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Innovate technologies to monitor and reduce Non-Exhaust Emission, particles and microplastics of Vehicles and pavements to improve air quality and human health.

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Deliverable D3.1:

Onboard module with the measurement instruments for non-exhaust particle emissions

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Life-NEEVE

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions





D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

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D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

SUMMARY

Deliverable D3.1 summarises progress in Life-NEEVE Task T3.1 on developing transferable onboard modules to measure non-exhaust particle emissions from brakes and tire–road interaction in view of emerging regulatory needs. It describes how established exhaust PEMS for solid particle number and filter-based gravimetric particle mass measurements are adapted for non-exhaust sampling and quantification. These instruments are complemented by laboratory analysers and collectors (e.g., EEPS/ELPI/OPS and impactors) to characterise size distributions, enable parallel measurements, and support cross-validation.

For brakes, the work follows the approach of the Global Technical Regulation No. 24 (GTR 24) and evaluates a dedicated brake enclosure with a HEPA-filtered cooling air flow, a downstream sampling tunnel and flow measurement. Said housing can be transferred from a brake dynamometer to a car which is then evaluated on the chassis dynamometer. Testing with the same brake hardware across different setups confirms that emissions show a comparable behaviour, i.e. distinct peaks during braking events with low background outside braking. The results indicate good repeatability even when variations occur between the different setups, highlighting the importance of temperature control, residence time, and potential leakage or pressure generated effects in the housing. Comparison of the dedicated onboard equipment to GTR 24 compliant laboratory analysers resulted in an excellent correlation also during highly transient events.

Brake particles collected during testing were used to develop and refine a protocol for post-analysis, enabling a systematic assessment of sample handling, analytical workflows, and the performance of the applied characterisation techniques. The analysis combined complementary physicochemical characterisation techniques. Particle size distribution and morphology were analysed using microscopic methods, enabling assessment of particle shape, surface structure, and agglomeration behaviour. Chemical and elemental composition were investigated using spectroscopic and spectrometric techniques to identify major constituents as well as trace elements. The results from the different techniques were systematically compared to assess method reliability, consistency, and suitability for brake particle post-analysis.

For tire–road wear, a controlled laboratory configuration presses pavement specimens against a rotating tire and captures the generated aerosol in a high-flow duct transporting the aerosol to particle number analysers and an impactor for size-segregated mass collection. Initial results show asphalt-dependent differences in aerodynamic mass size distribution, indicating the suitability of this approach for comparative measurements.

The report also identifies key constraints for future on road deployment like challenges associated to the mechanical design of housings, packing the required equipment into the car and the implications for the payload, the high electrical power demand for airflow generation and shortly ventures in the approval process for Spain and Germany authorities where on road testing will be conducted. Potential failures, safety hazards and countermeasures are presented in an FMEA at the end of document.



List of abbreviations and symbols

In this Deliverable abbreviations or symbols in the table below are often used.

Abbreviation	Explanation	Comment
Partners, companies or institutions related to this project		
US	Universidad de Sevilla	Partner
CHM	CHM Obras e Infraestructuras S.A.	Partner
CIEMAT	Centro de Investigaciones Energeticas Medioambientales y Tecnologicas	Partner
HORIBA	HORIBA Europe GmbH	Partner
ICER	ICER Brakes SA	Partner
PAUDIRE	Paudire Innova S.L.	Partner
RDT	RDT Ingenieros Madrid S.L.	Partner
UMH	Universidad Miguel Hernandez de Elche	Partner
VTI	The Swedish National Road and Transport Research Institute	Partner
CTCON	Centro Tecnológico de la Construcción de la Región de Murcia	Partner
Technical terminology		
C1 (tires)	Tires intended for passenger cars	
C3 (tires)	Tires intended for trucks and busses	
EV	Electric vehicle	
TRWP	Tire Road Wear Particles	Combined emissions from car/road interface
CV	Coefficient of variation	
TPN	Total particle number	
SPN	Solid particle number	
WLTP	Worldwide harmonized Light Vehicle Test procedure	
PEMS	Portable Emission Measurement System	
RDE	Real driving emissions	
UNECE	United Nations Economic Commission for Europe	
GTR 24	Global Technical Regulation No. 24	
OBD	On-board diagnostics	
VPRE	Volatile particle remover efficiency	
PHEV	Plug-in hybrid electric vehicle	
ICE	Internal combustion engine	
GAXRD	Grazing Angle C-Ray Diffraction	
Measures and units		
PN	Particle number	
PM	Particulate mass	



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1. Introduction

Over the past three decades, regulations targeting emissions from internal combustion engine vehicles have evolved from laboratory-based type approval cycles to increasingly stringent and globally coordinated standards. In Europe, successive stages of the Euro emission standards have progressively tightened limits for particulate mass (PM), and particle number (PN) since 1992. Parallel regulations in the United States, China, India, and other major markets have introduced comparable limit values, often with differing test procedures and boundary conditions. This fragmentation has underscored the need for harmonized test methodologies and metrics to ensure technical equivalence, regulatory fairness, and efficient vehicle development across jurisdictions.

A pivotal step toward harmonization was the development of the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), which replaced legacy driving cycles with a more representative laboratory test framework. However, discrepancies between laboratory and real-world emissions demonstrated that chassis dynamometer cycles alone were insufficient to guarantee on-road conformity. As a result, regulatory authorities introduced in-service conformity and real-driving verification mechanisms, culminating in the implementation of Real Driving Emissions (RDE) requirements in the European Union and analogous programs elsewhere.

Through the deployment of Portable Emissions Measurement Systems (PEMS) RDE established the technical and metrological foundation for on-road emissions assessment. These systems enable second-by-second quantification of gaseous pollutants and solid particle number under various boundary conditions defined by route composition, weather, altitude, and driving behaviour. The transition from laboratory to on-road exhaust measurements introduced new challenges in instrumentation robustness, drift management, dynamic response, and uncertainty evaluation.

While the focus has historically centred on exhaust emissions from combustion processes, the relative contribution of non-exhaust sources has become increasingly significant. Brake wear, tire wear, road surface abrasion, and resuspension generate particulate matter across a broad size spectrum, including coarse (PM_{10}), fine ($PM_{2.5}$), and the ultrafine fractions which often dominate the counted particle number (PN). As exhaust emissions decline due to electrification and advanced aftertreatment systems, non-exhaust emissions represent a growing proportion of traffic-related particulate pollution. Importantly, these sources are not limited to internal combustion engine vehicles; they are also intrinsic to battery electric and hybrid platforms, reinforcing the need for technology-neutral regulatory approaches.

In response, regulatory and technical working groups under the framework of the United Nations Economic Commission for Europe (UNECE) have initiated the development of harmonized methodologies for brake and tire wear measurement. Laboratory-based procedures—such as brake dynamometer cycles—are being standardized to define mass and particle number emissions under controlled conditions. However, analogous to the evolution from WLTP to RDE, there is increasing recognition that laboratory measurements require on-road validation to understand real-world variability due to braking behaviour, vehicle mass, regenerative braking strategies, and tire-road interactions.



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On-road measurement of non-exhaust emissions introduces additional layers of complexity compared to exhaust PEMS. Brake and tire wear particles generated at distributed locations around the vehicle, are subject to rapid dilution and dispersion, and exhibit wide variability in size distribution and chemical composition. Instrumentation concepts therefore extend beyond tailpipe sampling to include wheel-arch and brake enclosures, tracer-based source attribution techniques, and fast responding aerosol measurement systems capable of resolving transient events. Measurement systems must demonstrate defined performance characteristics with respect to detection efficiency across relevant particle size ranges, time resolution for dynamic braking events, resistance to vibration and contamination, and well-characterized measurement uncertainty under real driving conditions.

2. Purpose and objectives

This document provides an update about the current progress in the ongoing task T3.1 focusing on the development of the onboard NEE measurement modules and procedures to capture particles for further characterization. First measurements of brake, tire and pavement particles on chassis and brake dynamometers are presented. In the last chapter boundary conditions and restrictions for the planned on-road measurements are presented.

3. Instrumentation

This section describes the instruments used for the brake and TRWP measurements. Besides dedicated onboard systems, laboratory analysers and impactors have been also employed to provide additional data about size distribution.

3.1. OBS PN & PM

OBS-ONE PN 10 and OBS-ONE PM are part of HORIBAs broader OBS-ONE family of Portable Emissions Measurement Systems (PEMS). The units are designed for research purposes and to show regulatory compliance with the upcoming EURO 7 and the EURO 6 RDE legislation. Having the core know-how for both units and an inhouse calibration laboratory enables HORIBA to tailor these instruments to the requirements of the Life-NEEVE project in every aspect.

The HORIBA OBS-ONE PN 10 is an advanced on-board emissions measurement instrument designed to quantify solid (SPN) concentrations from vehicle exhaust under real-world driving conditions. It employs a condensation particle counter (CPC), a technology widely recommended by the UNECE-PMP (Particle Measurement Programme) for solid particle number detection. CPCs rely on using particles as nucleation seeds in a saturated vapor environment. By growing them into optically detectable droplets the particles can be counted individually, enabling highly sensitive detection of concentrations up to 5×10^7 particles/cm³ while covering a particle size range from 10 to 1000 nm. The sampled aerosol is pre-treated by a dedicated conditioning unit that dilutes the sample 100-fold and removes volatile particles, ensuring only solid particles are counted by the system's core CPC unit.



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Additional features tailored for robust and safe field operation include an automatic zero-check function to support measurement quality assurance with minimal operator intervention, plus the use of isopropyl alcohol vapor as working fluid supplied via a replaceable saturated wick.

The HORIBA OBS-ONE PM unit is an on-board measurement system enabling gravimetric determination of PM emissions under real driving conditions, complemented by real-time monitoring. The system extracts a representative fraction of the test aerosol at a constant volume flow regulated by a highly dynamic venturi-based flow measurement device. This ensures that the extracted sample volume remains constant even during transient events. The particulate matter is collected on a 47 mm filter made of borosilicate microfibers reinforced with woven glass cloth and bonded with PTFE. The flow rate of 16.67 litres per minute and the used filters have been established for exhaust emission measurements following the current legislation for heavy-duty and nonroad machinery.

After completion of the test, the filter is conditioned and weighed under controlled laboratory conditions to determine the deposited PM. These filters can be sent to the University of Seville and the University Miguel Hernandez to extract the particles for elemental and chemical characterization and to determine the toxicity with the developed organoids.

In parallel to the integrated gravimetric pathway, the OBS-ONE PM incorporates a diffusion charging sensor for real-time PM monitoring. In this method, particles are electrically charged in proportion to their active surface area giving rise to a current signal which can be converted into a real-time PM concentration value. This dual-measurement configuration provides both highly accurate cumulative mass results and second-by-second emission trends, allowing detailed temporal analysis of transient events. The availability of dynamic PM data is particularly valuable if emission spikes must be identified and attributed to specific operating conditions.

The sampling system includes particle pre-classification through a cyclone separator to remove coarse fractions above the targeted aerodynamic diameter range. In the Life-NEEVE project both metrics PM 2.5 and PM 10 will be measured by equipping the instruments with the appropriate cyclone.

The modular construction of the OBS-ONE units enables integration of OBS-ONE PN and PM with flow measurement modules, weather station- and On-board diagnostics (OBD) -data of the test vehicle under HORIBA's unified ONE PLATFORM software environment. This centralized architecture facilitates synchronized data acquisition, time alignment of multiple measurement channels, diagnostic monitoring, and data after treatment for regulatory evaluation.



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3.2. ELPI

The DEKATI ELPI+ (Electrical Low-Pressure Impactor) is a real-time particle size spectrometer designed to provide high-resolution measurements of aerosol number concentrations and size distributions across a wide aerodynamic diameter range (6 nm–10 μm). The instrument simultaneously determines particle number and size by combining inertial size classification with electrometer-based concentration measurement. In addition, filters can be mounted on individual impactor stages and loaded during operation, enabling subsequent size-resolved *ex situ* chemical and morphological analyses.

For brake, tire, and road wear emissions, the ELPI+ is particularly advantageous due to its capability to capture transient emission events with high temporal resolution and its robustness under conditions of elevated particle loadings.

However, electrometer-based concentration measurements introduce several limitations when applied to aerosols with undefined or highly variable charge states. Conversion of measured electrical current to particle concentration relies on mathematical charging efficiency models that assume defined charge distributions for each particle size. Although the ELPI+ employs a unipolar charger to condition particles before size classification, charging efficiency is strongly influenced by particle morphology, topology, chemical composition, and pre-existing charge states. These parameters are insufficiently characterized for brake, tire, and road wear particles, and prior studies indicate that friction-generated particles can exhibit unusually high electrical charge levels [1].

Additional constraints arise from the electrometers themselves, which exhibit significant noise at low currents and therefore limit detection to several thousand particles in the smallest size fractions. Moreover, the multi-stage impactor requires a pressure drop for operation, which results in an undefined loss of volatile particles. Because other instruments often use heated catalytic stripping or apply no volatile particle removal at all, cross-instrument comparability remains challenging.



3.3. EEPS

The TSI EEPS™ (Engine Exhaust Particle Sizer) is a real-time particle size spectrometer designed to measure size-resolved aerosol number concentrations in the nanometre range, covering particle diameters from approximately 5.6 to 560 nm. The instrument determines particle size distributions by combining electrical mobility-based size classification with an array of sensitive electrometers, enabling simultaneous measurement across 32 size channels with a temporal resolution of up to 10 Hz. This fast response makes the EEPS particularly well suited for capturing highly transient emission events during dynamic operating conditions such as braking events, accelerations, or load changes.

Employing electrometer for concentration measurements, the EEPS relies on pre-defined particle charging characteristics and mathematical inversion algorithms to convert measured electrical currents into particle number concentrations and size distributions. The accuracy of this conversion highly depends on the selected inversion matrix which builds upon assumptions regarding particle morphology, density, and charge state. For friction-generated particles such as brake and tire wear, these parameters are not yet fully characterized, which can introduce uncertainty in absolute concentration and size distribution measurements.

Differences in sampling and conditioning strategies in combination with the differing measurement principles lead to reduced cross-instrument comparability, particularly when EEPS data are compared with results from impactor- or CPC-based measurement techniques.

3.4. OPS

The Optical Particle Sizer is an aerosol measurement instrument designed to determine particle number concentration and size distribution by means of single-particle optical detection. The instrument operates by drawing the aerosol sample directly into the measurement region to minimize particle losses during transport. A sheath airflow surrounds and focuses the sample stream, which improves sizing resolution and helps keep the optical components clean during operation. The sample and sheath flow rates are controlled in real time, while sample temperature and humidity are simultaneously monitored and recorded.

Inside the optical chamber, the aerosol crosses a laser beam, and each particle generates a pulse of scattered light. The intensity of this light pulse is used to count individual particles and assign them to a size class. The OPS is designed to measure particles in the 0.3 to 10 μm size range, and its optical configuration, detector design, and signal-processing algorithms are optimized to provide high sizing resolution across this interval. In addition, the instrument uses 120° light collection ($90^\circ \pm 60^\circ$), which reduces Mie scattering effects and improves measurement quality.

After optical sizing, the sampled aerosol flows to a removable 37 mm filter cartridge, where particles can be collected for subsequent gravimetric, chemical, or microscopic analysis. This combination of real-time optical measurement and filter-based particle collection makes the OPS particularly useful in aerosol science, emissions monitoring, and environmental studies, where both particle size information and offline sample characterization may be required.

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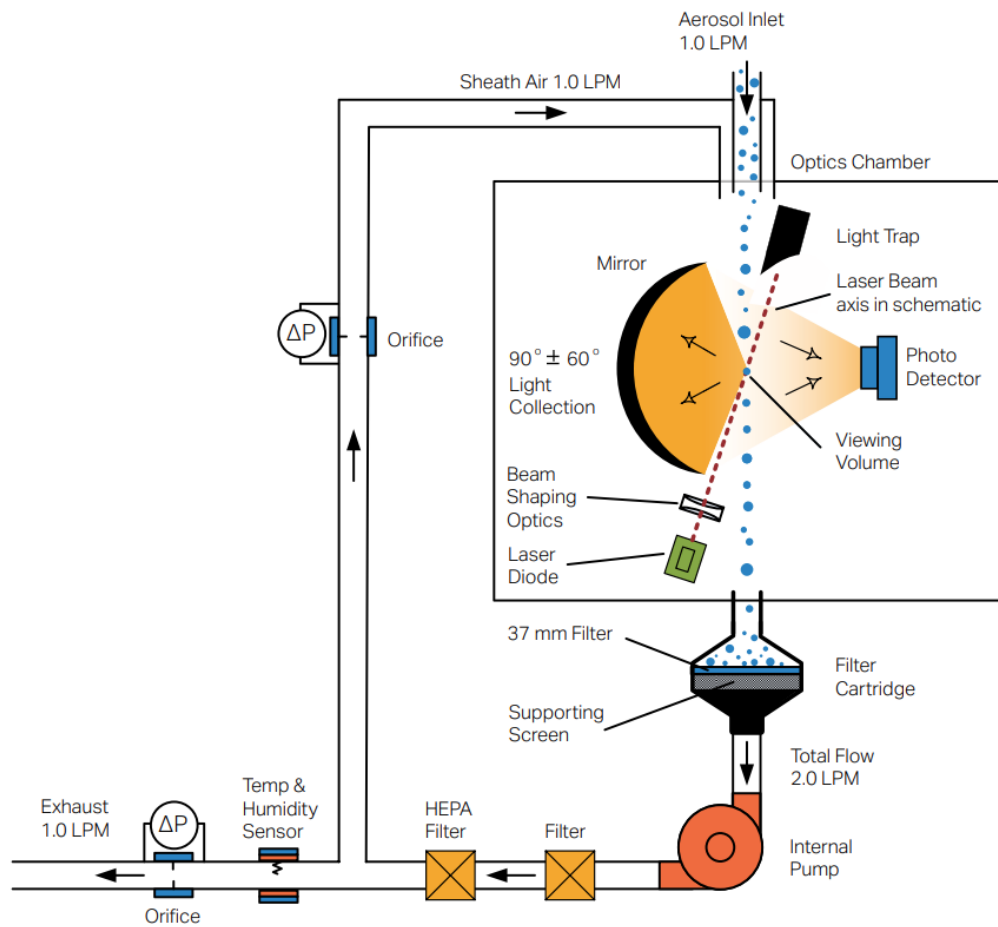


Figure 1: Flow scheme OPS

3.5. Impactor

A low-pressure impactor is an aerosol measurement instrument designed to classify and collect airborne particles according to their aerodynamic diameter. The device operates by drawing an aerosol sample through a series of stages with progressively smaller nozzles. As the air passes through each stage, particles with sufficient inertia deviate from the airflow and impact onto collection substrates, while smaller particles remain suspended and continue to the following stages. This mechanism allows the separation of particles into well-defined size fractions.

The impactor used in this study is a 10-stage Berner-type low-pressure impactor operating at a controlled flow rate of approximately $25 \text{ L} \cdot \text{min}^{-1}$. The instrument provides size-segregated particle sampling over a wide aerodynamic diameter range, covering both ultrafine and coarse particle fractions. The nominal cut-off diameters (d_{50}) of the stages are approximately 0.018, 0.032, 0.056, 0.10, 0.18, 0.32, 0.56, 1.0, 1.8, and $3.2 \mu\text{m}$, with an additional final filter stage allowing the collection of particles up to $16 \mu\text{m}$.

Low-pressure impactors are used in aerosol science, environmental monitoring, and emission studies because they provide particle size distributions and mass concentrations. Their ability to



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separate particles across a broad size spectrum makes them particularly valuable for studying fine and ultrafine particle emissions generated by combustion processes, brake wear, tire-road wear, or atmospheric sources.



4. Approach

This section describes the methods that have been developed and tested to measure tire and brake emissions. In a first approach the sampling methods and the instrumentation is tested in a laboratory environment, either on chassis or brake dynamometers at CIEMAT in Spain and HORIBA in Germany.

4.1. Brake emission sampling

Measuring particulate emissions originating from brake pads and discs in a reproducible and representative manner is a technically demanding task. Only in recent years a sufficiently robust and harmonized methodology has been established, culminating in the adoption of the United Nations GTR 24. This regulation defines a comprehensive framework specifying the experimental setup, operating conditions, and test procedures required for the determination of brake-related particulate emissions in the context of vehicle homologation under the EURO 7 regulatory framework.

In line with established exhaust emission regulations, EURO 7 requires brake particulate emissions to be quantified either as PN or PM, normalized to the distance travelled (i.e. per kilometre) over a representative driving cycle. Derivation of this distance-specific emission metric requires not only the accurate measurement of particle concentrations, but also reliable determination of the corresponding total volumetric flow. The total emission per kilometre is therefore obtained by integrating the measured concentration over time times the associated airflow. This fundamental measurement principle, which is well established for exhaust emission measurements, forms the conceptual basis of GTR 24 for brake emission measurements.

Under laboratory conditions, this requirement can be implemented with high accuracy using brake or chassis dynamometer setups, where airflow, temperature, and boundary conditions are tightly controlled and particle generation occurs in a fully enclosed environment. In contrast, transferring this approach to on-road measurements with a complete vehicle introduces substantial additional complexity as particles are generated at spatially distributed locations which are subjected to rapid dilution and dispersion. Capturing these particles in a representative manner while simultaneously quantifying the total airflow required for emission normalization therefore represents one of the central technical challenges of on-road brake emission measurements.

Several measurement concepts addressing this challenge have been proposed and evaluated in the literature [2,3,4], ranging from open wheel-arch sampling approaches to fully enclosed brake systems. These concepts differ significantly in terms of technical complexity, robustness, sensitivity to ambient background concentrations, and feasibility for deployment on public roads. Building on the findings documented in Deliverable D2.3 and on findings from the literature, the approach selected within the Life-NEEVE project is based on encapsulation of the whole brake assembly. This concept employs a dedicated housing mounted between the brake dust shield and the wheel hub, fully enclosing the brake disc and pads to capture the majority of particles generated during braking events. A schematic representation of the housing and the associated flow scheme are shown in figure 2 and 3.

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The encapsulation system was deliberately designed to allow the same housing to be used both on the brake dynamometer and on the test vehicle. This ensures methodological consistency between laboratory validation and on-road application, which is essential for meaningful comparison of results. Although the housing is not hermetically sealed, the airflow paths are defined such that the majority of the cooling air enters through a designated inlet located upstream of the brake pads with respect to the direction of disc rotation. This inlet air is supplied through a high-efficiency particulate air (HEPA) filter, providing a low and well-characterized background particle concentration and thereby improving measurement robustness.

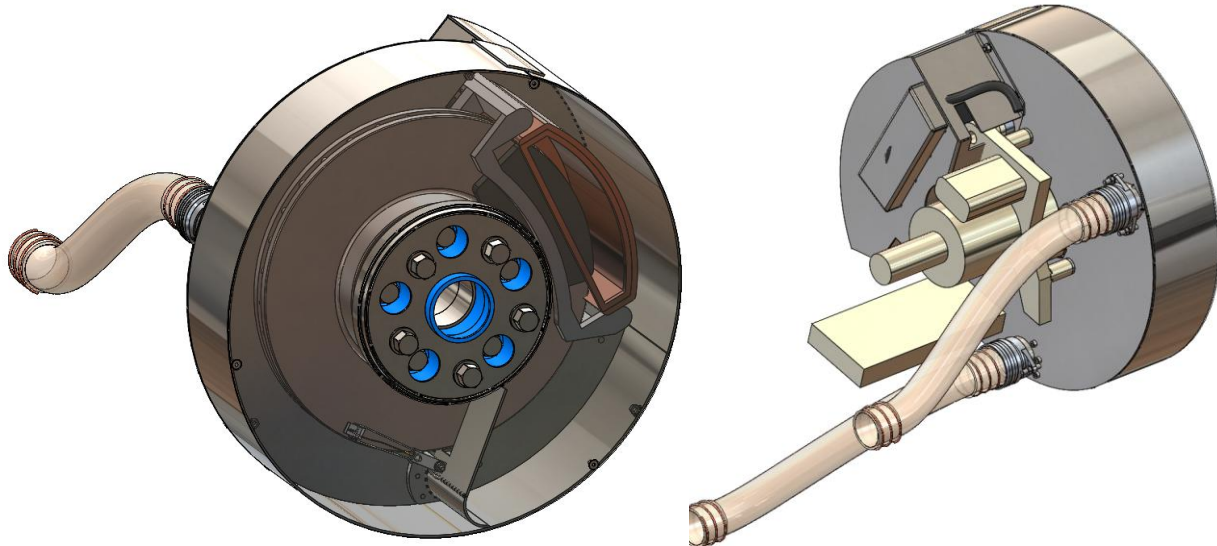


Figure 2 : 3 D model of the housing encapsulating brake pads and disc.

Figure 2 demonstrates the housing used for brake emission measurements. To improve visibility, the front lid which is facing to the rim, was removed. At the wheel hub, a spacer can be seen which is required to provide sufficient space between hub and rim. In the back only the inlet tube is visible. The guiding plate is mounted at the outlet next to a temperature sensor which measures the brake disc temperature. Right: back view of the housing and some light-coloured, simplified parts of the suspension. The protruding part behind the axis encloses the calliper. In front in and outlet tubing can be seen on top and bottom, respectively. A second opening, equipped with a guiding plate, directs the particle-laden airflow towards the outlet of the housing. The generated particles are extracted at a volumetric flow rate of approximately $1.2 \text{ m}^3 \text{ min}^{-1}$ and transported via antistatic tubing to a downstream sampling tunnel. The sampling tunnel is positioned approximately 2.5 m downstream of the brake enclosure, a distance selected to allow placement of the tunnel inside the vehicle during on-road operation. The tunnel incorporates a pitot tube for continuous volume flow measurement and offers additional sampling ports in a second tube, enabling simultaneous connection of up to 9 instruments for parallel measurements and direct comparison.

The pitot tube provides already two sampling points and allows real-time determination of the volumetric flow, enabling accurate time alignment between measured particle concentrations and the corresponding airflow, even under highly transient braking conditions.



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Downstream of the sampling section, a rotary pump is used to generate the required extraction flow from the brake housing while simultaneously supplying HEPA-filtered cooling air to the system. A key challenge of this single-pump configuration is the heat generated during gas compression. Under the applied operating conditions, the compression process increases the inlet air temperature to approximately 60 °C at the outlet of the pump, corresponding to a thermal load of roughly 1 kW that must be removed to avoid adverse effects on particle properties and measurement stability. In the laboratory setup, this excess heat was dissipated using a water-bath cooling system. The laboratory environment provides sufficient space and does not impose energy or weight constraints, allowing such thermal management measures to be implemented without restriction.

The laboratory configuration further enables the deployment of an extensive suite of measurement instruments for detailed characterization of the emitted particles and for validation of the onboard measurement candidates. At the pitot tube and selected sampling points, two MEXA SPCS 2000 systems were connected. These laboratory devices comply with the latest brake emission measurement requirements specified in GTR 24 and therefore serve as the primary reference systems for this study. One SPCS 2000 unit is equipped with a catalytic stripper operated at 350 °C, removing volatile particle fractions and enabling measurement of solid particle number only. The second unit operates without thermal treatment, allowing additional quantification of volatile particle contributions.

In parallel, the candidate onboard instruments intended for real-driving application, OBS-ONE PN 10 and OBS-ONE PM were connected to the same sampling system, enabling direct comparison with the laboratory reference instruments.

To obtain detailed information on particle size distributions, a TSI EEPS™ and a DEKATI ELPI+ were also connected, covering a particle size range from approximately 5 nm to 10 µm. Both instruments are widely reported in the literature for brake and tire-road wear particle (TRWP) measurements and provide valuable insight into size-resolved emission characteristics. In addition, for selected test cycles, a HORIBA PX-375 X-ray fluorescence analyser was employed to determine the elemental composition of the emitted particles, supporting source attribution and material characterization.

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Figure 3 left: Scheme of the setup utilized for brake emission measurements on the brake and on the chassis dynamometer. Right: Housing mounted on front wheel.

This comprehensive instrumentation strategy was selected to maximize the understanding of brake wear particle generation and properties under controlled laboratory conditions, while simultaneously enabling robust validation of the onboard measurement candidates OBS-ONE PN and OBS-ONE PM. An overview of the complete laboratory setup used for the brake and dynamometer measurements is shown in figure 4.



Figure 4 Vehicle with brake enclosure on chassis dynamometer. On the right side of the image pump, filters and all 9 measurement equipment units can be seen

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4.2. Tire-road emission sampling

The experimental setup has been designed to reproduce controlled tire–pavement interaction under laboratory conditions while enabling simultaneous characterization of the generated airborne particles. The system combines a mechanically controlled pavement loading assembly with a high-flow aerosol sampling line, allowing control of friction generation and particle measurement.

Friction is generated by advancing a replaceable pavement block toward the rotating tire using a mechanically actuated pressure jack. The pavement specimen is mounted on a rigid support structure with hinged elements that ensure stable alignment and controlled contact with the tire tread. The displacement induced by the pressure jack progressively increases the normal force at the tire–pavement interface, thereby producing wear and particle release. The applied load is continuously monitored by an in-line load cell installed between the jack and the pavement support structure, enabling real-time measurement and adjustment of the contact force. This configuration ensures reproducible normal loading conditions and controlled interaction throughout the test duration.

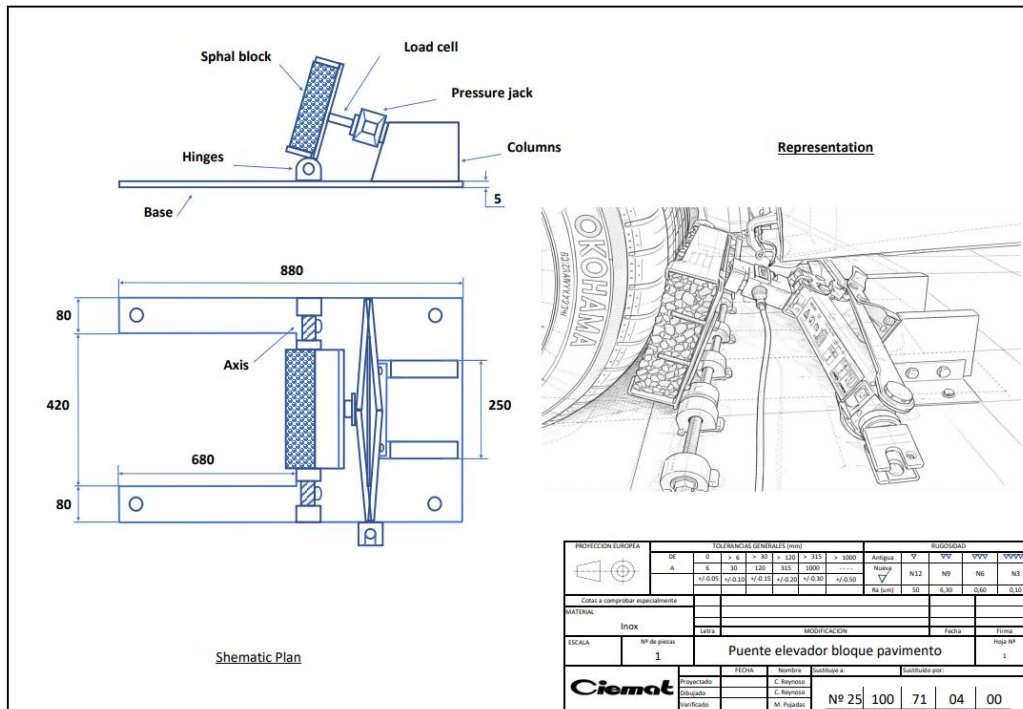


Figure 5 Scheme

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Figure 6 Tire testing assembly

The particles generated at the contact interface are captured downstream of the tire using a custom-designed sampling nozzle positioned close to the emission source. The nozzle directs the particle-laden airflow into a cylindrical main duct (internal diameter approximately 102 mm), where the aerosol is transported under high-flow suction conditions. The primary airflow, maintained at approximately 5400 L/min by an industrial vacuum cleaner (GS 83) supported by an auxiliary vacuum pump, ensures particle capture and minimizes deposition losses within the sampling line.

A controlled sub-sampling branch is extracted from the main duct to measure particle number concentration and size distribution in real time. This branch supplies an OBS ONE-PN10 instrument and an Optical Particle Sizer (OPS), operating at low flow rates (approximately 0.7 L/min and 1.0 L/min, respectively). In parallel, a Low-Pressure Impactor operating at 25 L/min enables size-segregated particle collection for subsequent gravimetric mass determination. Temperature within the duct is continuously monitored using a thermocouple, while a differential pressure gauge measures pressure drops across selected sections of the sampling line, ensuring flow stability and supporting interpretation of thermodynamic effects that may influence particle formation processes. The corresponding flow scheme and the experimental setup are shown in Figures 7 and 8, respectively.

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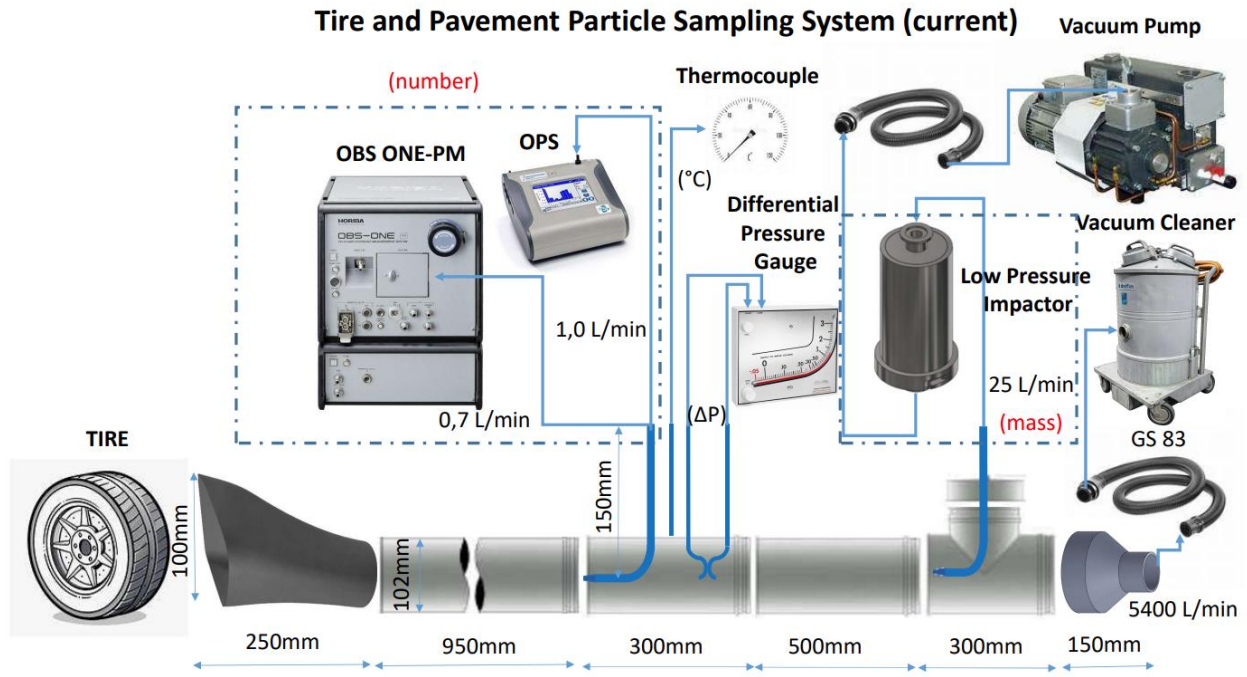


Figure 7 Flow scheme of tire-road emission sampling line.

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Figure 8 Experimental setup for tire-road emission measurements.

At present, we do not identify another experimental approach that allows an equally affordable and controlled comparison of particle emissions generated by different pavement materials under repeatable laboratory conditions. Although the present setup does not fully reproduce real tire–road interaction on public roads, it provides a practical platform for comparative assessment. In particular, the methodology is intended to evaluate relative differences in particle generation and size distribution between pavement types, rather than to reproduce absolute real-world emission factors. This controlled approach makes it possible to isolate the influence of pavement properties, such as porosity, on the emitted aerosol while minimizing the variability associated with traffic, meteorology, and road-surface heterogeneity.



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The integration of the mechanically pavement loading system with the sampling line provides a comprehensive experimental platform. The loading assembly guarantees control and quantification of the normal force applied to the tire, while the sampling system ensures capture and simultaneous characterization of particle number, size distribution, and mass under controlled and reproducible conditions. Together, these subsystems enable investigation of tire and pavement wear particle generation under defined tribological and aerodynamic parameters.

In addition to the system description, a fixed testing protocol was followed for all experiments to ensure repeatability and to distinguish background aerosol levels from particles generated by tire–pavement interaction. Each test was carried out on a chassis dynamometer at a constant wheel speed of approximately 8 km h^{-1} .

Before applying for any contact force, a 5 min background sampling period was recorded with the vehicle at rest and the pavement block not in contact with the tire. This stage was used to characterize the ambient and residual particle levels inside the sampling system. Afterwards, a second 5 min period was recorded with the wheel rotating at the target speed but still without contact between the tire and the pavement specimen. This step allowed the contribution associated with wheel rotation and air entrainment to be separated from the actual friction-induced emissions.

Following these preliminary stages, the pavement block was advanced toward the tire and the target normal force was applied through the mechanically actuated loading system, with the force continuously monitored by the in-line load cell. Under these conditions, particle measurements were recorded for 1 h during controlled tire–pavement friction. Throughout the test, both the applied load and the tire tread temperature were continuously monitored in order to track the stability of the operating conditions.

Each friction condition was repeated in triplicate. Between consecutive tests, the tire surface was cleaned using compressed air and manual cleaning procedures, and the system was allowed to cool down until the tire returned to ambient temperature (approximately $22 \text{ }^{\circ}\text{C}$).

For each pavement plate, the specimen was weighed before each friction test and rotated by 180° after every run to promote more homogeneous wear over its surface. A total of nine friction tests were performed per pavement plate, corresponding to 9 h of accumulated use for each material. In addition, the tire was weighed before the first test and again after completion of the full nine-hour testing sequence, enabling an overall assessment of tire mass loss during the campaign.



5. Evaluation laboratory

This section elaborates on the tests performed at HORIBA and CIEMAT with the developed setups and instruments. The particles collected on the filters have been analysed by the US

5.1. Evaluation brake-dyno

A set of commercially available brake pads and -discs for a SEAT Leon were characterized according to the homologation procedure for Euro 7, the GTR 24. The brake components for the SEAT Leon were selected as this car is available at HORIBA Europe for chassis dynamometer tests.

The GTR 24 procedure relies on a defined brake cycle, performed on a brake dynamometer under stringent flow conditions. A fully sealed housing ensures brake particles are transported away from the brake by a laminar flow at a constant flow rate, independently of the driven speed. A duct located in a straight line behind the brake enclosure transports the emitted particles to the sampling points where a representative sample is extracted and quantified. By multiplying the determined concentration or average mass deposition with the total volume flow through the duct the total number of particles or weight of airborne particles can be determined.

At first the WLTP Brake Cycle was repeated 5 times, as defined in the GTR 24 to ensure proper bedding of the specimen. Subsequently the actual particle measurement is repeated two more times with reference PN and PM devices connected. These two complete WLTP brake cycle repetitions are the basis of the GTR 24 procedure. Afterwards two additional repetitions of Trip#10 of the WLTP brake cycle were performed. The limited duration and the more severe braking events make Trip#10 more reliable for chassis-dynamometer measurements where background concentrations may interfere during small emission-events, and the number of possible repetitions is crucially dependent on the duration of the tests. While a brake-dyno can measure 24/7 due to the full automatization the chassis dynamometer measurements are only performed during regular working hours, due to safety constraints.

In a next step the enclosure was dismantled and the transferable housing described in chapter 4 was mounted on the brake dynamometer. The setup was prepared according to the flow scheme shown in figure 3. At a flow rate of 1.2 m³/min the brake disc temperature in the housing and in the GTR 24 compliant setup showed a reasonable agreement for the first 2000 seconds of Trip 10, see figure 9. In the remaining parts of Trip#10, where more frequent high temperature events occur the deviation increases as a function of temperature, indicating the need for a higher cooling air flow in future trials. However, a total of 20 repetitions of Trip#10 were performed with the transferable housing on the brake dynamometer to understand stability and reproducibility.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

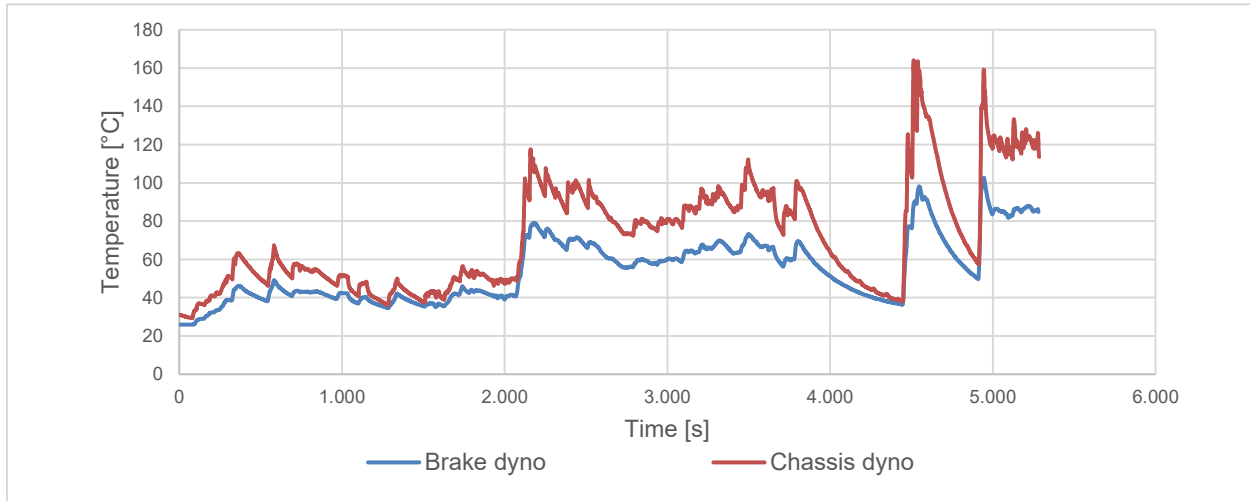


Figure 9 Temperature profile in brake housing. Measured with grinding sensor on brake disc for brake and chassis dynamometer measurements

In the next step the whole measurement setup was transferred to a chassis dynamometer, and the housing was mounted on the designated car with the very same brake disc and pads. A driving robot was used to drive the 1.5 hours long Trip#10. This not only enhanced reproducibility of the individual repetitions but simultaneously increased the number of possible repetitions during a working day. Similar to the brake dynamometer measurements multiple repetitions of Trip#10 were performed to understand the reliability of the measurements. Though it was originally planned to correlate these measurements to on road measurements, such measurements were not possible yet, as the housing interfered with the cornering position of the front wheels. As this impacts the road worthiness of the car, no attempts were made to use the housing for on road measurements. This demonstrates the challenges associated with the design of an appropriate housing as car manufacturers do not provide any kind of 3D-drawings as a basis for the design of a brake housing or a tire wear sampling cone.

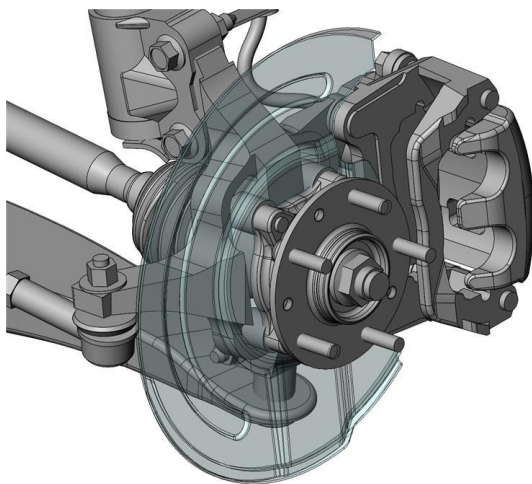


Figure 10 3D-scan of Mitsubishi Outlander front right wheel and suspension

In a second, currently ongoing, attempt to construct a housing for the front brakes, a 3D-scan of the car suspension was made. The result provides much more detail and accuracy than the manual measurements used for the SEAT Leon housing. This not only allows simulation of cornering but also helps to identify space constraints already at an early stage of the development. The 3D model of the scan can be seen in figure 10.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

Figure 11 shows the total solid PN emissions per second measured according to the GTR 24 method and compares it to the measurements with the transferable housing on the brake dynamometer and on the chassis dynamometer. For clarity two zooms are shown below. For all three configurations PN emissions are highly transient and occur as sharp and distinct peaks with similar duration, indicating the absence of hang-ups which could cause a continuous contamination in the transferable housing. Outside braking events, visible in the speed trace, emission rates are close to zero, indicating a low background concentration in all three cases. The only deviation from the low background can be seen in the high-speed part between 4000 and 5000 seconds where the housing shows a significantly higher background than the GTR compliant method. The correlation of this background to the vehicle speed makes contamination unlikely and rather favours under pressure induced contamination inside the housing. Similar observations have been reported previously [3].

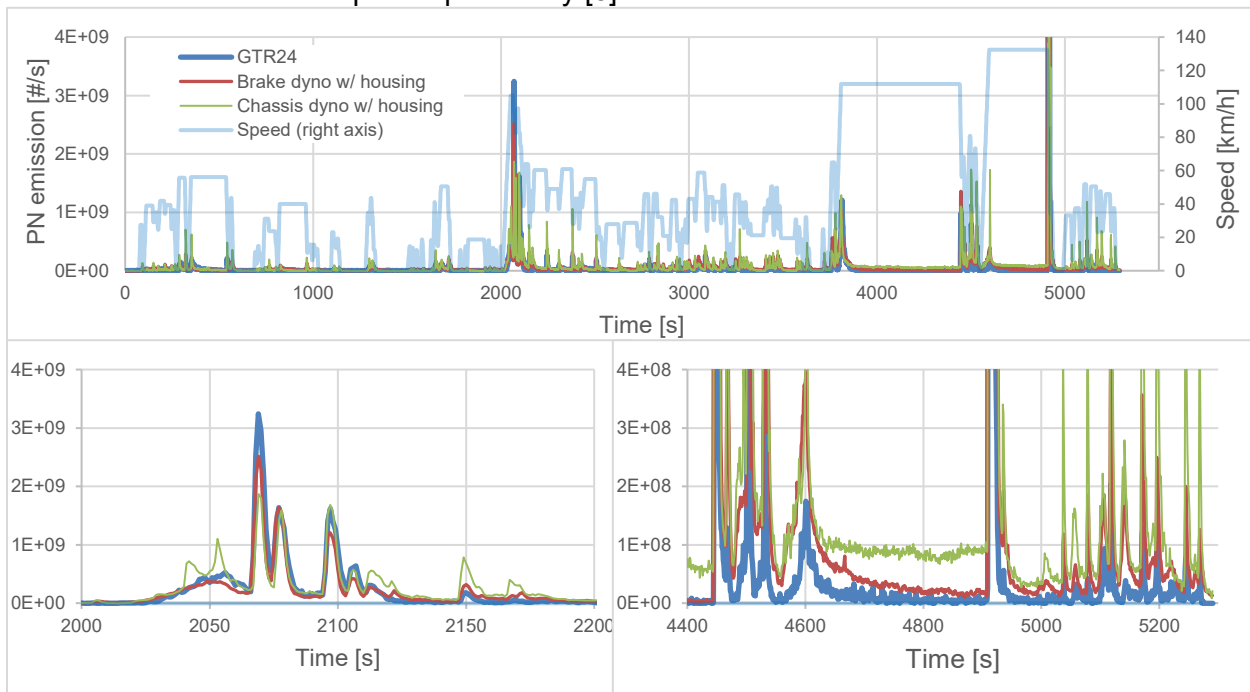


Figure 11 Total instantaneous PN emissions during Trip 10 of WLTP brake, measured according to GTR 24 or with the experimental housing on brake and on the chassis dynamometer. Please note that the y-axis intentionally cuts out the highest peak

Table 1 compares the emissions per km and the coefficient of variation (CV) during the repetitions on the brake and on the chassis dyno for the GTR compliant SPCS (TPN & SPN) and for the onboard instrument OBS-ONE PN to the classifier EEPS. A clear tendency can be seen on all instruments for the different configurations, with the lowest emissions in the GTR compliant setup and the highest emissions on the chassis dynamometer. As shown in figure 9 when the specimen is moving from the GTR compliant to the transferable housing an increase in temperature can be observed. Elevated temperatures are known to increase the particle emissions on brakes. Additional contributing factors are the reduced residence time of the particles between the origin of the brake dust and the sampling points. In the transferable housing this time reduces due to the high flow rate in the cooling air flow, as the diameter of the ducts is only 5 cm, compared to the 20 cm in the GTR housing.



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

The development of a reproducible methodology for on-road brake emission measurements is a central objective of the Life-NEEVE project. Accordingly, particular emphasis was placed on evaluating measurement repeatability across the different configurations. As summarized in table 1, all three configurations and all used instruments exhibit comparable coefficients of variation (the 1 % CV of the SPN counter in the GTR 24 compliant setup needs to be understood as an outlier. From experience the typical repeatability is comparable to the 8 % of the TPN unit). This demonstrates that, although the transferable housing yields absolute emission levels that differ from the GTR 24 reference, it nevertheless provides a stable and reproducible measurement platform suitable for comparative brake emission measurements under real-world conditions.

Table 1 Average particle emission per km and CV for all three tested configurations

	GTR 24		Brake dyno w/ housing		Chassis dyno w/ housing	
	#/km [E9]	CV	#/km [E9]	CV	#/km [E9]	CV
SPN	3.3	1%	5.9	8.4%	9.6	8.5%
TPN	3.8	8.8%	8.3	10.9%	14.2	6.8%
OBS-ONE PN10	-	-	7.2	14.1%	11.1	9.7%
EEPS	-	-	10.8	9.5%	15.7	7.7%
Repetitions	4		17		11	

Another key objective of these tests was the evaluation of the OBS-ONE PN 10 for non-exhaust particle emission measurements. As reference instruments, two MEXA SPCS 2000 particle number counters were employed for TPN and SPN, respectively. This reference devices fully comply with the latest requirements defined in GTR 24 and therefore provide a suitable benchmark for performance assessment. Figure 12 presents the correlation between the onboard OBS-ONE PN 10 and the two reference counters and additionally compares the results with measurements obtained from the EEPS particle sizer.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

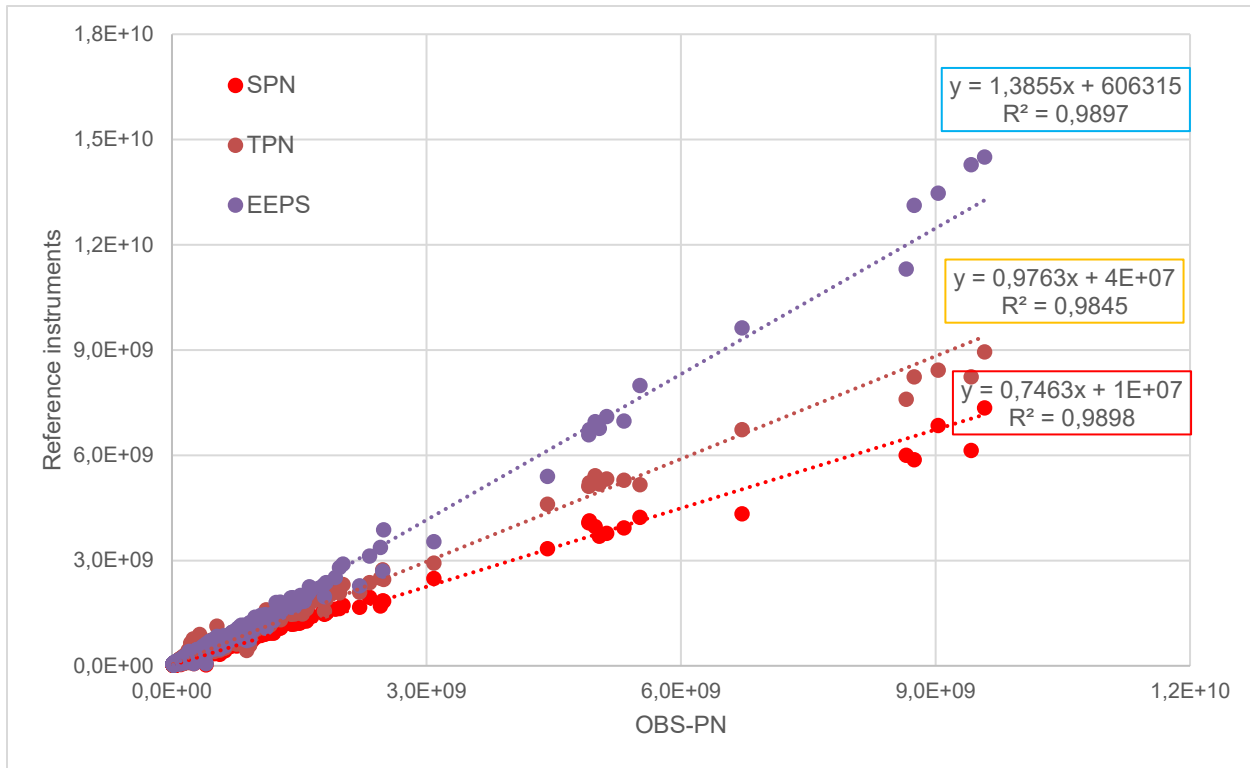


Figure 12 Correlation of laboratory PN counter to onboard module

Across all instruments, an excellent correlation is observed, with coefficients of determination exceeding $r^2 > 0.98$ for the onboard system. The largest deviations from linearity occur at the highest emission events. These deviations can be attributed to differences in particle residence time between the sampling location and the respective counters. Thermal diffusion and transport effects tend to reduce the sharpness of short emission peaks, leading to peak broadening and reduced maximum amplitudes at downstream measurement locations.

An additional and less expected observation is the close agreement between the OBS-ONE PN 10 and the TPN reference, whereas the SPN reference reports particle number concentrations approximately 25% lower than those measured by the onboard instrument. Both the SPN reference and the OBS-ONE PN 10 employ catalytic strippers to remove volatile particle fractions, which would suggest the closest agreement between these two instruments.

One reason for the deviation from the SPN unit could be that the removal of volatile particles in the SPN and the OBS-ONE PN10 shows considerably different characteristics for the volatile fraction of brake particles. Though the same type of catalytic stripper is heated to 350 °C in both cases differences in residence time and thermal conditioning may reduce their effectiveness and alter the removal efficiency. In addition, regulatory procedures specify different volatile compounds and test conditions for the verification of Volatile Particle Remover Efficiency (VPRE) in stationary PN counters compared to mobile PN measurement systems, which may further contribute to systematic differences.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

To identify the underlying root cause, all three units will be evaluated under controlled conditions in the calibration laboratory using both solid particles and volatile particles. This will allow to attribute the observed differences either to instrument-specific particle losses which can then be compensated by calibration or to the VPR methodology and its operating conditions.

The OBS-ONE PM was also used to collect brake emissions on filters, which have been sent to the University of Seville (US) and Miguel Hernández University (UMH) for further analysis. The US established a procedure for extracting the particles from the filters and preparing them for elemental and chemical analysis. The characterization of these particles is described in section 5.3 of this deliverable. Their toxicity will be described in D3.8, to be delivered in month 30, where their toxicity will be studied in recently developed organoids.

5.2. Evaluation chassis-dyno

The results from the low-pressure impactor compare the aerodynamic mass size distributions obtained for two different asphalt plates developed within the project under controlled tire-road contact conditions in the chassis dynamometer (225/50R17 98W). In both cases, the emitted particles were mainly distributed within the submicron-to-low-micron range, although differences were observed between the two materials, as shown in figures 13 and 14.

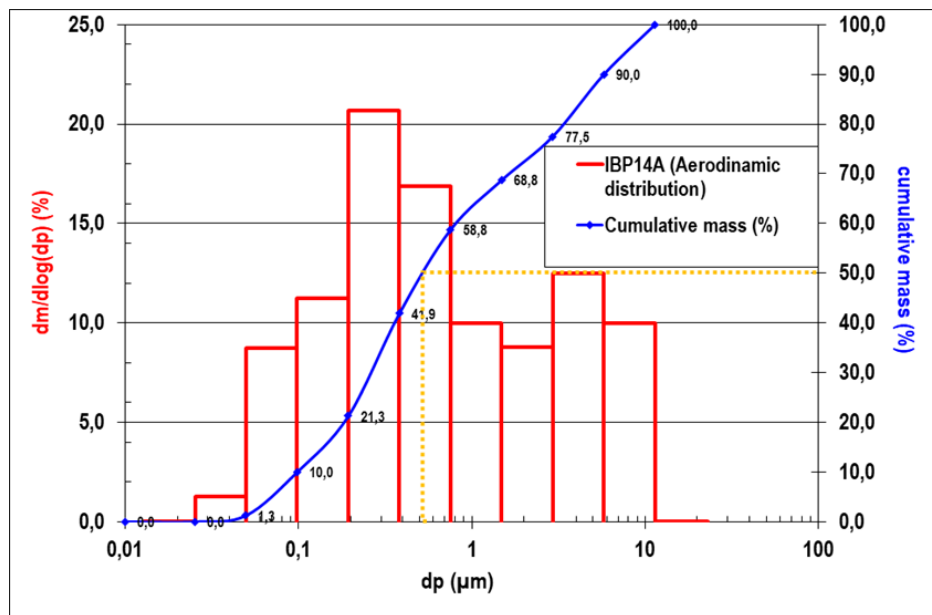


Figure 13 Mass distribution for IB14A (less porous pavement)

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

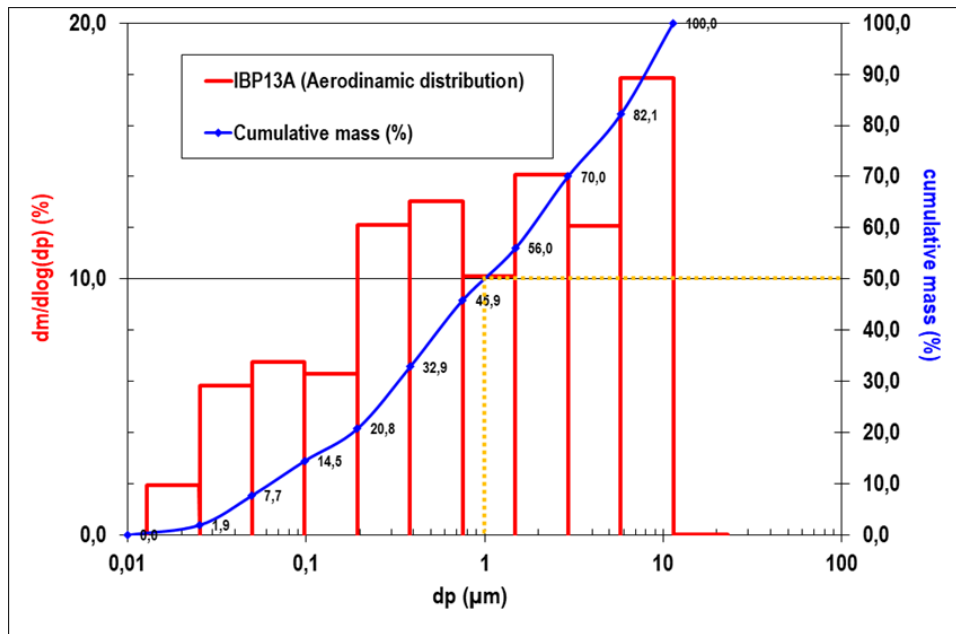


Figure 14 Mass distribution for IB13A (more porous pavement)

For IBP14A, the mass distribution was shifted towards smaller aerodynamic diameters, with the main contribution located approximately between 0.2 and 0.6 μm. The cumulative mass curve indicates a median aerodynamic diameter (d50) of roughly 0.5–0.6 μm, showing that a substantial fraction of the emitted mass was associated with relatively fine particles (Figure 13). By contrast, IBP13A showed a broader and coarser distribution, with a more pronounced contribution in the 1–10 μm range. In this case, the cumulative mass reached 50% at around 0.9–1.0 μm (Figure 14), indicating a larger characteristic particle size compared with IBP14A.

Overall, these results suggest that the asphalt composition influences not only the total particle generation, but also the resulting size distribution of tire-road wear emissions under laboratory conditions.

In addition, the setup was also complemented with a final collection filter placed downstream of the impactor and upstream of the vacuum cleaner. This additional filter was incorporated to collect a higher accumulated particle mass during the experiments, thereby enabling subsequent offline analyses by project partners. In particular, the collected material is intended to be sent to the University of Seville (US) and Miguel Hernández University (UMH), where further physicochemical and complementary characterization will be carried out. To ensure full traceability of the collected samples, each filter was identified using a structured labelling scheme containing the main experimental descriptors of the test. These descriptors included the asphalt plate code, the filter exposure time, the vehicle used, the test facility, the wheel speed, the mainstream suction setting, and the applied load recorded during tire–pavement interaction. The complete sample identification list is provided in the corresponding shared database file ([Sample identification list](#)), available through the project repository.

Photographs of the filter at different magnifications are included in Figure 15 and 16 to illustrate the visible particle loading obtained after the tests.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

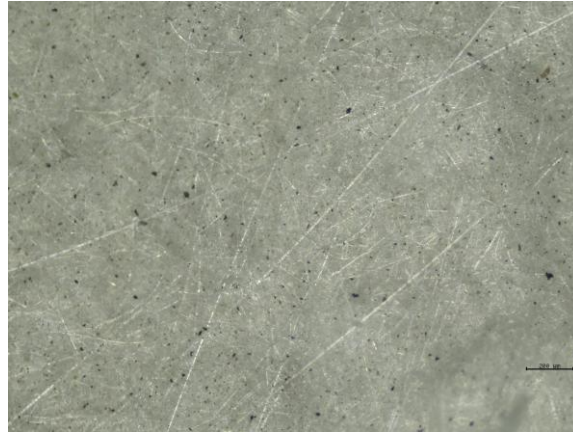


Figure 15 Downstream filter after the test campaign (x5)

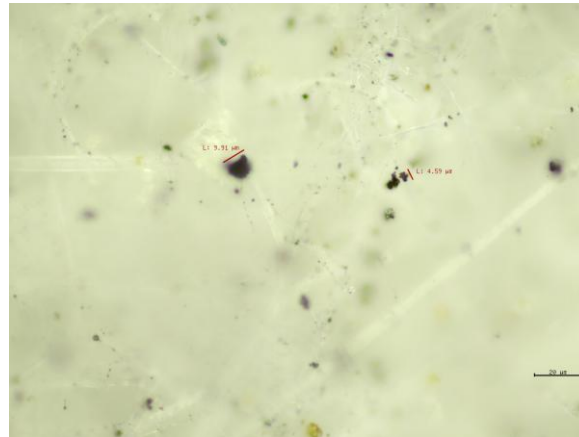


Figure 16 Downstream filter after the test campaign (x50)

In addition, the condition of the tire after approximately 9 hours of testing on one of the asphalt plates is presented (Figure 17). The post-test images reveal clear signs of tire-road interaction, including surface wear, adhered material and localised adhered material on the tire tread. These observations provide evidence of the mechanical degradation processes taking place during the experiments and help to contextualise the particle emissions measured in the chassis dynamometer.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions



Figure 17 Tire surface degradation after 9 hours of tests

5.3. Characterization of Particles

This section describes the chemical and physical analysis carried out on non-exhaust emissions from vehicles, specifically particles generated by brake wear (BWPs).

5.3.1. Methodology

Particles were collected on filters during brake and chassis dynamometer measurements at HORIBA with commercially available brake pads and – discs. Samples were collected on filters with the OBS-ONE PM which follows state-of-the-art procedures for PM emission sampling in exhaust- and non-exhaust applications. The particulate matter was deposited on filters made of borosilicate microfibers reinforced with woven glass cloth and bonded with PTFE. Dilution air was HEPA filtered during the measurements following the GTR 24 and partially mixed with ambient air during measurements with the transferable housing. This mixture was inevitable due to small



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

openings of the housing that allow rotation of the components. As the housing was also flushed with HEPA filtered air during the measurement, the amount of contamination is considered to be negligible. During the GTR 24 compliant measurement, the highest temperature reached by the brake disc surface was 100 °C. On the chassis dyno with the transferable housing up to 160 °C were reached. Few high-temperature tests were performed where the disc reached more than 300 °C.

5.3.1.1. Scientific equipment and analytical instrumentation

High-resolution imaging and elemental microanalysis were performed using a field-emission scanning electron microscope and an energy-dispersive X-ray spectroscopy system.

A Gemini SEM 300 Scanning Electron Microscope (ZEISS, Germany) was employed for microstructural characterisation. The instrument is equipped with a Gemini® field-emission (FEG) electron optical column, which enables excellent spatial resolution at low accelerating voltages and thereby minimises both electron beam-induced sample damage and surface charging effects. For signal detection, a conventional Everhart–Thornley SE2 detector is used to provide general topographical information while an in-Lens detector is integrated within the electron column allowing to detect low-energy secondary electrons to maximise surface-sensitive, high-resolution topographical contrast.

Elemental composition was analysed using an energy-dispersive X-ray spectroscopy system (Oxford Instruments, United Kingdom) coupled to the main chamber. The EDS detector is equipped with an ultra-thin window, allowing reliable detection of light elements from beryllium onwards (atomic number $Z > 4$), in addition to heavier elements. This allows to measure all elements of interest for NEE.

5.3.1.2. Sample preparation

Particulates emitted from the brakes are captured on a filter by the OBS-ONE PM. In order to make these particles accessible for analysis, they have to be removed from the filter and deposited on pin-stubs. The following protocol was developed to transfer the deposited particles from the filters to pin-stubs.

- A small fraction of the powder material was mechanically recovered directly from the surface of the borosilicate fibre filters. (Note: the possible presence of glass microfibrils from the filter as an artefact must be considered during morphological and compositional inspection).
- The fraction of powder extracted from each sample was suspended in an Eppendorf microtube using analytical-grade methanol as a dispersing agent.
- Using a micropipette, an aliquot of the methanol suspension was extracted and deposited (drop-casting) onto a semiconductor-grade monocrystalline silicon substrate (silicon wafers, 8×8 mm) (high purity and atomically flat surface). The use of Si substrates localises the background signal of the substrate into a single dominant EDS peak at 1.74 keV (Si $K\alpha$), facilitating the identification of the elements in the



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

sample. The expected absence of Si in the sample allows the use of this type of substrate.

The substrates were left to air-dry at ambient temperature and pressure. The necessary time was allowed for the methanol to evaporate completely, mechanically fixing the particles to the silicon substrate via physical adhesion forces without inducing thermal stress.

5.3.1.3. Measurement conditions

The scanning electron microscope was operated at an accelerating voltage of 15.0 kV. This value was selected to ensure efficient excitation of the characteristic K- or L-shell X-ray emission lines of the elements expected in the samples. In accordance with established EDS analysis practice, the accelerating voltage was chosen to be at least 1.5 to 2 times higher than the critical ionisation energy of the heaviest element of interest.

The working distance was set to approximately 8.5 mm, corresponding to the geometrically standardised analytical distance of the instrument where the solid angle of collection of the detector is maximized.

Energy-dispersive X-ray spectroscopy data were acquired in elemental mapping mode. Elemental distribution maps were generated by pixel-by-pixel scanning of the selected regions of interest, allowing assessment of the chemical homogeneity of individual particles and identification of potential phase segregation or compositional inhomogeneities.

5.3.2. Analysis of results

Of all the samples analysed, the most representative ones have been included in this report and are shown in figures Figure 18 to **Fehler! Verweisquelle konnte nicht gefunden werden.** The first two figures display two samples collected on the brake dynamometer. Figures 20 and 21 depict two samples collected on the chassis dynamometer.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

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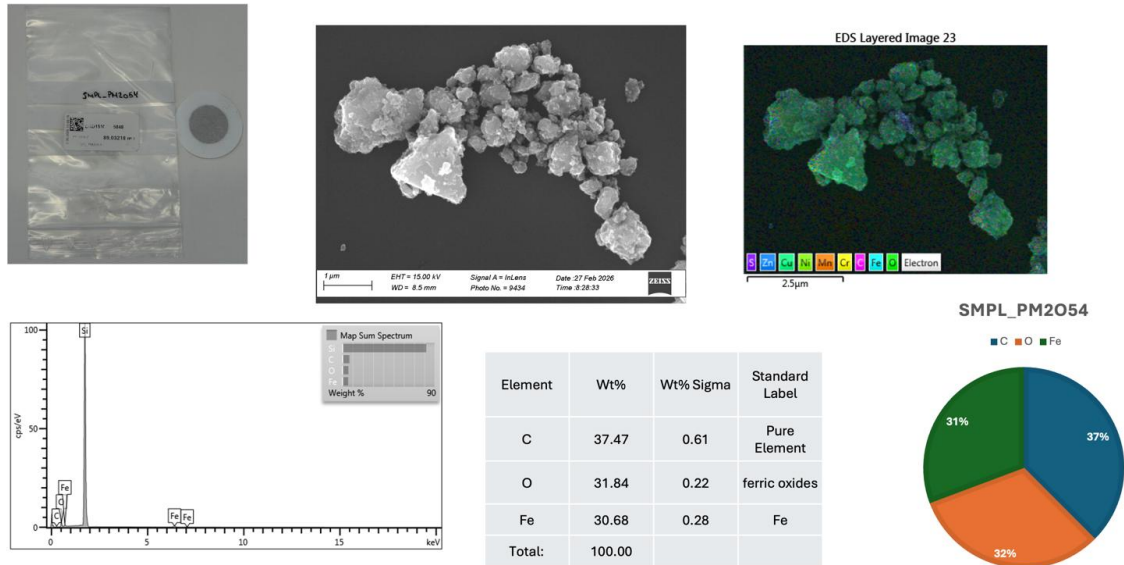


Figure 18: Analysis of brake dynamometer samples using SEM.

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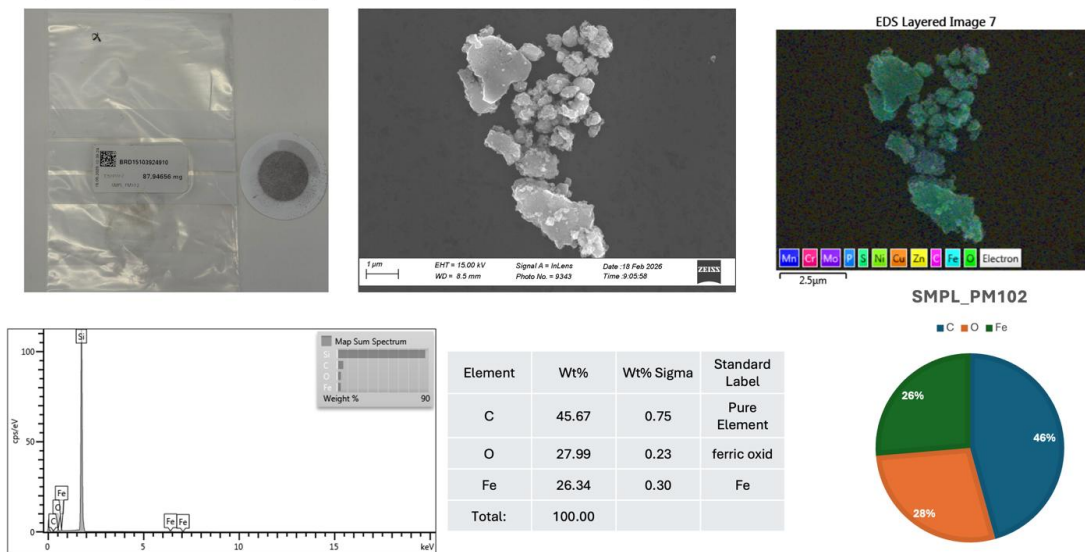


Figure 19: Analysis of brake dynamometer samples using SEM.

SEM micrographs of brake wear showed particles with irregular and jagged edges, typical of abrasion processes, which were found in all samples from both brake pads. Two main types of morphology spherical and flake-shaped particles were frequently observed in all samples. The flake-shaped particles, shown in Figures 18 and 19, were typically larger than 1 µm, while



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

spherical particles were found in various sizes. The flake-shaped particles can be attributed to brake disc wear.

SEM/EDX analysis confirmed that this observation was valid for all size ranges, including that of ultrafine particles. These small particles are of particular concern, as those with a diameter below $2.5\ \mu\text{m}$ can penetrate deep into the lungs, and nanoparticles smaller than 100 nm can enter the bloodstream via the blood-air barrier or through nasal absorption followed by translocation via the olfactory nerve.

EDX measurements revealed Fe content in almost all particles, ranging from 26% to 37%. Two other elements, C and O, were also detected in high concentrations in all particles, with O ranging from 22% to 33%, and C from 28% to 58%. Figures 18 to 21 provide an overview of the morphologies and elemental composition of the particles. The elemental composition of the particles showed wide concentration ranges, and no changes in this distribution were observed across the different sizes analysed.

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Test11_F021

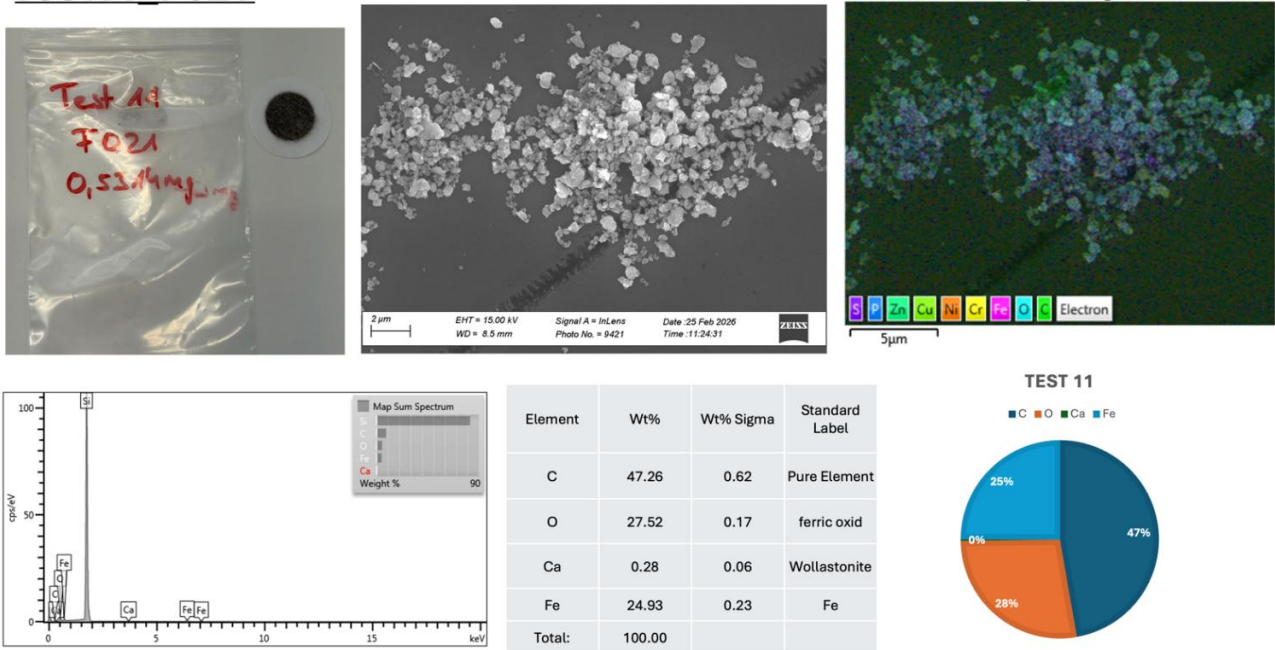


Figure 20 Analysis of sampled particles using SEM. Test shows Trip 10 cycle on chassis

F018

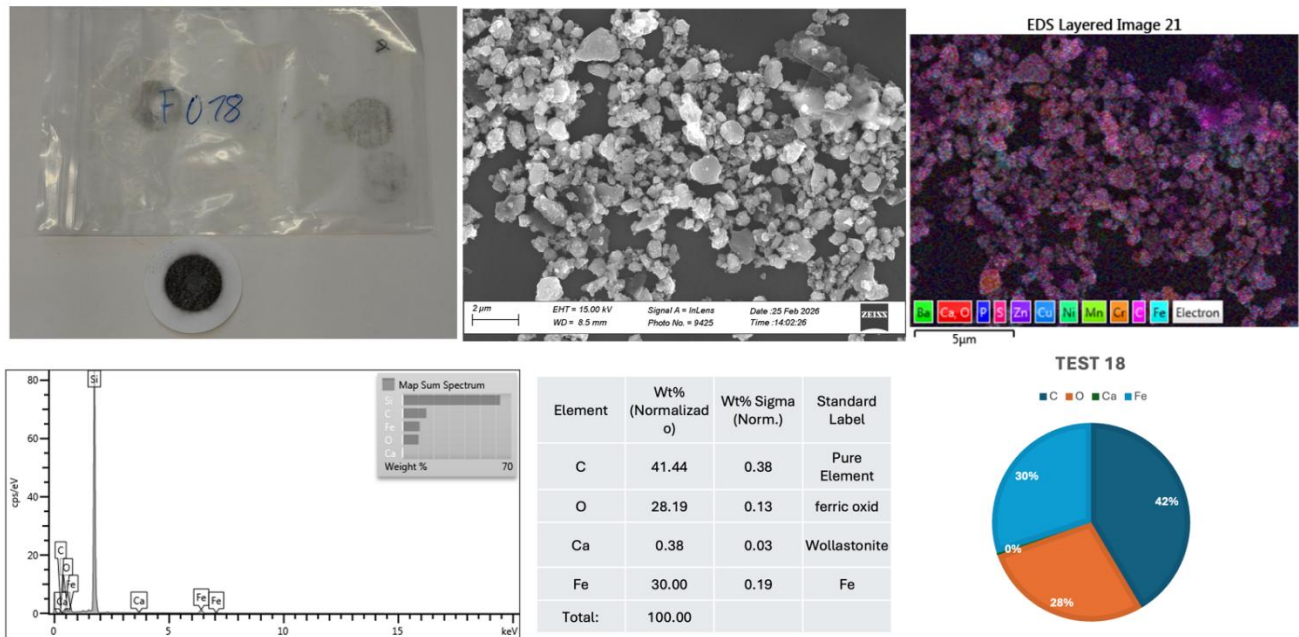


Figure 221 Analysis of sampled particles using SEM. Particles collected on chassis dynamometer during high-temperature braking events (> 300 °C)



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

As can be seen from figures 20 and 21 the C/Fe ratio is similar under both operating conditions (160°C and at temperatures above 300°C). In both cases, the carbon content is higher and is shown in pink on the EDS; O and Fe are present in smaller quantities, and Ca appear in trace concentrations. In these tests, particle sizes range from 250 nm to 2,700 nm.

5.3.3. Characterisation of brake discs and pads

The brake disc and pad materials used in the HORIBA test campaign, together with three particulate filter samples were characterised by X-ray diffraction (XRD) analysis. The objective of this analysis was to compare the crystalline phases present in the original brake components to the ones found in the collected wear debris.

5.3.3.1. Sample Preparation

To ensure representative phase identification and to minimise the influence of preferred crystal orientations, specific preparation protocols were applied depending on the sample type:

- Brake wear materials: Material was obtained by gently scratching the surface of the brake pad (PF) and brake disc (DF) using a diamond tip, generating fine chips suitable for diffraction analysis.
- Filter samples: The filters were analysed as received, without additional preparation, in order to preserve the integrity, morphology, and spatial distribution of the deposited particulate matter.

These preparation protocols were selected to maximise the representativeness of the analysed material while avoiding artefacts related to sample handling or processing.

5.3.3.2. Instrumentation and Measurement Conditions

μ -XRD measurements were carried out using a Bruker D8 Discover diffractometer. Standard Bragg–Brentano geometry was applied for bulk reference samples (pad and disc materials), while Grazing Angle X-Ray Diffraction (GAXRD) was used for the filter samples to enhance surface sensitivity. A 2 mm collimator was employed for all measurements.

The principal measurement parameters were as follows:

- Radiation: Cu K α ($\lambda=1.5406 \text{ \AA}$)
- Power: 50 kV and 1 mA.
- Scan range: 10° to 90° (2 θ) for reference samples and 20° to 60° for filters, due to technical limitations.
- GAXRD conditions: grazing incidence angle fixed at $\omega=1^\circ$ to maximise the signal from the surface layer of dust and minimise the signal from the filter substrate.
- Step parameters: 0.02° with an integration time of 0.2 s per step.

D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

This experimental configuration ensured sufficient phase discrimination for both bulk brake materials and fine particulate deposits collected on filters.

5.3.3.3. Analysis of results

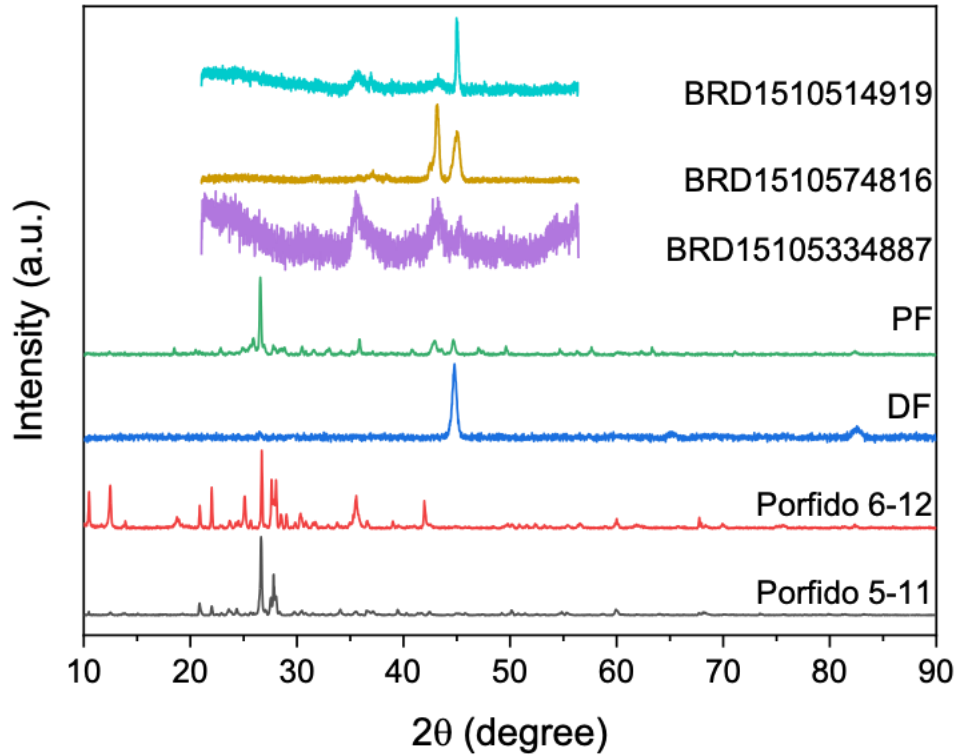


Figure 22 Diffractograms of particles on filter (Codes beginning with BRD), brake pads (PF) and brake discs (DF)

The brake pad material (PF) exhibits a highly complex diffraction pattern. Barite is clearly identified, together with graphite, the latter most likely serving as a solid lubricant within the pad formulation. In addition, the diffractogram shows an elevated background signal, indicating a significant contribution from amorphous phases, which is typical for composite friction materials containing resins and binders.

In contrast, the brake disc material (DF) displays a single-phase diffraction pattern characteristic of high-purity ferrite. The presence of extremely sharp and well-defined diffraction peaks confirms a highly crystalline material with a purely metallic microstructure.

Comparison of the filter samples with the reference materials reveals a complete absence of the diagnostic diffraction peaks associated with silicate minerals (e.g. quartz and albite), which are typical constituents of porphyritic rocks. This observation allows the exclusion of a geological or environmental origin for the collected particulate matter. Instead, the diffractograms of the filter samples are dominated by the ferrite (110) reflection at 44.7° , which coincides precisely with the main diffraction peak observed for the brake disc material.

However, in contrast to the original disc material, the filter samples additionally exhibit broadened secondary diffraction peaks attributable to magnetite. The formation of this iron oxide phase



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

provides direct evidence of thermo-mechanical degradation of the steel during the braking process. The high local temperatures generated by friction promote surface oxidation of iron-rich particles, which are subsequently detached from the disc and deposited onto the filters.

These XRD findings are fully consistent with previously conducted elemental analyses. The high iron content confirms the presence of ferrite and magnetite originating from the brake disc, while the detected carbon fraction is consistent with contributions from graphite and organic pad binder components.



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

6. Evaluation onboard

6.1. Test Specimen (car)

The Mitsubishi Outlander PHEV Motion 4WD, was selected as a representative test vehicle for investigating emissions originating from brake wear and tire-road interaction. This vehicle model provides a technically relevant and analytically valuable platform due to its plug-in hybrid architecture, vehicle mass characteristics, and drivetrain configuration.

As a plug-in hybrid electric vehicle (PHEV), the Outlander combines a conventional internal combustion engine with dual electric traction motors and regenerative braking capability. This configuration introduces a distinct braking behaviour compared to purely combustion-engine vehicles, as a portion of the deceleration energy is recovered electrically rather than dissipated through friction brakes. Consequently, the brake system is subject to reduced but highly variable usage patterns, which allows to influence particle emission profiles in terms of both quantity and particle size distribution by selecting the desired level of recuperation.

In addition, the vehicle's relatively high curb weight of approximately 1,900 kg—largely attributable to the traction battery and dual-motor all-wheel-drive system—results in increased tire load and contact forces at the tire-road interface. This makes the model particularly suitable for studying tire wear particle generation under realistic operating conditions. The presence of an electrically driven rear axle further allows for dynamic torque distribution, which may influence longitudinal and lateral slip characteristics and, consequently, tire abrasion behaviour.

The Outlander PHEV also reflects a widely adopted vehicle category within the European fleet, namely mid-size electrified SUVs and it is representative for the weight of new vehicle registrations in Germany in its class and in the upper middle class. Its inclusion in testing therefore supports the generation of data that is both representative and transferable to a broader class of modern vehicles. Furthermore, the ability to operate in different driving modes—ranging from fully electric to hybrid operation—provides a controlled framework for comparative testing scenarios, enabling the isolation of variables such as braking strategy, drivetrain load, and energy recuperation.

For these reasons, this specific vehicle constitutes a suitable and relevant test platform for the characterization and quantification of non-exhaust particulate emissions from braking systems and tires under contemporary driving conditions. Simultaneous development of the relevant brake enclosure and tire-sampling methods at HORIBA and CIEMAT allows to share and speed up the development work.

The experimental programme will also be extended to include two additional vehicles, namely a Skoda Yeti and a Nissan Leaf, to broaden the test matrix and assess non-exhaust emissions under different vehicle technologies and operating conditions.

The Skoda Yeti was selected as a representative conventional internal combustion engine vehicle. According to the vehicle technical documentation, it is equipped with an Otto engine with a rated power of 77 kW and a five-seat passenger car configuration. As a compact SUV, this



D3.1 Onboard module with the measurement instruments for non-exhaust particle emissions

model provides a relevant platform for investigating tire-road and brake-related emissions under conditions representative of conventional passenger vehicles, with braking demand fully reliant on friction braking and without energy recuperation. Its inclusion in the experimental campaign therefore enables comparison with electrified platforms and supports the assessment of how vehicle architecture and propulsion system may influence non-exhaust particle generation.

The Nissan Leaf, by contrast, was selected as a representative battery electric vehicle. The technical documentation indicates a rated power of 110 kW and a maximum authorised mass of 1995 kg. As a fully electric vehicle, the Leaf incorporates regenerative braking capability, meaning that part of the deceleration energy can be recovered electrically rather than being entirely dissipated through the conventional brake system. This characteristic makes it relevant for the study of non-exhaust emissions, since the altered braking demand may affect both brake wear generation and the overall balance between brake-related and tire-road emissions.

The inclusion of these two additional vehicles is expected to strengthen the comparative dimension of the study by covering both conventional diesel and battery electric propulsion technologies. In this way, the experimental campaign will provide a broader basis for analysing how vehicle type, mass, and braking strategy may influence the generation and characterisation of non-exhaust particulate emissions.

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6.2. Flow Scheme

A modification of the original sampling configuration is planned in order to optimize particle transport and minimize potential deposition losses, as illustrated in Figure 23. Specifically, the initial straight duct section downstream of the sampling nozzle, originally 950 mm in length, will be reduced to approximately 500 mm. This adjustment is intended to shorten particle residence time within the main sampling line while maintaining a high volumetric flow rate to ensure particle capture and stable instrument operation. By reducing the transport distance prior to sub-sampling and impactor collection, particle losses due to gravitational settling, diffusion, and wall impaction are expected to decrease, thereby improving overall sampling efficiency.

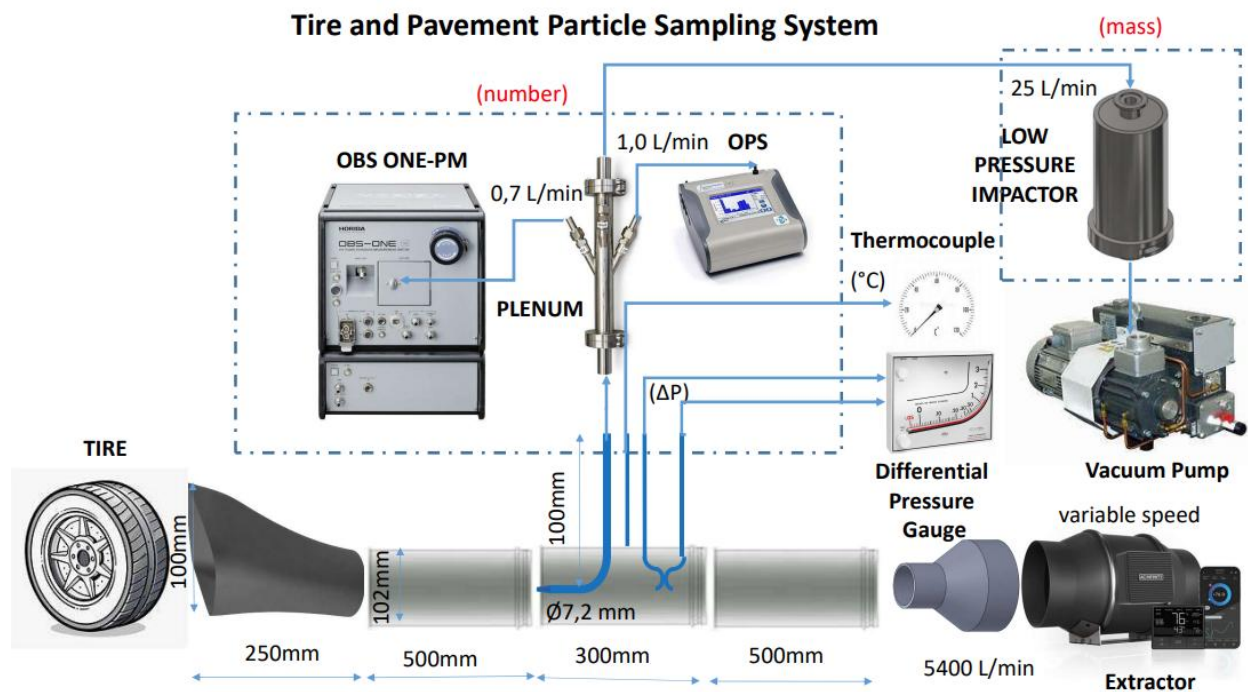


Figure 2323 Modified flow scheme for onboard tire-road emission measurements

For on-road brake emission measurements, the flow scheme largely follows the configuration used for the brake and chassis dynamometer tests. The OBS-ONE modules constitute the core of the measurement setup and provide the primary particle number, mass and volume flow metrics. Depending on the available installation space and permissible payload, additional instruments for size classification and / or size-resolved particle collection may be integrated to extend the characterization of particle properties.



6.3. Energy considerations

A robust energy concept is a prerequisite for on-road brake emission testing because the measurement setup must operate continuously and without interruption for the full duration of the route segment used for evaluation. In contrast to laboratory testing, there is no stable main supply and failure of the power supply compromises the entire test.

The instantaneous electrical power demand (kW) determines cable sizing, fusing, inverter rating and thermal management, whereas the required electrical energy (kWh) determines battery capacity and test duration. As an example, a 90 min on-road measurement window at an average consumption of 4 kW corresponds to ~6 kWh net energy at the load. When sizing an external battery, conversion losses (battery internal losses, DC/DC & DC/AC inverter), auxiliary consumers and degradation margin must be considered; therefore, the required battery capacity is typically higher than the net load energy. As a rule of thumb, assuming an overall efficiency of 80–90%, 6 kWh at the load translates to roughly 6.7–7.5 kWh drawn from the battery.

Many components exhibit a difference between steady-state and peak power. Fans/blowers and pumps draw elevated inrush current at start-up; analysers may show short peaks during heater warm-up, internal pump ramps, or automatic zeroing cycles. The power supply should therefore be dimensioned for both, continuous load (thermal rating) and also short-duration peaks (dynamic rating). Practically, this means the inverter and DC distribution should be specified with sufficient headroom above the arithmetic sum of nominal powers, and start-up sequencing should be defined to avoid simultaneous inrush events.

Two principal approaches can be considered for providing the required energy on the road: power from the test vehicle electrical system, or an independent auxiliary battery system. Using vehicle power can be attractive for hybrids and battery electric vehicles, but it requires safe and approved access to the high voltage or the 12 V networks, may interfere with vehicle energy management, and may introduce test-to-test variability if the vehicle state of charge changes. An independent auxiliary battery system provides a reproducible and vehicle-independent solution, but adds considerable mass and requires dedicated packaging, crash-safe mounting, and a suitable inverter/charger. The method of choice will be evaluated for the three test cars individually.

Portable measurement instruments and the laptops required for their operation are often supplied via 230 VAC (or universal 100–240 VAC) adapters and are sensitive to undervoltage, frequency deviations, and electrical noise. The use of an inverter therefore requires attention to output waveform quality, grounding concept, and electromagnetic compatibility. In addition to protecting the equipment, stable supply conditions reduce the risk of dropouts and hidden drift mechanisms (e.g., temperature control instability, pump speed variation) that could bias concentration measurements. Where possible, a single, centrally monitored distribution (main DC bus, inverter, protected AC outlets, and clear separation of high-current blower circuits from sensitive instrument supplies) supports both safety and data quality.

Electrical power consumed onboard is ultimately converted to heat either within the equipment (electronics, heaters, pumps) or in the airflow generation system (blower, compression losses). At several kW, the thermal load can become significant in the vehicle interior and may impact instrument operating temperatures, filter conditioning stability, and operator comfort. Adequate



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ventilation and defined air paths are therefore required, and hot components (inverter, battery, blower motor) should be placed and shielded such that they do not heat sensitive sampling lines or instruments. Thermal management of the sampling airflow is also part of the energy concept because cooling approaches (e.g., heat exchanger, active cooling) may add additional electrical demand or weight.

Since the blower dominates the power budget in our current configurations, the largest reduction potential lies in alternative means for airflow generation and flow control. Options include (i) reducing the required volumetric flow rate while maintaining representativity (validated by particle transport efficiency and brake temperature control), (ii) using larger duct diameters and minimizing pressure losses to decrease blower work, (iii) implementing closed-loop control to avoid excessive flow during phases where it is not needed, and (iv) replacing the blower with alternative air movers that provide sufficient flow at lower electrical power, provided that flow stability and pressure capability are adequate.

The energy concept of the NEE measurement system differs significantly from that of the exhaust-emission setup. In the present NEE configurations, the dominant electrical demand arises from airflow generation, since particle capture requires a high-flow extraction line downstream of the tire–road interface or the brake components.

The OPS 3330 has a low power demand, which makes it suitable for both laboratory and field measurements. The instrument is powered through an AC adaptor rated at 100–240 VAC, 50/60 Hz, with a power consumption of 15 W. In addition, it can operate with hot-swappable battery packs, providing up to 10 hours of runtime with one battery and up to 20 hours with two batteries. This energy requirement, together with its portable design, facilitates extended measurement campaigns without the need for continuous connection to the mains supply.

By contrast, the impactor itself does not require electrical power, as it is a passive sampling device. However, its operation relies on an external vacuum pump to generate the required airflow and pressure conditions. In the present setup, a Hauke VCA 60 vacuum pump is used, providing the necessary suction capacity to ensure proper particle size separation across the impactor stages.

The pump has a rated power of approximately 1.5 kW and operates with a three-phase power supply at 50 Hz. This configuration is well suited for laboratory and chassis dynamometer measurements, where stable power supply and space are available. Nevertheless, alternative vacuum pumps could be considered to improve portability and energy efficiency, if they meet the minimum operational requirements of the impactor, namely a final vacuum of approximately 40 mbar and a flow capacity of around 35–36 m³/h.

In addition to the vacuum pump required for the impactor, a vacuum cleaner is used during laboratory tests to support particle extraction and handling. Conventional laboratory vacuum cleaners require a high-power input and depend on a continuous connection to the mains supply, which limits their applicability in mobile or onboard measurements. Their size and power requirements can therefore become a constraint when aiming to replicate laboratory conditions under real driving scenarios. For this reason, ongoing efforts are focused on identifying more compact and energy-efficient alternatives that can operate using battery power. Such solutions

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would significantly improve the portability of the system and enable true onboard deployment, while maintaining sufficient suction performance for reliable sampling.

Table 2 lists the devices that have been used for tire-pavement emission measurements on the chassis dynamometer and summarizes their individual weight and nominal power consumption.

Table 2 Devices used for tire-pavement emission measurements on the chassis dynamometer

Component	Purpose	Nominal power consumption (kW)	Weight (kg)
Vacuum cleaner (Nilfisk GM 83)	Generate main sampling flow (~5400 L/min)	2.6	15
Hauke VCA 60 vacuum pump (impactor)	Provide flow for impactor (~25 L/min)	1.5	20
OPS 3330	Optical particle sizing	0.015	2
OBS-ONE PN	Particle number measurement	0.35	18
Low-pressure impactor	Size-segregated particle collection	-	8
Sensors (T, ΔP, flow)	Monitoring and control	0.01	2
Tire-pavement system	Measure particles	-	5
DAQ / Laptop	Data acquisition and control	0.1	3
Battery x2	Energy supply (≈1–2 h operation)	-	90
Inverter & auxiliaries	Power conversion and distribution	-	19
Sum		4.58	~182

Table 3 lists the devices that have been successfully used for brake emission measurements on the brake and on the chassis dynamometer and summarizes their individual weight and nominal power consumption.

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Table 3 Devices used for brake emission testing on brake and chassis dynamometer

Component	Purpose	Nominal power consumption (kW)	Weight (kg)
Blower	Provide cooling air flow	2.2	25
OBS-ONE PN	PN counter	0.35	18
OBS-ONE PM	PM weighting	0.6	45
OBS-ONE auxiliary units	Control, DAQ, Power	0.2	20
EEPS	Size distribution scans	0.25	32
Pitot tube & Box	Flow measurement	0.1	12
Tubes, housing, fixation	Encapsulate brake	-	40
Battery	For 1 hour operation		50
Inverter & auxiliaries			15
Sum		3.7	273

6.4. Weight and size considerations

The Mitsubishi Outlander has a maximum permissible vehicle mass of 2,390 kg, corresponding to a nominal payload capacity of 425 kg. After installation of the complete onboard measurement equipment, a remaining payload of approximately 152 kg is available. This residual payload is sufficient to accommodate a co-driver during on-road testing, whose role is to continuously monitor critical operating parameters such as temperatures, volumetric flow rates, and system pressures, thereby ensuring safe and reliable operation of the measurement setup.

A limitation of this configuration is that the remaining payload margin does not allow systematic investigation of vehicle mass effects on brake or tire particle emissions through ballast variation. Assessing the influence of vehicle weight on non-exhaust emissions therefore requires the use of alternative vehicle platforms with different curb weights and payload capacities.

In addition to mass constraints, the physical size and packaging volume of the measurement equipment play a critical role in on-road testing. The deployed instruments were originally designed for exhaust emission measurements and therefore do not inherently integrate auxiliary components such as dedicated cooling airflow systems. With a usable cargo volume of approximately 1,590 L when the rear seats are removed, the Mitsubishi Outlander provides sufficient space to accommodate the complete instrumentation suite, power supply components, and the sampling tunnel within the vehicle interior. Integration into smaller vehicle classes will be



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considerably more challenging due to reduced available volume and tighter packaging constraints and may require alternative system layouts.

6.5. Road safety requirements

6.5.1. Germany

An *Ausnahmegenehmigung* (i.e. an exemption) pursuant to §70 of the German *Straßenverkehrs-Zulassungs-Ordnung* (StVZO, i.e. Road Traffic Licensing Regulations) provides a legal mechanism for permitting deviations from otherwise mandatory technical and operational vehicle requirements in Germany. This provision is particularly relevant for companies, engaged in research and development, that need to test modified or prototype vehicles on public roads even though those vehicles do not fully comply with existing regulations. The granting of such an exception is at the discretion of the competent authority and is subject to strict evaluation criteria, with the primary objective being the preservation of road safety and regulatory integrity.

To obtain an *Ausnahmegenehmigung*, the applicant must submit a comprehensive and well-structured application that clearly explains both the technical nature of the vehicle and the rationale for the requested deviation. The application begins with a detailed description of the base vehicle, including its make, model, and vehicle identification number, followed by a precise account of all modifications that have been carried out. It is essential to explicitly identify which provisions of the StVZO the vehicle no longer complies with and for which an exemption is being requested. This level of specificity ensures that the authority can accurately assess the scope and implications of the deviation. For brake and tire-road emission measurements exemptions from several paragraphs will be required:

- §30 protruding outer edges, front protection systems
- §64 brakes

A central component of the application is the technical justification for the modification. The applicant must explain why compliance with the standard regulatory requirements is not feasible or would significantly hinder the intended development or testing objective. This justification typically includes an engineering-based explanation of the design choices, the innovative aspects of the modification, and the purpose of the testing activity. In cases involving emerging technologies or experimental systems, it is particularly important to demonstrate that the deviation is necessary to advance technical understanding or product development.

Equally important is the requirement to provide a thorough safety assessment. The applicant must demonstrate that, despite the deviation from standard requirements, the vehicle does not pose an unacceptable risk to road users or the environment. This involves conducting a structured risk analysis, identifying potential hazards, and describing the mitigation measures that have been implemented. Such measures may include redundant systems, fail-safe mechanisms, or operational limitations designed to reduce risk exposure. In many cases, applicants align their safety assessments with established engineering standards, such as functional safety methodologies used in the automotive industry, to provide a credible and systematic evaluation.



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In practice, HE will involve an independent technical service to support the application. Organizations such as TÜV or DEKRA are typically engaged to produce an expert report assessing the roadworthiness of the modified vehicle and the implications of the regulatory deviations. This report provides an objective evaluation of the vehicle's condition and may include recommendations for operational restrictions or additional safeguards. The authority relies heavily on such expert opinions when making its decision.

Another key aspect of the application is the definition of the operational framework under which the vehicle will be used. The applicant must clearly specify how, where, and under what conditions the vehicle will be operated. This may include geographic limitations to certain test routes, time restrictions such as operation only during daylight hours, and requirements regarding the qualification and training of the test drivers. By defining these parameters, the applicant demonstrates that the use of the vehicle will be controlled and that potential risks are being actively managed.

Once the application has been submitted, the competent authority evaluates it based on several criteria, including the impact on public safety, environmental considerations, and the necessity and proportionality of the requested exemption. The authority must be satisfied that the deviation is justified by the intended purpose and that adequate control measures are in place to ensure safe operation. The review process may involve requests for additional information or clarification, and in some cases, consultation with technical experts or other regulatory bodies.

If the *Ausnahmegenehmigung* is granted, it is typically subject to specific conditions and limitations. These permits are usually time-limited and restricted to the defined purpose outlined in the application. The authority may impose conditions such as mandatory documentation of test activities, reporting obligations, or requirements to carry the permit in the vehicle at all times. In addition, the vehicle may need to be clearly identified as a test vehicle. Failure to comply with these conditions can result in the revocation of the permit.

It is important to note that an *Ausnahmegenehmigung* under §70 StVZO does not automatically replace other regulatory requirements. Depending on the nature of the project, additional approvals will still be necessary, such as vehicle registration, insurance coverage, or compliance with European type-approval frameworks. Therefore, the exemption can only be understood as one component within a broader regulatory context.

6.5.2. Spain

In Spain, a legal mechanism comparable to the German *Ausnahmegenehmigung* exists through exceptional authorizations and special permits granted by the competent authorities under the framework of the *Reglamento General de Vehículos* and related national and European regulations. These authorizations allow deviations from standard vehicle requirements, particularly in the context of research, development, and testing of modified or prototype vehicles on public roads.

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Such permits are typically issued by the Dirección General de Tráfico (DGT) in coordination with the Ministry of Industry, Trade and Tourism, depending on the nature of the vehicle and the type of deviation requested. As in Germany, these authorizations are discretionary and subject to evaluation, with road safety and environmental protection as primary considerations.

To obtain an authorization, the applicant must submit a detailed and structured application dossier. This includes a full description of the base vehicle (make, model, VIN), along with a comprehensive explanation of all modifications performed. The applicant must identify which provisions of the applicable regulations (such as the Reglamento General de Vehículos or EU type-approval requirements) are not met and for which an exemption is requested. For example, deviations may concern braking systems, external projections, or emissions-related requirements.

A key element of the application is the technical justification. This justification the objectives of the testing program. Another important component is the definition of the operational framework. The applicant must specify the conditions under which the vehicle will be used, including geographic areas (e.g., specific test routes), time restrictions (such as daylight operation), and driver requirements (e.g., trained test personnel). These conditions demonstrate that the testing activity will be controlled and that risks are being managed.

Once submitted, the application is assessed by the competent authority based on criteria such as road safety impact, environmental considerations, and the necessity and proportionality of the exemption. The authority may request additional information or clarifications and may consult technical experts during the evaluation process.

If the authorization is granted, it is usually subject to specific conditions and limitations. These permits are typically time-bound and restricted to the defined testing purpose. Conditions may include reporting obligations, documentation of test activities, or requirements to carry the authorization on board the vehicle. The vehicle may also need to be identified as a test or prototype vehicle, for instance through the use of a V-12 registration plate, which is designated in Spain for testing or research vehicle (see figure 24). Non-compliance with these conditions may lead to revocation of the permit.



Figure 24 Spanish registration plate

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It is important to note that such authorizations do not replace other regulatory obligations. Depending on the project, additional requirements may apply, including vehicle registration, insurance, and compliance with applicable EU type-approval legislation. Therefore, the authorization should be understood as part of a broader regulatory framework governing vehicle operation in Spain.

6.5.3. Failure Mode and Effects Analysis

In this section, Tables 4 and 5 summarize the risks identified for the TRWP and brake-emission measurement systems, respectively. Potential failure modes are grouped by component. The parameters S, O, and D denote Severity, Occurrence, and Detection, each rated on a 1–10 scale (10 = highest severity, highest likelihood of occurrence, and lowest likelihood of detection). The Risk Priority Number (RPN) is calculated as $RPN = S \times O \times D$.”

Table 4 FMEA for on road TRWP measurements

Sub-system	Failure Mode	Effect	Cause	S	O	D	RPN	Mitigation
Sampling cone	Misalignment to tire	Loss of particle capture accuracy	Mechanical vibration, improper mounting	7	5	4	140	Rigid mount, alignment fixture
Sampling cone	Detachment during driving	Road hazard, damage to car	Fastener Failure, fatigue, obstacle on road	10	2	3	60	Redundant fixation, safety tether, trained driver
Sampling cone	Blockage (debris, water)	Reduced/biased sampling	Road debris, wet conditions	6	6	5	180	Dry conditions, trained driver, convoy testing
Ducting	Leakage	Loss of sample integrity	Poor sealing, aging hoses	7	5	5	175	Pressure monitoring, leak test
Ducting	Particle deposition in tubing	Underestimation of mass/number	Electrostatic effects, bends	8	6	6	288	Conductive tubing, minimize bends
Pump	Flow rate deviation	Invalid measurement results	Pump wear, voltage fluctuation	9	5	4	180	Flow sensor + closed-loop control
Pump	Complete failure	No sampling	Mechanical/electrical failure	8	3	3	72	Redundant pump or alarm
Pump	Overheating	Fire risk, system shutdown	Continuous high load	10	2	4	80	Thermal cutoff, ventilation
Measurement instruments	Calibration drift	Systematic measurement error	Aging sensors, contamination	9	3	1	27	Regular calibration schedule
Electrical system	Power loss	Total system failure	Wiring faults, battery load	8	4	3	96	Independent power supply
Installation in vehicle	Poor ventilation	Heat buildup, instrument damage	Enclosed space	7	4	5	140	Forced ventilation
Vehicle safety	Obstruction of wheel movement	Accident risk	Incorrect installation or clearance	10	3	3	90	Position and clearance validation
Vehicle safety	Altered aerodynamics	Instability at speed	External geometry change	9	3	6	162	Trained driver, road testing
Data acquisition	Data loss	Incomplete test results	Storage failure, software crash	6	5	4	120	Four eyes principle, continuous

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									monitoring by co-driver
Main extractor (vacuum cleaner)	Insufficient suction capacity	Reduced particle capture efficiency, biased emissions results	Motor degradation, partial blockage, battery voltage drop	9	4	4	144		Flow verification before test, suction monitoring, maintenance schedule
Main extractor	Complete failure during driving	Loss of sampling, invalid test, possible overheating of system components	Electrical fault, inverter trip, motor failure	8	3	3	72		Alarm, redundant shutdown logic, pre-test functional check
Battery / inverter system	State of charge lower than expected	Premature end of test, incomplete dataset	Insufficient charging, battery aging, underestimation of power demand	7	5	4	140		Pre-test SOC verification, conservative autonomy margin, spare battery strategy
Battery / inverter system	Inverter overheating or shutdown	Loss of power to instruments and sampling devices	Continuous high load, poor ventilation, oversizing error	8	3	4	96		Forced ventilation, thermal monitoring, inverter derating margin
Impactor line	Flow below nominal 25 L/min	Incorrect size-segregated sampling, invalid mass distribution	Pump instability, leak, stage loading, tubing restriction	8	4	5	160		Flow calibration before and after run, pressure monitoring
OPS / PN instrument	Synchronization or logging failure	Loss of time correlation between emissions and vehicle operation	Software crash, communication failure, DAQ error	6	4	4	96		Time synchronization check, mirrored logging, operator monitoring
Sampling inlet near tire	Contact with debris or splash water	Sampling bias, blockage, possible mechanical damage	Road debris, wet pavement, insufficient clearance	7	5	5	175		Dry-weather testing, clearance validation, protective geometry

Table 5 FMEA for on road brake emission measurements

Sub-system	Failure Mode	Effect	Possible Causes	S	O	D	RPN	Mitigation
Brake housing	Structural failure or detachment	Interference with wheel, loss of braking performance, accident risk	Fatigue from vibration, insufficient structural design, poor fastening, corrosion	10	2	3	60	Robust mechanical design, fatigue validation, secure mounting, testing on chassis dyno
Brake housing	Insufficient cooling airflow	Brake overheating, brake fade, reduced braking efficiency	Pump degradation, blocked inlet/outlet, leaks, incorrect design flow rate	10	4	2	80	Airflow monitoring, temperature sensors
Airflow system (pump)	Pump failure (no airflow)	Brake overheating + loss of emission sampling	Electrical failure, motor burnout,	10	3	2	60	Airflow, pressure and temperature monitoring

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			bearing failure, wiring defect					
Airflow system	Flow rate deviation	Altered brake temperature and biased particle measurement	Voltage fluctuation, partial blockage, pump wear, control instability	9	5	2	90	Airflow, pressure and temperature monitoring
Housing-brake interaction	Thermal accumulation in housing	Accelerated brake wear, material degradation, safety risk	Poor thermal design, insufficient ventilation, high braking load	9	4	5	180	Temperature monitoring, chassis dyno testing, heat-resistant materials
Tube (transport line)	Leakage	Particle loss, exposure inside vehicle, incorrect measurements	Loose connections, seal degradation, vibration-induced cracks	7	5	5	175	Leak testing, sealed connections, pressure monitoring
Tube (transport line)	Particle deposition	Underestimation of particle mass and number	Electrostatic effects, low flow velocity, bends, rough inner surfaces	8	6	6	288	Conductive tubing, minimize bends, maintain flow velocity
Tube (transport line)	Blockage	Increased backpressure, reduced cooling, measurement failure	Particle accumulation, moisture condensation, foreign objects	8	4	5	160	Pressure monitoring, periodic cleaning
Measurement system	Calibration drift	Systematic measurement error	Contamination, temperature variation	9	5	3	135	Regular calibration, reference checks
Electrical system	Power failure	Loss of cooling and measurement	Battery overload, wiring faults, connector failure	9	4	3	108	Independent power supply, voltage monitoring
Electrical system	Short circuit	Fire hazard inside vehicle	Insulation damage, improper routing, moisture ingress	10	3	4	120	Fuses, proper wiring
Vehicle integration	Interference with suspension/steering	Loss of vehicle control	Incorrect installation, insufficient clearance, dynamic movement not considered	10	2	3	60	Clearance validation, chassis dyno testing
Vehicle integration	Altered brake behaviour	Unpredictable braking performance	Heat buildup, airflow disturbance, uneven cooling	10	3	5	150	Temperature monitoring, Chassis dyno testing
System (overall)	Particle leakage into cabin	Health risk to occupants	Leaks in tubing, poor sealing, system overpressure	7	4	5	140	Sealed system, filtration, cabin isolation



7. Conclusion

7.1. Tire-Pavement Measurement System

The tire–pavement measurement system developed in this work provides a robust experimental platform for the controlled generation, collection, and characterization of tire–road wear particles under laboratory conditions. Combining a mechanically regulated loading system with a high-flow sampling line ensures reproducible tire–pavement interaction, efficient particle transport, and simultaneous measurement of particle count, size distribution, and mass.

The integration of real-time instruments such as OPS and OBS-ONE PN10 with size-segregated sampling via a low-pressure impactor enables comprehensive analysis across a wide range of particle sizes. Moreover, the downstream collection filter allows for sufficient particle mass accumulation for advanced physicochemical and toxicological studies by project partners, thereby broadening the analytical scope beyond online measurements.

Operationally, the system demonstrates strong repeatability, supported by a structured sample identification scheme and a clearly defined testing protocol covering background measurements, controlled loading conditions, and replicated experiments. These features are key to ensuring data comparability and reliability across different campaigns and research teams.

Currently, the system is optimized for laboratory and chassis dynamometer applications. Its energy demand is primarily driven by the high-flow extraction necessary at the tire–road interface, with the industrial vacuum cleaner and impactor pump being the main sources of power consumption. Given the available battery capacity, this results in limited autonomous operation time, posing a constraint for fully independent on-road use. Future developments should focus on reducing airflow-related energy needs, minimizing pressure losses in the sampling line, and exploring more efficient suction technologies. Additionally, optimizing the sampling inlet and transport line geometry will be crucial to minimize particle losses and enhance measurement representativity under real driving conditions.

Overall, the current setup forms a solid methodological foundation for the investigation of tire–pavement emissions, offering valuable insights into particle generation mechanisms and size distributions under controlled circumstances. It also identifies the primary technical challenges that need to be addressed for reliable and practical onboard measurements in subsequent project phases.

7.2. Brake Emission Measurement System

For brake emission measurements, the approach featured here demonstrates that a transferable brake enclosure with a downstream sampling tunnel is a practical solution for comparative studies beyond the laboratory. The housing is designed to be used both on a brake dynamometer and on a vehicle, thus bridging the methodological gap between the GTR 24-compliant reference setup and the intended on-road application. Measurements performed across the reference setup, the movable housing on the brake dynamometer, and the chassis dynamometer confirm that the



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sampling concept is capable of capturing real braking dynamics without persistent hang-up effects leading to continuous contamination signals.

Repeatability results, both in laboratory and on test stands, show that the system operates stable and is well suited for comparative studies. Despite differences in absolute emission levels between configurations, the main particle count instruments report similar coefficients of variation, underscoring system reliability under controlled conditions. The data further highlight that enclosure design and operational parameters remain critical for quantitative comparisons to regulatory references. Specifically, differences in brake temperature management, cooling airflow, and the residence time between particle generation and sampling point can influence measured concentrations and peak shapes. Elevated backgrounds observed in certain modes suggest that under-pressure or leakage effects can introduce external contamination, which should be addressed through improved sealing, pressure management, and diagnostic monitoring during testing.

A key finding is the strong agreement between onboard instruments and laboratory reference counters, even under highly dynamic braking conditions. The correlation between OBS-ONE PN10 and GTR 24-compliant reference counters for solid and total particle number (SPCS) was excellent ($r^2 > 0.98$), confirming that onboard instruments can reliably track rapid emission peaks and are suitable for future real-world brake emission measurements. However, a linear offset between devices points to factors such as volatile particle removal efficiency, device history, and calibration procedures affecting results. Controlled calibration with representative solid and volatile aerosols is essential before absolute on-road emission levels can be interpreted with confidence.

In summary, laboratory and test stand results demonstrate that the onboard module is technically ready for initial on-the-road tests. The main challenges—particularly mechanical integration on the vehicle and energy demand for cooling and sampling—are currently being addressed. For instance, 3D scans of the vehicle suspension are conducted prior to enclosure design to ensure precise integration. Moreover, the cooling and flow concepts, as well as pressure regulation mechanisms, are optimized to minimize contamination risks and enhance instrument comparability.

With these preparations, the conditions are met to begin the first phase of real-world testing with the onboard module and gather practical experience under real driving conditions. Insights gained from these initial on-the-road tests will further support system optimization and lay the groundwork for reliable brake emission measurements in real-world applications.

7.3. Chemical analysis

EDX measurements revealed Fe content in almost all particles, ranging from 26% to 37%. Two other elements, C and O, were also detected in high concentrations in all particles, with O ranging from 22% to 33%, and C from 28% to 58%.

SEM micrographs of brake wear showed particles with irregular, jagged edges, typical of abrasion processes. Two main types of morphology were frequently observed in all samples: spherical and flake-shaped particles. The flake-shaped particles were usually larger than 1 μm , whilst the spherical particles were found in a different size range.



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Iron (Fe) was identified as the dominant component of brake wear emissions, reflecting its high abundance in brake disc materials. This finding is consistent with previous studies reported in the literature [5].

Comparison of the elemental analysis of the filter samples to the brake pads and discs further confirms the origin of the collected material. The high iron content of the brake disc supports the presence of ferrite and magnetite phases, while the detected carbon is consistent with contributions from graphite and organic binder materials present in the brake pads.

Overall, the combined morphological and compositional evidence indicates that the applied sampling methodology for isolating and collecting non-exhaust brake wear particles is robust and reliable, effectively capturing particles generated by the braking process rather than external or exhaust-related sources.

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