

Comparative analysis of methods for the investigation of brake wear particles emission of railway vehicles

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ARTICLE INFO

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DOI: <https://doi.org/10.46793/ET26.B06G>

PAGES: B41 – B49

ABSTRACT

The braking systems of railway vehicles are a key element for the safe and efficient operation of trains. Although according to official reports, the railway sector contributes less than 1% to total PM emissions in Europe, PM concentrations in enclosed spaces of underground railways are of great concern due to the confined nature of these spaces. Numerous studies have identified brake wear as the primary source of these emissions, as particles are generated during the braking process, under conditions of intense heating and wear in the contact zone between brake pads and discs. The aim of this paper is to critically analyze previous experimental studies to arrive at the most efficient and appropriate methodology that would provide knowledge about the mechanisms of particle generation caused by wear of brake pair elements in order to find ways to control the number and size distribution of particles in the air. In this regard, the advantages and disadvantages of various field tests with full-size brakes, laboratory tests on real brakes and reduced-scale brakes, as well as laboratory tests with a pin-on-disc machine were analyzed.

KEYWORDS

Railway vehicles, brakes, particle matter, methodology.

1. INTRODUCTION

In most cases, the transport of passengers and goods by rail is considered the most environmentally friendly mode of transport. With the increasing use of electrically powered motors in railway vehicles, exhaust emissions are no longer a main concern and attention is shifting to particulate matter from wear of brakes and others materials, as well as re-suspension from the ground. The task of the brakes is to maintain or reduce speed, that is, to stop vehicles in motion within a prescribed stopping distance, as well as to secure vehicles against self-movement.

The regulation on Brakes and Braking of Trains and Vehicles prescribes the types of brakes on vehicles and their parts, inscriptions and markings of brake devices, the method of braking trains and vehicles, the composition of trains with regard to the type of brakes, checking the correctness of brakes, calculating the brake power of a train and securing it against self-propulsion [1].

Mechanical friction brakes are the most important component necessary to achieve reliable, safe train traffic. Trains are generally considered a green energy and environmentally friendly transportation system, but airborne particulate emissions affect the accuracy of this picture. Metro systems around the world have been found to exhibit worrying levels of particulate pollution, exceeding those found in above-ground urban environments. Although human exposure in metro stations is relatively short, the intensity and the large number of people affected, including vulnerable groups such as the elderly or asthmatics, make the potential toxicity of particulates and emission reductions an urgent subject of research.

It must be noted that particulate emissions from rail transport have been much less studied than from road transport. Progress in legislation, toxicity studies or even mitigation alternatives in road transport can be used as a basis for future studies of rail transport emissions. Unlike road vehicles, a similar methodology is lacking for non-exhaust emissions from

rail transport. Abbasi et al. [2, 3] proposed a method for measuring the airborne wear particle emission rate (AWPER) from wheel-rail contacts and brake materials. This method can be used by manufacturers to demonstrate the competitive advantage of their products.

Studies of particle concentrations in metro systems around the world have attracted considerable attention in the past few decades. In 2011, Abbasi et al. [2] found that particle concentrations in metro systems in Stockholm, London and Budapest reached values of 300-1000 $\mu\text{g}/\text{m}^3$, which significantly exceeded the maximum limit of 50 $\mu\text{g}/\text{m}^3$ per day set by the EU for urban transport. By analyzing the materials present in the studied PM emissions from rail transport, about 84% can be attributed to mechanical friction processes, such as friction between the rail, the wheel, and the brake disc and pad. In situations of lower speed, such as approaching a metro station or in emergency situations, the mechanical braking system is activated and the brake system becomes one of the primary sources of airborne wear particles. Studies on brake wear emissions are still scarce, especially for disc brakes of high-speed trains. Available studies indicate that factors that have a significant influence on brake wear emissions include material composition, brake pressure, initial speed and contact temperature. Higher train speeds resulted in an increase in the total and maximum particle number concentrations, but also led to an increase in the particle number concentration for the peak diameter in the size distribution analysis. Higher speeds can also be associated with increased contact temperatures due to increased frictional heat and the thermal and chemical processes involved. The high temperatures resulting from increased disc speed and braking force can facilitate the formation of nanoparticles. Technical specifications of the vehicle, such as axle loads, technical specifications of the lifting table, material properties of the wheels and brakes, braking system and braking scheme, are important for particulate matter emissions. But in addition to factors related to the railway vehicles, emissions are also influenced by railway infrastructure conditions, such as technical specifications of the railway, track gauge, track substructure and track superstructure, track layout, switches and type of power transmission [4].

There are only few studies investigating the emission of wear particles from railway above ground. The aim of this paper is to perform a qualitative analysis and select the most optimal methodology to investigate the influence of railway braking conditions, such as contact pressure and disc temperature, in particular in terms of the range of emitted particles, their shape, size and composition. Knowledge of the nature of these particles (size, shape and composition) and their emission in real time is necessary for the development of efficient numerical models that can successfully predict the spread of particles near their origin. Based on the measurements, conditions would be obtained for the correct selection of friction conditions that give lower particle emission for a given dissipated kinetic energy and given rules for the injection properties of particles in a CFD model for studying their spread in a confined space, such as a metro station. In order to assess the influence of individual parameters on the nature of emitted PM, an experiment will be performed on a pair of railway braking materials, varying one parameter at a time, while maintaining the equivalent dissipated energy.

2. RAILWAY BRAKING SYSTEM

2.1. Railway Brakes

In the past, trains were equipped almost exclusively with mechanical brakes. Today, on modern high-speed trains, the braking system is usually controlled by a computer that allows variable distribution of braking power between different subsystems. The aforementioned braking subsystems usually include electro-dynamic and mechanical (friction) brakes. The application of newer technologies in railway vehicles and track infrastructure has also led to the introduction of inductive braking systems. Research into new linear induction motor techniques has been accompanied by increased weight. An overview of the different categories of brakes for rail vehicles is shown in Figure 1.

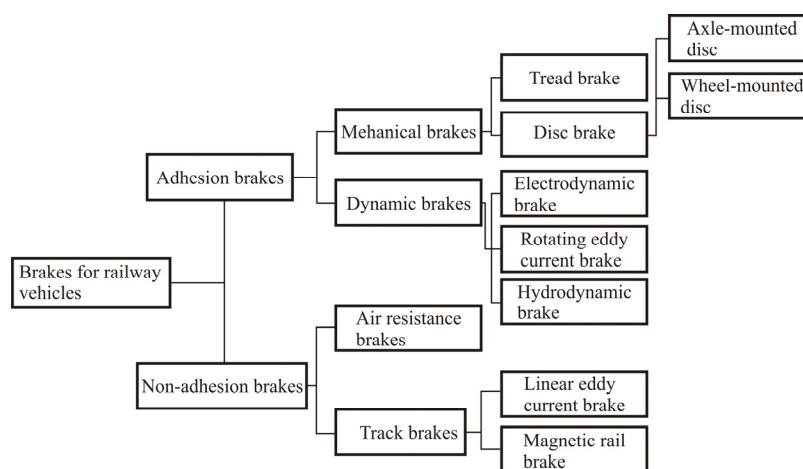


Figure 1: Different types of brakes on railway vehicles

Due to the frictional force developed between the brake pad and the brake disc, mechanical (friction) disc brakes are subject to a significant degree of wear, in contrast to electro-dynamic brakes which are much less susceptible. However, as the efficiency of electro-dynamic brakes depends on the speed of the railway vehicle, mechanical brakes are still

necessary for additional braking, especially at lower speeds. Usually below 60 km/h, friction brakes are activated to provide additional braking, and at speeds below 20 km/h, mechanical brakes take over the entire braking force. Mechanical brakes are also critical in the event of electro-dynamic brake failure or if it is necessary to reduce the speed of the train quickly, such as in emergency braking.

The two main types of friction braking systems are tread brakes (block brakes) and disc brakes. Tread brakes (Figure 2c) are still widely used on most freight trains in the EU, and disc brakes are fitted to many passenger trains, especially those operating at high speeds. The friction coefficient, and thus the efficiency of a disc brake, is very stable and almost independent of speed, and they exhibit good thermal properties and robustness. This type of brake can be mounted directly on the wheel or on the axle. Figure 2a shows a high-speed train, which uses axle-mounted disc brakes. Here, each axle is equipped with four brake discs and two pairs of brake pads on each side. A photograph of a disc brake pad mounted on a train wheel is shown in Figure 2b.

Brakes for high-speed trains must demonstrate superior properties and ensure safety, which means that they must withstand maximum temperatures during operation. This includes a high and stable coefficient of friction (COF), high thermal conductivity, as well as resistance to heat and wear, low absorption of water, oil or brake fluid, low aggressiveness towards the brake disc, high comfort properties, as well as reduced particle emissions and noise minimization. Organic brake pads have poor thermal stability and can therefore only be used when temperatures do not exceed 300°C. Since temperatures of up to 900°C can occur at the disc/pad interface during sudden braking of high-speed trains, sintered metal matrix composites are a suitable choice for this application because they can withstand temperatures of over 1000°C. These friction materials are obtained by powder metallurgy, i.e. they are pressed and sintered from a uniform mixture consisting mainly of metal powders as a matrix, matrix reinforcement materials, friction enhancers, and lubricants. Common matrix and matrix reinforcement materials are iron and copper, while metal and non-metal oxides or carbides are used as friction enhancers. To improve wear resistance, a lubricant such as molybdenum disulfide (MoS_2) is often used [5, 6].



Figure 2: High-speed train disc and tread brake pad [7]

Research has proven that the friction and wear behavior of brake pad materials is primarily influenced by material characteristics, braking conditions, environmental conditions, surface conditions, and structural parameters. Train brake discs wear mainly due to the sliding contact between the pads and the disc. Abrasive and adhesive wear are the two primary wear mechanisms associated with disc brakes. The formation of brake wear particles is a result of abrasive and adhesive wear with oxidative processes. Two more specific wear modes that often occur in brake pads are fiber delamination, as well as fragmentary wear, such as induced pitting.

2.2. Brake Wear Particle Emission

Particulate matter can have harmful effects on the environment, climate, and human health, but the potential health risks of PM pollution were not widely investigated until the early 2000s. Results from many studies have indicated a link between exposure to PM particles and adverse health effects, but it has been established that health effects depend not only on particle concentration, but also on particle composition, as well as size, shape, and morphology. Larger particles are usually trapped and filtered in the nose and throat, while particles with a diameter of less than 10 μm can reach the lower respiratory tract. Ultrafine particles can further enter the bloodstream by penetrating the respiratory system, making them even more harmful than larger particles, as seen in Figure 3.

The travel distance and time until the particles settle on the ground due to gravity are dependent on the size and density of the particles. While coarse particles settle within hours, fine particles can remain suspended in the air for multiple weeks. About 90 % of PM is made up of fine and ultrafine particles under typical conditions. Non-exhaust emissions are a result of wear processes such as from the brakes, tires, clutch, engine and road surface, corrosion of vehicle parts, street signs and barriers as well as the re-suspension of settled particles on the road.

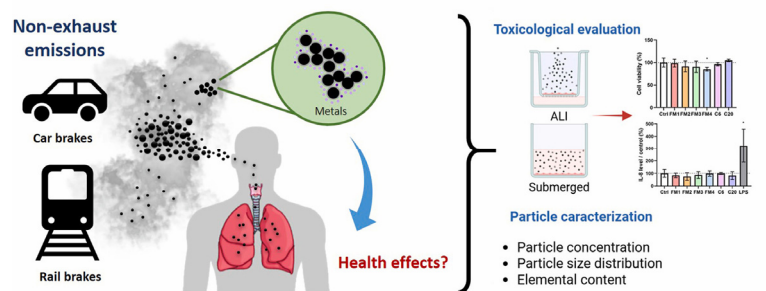


Figure 3: Human respiratory tract and deposition location of particles of different sizes.

2.3. Wear Particle Emissions in Rail Traffic

The data show that as of 2021, around 129,200 tonnes of $\text{PM}_{2.5}$ emissions and 201,400 tonnes of PM_{10} emissions in the EU are linked to transport as an industry, of which 171,300 tonnes of PM_{10} and 105,500 tonnes of $\text{PM}_{2.5}$ are from road transport alone. Rail vehicles contribute 38% of non-road PM_{10} emissions and 25% of $\text{PM}_{2.5}$ emissions. Strict regulations in the EU have contributed to a 55% reduction in annual $\text{PM}_{2.5}$ emissions and a 40% reduction in annual PM_{10} emissions between 2010 and 2019. However, 96% of urban residents are still exposed to levels of fine PM particles above the latest WHO (World Health Organization) guidelines. With stricter control of exhaust emissions, the relative share and importance of non-exhaust emissions are increasing. It has been found that up to 50% of non-exhaust PM_{10} emissions from road traffic are caused by disc brake wear. In car disc brakes, the braking torque on the rotor is generated by the friction force between the rotor and the brake pads. Since the rotor and the wheel are connected, the car will slow down due to the friction between the tire and the road. A similar situation applies to trains, where the braking force is transmitted by the contact between the wheel and the rail. During the friction braking process, wear occurs on the brake pads as well as on the rotor due to sliding contact. These brake wear particles can either deposit on the surface or be dispersed into the air. They have the potential to harm the environment and human health, as previously established. Studies have shown that it can be assumed that 35-50% of brake wear particles are in the air. Furthermore, brake wear has been found to be one of the main sources of metal particles in the air in cities.

Different types of brakes are widely used in railway transport, such as disc brakes and tread brakes. Fridell et al. [8, 9] observed in their research characteristic peaks in particle number concentration during deceleration phases, which, however, were not present in every braking process. The reason for this is the type of brake used in the braking process. Modern passenger trains are equipped with mechanical brakes as well as regenerative brakes (electric). Peaks in particle number concentration only occur if mechanical brakes are used for deceleration. Furthermore, the category of mechanical brakes must be divided into block brakes, which are widely used for freight trains, and disc brakes, which represent the standard braking system for passenger trains. While a wheel is usually equipped with one brake disc, axles can be equipped with two, three or even more brake discs.

The Euro 7 standard extends the regulatory requirements for the type-approval of braking systems and tyres with regard to particulate emissions and the abrasion process that occurs. The regulation applies to tyres of classes C1 (passenger cars and commercial vehicles), C2 (light commercial vehicles) and C3 (heavy commercial vehicles), in accordance with UN Regulation 117. As a result, the Euro 7 standard includes a requirement to limit the maximum emissions of PM_{10} particles from brake pads and tyres. Generally speaking, for electric cars the limit will be 3 mg/km, for combustion passenger cars, hybrids and hydrogen cars 7 mg/km, and for large vans and delivery vehicles 11 mg/km. The Euro 7 emission standard will first apply to the type-approval of new models of light vehicles and their braking systems 2.5 years after the entry into force of the regulation. A year later, all newly registered vehicles will have to meet the new Euro 7 requirements. Euro 7 for heavy goods vehicles will apply to new vehicle models 4 years after entry into force, and after 5 years to all new vehicles [10]. However, emission level limits have so far been based solely on the mass of particles per unit volume

of air, without considering particle number, composition and toxicity. The research community therefore suggests that this be taken into account for future limit values and assessment.

3. METHODS TO ANALYZE BRAKE WEAR EMISSIONS

The lack of standardized sampling and measurement methods for brake wear particle emissions in existing studies further complicates the comparison of results and conclusions. A major problem is that most studies are limited to automobile disc brakes, with very few examining other modes of transport, such as rail transport [11]. In order to evaluate braking performance and the influence of applied brake material, as well as to simulate different braking scenarios, a number of braking systems can be used, from small-scale ones, such as pin-on-disc tribometers, to component testing on a brake dynamometer, and even full-scale field tests (Figure 4). Compared to brake dynamometers, their main advantages are the small dimensions of the test platform and lower operating costs. Brake dynamometers with disc brakes are mainly used for homologation testing and evaluation of damage mechanisms of various disc brake systems. However, in recent years, these devices have been used more frequently to generate brake wear particles due to their ability to replicate vehicle and kinetic energy data under controlled laboratory conditions that are very close to those in the real world.

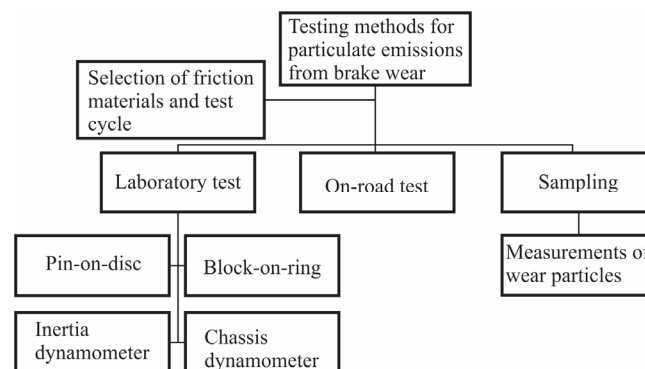


Figure 4: Overview of different laboratory and on-road testing methods for particulate emissions from brake wear

The pin-on-disc test is a robust method for studying the formation of airborne particles, based on the similarity of morphology and size distribution, with the prerequisite that the same contact conditions are used in laboratory tests as in field tests. Pin-on-disc tribometers are often used to generate brake wear particles in air under controlled operating parameters (contact pressure, sliding speed and friction material temperature) [12, 13, 14].

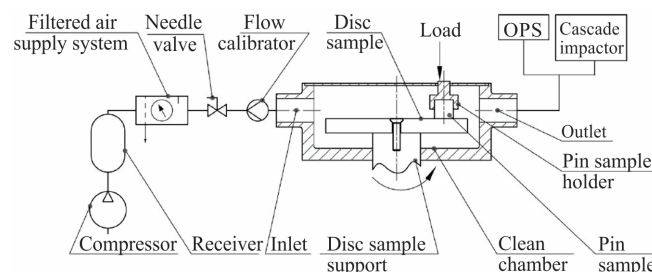


Figure 5: Schematic of the experimental set-up based on a pin-on-disc tribometer [12]

One of the few published on-board measurements was conducted by Fridell et al. [8, 9], who reported particle characteristics and emission factors for wear particles from a running Regina train. They investigated particles size in 7 intervals and aimed to investigate 27 elements among collected particles. The curve negotiation effects were not traceable in his work as they used one sampling point that was located between the two coaches. The main objective of field test conducted by Abbasi et al. [3] was to study the characteristics of particles generated by disc brakes on a moving train using a measurement system installed on the train. Two points were defined for sampling airborne particles, one close to the disc brake pad-rotor contact and the other below the frame, not close to the mechanical brake or wheel-rail contact; the number and size distribution of the detected particles were recorded and evaluated under different conditions (Figure 6). The difference in the distance from the sampling point to the main sources of particles resulted in different results. The morphology and elemental composition of the collected particles were also studied. Different realistic operating conditions were taken into account, such as train acceleration, train deceleration or train movement through a curve. This type of research could pave the way for the development of significantly simpler and cheaper sensors that can be mass-produced and used in a wide range of applications, e.g. where there are potential operational disruptions (e.g. due to faulty braking systems), thereby reducing particulate emissions to an absolute minimum.

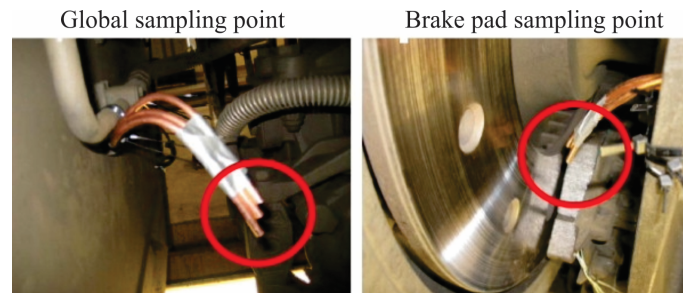


Figure 6: Particle measurement devices, along with connecting tubes arrangement [3]

To study the emission of wear particles from subway trains, it is necessary to measure both the particle concentration and the air flow. A common method for this is to use a tunnel because the tunnel design provides a given volume and cross-section that facilitate air flow estimates (Figure 7). The particle concentration is usually measured at the tunnel exit with a sampling frequency of the order of 1 Hz, together with two-dimensional wind flow measurements. Two pairs of diode laser/photodetectors placed on the side of the track can be used to measure the speed and length of the test trains. To assess the emission from individual trains, the particles emitted in the tunnel must be ventilated between each train passage, and therefore it is necessary to choose a tunnel where the train frequency is low, from only one to a few trains per hour. The tunnel is ventilated by both the flow caused by passing trains and the ambient wind, but choosing a tunnel whose length is the same as the length of the train facilitates wind-induced ventilation. The small cross-sectional area facilitates train-induced ventilation, but probably limits wind-induced ventilation. The use of a stationary particle measurement method allows for the estimation of the emission coefficient at the tunnel exit, where there is a well-defined measurement volume, and allows for the comparison of emission levels between passenger and freight train types [8].

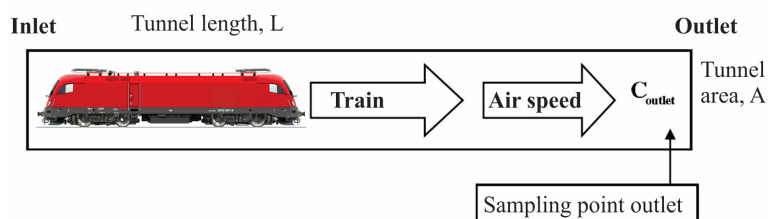


Figure 7: Tunnel measurements of particle emissions [8]

A tribological test in the laboratory can be carried out on an inertial dynamometer type test bench to simulate the braking performance of a high-speed train and to examine the influence of the residual height of the friction block on the vibration and noise characteristics caused by friction [7]. A customized test bench for simulating the braking performance of a high-speed train is shown in Figure 8. Test bench of this type are often also made in a reduced scale of 1:2 to simulate the friction, load and speed ratios of a real braking system. This test device can be used to test the friction of brakes under different conditions and operating modes (traction braking, emergency braking, etc.), as well as to simulate the tribological behavior and particle emissions of the braking system. The samples of discs and blocks used in this study must be reduced to an appropriate scale.

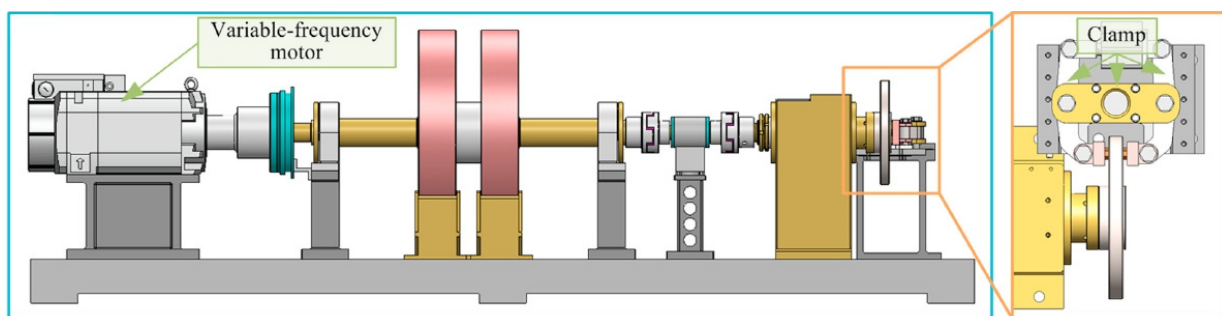


Figure 8: The test device to analyze high-speed train braking performance: control console schematic diagram of test device [7]

The newly built test bench for railway brakes (Figure 9) was put into operation in 2023 at the Graz University of Technology. This test bench allows the testing of disc brake systems as well as tread brakes (block brakes). The kinetic energy of the vehicle is simulated using an electric mass simulation. The drive motor accelerates the drive train of the test bench to any speed in the range from 0 to 3,000 rpm. This also allows the testing of brakes on high-speed trains, which operate at a maximum speed of 500 km/h [15, 16, 17].

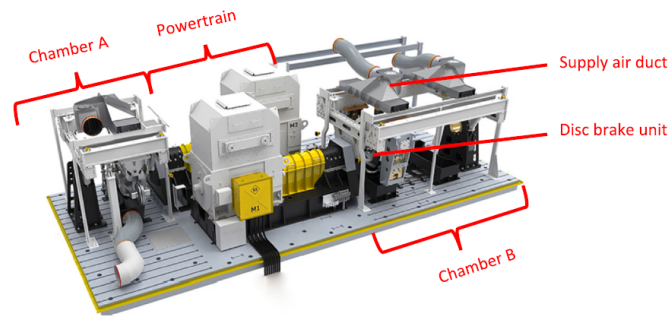


Figure 9: Scheme of the brake test bench at Graz University of Technology [15, 16]

4. DESIGN OF EXPERIMENTS

Two approaches are used for particle characterization: a particle collection approach for off-line analysis and an instantaneous measurement approach with on-line particle size distribution measurement.

The aim of future research is to analyze the influence of railway braking conditions, such as contact pressure and disc temperature, in particular with regard to the range of emitted particles, their shape and composition. Knowledge of the nature of these particles (size, shape and composition) and their emission in real time is necessary for the development of numerical fluid models that can correctly predict their propagation near the zone of their generation. An important aspect of the research is the selection of friction conditions that give lower particle emission for a given dissipated kinetic energy and the given rules for the particle injection properties in the CFD model to study their propagation in a confined space, such as a metro station. The assessment of the influence of these parameters on the nature of emitted PM particles will be carried out on a different railway braking materials, varying one parameter at a time, while maintaining the equivalent dissipated energy.

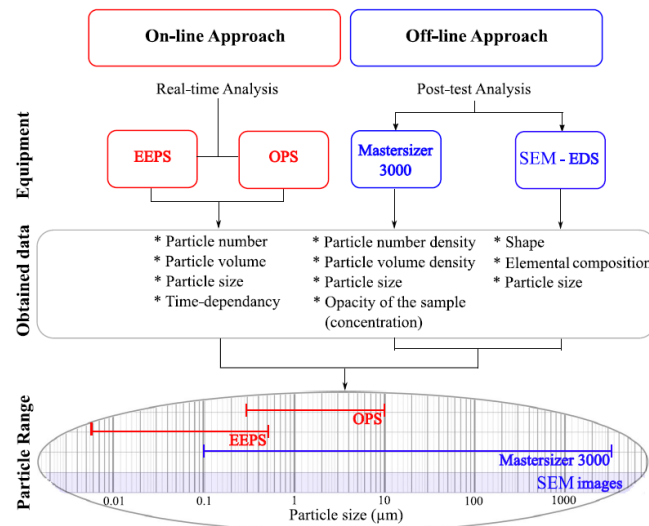


Figure 10: Description of the experimental approach [18]

4.1. On-Line Measurements of Particle Emissions

It is important to recognize that this type of experiment only provides qualitative insight into how sliding speed and contact pressure can affect wear, friction, and airborne particle emissions. The quantitative results cannot be translated into real-world scenarios, as factors such as the detection range and calibration of particle sampling instruments and the difference in contact area compared to actual disc brakes affected these results. In addition, many studies have found that the brake temperature has a significant effect on the generation of brake wear particles. Therefore, many experimental setups include thermocouples or infrared cameras to record the temperature at the contact surface [5].

The advantage of inertial brake dynamometers is that the device tests real brakes that are also used on road vehicles under controlled conditions. Such tests belong to the group of tests that are closest to the actual braking process on a vehicle. 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, an inertial mass is applied, which is driven by an electric motor, and at the end of the shaft is the rotor itself, i.e. disc brakes. Changing the number of revolutions of the flywheel enables the selection of the value of the kinetic energy, thus changing the simulated initial braking speed and the load of one quarter of the vehicle. The brake is activated using pneumatic and hydraulic mechanisms. The entire braking process, starting speed, pressure and load of one quarter of the vehicle is controlled

electronically. BrakeDyno 2020 contains a series of sensors that can be used to monitor various output parameters (brake pad temperature, braking torque, braking time, ...). Bearing in mind that the inertial dynamometer has been developed so that adaptations can be made for various measurements and research, Figure 11 shows the appearance of BrakeDyno 2020, which has been modified in order to measure the concentration of particles that result from the wear of friction pairs of brakes.

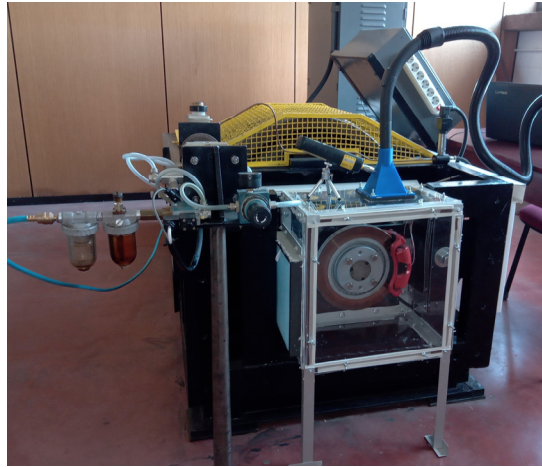


Figure 11: BrakeDyno 2020 in the process of adaptation for particle measurement

The directly measured variables are: angular velocity of the disc, number of revolutions of the disc, braking time, brake pressure, i.e. pressure in the brake installation, both in the hydraulic and pneumatic parts of the brake installation, braking torque, brake pad temperature, ambient temperature, air humidity, PM_{2.5} and PM₁₀ particle concentrations.

The variables determined by recalculation are: simulated vehicle speed, kinetic energy, deceleration, coefficient of friction between friction pairs. Such research, which would require modification of the test bench for railway vehicle brakes, could:

- Identify the factors influencing the concentration of particles generated by the wear of brake friction pairs;
- Determine whether factors (parameters) can differently affect the concentration of particles by changing their intensity, depending on the brake pad used;
- Identify whether the applied brake pads also have an impact on the concentration of particles in terms of their composition and design characteristics;
- Analyze the influence of individual factors on the resulting concentration of PM₁₀ and PM_{2.5} particles individually;
- Determine the influence of individual factors on the relationship between the concentrations of PM₁₀ and PM_{2.5} particles individually.

4.2. Off-Line Analysis of Particles

In the post-test characterization approach, collection experiments are conducted to further characterize the generated particles and compare different size analysis methods. These results provide information about the nature and shape of the large particles.

5. CONCLUSIONS

As we have not yet reached definitive conclusions regarding the toxicity of railway brake wear particles, it is essential to pursue a preventive approach aimed at reducing particle emissions. This is particularly important given evidence from previous research suggesting that brake wear particle components, such as iron, can induce oxidative stress in cells. As trains continue to rely on mechanical brakes without the widespread adoption of alternative technologies such as inductive braking, it is crucial to develop strategies to reduce particle emissions. These efforts are essential to minimize potential adverse health and environmental impacts.

A test that provides results similar to real conditions is the use of an inertial brake dynamometer, where the same friction elements as those on a real vehicle are used. Since the measurement is performed in laboratory conditions, it is much easier to isolate the emissions resulting from brake wear. The inertial brake dynamometer is usually modified by installing a housing in which the brake assembly is located. In laboratory conditions, it is much easier to set and control the braking factors, but also to identify other parameters that have an impact on the resulting particle emissions, such as the temperature between the friction pairs, relative humidity, ambient temperature, etc.

ACKNOWLEDGEMENTS

Paper is financially supported by The Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-65/2024-03/200107.

REFERENCES

- [1] Pravilnik o kočnicama i kočenju vozova i vozila, ("Sl. glasnik RS", br. 68/2021)
- [2] S. Abbasi, J. Wahlström, L. Olander, et al. "A study of airborne wear particles generated from organic railway brake pads and brake discs", *Wear*, Vol. 273(1), pp. 93-99, <https://doi.org/10.1016/j.wear.2011.04.013>, (2011)
- [3] S. Abbasi, L. Olander, C. Larsson, U. Olofsson, A. Jansson, U. Sellgren, "A field test study of airborne wear particles from a running regional train", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 226(1), pp.95-109, <https://doi.org/10.1177/0954409711408774>, (2012)
- [4] S. Abbasi, A. Jansson, U. Sellgren & U. Olofsson, "Particle Emissions From Rail Traffic: A Literature Review", *Critical Reviews in Environmental Science and Technology*, Vol. 43(23), pp. 2511–2544, <https://doi.org/10.1080/10643389.2012.685348>, (2013)
- [5] L. Tanzeglock, "Particle Emissions of Train Brakes", Master Thesis, Division of Production and Materials Engineering, Lund University, Lund (Sweden), (2024)
- [6] Y. Lyu, L. Tanzeglock, Q. Zhang et al. "Friction, wear and particle emissions from copper-based train brakes", *Proceedings 22st Nordic Seminar on Railway Technology*, KTH Royal Institute of Technology, Stockholm (Sweden), 18-19 June 2024, (2024)
- [7] Z.Y. Xiang, J.K. Zhang, S.L. Xie, et al. "Friction-induced vibration and noise characteristics, and interface tribological behavior during high-speed train braking: The effect of the residual height of the brake pad friction block", *Wear*, Vol. 516–517, pp. 204619, <https://doi.org/10.1016/j.wear.2023.204619>, (2023)
- [8] E. Fridell, A. Björk, M. Ferm, A. Ekberg, "On-Board Measurements of Particulate Matter Emissions from a Passenger Train", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 225(1), pp. 99-106, <https://doi.org/10.1177/09544097JRRT407>, (2011)
- [9] E. Fridell, M. Ferm, A. Ekberg, "Emissions of particulate matters from railways – Emission factors and condition monitoring", *Transportation Research Part D: Transport and Environment*, Vol. 15(4), pp. 240-245, <https://doi.org/10.1016/j.trd.2010.02.006>, (2010)
- [10] Z. Stępień, "Vehicle related non exhaust particle emissions – Euro 7 requirements", *Combustion Engines*. Vol. 199(4), pp.15-29, <https://doi.org/10.19206/CE-190606>, (2024)
- [11] A. T. Juárez-Facio, M. Introna, A. M. Montes, et al. "In vitro toxicity of car and train brake wear emissions using Air-Liquid Interface and submerged exposure models", *Atmospheric Environment: X*, Vol. 29, p. 100426, <https://doi.org/10.1016/j.aeaoa.2026.100426>, (2026)
- [12] Y. Lyu, Q. Zhang, L. Tanzeglock, et al. "Mapping of friction, wear and particle emissions from high-speed train brakes", *Wear*, Vol. 572–573, p. 206027, <https://doi.org/10.1016/j.wear.2025.206027>, (2025)
- [13] Y. Tsybrii, I. Zglobicka, M. Kuciej, et al. "Airborne wear particle emission from train brake friction materials with different contents of steel and copper fibres", *Wear*, Vol. 504–505, p. 204424, <https://doi.org/10.1016/j.wear.2022.204424>, (2022)
- [14] Y. Tsybrii, O. Nosko, I. Zglobicka, M. Kuciej, "Emission and properties of airborne wear particles from train brake friction materials based on novolac phenolic resins and butadiene rubbers", *Wear*, Vol. 546–547, p. 205332, <https://doi.org/10.1016/j.wear.2024.205332>, (2024)
- [15] D. Fruhwirt, P. Sturm, T. Nöst, et al. "PM emissions from railways – Results of tests on a wheel-rail test bench", *Transportation Research Part D: Transport and Environment*, Vol. 122, p. 103858, <https://doi.org/10.1016/j.trd.2023.103858>, (2023)
- [16] D. Fruhwirt, T. Nöst, P. Leonhardt, et al., "Characterization of emissions from axle-mounted rail disc brakes", *Transportation Research Part D: Transport and Environment*, Vol. 130, p. 104181, <https://doi.org/10.1016/j.trd.2024.104181>, (2024)
- [17] D. Fruhwirt, T. Nöst, P. Leonhardt, et al. "Emission characteristics of railway tread brakes", *Atmospheric Environment: X*, Vol. 25, p. 100320, <https://doi.org/10.1016/j.aeaoa.2025.100320>, (2025)
- [18] C. Octau, D. Méresse, M. Watremez, J. Schiffler, M. Lippert, et al. "Characterization of particulate matter emissions in urban train braking - An investigation of braking conditions influence on a reduced-scale device", *Environmental Science and Pollution Research*, Vol. 27(15), pp.18615-18631, <https://doi.org/10.1007/s11356-020-08337-8>, (2020)