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Influence of different Friction Materials on the Particle Size Distribution of Brake Emissions

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ABSTRACT: In this study, particle size distributions are analyzed with regard to additional influencing factors. Especially the influence of the friction material is put into the focus as the friction material is an integral part of a brake system and is often not considered properly in the context of brake emissions. Due to the very diverse physical and chemical properties that different classes of friction materials possess, it is highly probable that they can have a significant influence on total brake emissions and also on particle size distribution. Apart from that, the influence of hard-coated discs on particle size distribution of brake emissions is investigated and it is shown that both friction material and disc coating constitute promising approaches to handle the challenge of brake emission reduction. The influence of friction material and brake disc on the tribology that takes place in a friction brake also leads to potentially different temperature regimes. The present study sets an additional focus on the investigation of the temperature effect on particle size distribution.

KEY WORDS: Brake emission, Particle size distribution, Friction material, Particle number concentration, Disc temperature

1. Introduction and Background

In recent years, non-exhaust particulate matter (PM_{10}) emissions were intensely discussed both in the industry and in academia. This is amongst others due to the expected upcoming regulation of non-exhaust particle emissions by the European Union and other authorities as they account for a growing portion of particle emissions to the environment. This holds true especially in the context of the transition from internal combustion engines to electrified powertrains.

The exposure to ambient PM_{10} has been associated with increased mortality and morbidity among certain risk groups ([1]). Special focus lies on the emission of fine particles with sizes below 100nm, as they can enter the lungs easily and deposit in the alveoli. It was shown that they might cause stronger toxicological effects than larger particles ([2]). Those fine particles contribute little to the emitted particle mass and are therefore quantified by their particle number concentrations (PN).

Consequently, reduction strategies for brake emissions have to take into account not only the mass of the emitted particles but also the number of the emitted particles. It has been reported in various studies, that the number concentration of emitted PM_{10} is dominated by very small particles and that the number concentration does not correlate to total wear. It was also shown that the particle number size distribution of emitted particles varies according to different load collectives ([3], [4], [5]).

The present study aims at confirming and illustrating these findings with a special focus on the influence of the tribological partners of friction material and brake disc as well as the influence of the temperature regime on the particle size distribution.

2. Methodology

To achieve the formulated objectives, the experimental setup defined in chapter 3 is chosen as it provides the opportunity to compare the PN emissions and the particle size distribution (PSD) of emitted particles of different material combinations of friction material and brake disc in the same brake system under the same environmental conditions using realistic load collectives. Thereby, comparable PN emission results are available for the different material combinations and the respective differences can be evaluated. To ensure an adequate statistical certainty, three tests were conducted for each material combination with identical test setup and environmental conditions as well as utilizing test samples out of the same batch.

The evaluation focuses on the particle size distribution based on the PN emission measurement. Main criteria are the position of the main PSD peak and the existence and position of a potential second peak. To give a realistic impression of the emission behavior of a material combination also the total PN emissions are given. In a second step the study investigates the changes that occur in PSD and total PN emissions at different disc temperatures. This information then allows to draw conclusions regarding the load collectives and temperature levels at which the PN emissions are mainly generated.

3. Experimental

In the framework of this study, five material combinations of friction material and brake disc are investigated. For each combination three tests are conducted on a full scale brake dynamometer. A Daimler rear axle brake system with fixed caliper design is chosen and the temperature measurement is implemented into the disc.

3.1. Test setup

The brake dynamometer used in the scope of this study is equipped with a brake emission setup consisting of filtered and climate controlled incoming air, a brake emission enclosure and PN measurement in the air flow leaving the enclosure. The test setup is basically the one described in [4] and is depicted in Figure 1.

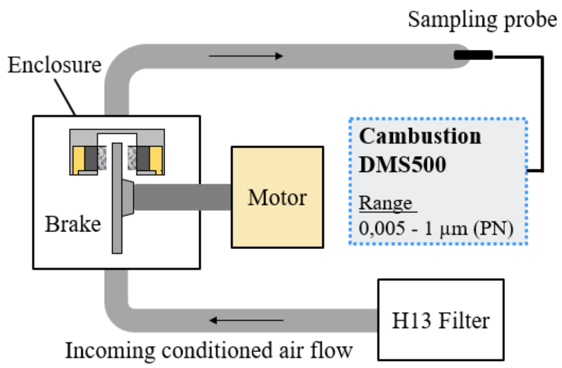

Figure 1 Test setup based on [4]

Filtered and conditioned air is entering the enclosure and generated particles are transported through the duct to the sampling probe. The constant air flow rate is $70m^3/h$ and the duct diameter is 125mm, which corresponds to an airspeed of 5,7kph. The temperature of the cooling air is set to 20°C and the relative humidity to 50%r.h.

The PN emissions are measured using the Cambustion DMS500 device, which is a Fast Mobility Particle Sizer (FMPS) type device that electrically charges the particles passing the device and makes use of the correlation of particle size and electrical mobility to separate the particles according to their size ([6]). The DMS device can measure very small particles starting from a diameter of ~5nm up to 1µm. It is also possible to evaluate the distribution of emitted particles over the particle diameter, which is a crucial ability of the device when considering the main goal of this study.

3.2. Test procedure

In the present study, a test cycle based on real driving data is used. The base data were obtained at a vehicle test in an urban area in Cologne city as well as in an extra-urban area near Cologne. The urban part of the test cycle consists of 188 brake events with a mean initial braking speed of 42,9kph and a mean deceleration of 18,7%g. The extra-urban part of the test cycle consists of 322 brake events with a mean initial braking speed of 62,1kph and a mean deceleration of 21,8%g. The whole cycle is referred to as Cologne cycle (rf. [4]).

For brake emission testing, one extra-urban cycle is run as bedding followed by one urban cycle and one extra-urban cycle incorporating brake emission measurement.

3.2. Test samples

To enable the analysis of friction material and brake disc influence on PN emissions, a wide variety of commonly used material combinations are chosen to be part of this study. Today most friction brakes in the automotive sector rely on grey cast iron brake discs in combination with low metallic (LM) or non-asbestos organic (NAO) friction materials. From each of those friction material classes, one high wear and one low wear material is investigated. Additionally, a combination of an adapted low metallic friction material and a grey cast iron brake disc with tungsten-carbide (WC) coating is investigated. This type of material combination is increasingly coming into the focus of the brake industry because of an observed positive effect on brake emissions. Apart from that, the corrosion resistance of the brake disc is increased by such a type of coating.

An overview of the investigated material combinations in the scope of this study is given in Table 1.

Table 1: Overview of friction materials and brake discs

Name	Friction material	Brake disc
LM1	Standard high wear low metallic	Grey cast iron (GCI) disc
LM2	Standard low wear low metallic	
NAO1	Standard high wear non-asbestos organic	
NAO2	Standard low wear non-asbestos organic	
LM3	Adapted low metallic for WC-coated disc	WC-coated GCI disc

4. Results

4.1. Influence of material combination

In the course of this study, for each of the five combinations of friction material and brake disc three dynamometer tests were conducted. In a first step, the total summarized particle number concentrations (total PN emissions) over the whole test cycle are analyzed. For this purpose the normalized total PN emissions of all material combinations are depicted in Figure 2. It can be seen that material combination LM1 leads to the highest PN emissions, while LM3 and thus the case of WC-coated brake disc shows the lowest PN emissions. The standard deviation is highest for LM1 and NAO1, which corresponds to the high wear friction materials.

Figure 2 also gives the normalized total gravimetric wear, which is the sum of disc wear and pad wear, for each material combination.

The highest total wear is measured for the high wear LM and the high wear NAO, which is an intuitive result. It can also be stated that, in line with past results, no correlation between total wear and total PN emissions exists.

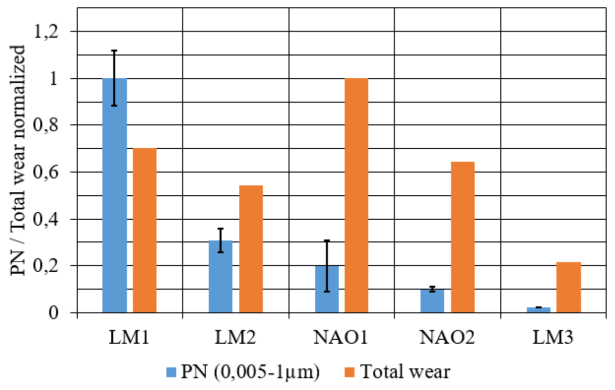

Figure 2 Normalized total PN emissions and normalized total wear of investigated material combinations

In the next step, the mean particle size distribution (PSD) of PN emissions over the whole test is analyzed. Figure 3 shows the PN emissions over the particle diameter. The PN emission values are normalized to the maximum value of each material combination to allow for a direct comparison of the position of the peaks in the respective PSD. It has to be emphasized that the absolute values of PN emissions are very different from material to material as depicted in Figure 2.

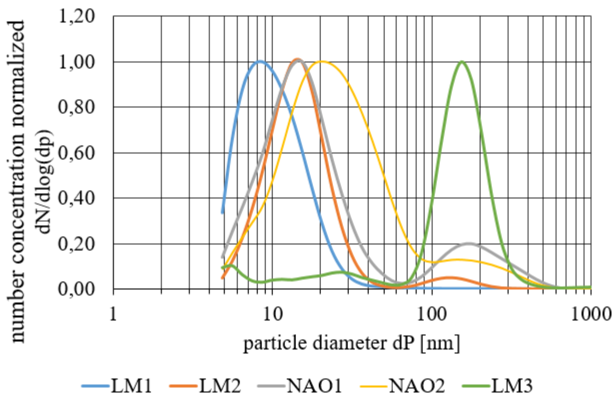

Figure 3 Particle size distribution of investigated material combinations

It can be seen that all materials except for LM3 possess a main peak in the PSD at a relatively small particle size of ~8-20nm. The material LM3 has the main peak at ~150nm and a much smaller peak at the lower end of the measurement range of the DMS500 device at ~5-6nm. The material NAO1 shows a pronounced bimodal PSD with one peak at ~15nm and a second peak at ~160nm. In a less pronounced way, also NAO2 has a similar bimodal characteristic.

The distribution of PN emissions over the particle diameter provides a promising approach for an explanation of the total PN emissions of a material combination. While the two LM friction materials that were run in combination with a grey cast iron brake disc have their main PSD peak at relatively low particle diameters of ~15nm with only minor peaks at higher particle diameters, the NAO friction materials show an additional peak at particle diameters of ~160nm. This means that the total wear amount of the NAO materials consists of larger particles in average than for the LM materials, which ultimately leads to higher total PN emissions for the LM materials. This holds true despite of the fact that the materials NAO1 and NAO2 show a total wear on the same level or even higher than the materials LM1 and LM2 (rf. Figure 2).

Similarly, the relatively very low PN emissions of the adapted LM friction material that was run on a WC-coated disc can be explained by the high average particle diameter of the emitted particles. The main peak of the PSD for LM3 lies at ~150nm with only a minor peak at ~5-6nm.

The repeatability of the PSD within the three tests representing the same material combination is good for all materials except for NAO1, where one test had the main peak at ~150nm instead of ~15nm. This outlier is not evaluated in the course of this study. As an example, the PSD for the three tests conducted with the material combination LM1 is shown in Figure 4. It can be seen that the position of the peak is nearly identical with a deviation of ~1nm. Also the height of the peaks and the distribution over the whole particle size range are very similar.

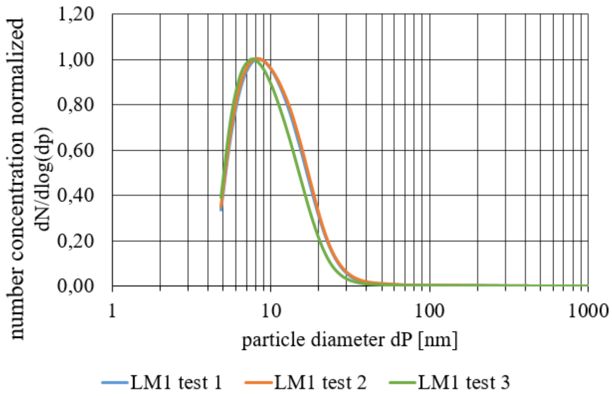

Figure 4 Evaluation of LM1 PSD repeatability

4.2. Influence of temperature level

It has been shown in the past that the disc temperature can have a massive influence on PN emissions in the case of the use of GCI discs. This behavior for the material LM1 is shown in Figure 5 based on results published in [4]. The disc temperature in the course of the test shows three distinct peaks at the beginning of the extra-urban part of the test cycle, where the temperature reaches or exceeds 160°C. Considering the green line representing the cumulated PN emissions it gets clear that the predominant part of PN emissions is emitted during those three high temperature sections.

To analyze the influence of disc temperature on PSD, the brake events of each test are split into two parts according to the maximum disc temperature during a brake event. The threshold temperature is chosen as the temperature of the 4th highest peak temperature in the course of the test. Due to different frictional behavior of the different material combinations and consequently a different temperature regime, this threshold temperature is potentially different for each material combination.

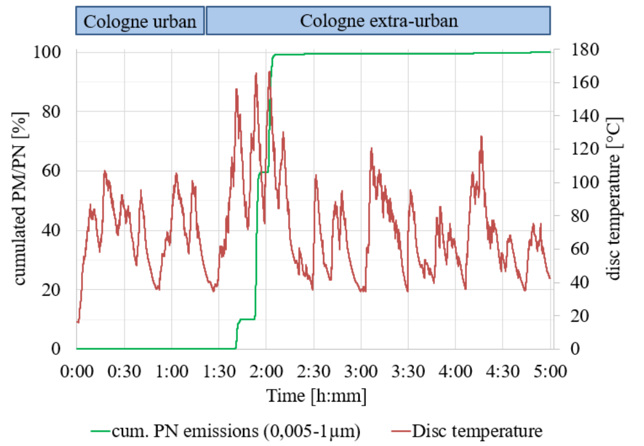

Figure 5 Cumulated PN emission and disc temperature for material combination LM1 ([4])

In case of LM1 this threshold temperature is ~130°C. Only the three high temperature sections show temperatures higher than this threshold temperature. For each of the two parts of the test, i.e. disc temperatures above 130°C and disc temperatures below 130°C, the mean PSD is plotted in Figure 6.

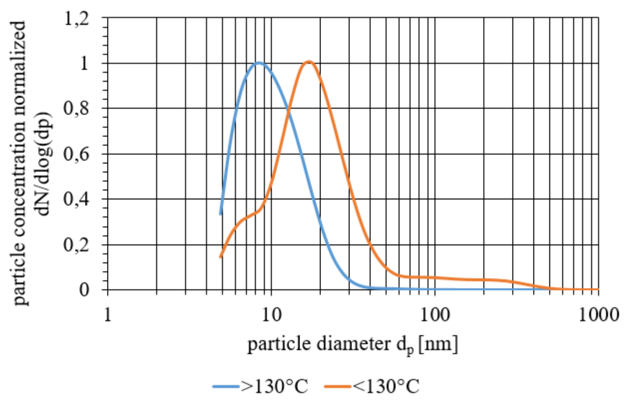

Figure 6 Mean PSD of high and low temperature sections of LM1 test

It can be seen that the PSD peak is shifted to a higher particle diameter for lower temperature brake applications which seems to be the main reason for the much lower PN emissions in the low temperature sections of the test. As a result, ~96% of PN emissions are detected during the high temperature sections of the test (above 130°C), while those sections only represent ~3% of all brake applications. Again it has to be noted that each of the curves in Figure 6 is normalized to their respective maximum value for the sake of comparability. As already mentioned the absolute values of PN emissions for the lower temperature sections are much lower than for the high temperature sections.

A similar behavior can be observed for the material LM2. On the other hand, the NAO materials show a different behavior as depicted for NAO2 in Figure 7. The threshold temperature is determined to be 145°C.

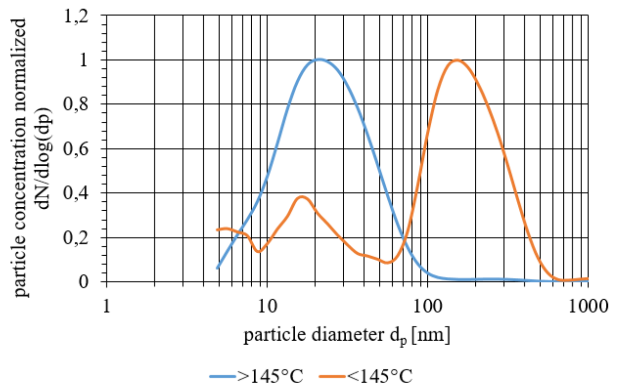

Figure 7 Mean PSD of high and low temperature sections of NAO2 test

In the case of material combination NAO2 the peak for the lower temperature section is shifted to a much higher particle diameter of ~150nm in comparison to the material combinations LM1 and LM2. Nevertheless, the share of PN emissions in the high temperature section is on a similar high level, specifically ~88% of PN emissions for NAO2 are measured in the high temperature section that only represents ~3% of the brake applications of the test. A similar behavior can be observed for NAO1.

As could be expected from previous investigations, the material combination of adapted LM friction material and WC-coated brake disc shows a very different behavior. The threshold temperature is 165°C in this case, which corresponds to a generally higher temperature level that is observed in this test. Nevertheless, the total PN emissions are relatively low (rf. Figure 2). The mean PSD of the high and low temperature sections of LM3 are depicted in Figure 8.

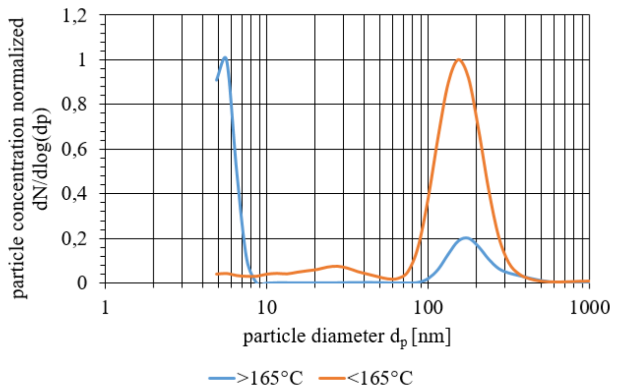

Figure 8 Mean PSD of high and low temperature sections of LM3 test

The diagram shows that for the high temperature sections the main PSD peak lies at a particle diameter of ~5-6nm while a second peak exists at a particle diameter of ~180nm. In the low temperature sections only one peak is present at a particle diameter of ~170nm. Apart from that, the share of PN emissions in the high temperature sections is ~3% and thus corresponds to the share of brake applications in this section, which is also ~3%.

An overview of the share of PN emissions in the high temperature sections for the five investigated material combinations can be found in Figure 9.

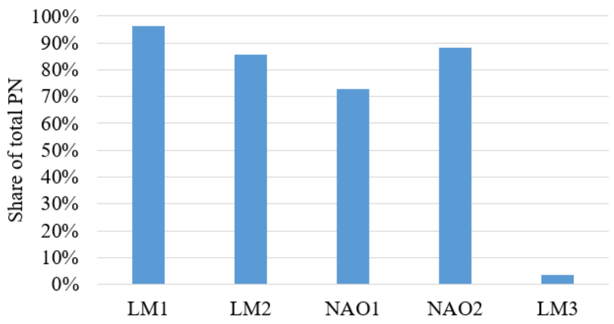

Figure 9 Share of PN emissions in the high temperature sections of the respective material combinations

This diagram illustrates that there exists a strong correlation between PN emissions and disc temperature for all tested material combinations incorporating grey cast iron brake discs. For the case LM3 incorporating a WC-coated brake disc no such correlation exists and thus the total PN emissions are relatively very low in this case.

5. Outlook

It has to be pointed out that the test cycle used in this study, namely the Cologne cycle, is not a representative test cycle for average worldwide driving behavior. It does not represent a standardized test procedure and cannot provide resilient absolute brake emission results. Despite this fact, some basic insights like e.g. temperature dependency can be drawn from tests utilizing this non-standard test procedure.

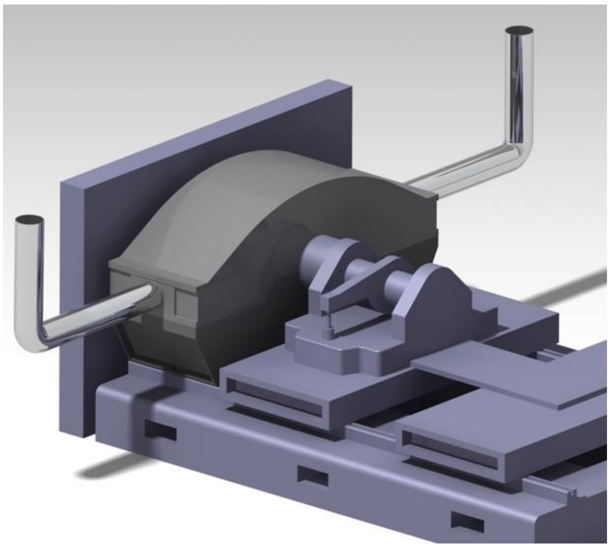

Figure 10 New brake emission dynamometer setup

In the future though, brake emission measurements at TMD will be conducted on the basis of the novel WLTP-based brake emission test cycle ([7]) and according to the standards regarding e.g. cooling air setup and particle sampling defined by the UNECE Particle Measurement Programme (PMP) informal working group.

As an integral part of compliance to future PMP standards, a new brake emission enclosure has been developed and is integrated in the emission setup for all future brake emission measurements at TMD. The new setup is depicted in Figure 10.

Based on the findings presented in this study and other similar studies, the medium-term aim is to develop an effective method to optimize the brake emission behavior of a brake system while fulfilling all the customer requirements. Such an effective method is in great demand especially in the context of the automobile megatrends of electrification and autonomization. Those will lead to new requirements for the brake system with a special focus on brake emissions, corrosion, NVH and lifetime.

6. Conclusion

In the scope of this study the particle size distribution (PSD) of PN emission measurements of five different material combinations of friction material and brake disc are investigated. The focus lies on the influence of different material combinations as well as the disc temperature on the PSD. The following main conclusions can be drawn:

- Considering the mean PSD over the whole test cycle, different characteristics depending on the material combination can be observed. For low metallic friction (LM) materials in combination with grey cast iron (GCI) brake discs, the main PSD peak is found to be at relatively low particle diameters in the range of ~8-15nm with only minor contributions in other size ranges. Material combinations consisting of NAO friction materials and grey cast iron brake discs also show the main peak at low particle diameters of ~15-20nm but an additional peak at ~150-180nm is also present. Generally speaking, NAO friction materials in this study generate wear particles with higher average particle diameter than LM friction materials, which leads to lower total PN emissions for NAO materials in case of similar total wear.
- The combination of adapted LM friction material and WC-coated grey cast iron brake disc leads to a main peak in the PSD at a relatively high particle diameter of ~150nm. This corresponds to relatively very low total PN emissions while the total wear is not lower in the same relation.
- For all five investigated material combinations a temperature dependent PSD is observed. For all cases incorporating a GCI brake disc, higher disc temperature leads to a reduction of the particle diameter of the emitted particles. This corresponds to the previous findings that the main contribution to total PN emissions is observed during the high temperature sections of the test. For those material combinations including GCI discs, between ~72% and ~96% of the total PN emissions occur at the ~3% of brake applications with the highest temperatures. The fact that NAO materials lead to lower total PN emissions in the scope of this study can be explained by

the higher particle diameters of emitted NAO particles during the respective high temperature sections.

- The material combination of adapted LM friction material and WC-coated GCI brake disc (LM3) represents a special case in the sense that no correlation between disc temperature and PN emissions can be observed. The ~3% of brake applications with the highest temperatures are responsible for ~3% of the total PN emissions. This corresponds to the fact that the PSD shows a bimodal characteristic even for the high temperature sections. The main PSD peak shifts to a low particle diameter of ~5-6nm but a second peak at ~170nm is also present. This is one important reason for the relatively very low total PN emissions for this material combination.

The present study illustrates that an analysis of the particle size distribution for different friction materials, brake discs and temperature regimes can provide valuable insight into the reasons of different total PN emissions. It has been shown that, at least for the tests conducted in the scope of this study, the WC-coated disc in combination with an adapted LM friction material, leads to the emission of larger particles even for high disc temperatures and thus to a massive reduction of total PN emissions. Also the friction material has a significant influence on PN emissions and has to be taken into account when dealing with the challenge of break emission reduction.

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References

[1] K. Bagate, J. J. Meiring, M. E. Gerlofs-Nijland, R. Vincent, F. R. Cassee, and P. J. A. Borm, "Vascular effects of ambient particulate matter instillation in spontaneous hypertensive rats," *Toxicol. Appl. Pharmacol.*, vol. 197, no. 1, pp. 29–39, May 2004, doi: 10.1016/j.taap.2004.02.005.

[2] G. Oberdörster, "Toxicology of ultrafine particles: In vivo studies," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 358, no. 1775, pp. 2719–2740, 2000, doi: 10.1142/9781848161221_0012.

[3] T. Grigoratos and G. Martini, "Brake wear particle emissions: a review," *Environ. Sci. Pollut. Res.*, vol. 22, no. 4, pp. 2491–2504, 2015, doi: 10.1007/s11356-014-3696-8.

[4] A. Paulus, "Investigation of Brake Emissions of Different Brake Pad Materials with Regard to Particle Mass (PM) and Particle Number (PN)," in *XXXVIII. Internationales μ-Symposium 2019 Bremsen-Fachtagung*, 2019, pp. 81–94, doi: 10.1007/978-3-662-59825-2_11.

[5] C. Asbach, A. M. Todea, M. Zessinger, and H. Kaminski, "Generation of Fine and Ultrafine Particles During Braking and Possibilities for Their Measurement," in *XXXVII. Internationales μ-Symposium 2018 Bremsen-Fachtagung*, 2018, pp. 143–164, doi: 10.1007/978-3-662-58024-0_10.

[6] H. Kaminski *et al.*, "Comparability of mobility particle sizers and diffusion chargers," *J. Aerosol Sci.*, vol. 57, pp. 156–178, 2013, doi: 10.1016/j.jaerosci.2012.10.008.

[7] M. Mathissen *et al.*, "A novel real-world braking cycle for studying brake wear particle emissions," *Wear*, vol. 414–415, pp. 219–226, Nov. 2018, doi: 10.1016/j.wear.2018.07.020.