanity today [1]. There are a large number of pollutants that are most often associated with industry, traffic, households, etc. Also, in addition to pollutants, the substances that are released and which we identify as pollutants are also important factors. Among such substances are also particles, which are perhaps one of the most dominant pollutants, which are released into the air and thus into the environment [2]. The harmfulness of particles is expressed through several parameters, but most often their size and composition of particles are taken into account, which depend on the source itself [3].

When it comes to environmental pollution caused by traffic, the dominant source of particles is vehicles [4]. In addition to the emission of exhaust gases, the vehicle can emit particles through combustion in the engine and wear of certain elements (so-called non-exhaust particles emission) [5]. Today, when there are various highly efficient systems for the reduction of engine exhaust gases emission, strict Euro emission standards and the intensive development of hybrid and electric vehicles, other sources of particles have been identified. One of those sources is the brakes, which emit particles that are caused by the wear of elements of friction pairs during braking (Fig. 1) [6].

Bearing in mind various researches that have concluded that this is one of the significant problems of environmental pollution, there is a certain potential and opportunities for the introduction of legal regulations and standards for the reduction of particle emissions caused by brake wear [7].

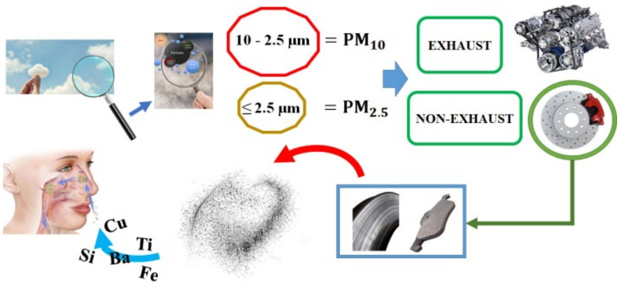

Figure 1. Mechanism of the brake wear particles formation

Brake wear is most often investigated using computer simulations, laboratory tests on an inertial brake dynamometer and pin-on-disc tribometers, but also by testing in real road conditions [8]. However, the problem in brake research is that standard driving cycles and tests for testing concerning the formation of particles in the braking process have not yet been defined. A large number of authors in research use driving cycles that are defined for testing brakes in the automotive industry. Often, researchers identify the formation of particles during braking using their own developed tests. However, there are indications from the UNECE (United Nations Economic Commission for Europe) that there will be a prescription of a driving cycle or tests for this area [9].

The influencing factors that would be analysed are the passenger vehicle wheel load, the initial speed in the braking process and the pressure in the brake system, along with the analysis of the impact of the application of different brake pads (of different manufacturers, composition and geometry). Furthermore, using statistical methods, the dominant influencing factors on the concentration of the resulting particles would be identified and a conclusion drawn as to whether the working parameters change their influence with the use of different brake pads.

The aim of this paper is to review driving cycles and tests applied in brake tests from the aspect of wear and particle formation, only on an inertial brake dynamometer. Based on experiment planning as a method by which the optimal formula of all influential parameters is found, the authors of this paper developed their own methodology for testing brake particles emission in laboratory conditions. An inertial brake dynamometer with the extraction of airborne particles from the chamber was developed in order to simulate the kinetic energy of a vehicle for one brake disc-pads friction par. The test program provides a specific combination for each test so that when processing the results, it can be determined which of the factors has the greatest influence on the emission of $PM_{2.5}$ particles. Four types of brake pads from different manufacturers, intended for the same passenger vehicle model, were tested.

2. Standard driving cycles/tests applied in particle emission research

In the research [10], the driving cycle used for testing exhaust gas emissions was applied, and the research was done according to the Japanese driving cycles JE05 and JC08. The driving cycle JC08 is applied to test the gas emissions of gasoline-powered passenger vehicles, while the driving cycle JE05 is used for the gas emissions of diesel-powered trucks, where both cycles are related to urban tests. This is the reason that these tests include numerous braking and acceleration. The maximum speeds achieved in this case are 81.6 km/h for JC08 and 87.6 km/h for JE05. According to [11], the average speed for the JE05 driving cycle is 26.94 km/h, the maximum speed is 88 km/h and the duration of one cycle is 1800 s. For cycle JC08, the duration of the test was 1230 s. Figure 2 shows graphical representations of these tests.

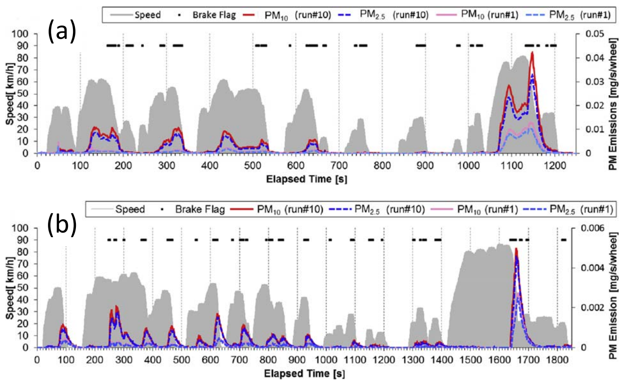

Figure 2. Japanese driving tests: (a) JC08 and (b) JE05; adapted from Hagino et al. [10], licensed under CC BY 4.0

It is certainly important to mention two tests that are also applied in the automotive world, and which can be a significant indicator for the choice of braking parameters. The mentioned two tests are NEDC (New European Driving Cycle) and WLTP (Worldwide harmonized Light vehicles Test

Procedure). The NEDC test is performed so that the maximum speed is varied up to a maximum of 120 km/h, while the average speed is 34 km/h, the maximum deceleration is 1.04 m/s^2 and the average deceleration is 0.5 m/s^2. In the case of the WLTP test, the maximum speed is 131 km/h (56.5, 76.6, 97.4 and 131.3 km/h). In this case, the maximum deceleration is 1.58 m/s^2, while the average deceleration is 0.39 m/s^2 [12].

For the particle emission test by Woo et al. [13] FTP-75 (Federal Test Procedure) was used and it should be noted that this is one of the tests conducted in the USA. Based on [14], it was found that the average speed is 34.12 km/h, the length of the simulated journey is 17.77 km, and the duration is 1877 s, while based on [15] it can be concluded that the maximum speed was 91.25 km/h. Some of the speed values that vary are 36.86, 49.57, 51.82, 76.44 and 91.25 km/h. Figure 3 is a graphical representation of this test.

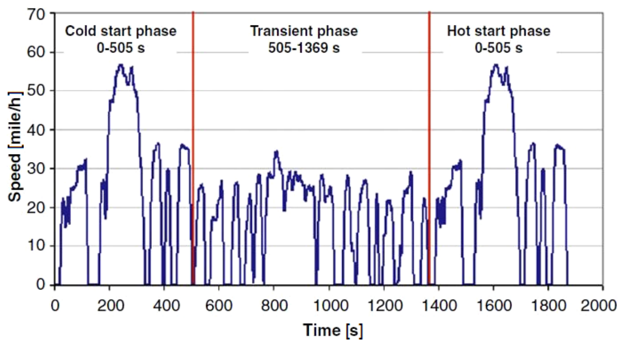

Figure 3. Graphical representation of FTP-75; adapted from [14]

In the research [13], another cycle that can be used for testing particles produced by brake wear is presented, namely 3h-LACT (Los Angeles City Traffic). This is one of the tests intended for vehicles intended for the American market [16]. Based on [17], it can be seen that a shortened version of this test was applied in the LOWBRASYS (LOW environmental impact BRAke SYStem) project. The maximum speed achieved in this test is 154.33 km/h, the minimum value is 16.90 km/h, and the average speed value is 53.79 km/h. During the test, 217 brakes were applied, and the pressure in the brake system was 15 bar [18] (Fig. 4).

Sanders et al. [19] applied two different tests, the Urban Dynamometer Program (UDP) and the test that is a braking simulation according to Auto Motor und Sport magazine (AMS). In the case of UDP, the simulated initial braking and deceleration speeds were varied. Speeds are simulated in the range from 37 to 89 km/h, and the deceleration varied from 0.6 to 1.6 m/s^2. The initial temperature depended on the vehicle for which the research was conducted, but for passenger vehicles, it ranged from 54 to 177 °C. There were exactly 24 different parameter variations, and each test was repeated 41 times. The AMS test consisted of a total of 10 repetitions of braking with a deceleration of 0.8 g from the vehicle's initial speed of 100 km/h, the test was repeated 3 times, and i.e. a total of 30 brakings were performed.

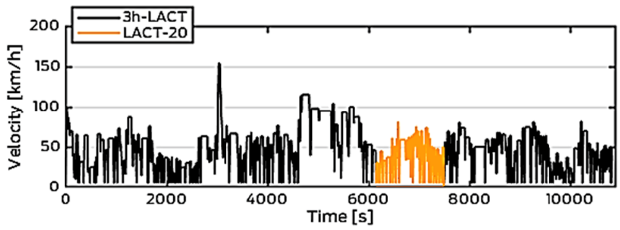

Figure 4. Graphical representation of 3h-LACT and LACT-20; adapted from Mathissen et al. [18], licensed under CC BY 4.0

Perricone et al. [20] used modified SAE 2707 braking cycles in their test, where parameters were varied, namely initial speed, deceleration and initial temperature. The entire test was divided into several phases and each of the phases (braking cycle) had several repetitions in the presented research. Each phase in this cycle was supposed to simulate certain road conditions and road categories. Initial speed (v_o), final speed (v_e), initial temperature (T_o), deceleration (a) and braking number (n) are defined.

In the research [21], a brake cycle based on the SAE J2707 method B standard, which is used in the automotive industry to evaluate the wear of friction pairs of the braking system and is known as Block Wear Evaluation, was applied. The initial speeds applied in this case are 50, 80, 100, 150 and 180 km/h, and the deceleration is also varied. The number of brakes varies depending on the brake section, but generally, they are 5, 10, 20 and 50 brakes. In this case, half of the braking (stopping) prescribed by the SAE J2707 standard for running-in friction pairs was performed.

A similar methodology was also applied in research [22], where the same test was applied, only a shortened version of it. In the research of the authors Ferrer Almirall and Mateu Cabre [23], a comparative analysis of different driving tests used around the world, such as those performed in China, Europe and the USA, was performed. The tests used in China are Yellow Mountain and Shanghai, Mojacar and Barcelona are shown as European tests, while the Los Angeles test was used as a test from the USA. The minimum and maximum speeds of the driving cycles vary, but the minimum speed in the comparison of all tests is 20 km/h, while the maximum speed is 120 km/h, but depending on the test these values differ. Average speeds per test are Yellow Mountain: 42 km/h, Shanghai: 42 km/h, Mojacar: 61 km/h, Barcelona: 39 km/h, and Los Angeles: 39 km/h. It can also be observed that the deceleration values range from 0.5 to 4 m/s^2.

Research [24,25] showed that in the tests of brake wear and the formation of particles, they used the so-called AK Master test that is normally conducted under the SAE J2522 standard [26]. It was observed that during the test, various tests prescribed by the standard can be carried out, but when analysing the resulting particles, speed/pressure tests are most often carried out, where the initial speeds, final speeds and pressures in the brake system are varied. In Table 1, according to the previously mentioned references, the values of the speed parameters are shown, while for each test in reference [25] the pressure (p_k) was varied from 10 to 80 bar.

Table 1. Applied pressure and speed values according to the AK Master test

Pressure series	Initial speed, km/h	Final speed, km/h	Brake pressure, bar
4.1	40	5	10, 20, 30, 40, 50, 60, 70, 80
4.2	80	40	
4.3	120	80	
4.4	160	130	
4.5	200	70	

Furthermore, one of the tests that are carried out, which is outside the brake cycles, is the European directive for brake testing. This directive [27] is not specifically related to brake wear, but it is related to the testing of brakes, more precisely replacement disc brakes and elements. According to the source [27], these tests are performed based on the change of braking parameters and are applied to vehicles of categories M1 and M2. According to ECE R90, it is prescribed what equipment an inertial brake dynamometer must have. Two tests are defined, namely pressure variation and initial temperature. In the first test, brake pressures varied in the range from 1.5 to 5.1 MPa, at an initial speed of 80 km/h, while the final speed is 30 km/h; 32 repetitions are prescribed. In the case of the second test, the initial temperatures are in the range of 100 to 483 °C. The initial speed is 100 km/h, while the final speed is 5 km/h. The pressure is always 16 MPa.

A braking test cycle based on the Worldwide harmonized Light vehicles Test Procedure (WLTP) database that is used to measure exhaust emissions from cars has already been developed. Further work will be needed to determine how to handle conventional and non-conventional light-duty vehicles (i.e. hybrids, electric cars), as well as trucks. In addition, Working Party on Pollution and Energy (GRPE) will also need to assess how to take into account technologies such as regenerative braking systems used to recharge batteries in electric and hybrid vehicles, and more generally Advanced Driver Assistance Systems (ADAS), which are changing the way braking systems are used.

3. Custom brake tests developed by different researchers

The overview of standard tests shown above is significant for researchers in the field of tribological characteristics of brakes and the formation of particles, who can develop their tests [28].

In the research [29] of vehicle brakes with an inertia of 50 kgm^2, a test was carried out in 5 cycles of 500 braking at speeds from initial 60 km/h to stopping. Braking was performed with a constant deceleration of 2 m/s^2. Each cycle has a constant temperature at the start of braking, the first at 100 °C, the second at 200 °C, the third at 300 °C, the fourth at 400 °C and the fifth again at 100 °C. The purpose of repeating the cycle at 100 °C is to check whether the wear repeats at the same intensity even after exposure to high temperatures.

In [30], a comparative measurement was performed on a tribometer and a dynamometer using a driving cycle designed to simulate urban driving for air brake emission measurements. This cycle is based on vehicle tests carried out in the city of Bergamo, Italy. Interesting for our research are the deceleration values in this test, which change from 0.16 to 0.31 m/s^2, and depending on the initial speeds, which had values of 36, 52, 57, 70 and 79 km/h.

In the research conducted by Hagino et al. [31] an analysis of the concentration of particles produced by brake wear, as well as particles released by re-accelerating the vehicle, was performed. In relation to research [10], in this case, no braking cycle was applied, but only certain braking parameters were varied. As in the previous research, two passenger vehicle brakes and one light truck brake were used. In this case, the speed of the vehicle was varied, i.e. the simulated speed on the inertial brake dynamometer and deceleration. Thus, the speeds had values of 20, 40 and 60 km/h, while the decelerations were 0.5, 1.0, 1.5 and 3.0 m/s^2. A deceleration of 3.0 m/s^2 was not applied for the truck due to the load. The release of particles during the re-acceleration of the vehicle was also examined.

Iijima et al. [32] varied the deceleration and speed in their research on the formation of particles due to brake wear. It should be kept in mind that in the research they examined more brake pads, while the number of parameter variations differed depending on the brake pad. The number of brakes at certain parameters also differed. The simulated speeds were 40, 50 and 60 km/h, while the applied decelerations were 1.0, 2.0 and 3.0 m/s^2.

In the study of the emission caused by brake wear during braking [33], the pressure in the braking system and the simulated speed of the vehicle were varied. The varied speeds were 80 and 100 km/h. The pressures applied in this case were 5 and 10 bar. For a speed of 100 km/h, both pressure values were varied, while for a speed of 80 km/h, only a pressure of 10 bar was applied.

4. Development of inertial brake dynamometer for brake particle emission measurement

Inertial brake dynamometers are one of the most commonly used brake testing devices. The advantage of inertial brake dynamometers is that it enables the testing of real, serially produced car brakes that are mounted and activated in the same way as on a vehicle, but can be tested under controlled conditions. Such tests belong to the group of tests that are closest to the actual braking process on the road. An inertial brake dynamometer (BrakeDyno 2020) was developed at the Faculty of Engineering of the University of Kragujevac. In order to simulate the kinetic energy of one-quarter of the vehicle, a flywheel is applied, which is driven by an electric motor, and at the end of the shaft there is a rotor, i.e. passenger vehicle brake disc. The selection of the kinetic energy value, instead of the usual use of a combination of different inertial masses, is achieved by changing the rotation speed of the flywheel mass. In this way, the change in the simulated initial braking speed and a load of one-quarter of the vehicle is achieved according to the mathematical model shown in Grujić et al. [34]. The disc brake is activated using pneumatic and hydraulic mechanisms. The entire braking process, selection of the initial speed, pressure and load corresponding to one-quarter of the vehicle, is controlled electronically.

BrakeDyno 2020 uses a series of sensors through which different output variables can be monitored (brake pad temperature, braking torque, pressure, braking time, etc.) [35]. It should be kept in mind that the inertial dynamometer is designed to allow easy adaptations for various measurements and research. Figure 5 shows the appearance of BrakeDyno 2020, which has been modified in order to measure the concentration of particles produced by the wear of friction pairs of brakes.

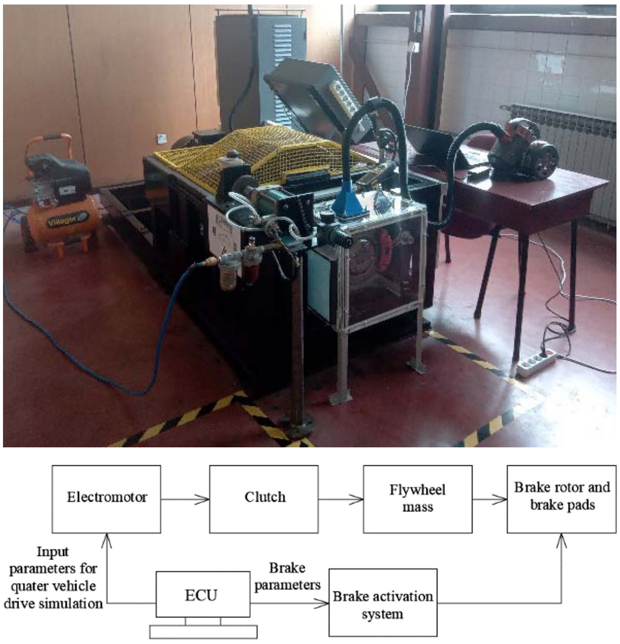

Figure 5. BrakeDyno 2020 adapted for particle emission measurement

Having in mind the problem of the presence of particles that do not occur due to brake wear, during the test it is necessary to enable the measurement of only the particles formed by the brakes. This is solved by isolating the brake itself in a closed chamber from which the particle measuring device draws air with brake wear particles. In this way, the particle measuring device retracts and measures only the airborne particles formed during the braking process, while the other particles remain outside the chamber and the device does not retract those particles. The appearance of the chamber itself is different depending on the experimental installation used for measurement and the volume of the chamber does not affect the measured average airborne particle concentration.

Figure 6 shows the chamber and the installation that was used to measure the average concentration of airborne wear particles. As shown, the disc brake is located inside a chamber that is hermetically sealed. The chamber is closed with plexiglass on all sides, except in the parts through which air passes inside the chamber and when air is extracted from the chamber with the particles being measured. Before the air enters the chamber, it is purified through an HEPA filter, which aims to keep all particles from the environment, and thus clean air enters the chamber. This eliminates the possibility of measuring particles that are not the product of brake wear. The resulting particles are measured using the Trotec PC220 (Fig. 7). The device has its air extraction pump, but there was a need for an additional device that helps the extraction of particles by reducing the pressure. This extraction of particles and air from the chamber can lead to the creation of a vacuum, and for that reason, there is a filter and a part of the chamber from which air enters the chamber, and it is purified through a filter. Thus, as much air is extracted from the chamber, as much air is drawn into the chamber through the filter.

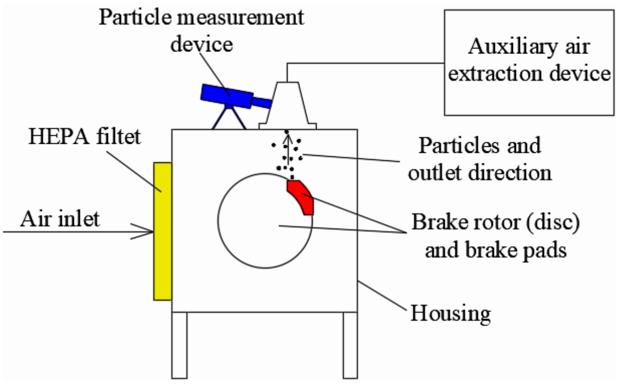

Figure 6. Scheme of chamber and installation for measuring particles on BrakeDyno 2020

Control of the test bench for testing disc brakes is realised through a computer, where automatic control is made in the software package LabVIEW™, as well as defining the initial data about the simulated vehicle and setting the braking parameters. The computer communicates with the test bench through the A/D converter, which has the task of sending command signals and collecting signals from the encoder. The command signal that is sent from the computer to the test bench, through the A/D converter, is a signal for defining the angular velocity of the engine. In addition, the role of the A/D converter is to discretise analogue signals from the sensors and transfer them to the computer, where the obtained measurement results will be stored in the computer's memory, and which will later be processed and analysed.

Figure 7. Position of the particle-measuring device

Extraction of air and particles from the chamber is done from the upper side of the chamber. The position of the particle-measuring device is shown in Figure 7, as well as the construction of the adapter by which the device is connected to the chamber.

An asynchronous electric motor with a nominal power of 18.5 kW is used to drive the test bench, i.e. to drive the flywheel. The connection between the electric motor and the flywheel shaft is achieved via an electromagnetic coupling. That is why it is important to enable precise geometric adjustment both horizontally and vertically of the electric motor shaft axis with the axis of the flywheel mass shaft, so that vibrations do not occur during operation, which would, in the worst case, cause the electric motor shaft to break.

The flywheel shaft is supported on both sides via two rolling bearings on the support structure of the test bench base. At the other end of the flywheel shaft, there is a brake disc that is firmly connected to the shaft. The floating brake calliper is attached to the support base via the calliper bracket and the force sensor, so when the brake is activated, there is a slight movement of the calliper carrier. As the sensor measures the force, and the moment arm is known, the braking torque can be simply calculated. It was found in the research of other authors that the temperature of the brake friction pairs influences the emission of particles. Two temperature sensors are installed inside the brake pads to measure the temperature at the inlet and outlet of the outer and inner brake pads. The brakes are activated via a hydraulic brake installation that corresponds to a real passenger vehicle, and the hydraulic brake installation is activated via a pneumatic part that is supplied with air from the compressor. The signal to activate the brakes comes from the A/D converter. First, the pressure in the pneumatic installation increases, so that the air from the compressor reaches the pneumatic installation through the lines. Then the brake cylinder is activated, and by further increasing the pressure in the hydraulic brake installation, the brake pads press against the brake disc with increasing force, whereby the pressure of the brake pads is defined before the start of the measurement. During operation, the pressure is measured by pressure sensors, both in the pneumatic and hydraulic brake installation. The A/D converter is connected to a frequency regulator, which supplies the electric motor in order to start it or turn it off.

The movement of the vehicle is realised at different speeds in laboratory conditions, and the braking process is realised in a predefined sequence, in certain time intervals and with certain braking parameters, such as e.g. deceleration. Brake cycles simulate the movement of vehicles in urban or non-urban conditions, which enables a comparative analysis in certain defined conditions. Bearing in mind that there are no brake cycles defined by the standard for the analysis of particle emissions that occur during braking, various authors use driving cycles that are used in numerous researches on motor vehicles, which have, in this case, the objective of examining the formation of brake wear particles.

On the other hand, in a certain number of studies, some of the previously prescribed driving cycles are not applied, to any research area. In this case, the authors of the research, based on their own experience or that of other researchers, define and choose the ways of performing the tests themselves. The aforementioned refers to the formation of own tests, in terms of the selection of braking parameters (e.g. simulated initial speed, braking pressures, initial temperature, deceleration, etc.).

5. Research results

Based on the previously presented research, the authors of this paper decided on the approach that no standard braking cycle will be applied, but only certain braking parameters will be varied. The test program provides a specific combination for each test so that when processing the results, it can be determined which of the factors has the greatest or least influence on the emission of $PM_{2.5}$ particles. Test brake parameters are shown in Table 2 [36].

Table 2. Test brake parameters

Parameter	Value
Simulated vehicle's load per one brake disc-pads friction pair, kg	150, 250
Simulated vehicle speed, km/h	20, 40, 60, 80
Brake pressure in a hydraulic system, MPa	1, 2, 3, 4

It was found that depending on the disc material, the temperature has a different effect on the resulting particle emission. The importance of disc coating in order to reduce the emission of particles generated in the braking process and to reduce the intensity of wear was presented in research [37]. In this research, it was shown that different materials can be used to cover the surface of the brake discs, as well as technologies that can reduce the intensity of brake wear and the resulting emission of particles.

Four types of brake pads from different manufacturers, intended for the same passenger vehicle model, were tested (Fig. 8). The brake pads differed in their structural details, as well as their composition (the presence of, for example, Cu). The average concentration of wear particles was measured by varying the operating parameters shown in Table 2.

Table 3 shows the material types and geometry of the brake pads labelled from A to D. In the case of formulation of brake pads B, the manufacturer used environmentally clean materials and a small percentage of metals in them. Brake pads C correspond to the N category of the formulation, which prescribes the maximum percentage values of metals that are allowed to be in the composition of brake pads.

When defining the experiment, in order to apply the Taguchi method, it is necessary to adhere to the plan of the experiment. With this approach, the experiment plan is obtained much faster. Based on the latest literature available, the Taguchi method has proven to be a reliable method for planning experiments. The program provides a specific combination for each test so that when processing the results, it can be determined which of the factors has the greatest or least influence.

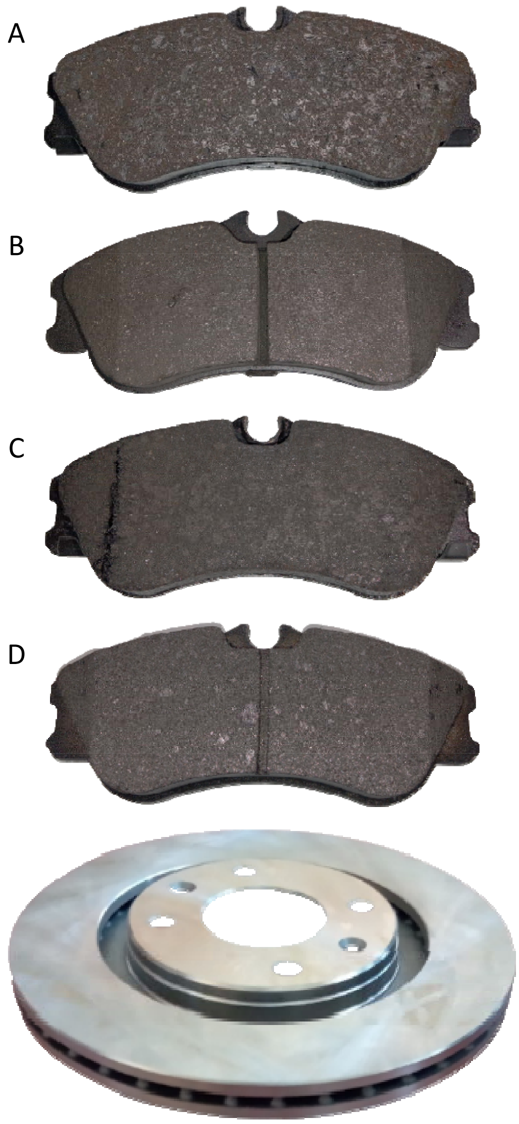

Figure 8. Brake pads and disc used in the research

Table 3. Brake pads

Brake pad code	Brake pad type	Brake pad geometry
A	semi-metallic	no lots and chamfer
B	low-metallic, eco-friendly formulation	parallel single slot, parallel single chamfer
C	N category of formulation	parallel single chamfer
D	semi-metallic	parallel single slot, parallel single chamfer

Table 4 shows which of the working parameters has the greatest influence on the emission of, e.g. $PM_{2.5}$ particles for brake pad type A. The behaviour of other brake pad materials shows similar dependence so only the representative type A is shown in this paper.

The conclusion is reached that the initial speed of the vehicle has the greatest influence, and the same conclusions are reached if the difference between the maximum and minimum values (delta) for each factor is observed. The higher the value of the difference of a factor compared to another, it only means that it has a great influence on the output size.

Table 4. S/N ratio where the smaller-is-better

Level	Load	Speed	Pressure
1	– 33.89	– 10.84	– 39.74
2	– 41.21	– 32.84	– 35.81
3		– 48.09	– 37.06
4		– 58.41	– 37.58
Delta	7.32	47.57	3.94
Rank	2	1	3

The value of the S/N ratio (brake pad type A) was calculated for each level of the control factor (Table 4) and the diagram in Figure 9 was drawn based on these values.

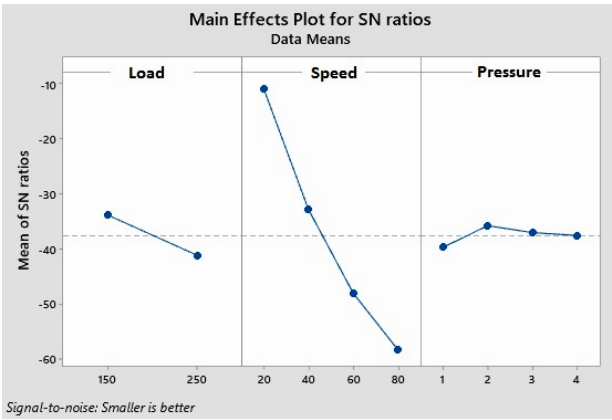

Figure 9. The influence of the considered factors on the average S/N ratio for the mean value of the stopping time for $PM_{2.5}$ particles (brake pad type A)

By optimising the data using ANOVA analysis, the conclusion is reached that vehicle speed is the most influential when it comes to the emission of $PM_{2.5}$ particles (Table 5).

Table 5. Variance analysis (brake pad type A)

Factor	DoF	Seq SS	Adj MS	F-ratio	%
Load	1	429.0	428.97	51.21	3.918
Speed	3	10,254.7	3418.24	408.09	93.654
Pressure	3	64.8	21.60	2.58	0.592
Error	24	201.0	8.38		1.836
Total	31	10,949.5			100.00

The effects of the considered factors on the average concentration of particles for brake pad type A are shown in Figure 10.

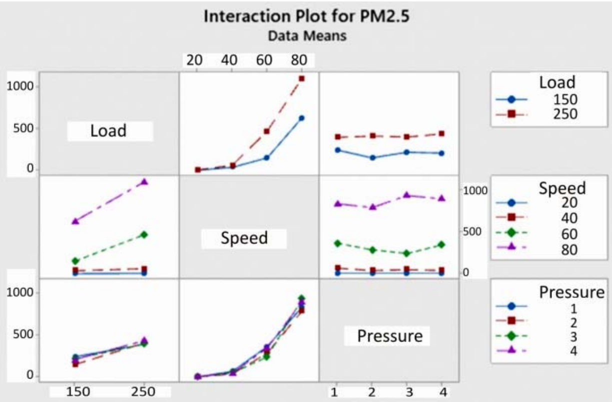

Figure 10. Graphical interaction for the S/N ratio for the average concentration of particles (brake pad type A)

Looking at factor X (vehicle speed), the lowest concentration is when the speed is the lowest, which is logical. Also, the lower the mass of the considered vehicle (factor Y), the lower is the concentration. However, the greater the pressure achieved in the brake installation (factor Z), the lower is the concentration. If the control factor line is close to the horizontal, then it has the least impact on particle emissions. In the case where the control factor is represented by a line that has a large slope in relation to the horizontal, it has a greater influence. Taking into account these rules, the minimum $PM_{2.5}$ particle concentration is obtained for the case X1-Y1-Z4.

Figure 11 shows an example of the obtained results for the analysis of the influence of vehicle speed at the beginning of the braking process for four types of brake pads on the average concentration of particles.

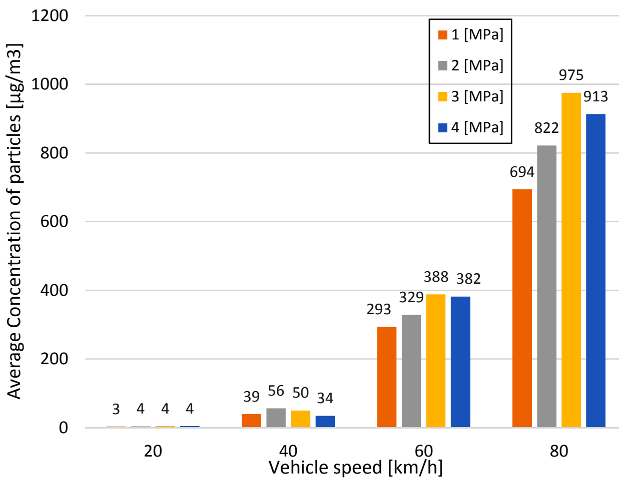

Figure 11. Influence of initial vehicle speed and brake pressure during measurement of $PM_{2.5}$ particle emission

Figure 12 is a 3D representation of the influence of braking parameters (brake pressure and vehicle speed) for different brake pads materials, i.e. design characteristics of brake pads on the average concentration of particles $PM_{2.5}$ for a load of 150 kN (simulated mass of quarter vehicle).

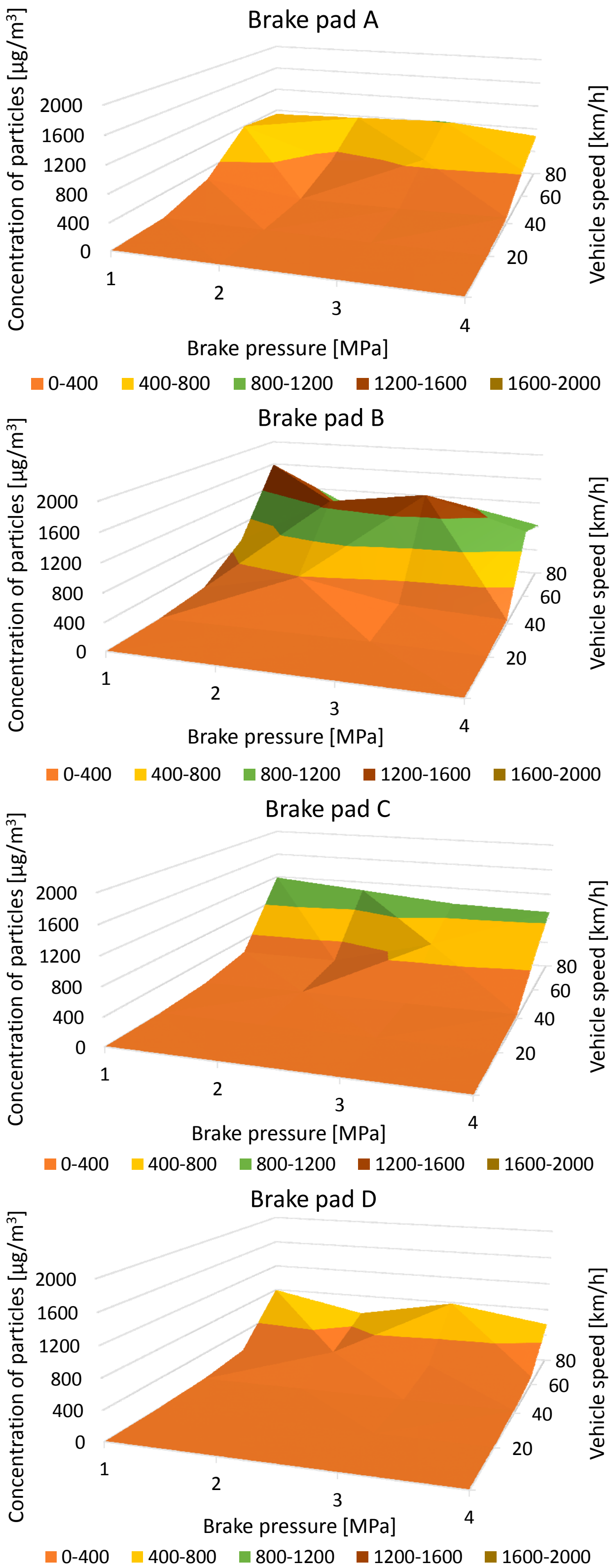

Figure 12. Analysis of average concentration $PM_{2.5}$ particles

6. Conclusion

Based on the presented research that studies the particles produced by brake wear, which were carried out on an inertial brake dynamometer, the following can be concluded.

The test/driving cycle/standard that is intended to investigate the formation of particles due to wear of friction pairs has not yet been precisely prescribed or developed.

Most researchers use brake cycles or tests prescribed for research in other areas of the automotive industry or list/develop their own driving cycles/tests.

In the tests that were applied, different parameters of braking or simulated braking in real conditions were varied. The variation of the parameters depends on the driving cycles that have been applied or on what the researcher himself wants to examine. In most of the research, vehicle speeds, pressures in the brake system, braking torques, decelerations, etc. were varied.

This review was important for the authors because they planned their research based on it and developed their methodology to study the influence of certain braking parameters and the type of brake pads on brake wear and the formation of particles.

The inertial brake dynamometer developed for this research is a very complex installation that allows several different tests of vehicle brakes and changes of the various parameters with an additional chamber that retains the airborne emission product that can be breathed in by humans and carries a portable particle counter. The advantage of this measurement method is that the particle measuring device retracts and measures only the airborne particles formed during the braking process, while the other particles remain outside the chamber. With this method, it is not possible to measure the total wear material, and after each test, the brake pads must be thoroughly cleaned of the particles that remain trapped in micro-roughness on the friction surfaces and the chamber of heavier particles that the device did not extract.

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