Heavy duty brake wear emissions: an on-road measurement campaign using a novel fully open sampling system.

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In UNECE GTR24 a test procedure for brake wear emissions of light duty vehicles has been determined. In the Euro 7 regulation limit values have been agreed upon for light duty brake wear emissions. Meanwhile, official test procedures or Euro 7 limit values for heavy duty have not yet been determined. A lot of research is currently ongoing on heavy-duty test procedures and limit values. The research provides important insight into real-world heavy duty brake wear emissions by taking a novel approach to on-road measurements with a fully open sampling system.

Current research into on-road brake wear emissions almost exclusively involves some form of encapsulating the braking system. Although this provides clear advantages w.r.t. high emissions capture rate and elimination of external particle sources, this will influence the heating and cooling behaviour of the braking system compared to the original configuration. The open design measurement setup provides the possibility to measure the brake wear emissions and vehicle conditions in an on-road setting, without artificially influencing the system temperature significantly. Most importantly a nozzle is designed for sucking in the brake wear emissions nearby the source while also fitting within the wheel of the vehicle. The design of the nozzle together with high flow suction provide the opportunity to measure the total brake wear emissions.

Extensive analysis of the on-road measurement campaign has provided valuable insights in temperature distributions and corresponding particle emissions of on-road brake wear emissions allowing for the calculation of emission factors. Highest particle number emissions per kilometre were seen during urban driving and the lowest during motorway driving. Moreover, additional analyses were performed to study brake wear emissions during a typical delivery route, hilly driving and congested motorway driving. After some filtering, brake temperature heating and cooling models were fitted and a model for the number of emitted brake wear particles was derived.

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Effect of pad material and regenerative braking on brake wear emissions

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Non-exhaust sources, including brake, tire and road wear, have been identified as a major source of current traffic-related particle emissions [1]. Brake wear particle characteristics and quantity depend on factors such as vehicle properties, brake material composition and driving characteristics. Recent studies have been conducted to analyze effect of these topics. For instance, composition and structure of brake wear particles has been analyzed [2] as well as the effect of regenerative braking on particle emissions [3], which is important topic due increasing number of hybrid and electric vehicles on roads.

In our study, a set of brake pads, from different manufactures, was purchased from local spare part suppliers. In total of 7 pads were tested with X-ray fluorescence (Olympus Vanta VMR) to obtain their elemental composition. Two of the pads were selected for testing in a dynamometer bench: original pads and pads with low Cu and Fe content.

Brake particle emissions were tested in a measurement campaign using a dynamometer with WLTP brake cycle and with repetitive from constant speed to stop cycle. Increased mass of the vehicle was simulated by increasing the brake torque demand and effect of regeneration by decreasing the torque demand. Several type of particle properties were measured, for instance PM10, PN10 and size distribution.

There were significant differences in the chemical composition of the analyzed pads. Light elements (LE<Mg) were the most abundant and could not be specified with the XRF. Amount of Fe (0.7-35%), Cu (0-11%), Zn (0-10%) and Ba (0.1-30%) varied significantly between the pads. Mg, Al, Si and S were detected from all the pads.

The brake pads with low Cu and Fe content were consistently found to produce lower (-30…-90%) PM and PN emissions than the original pads. Regenerative braking reduced PM10 and PN10 emissions significantly in most cases, often more than -50%. However, in some cases, relatively high PN10 concentrations were observed during regenerative braking although the brake pressures and resulting torques were low compared to normal braking. Also during heavy braking, where the share of the regeneration is low, the particle concentrations were close to conventional braking.

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Beyond Emission Factors: Brembo's Protocol for Chemical and Toxicological Analysis of Brake Wear Particles

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Air quality remains one of the significant risks to both human health and environment. To address this challenge, regulations like EURO 7 have been introduced to reduce harmful emissions and improve air quality. Notably, introduction of EURO 7 marks a turning point by including, for the first time, limitations on non-exhaust emissions, such as those generated by brakes. However, the emission factor defined in EURO 7, expressed in terms of mass of PM_{10} particles generated per kilometer, provides only a partial understanding of the impact of brake emissions on air pollution. To fully assess their effects, it is essential to go beyond quantity and investigate the chemical composition and toxicological response of these emissions, offering deeper insights into their potential risks to health and environment.

This work presents analytical protocols for the chemical and toxicological characterization of brake emissions. Emissions are collected using a GTR-compliant dynamometric bench at the Brembo Testing Department, simulating standard driving and braking conditions under the WLTP (Worldwide Harmonized Light Vehicle Test Procedure) cycle. Key parameters such as emission factors, relative wear of pads and discs, and particle number (PN) are recorded during sampling.

For chemical characterization, emissions are analyzed using a range of techniques: SEM/EDS for morphology and elemental composition, XRD for crystalline compounds, Raman spectroscopy for crystalline and amorphous compounds, XANES for metal speciation, ICP-MS for trace element quantification, and SEM with Image Analysis for particle size distribution. The presence of specific organic compounds, such PAHs and PCBs, is also evaluated using additional analytical methods, such as GC-MS analysis.

Toxicological characterization assesses both cytotoxicity and ecotoxicity. For cytotoxicity, A549 lung epithelial cells are exposed to emissions in submerged conditions via drop deposition, with endpoints such as cell viability (Alamar Blue), ROS generation, mitochondrial membrane potential (JC-1), and caspase activity. Ecotoxicity evaluations include a chronic aquatic toxicity test with Raphidocelis subcapitata (OECD 201, 2011), an acute immobilization test with Daphnia magna (OECD 202, 2004) and assessments using Vibrio fischeri (ISO 11348-3, 2007). Phytotoxicity is examined using Lepidium sativum in accordance with UNICHIM guideline 1651 (2003).

This comprehensive protocol provides a robust framework for understanding the environmental and health impacts of brake emissions. For each methodology presented above example of results obtained for $PM_{2.5}$ brake wear emissions using friction couple composed by grey-cast-iron brake disc and ECE R90 Low Metallic brake pads will be presented and discussed.

Characterization of UFP Emissions at a Railway Brake Test Bench

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Introduction: Although non-exhaust emissions have been the focus of attention in recent years, even more so with the introduction of the Euro-7 vehicle legislation, these emissions in rail transport have been neglected or little investigated, especially in the range of UFP[1].

A report published by the German Federal Environmental Agency compared PM emissions from various passenger and freight transport modes (land, sea, and air). While rail transport emits fewer pollutants than road transport, it still has environmental impacts. However, this analysis omitted non-exhaust emissions creating a significant data gap regarding rail transport's total PM contribution [2].

The present study focuses on addressing this issue by determining the brake related emissions.

Methodology: Measurements of UFP were carried out on a railway brake test bench using a measuring program based on the technical standard UIC 541-4 [3] and DIN EN 16452:2019 [4]. 7 braking cycles were performed, consisting of 50 repetitions each, in which operating parameters such as initial speed (30, 60 and 100 km/h), mass to be braked (loaded and empty train) and contact force (9 and 38 kN) were considered.

To measure UFP (10–300 nm) within the exhaust tube, a diffusion charger (DISCmini from Testo) was employed. Fine and coarse particle concentrations were determined using an impactor (3 levels from Dekati) and an aerosol spectrometer (GRIMM EDM 180). A Prandtl pipe was used for flow measurement.

Results: A peak in UFP concentrations was clearly observed in each repetition of the braking in all cycles. While, for the lowest initial speeds, the concentration of particles emitted was around 1E4 $1/cm^3$, in the case of the highest speeds, an exponential increase in the emission was evidenced and reached outside the upper measurement limit of the device (> 3E6 $1/cm^3$). With respect to the average particle size, when the initial speed was 30 km/h, the average particle size was slightly reduced in the first seconds of the braking, reaching 35 nm and then increasing during the rest of the braking to more than 100 nm.

When the initial speeds were 60 and 100 km/h, the braking times were considerably longer, leading to more complex relationships between the two variables analyzed (number and average particle size). The average size was repeatedly below 15 nm and the number concentrations above 1E6 $1/cm^3$.

Conclusions and outlook: This study provides data to fill the gap by using standardized test for the quantification of UFP emissions under varying braking conditions. The results show exponential relation between initial speed and particle number emission with complex variations in particle sizes. Additional research is required to fully characterize the UFP emissions including different kind of braking pads, as well as the chemical composition of particles in the ultrafine range, to assess their impact and develop solutions to reduce their emission.

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Physical and chemical characterization of brake and tyre wear measured on a custom-built combined dynamometer

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Automotive non-exhaust emissions, such as brake- and tyre wear are of rising interest, since they will be regulated for the first time with the EURO 7 regulation. While the majority of the particle mass of these abrasion derived particles is between 1 and 10 µm, a considerable percentage of the particle number is also generated in the nanoparticle range [1]. These particles can penetrate deep into the lungs, where they deposit in the alveoli and eventually reach the bloodstream via the blood-air barrier [2].

In this study particles generated from non-asbestos organic brake pads (NAO) and so called low metallic brake pads (LM), as well as summer, winter and all-season tyres were characterized regarding their emitted particle mass (PM), particle numbers (PN), as well as their size and morphology utilizing the WLTP brake cycle. A newly developed custom-built dynamometer that is capable of individual and simultaneous measurement of brake and tyre wear, was employed. This unique combined testing approach, which is the first dynamometer of its kind worldwide, allows for a more accurate comparison of contributions from the individual sources, compared to studies from single source dynamometers, which each have varying designs and particle transport efficiencies. To minimize particle losses and ensure realistic testing procedures, the dynamometer components, where applicable, were derived from the GTR24 specifications that regulate brake wear emission testing as part of the EURO 7. The custom-built brake and tyre wear dynamometer is depicted in figure 1.

Elemental analysis carried out via ICP-MS was used to determine heavy metal emission factors for individual sources. Furthermore SEM/EDX analysis was conducted to study the distribution of elements among different size ranges that were generated. Extracts of tyre particle containing filters were further analyzed for 20 organic tyre marker molecules. Distinct chemical changes, caused by processes such as thermal degradation and tribo-oxidation, that significantly changed compositions from the initial material to emitted particles, as well as a large contribution of the brake disc were observable based on chemical patterns.

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