re-breath | Reduction of brake wear emissions in the transport sector

Project: [101074269] — [REBREATH] — [LIFE-2021-SAP-ENV-ENVIRONMENT]

REduction of Brake weaR Emissions in the Transport sector "RE-BREATH"

Deliverable 5.4 Guidelines

Call	LIFE-2021-SAP-ENV-ENVIRONMENT
Related Work Package	WP5
Deliverable No.	Deliverable 5.4 Guidelines
Dissemination level	Public
Deliverable type	Report
Lead Beneficiary	CNR
Authors	Mattia Perilli, Cristina Leonardi, Marco Torre, Ettore Guerriero, Francesca Battistelli, Valerio Paolini
Due date	31/07/2025
Submission date	29/07/2025

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Executive summary

Urban air quality has significantly improved over the past decades due to stricter regulation of tailpipe emissions. However, non-exhaust emissions (NEEs), particularly those from brake wear, remain an under-regulated and persistent source of urban particulate matter (PM10 and PM2.5), with growing implications for public health and environmental quality. The LIFE REBREATH project addresses this regulatory and technological gap by providing science-based guidelines for the measurement, reduction, and regulation of brake wear emissions.

This deliverable synthesizes the project's findings into comprehensive guidelines structured across regulatory analysis, technical methodologies, and implementation pathways. The project employed a multi-work package strategy, combining laboratory-based testing, in-situ monitoring, chemical characterization, and exposure modelling. Friction materials were reformulated to reduce particulate emissions, and their performance was tested under real-world and simulated driving conditions. The project introduced a method to scale HDV brake systems to LDV dynamometer settings and confirmed its validity with later-stage testing on HDV benches.

The guidelines include: best practices for eco-design of friction materials, especially for electric vehicles and heavy-duty vehicles (HDVs); standards aligned with the forthcoming Euro 7 regulations and UNECE-led test procedures; and protocols for monitoring NEEs using chemical and morphological analyses. In parallel, the document outlines a policy roadmap, calling for the integration of brake emissions in EU vehicle regulations, updated green procurement criteria, and harmonized monitoring methodologies.

Implementation recommendations target both industry and public authorities. For industry, the adoption of low-emission technologies and adherence to new performance and monitoring protocols are critical. For public authorities, incorporating brake emissions into urban air quality plans, updating emission factors, and raising public awareness are essential for achieving compliance with the revised Ambient Air Quality Directive (EU) 2024/2881.

Through these guidelines, the LIFE REBREATH project provides a robust evidence base and a practical roadmap for integrating non-exhaust emissions into environmental governance. These guidelines serve as a foundational step for bridging regulatory, technical, and operational gaps, enabling a healthier, cleaner, and more sustainable urban mobility system.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Table of contents

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

1 Introduction

Urban air quality policies have traditionally focused on controlling tailpipe emissions from vehicles. As a result of decades of progressively stricter regulations on engine efficiency, fuel quality, and vehicle emission control technologies, exhaust emissions have markedly decreased in many European cities. However, this regulatory success has exposed a growing proportion of airborne particulate matter (PM) originating from non-exhaust sources — a class of emissions that includes brake wear, tire wear, road surface abrasion, and resuspension of road dust.

Among these, brake wear emissions are a particularly persistent and under-regulated source of PM10 and PM2.5 in urban environments. During braking, friction between the brake disc and pad leads to the generation of fine particulate matter containing heavy metals and other compounds. These particles are typically emitted at ground level in areas of high pedestrian exposure, such as bus stops, intersections, and dense traffic zones. Their composition often includes copper, zinc, iron, manganese, and other trace elements known for their potential toxicity.

Growing epidemiological evidence has linked exposure to non-exhaust emissions with a range of adverse health outcomes, including respiratory inflammation, cardiovascular stress, and neurodevelopmental effects. The issue is especially pronounced in the urban microenvironments where vulnerable groups — including children, the elderly, and individuals with pre-existing conditions — are more likely to be exposed.

While electric vehicles (EVs) are expected to dramatically reduce tailpipe emissions, they do not eliminate the problem of non-exhaust emissions. In fact, some EVs may exacerbate it due to heavier weight and higher torque, leading to increased brake and tire wear if not mitigated by advanced regenerative braking or system optimization. Consequently, urban transport decarbonization strategies must be complemented by a coherent framework for addressing non-exhaust sources of pollution.

Despite its relevance, the policy landscape surrounding non-exhaust emissions remains fragmented. There is currently no dedicated EU-wide regulatory framework directly targeting brake or tire wear. Most air quality directives (e.g., Directive 2008/50/EC) set ambient concentration limits for PM10 and PM2.5, but do not specify source-based emission standards. As such, non-exhaust emissions are indirectly addressed through urban air quality management, rather than targeted vehicle design or fleet operation standards. Moreover, technical harmonization of measurement protocols for brake wear emissions is still evolving, leading to difficulties in comparison, compliance, and enforcement across regions.

This regulatory and technical gap calls for specific, science-based guidelines that can support both policy formulation and industrial innovation. The formulation of coherent guidelines can help bridge the gap between scientific research, technological development, and effective air quality governance. Such guidelines should articulate technical specifications for emission-reducing technologies, measurement and monitoring protocols, performance benchmarks and environmental thresholds, and implementation pathways for transport operators and local authorities. This deliverable aims to respond to this need by building on empirical research and demonstration activities carried out under the LIFE RE-BREATH project, while also considering broader EU policy developments and regulatory priorities.

2 Policy and Regulatory Framework

2.1 Overview of Current Regulations and Identified Gaps

The issue of non-exhaust emissions (NEEs) occupies a challenging and often ambiguous space in current air quality regulation. While scientific evidence on the health impacts and environmental significance of NEEs has grown, regulatory frameworks remain predominantly tailored to exhaust emissions. As a result, NEEs — particularly those from brake and tire wear — fall into a regulatory blind spot across most jurisdictions.

At the European level, the primary legislative instrument governing ambient air quality is Directive 2008/50/EC on ambient air quality and cleaner air for Europe. This directive establishes limit values for pollutants such as PM10, PM2.5, NO_2, and ozone, to be enforced by national and local authorities through air quality plans. However, the directive does not distinguish between exhaust and non-exhaust sources in its monitoring or target-setting procedures. Consequently, while exceedances of PM10 may be registered in cities with heavy traffic, there is little to no regulatory basis for attributing that pollution to specific vehicular components like brake systems.

Another relevant legal framework is the EU Regulation 2019/631, which defines CO_2 emission performance standards for new passenger cars and vans. While this regulation has successfully driven improvements in fuel efficiency and electrification, it does not account for non-exhaust emissions, which can remain high or even increase in EVs due to regenerative braking limitations, vehicle mass, and usage patterns.

Similarly, the Euro vehicle emission standards, which have progressively tightened over the past decades (from Euro 1 to the proposed Euro 7), continue to focus exclusively on tailpipe emissions. However, the Euro 7 regulation, approved and in

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

force from 2026, introduces for the first time concrete limits on brake particle emissions for light-duty vehicles — a potentially historic development.

Emission limits in mg/km per vehicle	Vehicles of categories M_1 and N_1, excluding N_1 Class III (*)				
Powertrain technology	PEV	OVC-HEV	NOVC-HEV	FCV/FCHV	ICEV
Brake particle emissions (PM_{10})	3	7	7	7	7

(*) For N1, Class III vehicles, the applicable limits are as follows: PEV 5 mg/km; OVC-HEV, NOVC-HEV, FCV/FCHV and ICEV 11 mg/km.

Figure 1. Extract from Euro 7 legislation. Brake particle emission limits driving cycle applying until 31 December 2029, by powertrain technology

Outside the EU, similar gaps exist. The United States Environmental Protection Agency (EPA) regulates ambient PM2.5 and PM10 concentrations under the Clean Air Act but does not mandate specific controls on brake or tire wear emissions. Japan and South Korea also focus largely on tailpipe emissions. Only in recent years have some countries begun to invest in research and advisory documents on NEEs, often referencing the need for international harmonization of standards.

Technical guidance on NEEs exists, but is non-binding. The EMEP/EEA Air Pollutant Emission Inventory Guidebook includes a methodology for estimating PM10 and PM2.5 from brake wear, based on activity data and emission factors. However, this guidance is oriented toward national emission inventories and not enforceable at the product or fleet level. Moreover, the emission factors used are highly generalized and do not capture real-world variability in driving conditions, brake system design, or fleet composition.

At the city level, local authorities have more discretion to address NEEs within air quality plans, low emission zones (LEZs), and sustainable urban mobility plans (SUMPs). Yet, the lack of harmonized measurement protocols and technical standards hampers their ability to isolate and regulate NEEs effectively. Few cities have the capacity to monitor PM source composition or to differentiate brake wear from other sources like domestic heating or construction dust.

As for product regulation, brake systems are currently approved through ECE R90 homologation, which tests replacement brake components for safety and performance. However, no environmental criteria (e.g., PM emission rates, toxic metal release) are included in the ECE R90 framework. As a result, brake pad and disc materials are optimized for performance and cost, with limited regard for environmental externalities.

This regulatory gap is now partly addressed by the Euro 7 (EU7) regulation, which represents a major step forward in the European Union’s efforts to reduce air

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

pollution from road transport. Unlike previous standards, EU7 also targets non-exhaust emissions, such as those produced by brake and tire wear. These emissions, especially from brakes, are now recognized as a source of fine particulate matter (PM), particularly in urban areas.

For light-duty vehicles (passenger cars and vans up to 3.5 t), the new limits on brake particle emissions will apply starting from November 2026 for new vehicle types and from November 2027 for all new vehicles placed on the market. The regulation sets a limit of 7 mg/km of PM10 for internal combustion engine (ICE), hybrid electric, and fuel cell vehicles, while a stricter limit of 3 mg/km applies to pure electric vehicles (PEVs). In 2028, a decision will be made regarding the emission limits for 2030, taking into account the technological advancements achieved by that time.

To measure these emissions, the regulation uses a standardized laboratory test called UN GTR24, developed under the United Nations framework. This test simulates real driving conditions using a dynamometer and includes 303 braking events based on the WLTP Brake Cycle. Although the EU7 legislation sets limits only for PM10, the testing procedure developed under GTR24 also measures both the mass of particles (PM10 and PM2.5) and the number of particles (PN10) released during braking. The Particle Measurement Programme (PMP) group played a key role in developing GTR24, ensuring that the procedure is scientifically reliable and suitable for different types of vehicles and brake systems.

A shift in regulatory priorities occurred with the emerging focus on NEEs in the Euro 7. Preliminary discussions have included the need for lab-based emission measurement procedures for brake wear, certification protocols for new brake components and in-use compliance testing requirements. However, translating these elements into enforceable standards will require significant work in terms of methodological consensus, industry adaptation, and technical infrastructure for testing and compliance.

The current lack of binding regulation is also mirrored in the fragmented innovation landscape. While several OEMs and Tier 1 suppliers are developing low-emission brake systems, these innovations face barriers in market uptake due to the absence of clear standards, incentives, or procurement guidelines.

In response to these new requirements, manufacturers are introducing several innovations. These include low-wear brake materials and brake dust filters. Additionally, regenerative braking in electric vehicles is being optimized to limit the use of traditional brakes. These technologies are essential for meeting EU7 targets.

The regulatory framework for heavy-duty vehicles (HDVs) is still under development. HDVs, such as trucks and buses, are significant contributors to non-exhaust particulate emissions due to their greater mass and braking energy. As

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

such, EU7 extended brake emission to this vehicle category as part of the broader strategy of the European Union to reduce air pollution from road transport. The tentative timeline for the introduction of brake emission limits for HDVs is set for 1 January 2030. However, the specific emission limits are expected to be defined by 2027.

Unlike light-duty vehicles, for which the GTR24 procedure has already been adopted, there is currently no finalized test procedure for HDVs. This presents both a challenge and an opportunity to develop a robust and harmonized methodology tailored to the unique characteristics of heavy vehicles.

To address this, a dedicated technical group known as Task Force 5 (TF5) has been established under the UNECE framework. TF5 is actively working on the development of a dynamometer-based test procedure for HDVs, inspired by the GTR24 approach used for light-duty vehicles. The group is focusing on several key aspects, including the design of the test cycle, which must reflect the typical braking behaviour of HDVs in real-world conditions, and the layout of the test enclosure, which must be capable of accurately capturing and measuring brake particle emissions under controlled laboratory settings.

The work of TF5 is crucial to ensuring that the future regulation is both scientifically sound and practically applicable. It must account for the diversity of HDV configurations, braking systems, and duty cycles, while also ensuring repeatability and comparability of results across different testing facilities. Once finalized, the procedure will enable the EU to set enforceable limits for PM10 emissions from HDV braking systems.

In the meantime, manufacturers and research institutions are already exploring low-wear brake materials, dust filtration systems, and advanced braking technologies for HDVs. These innovations will be essential not only for compliance with future regulations but also for improving the environmental performance of commercial transport fleets across Europe.

2.2 Recommendations for Enhancing Policy Frameworks

To effectively address non-exhaust emissions from braking systems, a suite of policy enhancements is required at multiple governance levels. These should be grounded in scientific evidence, aligned with technological readiness, and adaptable to different urban and regulatory contexts.

The European Union should expedite the integration of brake wear emissions into vehicle-level regulations, starting with the finalization of the Euro 7 standard. This should include clear emission thresholds for brake-derived PM, standardized test cycles using reference dynamometers, and provisions for in-use compliance. These

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

measures would provide regulatory certainty for manufacturers and accelerate the development of low-emission braking technologies.

A harmonized measurement methodology for real-world non-exhaust emissions should be developed and adopted at the European level. This includes protocols for sampling, filter analysis, and data reporting. Harmonization would improve data comparability across cities and support the integration of NEEs into national and regional air quality plans.

Urban mobility policies should explicitly incorporate non-exhaust emissions. SUMPs, LEZs, and public procurement policies should include criteria for brake system emissions. Municipalities should be supported through technical assistance and funding mechanisms to implement monitoring infrastructure and pilot interventions.

Green public procurement guidelines should be updated to include environmental performance indicators for braking systems. By making low-emission brakes a requirement in tenders for public transport vehicles, authorities can create market demand and drive innovation.

Emission inventories should be refined using empirical data, such as that generated by the LIFE RE-BREATH project. National authorities should invest in data collection and modeling efforts to improve the accuracy of brake wear estimates and support evidence-based policymaking.

Finally, international coordination is essential. European institutions should engage with UNECE, ISO, and CEN to align emerging standards and avoid regulatory fragmentation. These collaborations can facilitate global innovation and ensure consistency in compliance and reporting.

2.3 Proposed Roadmap for Regulatory Changes

A structured and time-bound roadmap is essential for integrating non-exhaust emissions into environmental regulation and urban mobility policy. The roadmap should encompass short-, medium-, and long-term objectives, reflecting both immediate opportunities and systemic transitions.

In the short term (2025–2027), the priority should be on establishing foundational elements. This includes contributing to the finalisation and implementation of the Euro 7 regulation with brake wear emission thresholds and validating standardized testing procedures. Concurrently, CEN and other standardization bodies should release technical guidance for real-world PM10 measurement, enabling cities to initiate monitoring. Pilot programs should be launched in selected municipalities to test implementation models and build administrative capacity.

In the medium term (2027–2030), regulatory requirements should be mainstreamed. Certification of low-emission braking systems should become mandatory for new public transport vehicles. Urban mobility funding mechanisms, such as those under the EU Green Deal, should include eligibility criteria based on brake emission performance. Green public procurement guidelines should be revised to reflect new standards. Cities should be encouraged to incorporate NEE metrics into LEZ and SUMP frameworks.

By the long term (2030–2035), non-exhaust emissions should be fully integrated into environmental governance. National air quality targets should include reduction goals for brake-derived PM10. Vehicle type approval processes should assess long-term brake system performance, including wear rates and material degradation. Health impact assessments for major transport projects should account for NEE exposure. Monitoring data should feed directly into policy evaluation and compliance mechanisms.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

3 Methodology

3.1 Data sources within the project and literature review

The development of the guidelines presented in this document was grounded in a combination of empirical evidence generated by the LIFE RE-BREATH project and an extensive review of existing academic and technical literature. This dual-source methodology was adopted to ensure that the guidelines rest on both real-world observations and a comprehensive understanding of the broader scientific and regulatory context.

The core of the empirical evidence comes from the LIFE RE-BREATH project itself. As a demonstration project funded under the European LIFE Programme, RE-BREATH has been structured to generate both technological advancements and field-based insights into the nature, mitigation, and monitoring of non-exhaust particulate emissions. Data were gathered across multiple work packages, each contributing a distinct perspective and dataset relevant to the formulation of the guidelines.

Work Package 2 (WP2) focused on the technological development of innovative braking systems. Within this work stream, brake pad and disc materials were reformulated to reduce particulate emissions during deceleration events. Laboratory testing, particularly using dynamometer benches, enabled the evaluation of wear behaviour, emission rates, and material integrity. These lab-based assessments provided baseline emission profiles against which real-world outcomes could be compared. In addition to mechanical and chemical testing, WP2 included preliminary assessments of recyclability and circular economy potential—factors increasingly relevant in both environmental and industrial standards.

Work Package 3 (WP3) transitioned from lab testing to in situ validation. Through a carefully designed set of demonstration activities in urban transport environments, WP3 offered critical insights into the performance of braking systems under real-world conditions. Five buses equipped with conventional and newly formulated brake components were deployed along regular routes in a typical European city. Monitoring campaigns were conducted in both summer and winter seasons to capture variations due to meteorological and operational factors. Ambient particulate concentrations were measured at key exposure points—particularly at bus stops—using standardized air sampling equipment. The campaigns were designed not only to assess total PM10 concentrations but also to support deeper chemical and morphological analyses, thus bridging the gap between emission measurement and source attribution.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Work Package 4 (WP4) played a central role in environmental monitoring, data analysis, and source apportionment. PM samples collected from the field were analysed using a range of techniques, including gravimetric determination of mass concentration, inductively coupled plasma mass spectrometry (ICP-MS) for elemental composition, and scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS) for morphological characterization. These analyses confirmed the presence of brake-wear-associated tracers such as copper, zinc, and barium, often found in distinct particle morphologies indicative of high-temperature friction processes. The chemical fingerprinting derived from these data was instrumental in isolating brake wear emissions from other urban sources of PM10, such as domestic heating or industrial activities.

Further analytical depth was provided by the development of dispersion and exposure models. These models were calibrated using the empirical data collected during WP3 and WP4 and supported by local meteorological datasets. By simulating how particulate matter spreads across the urban environment, the models allowed for the estimation of population-level exposure to brake wear emissions under various conditions. This level of analysis was crucial not only for understanding health impacts but also for identifying potential regulatory levers and prioritizing intervention zones.

Beyond the internal project data, the development of the guidelines also drew upon a wide-ranging review of existing literature. The purpose of this literature review was to frame the empirical findings within a broader scientific and regulatory discourse, identify best practices and methodological gaps, and ensure alignment with ongoing European and international efforts.

Scientific literature on brake wear emissions has expanded significantly in recent years, driven by increasing recognition of non-exhaust emissions as a significant source of urban air pollution. Studies documenting the chemical composition, particle size distribution, and toxicological impacts of brake-derived PM formed the scientific basis for several aspects of the guideline development. Particular attention was given to research identifying characteristic tracers of brake wear, such as Cu/Sb ratios, and to studies demonstrating the inefficiency of conventional PM mitigation strategies (e.g., filters) in capturing mechanically generated particles.

In parallel, policy and technical literature offered insight into the regulatory treatment of NEEs. Reports by the European Environment Agency, the World Health Organization, and the Joint Research Centre of the European Commission were reviewed to contextualize the state of policy readiness. In addition, documents such as the EMEP/EEA Air Pollutant Emission Inventory Guidebook provided methodological reference points for emission factor development and inventory design.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Particular emphasis was placed on reviewing the emerging standards and regulatory developments associated with Euro 7 proposals, UNECE working documents, and initiatives by standardization bodies such as CEN and ISO. These sources were critical for identifying the evolving technical expectations and compliance mechanisms likely to shape the future regulatory landscape. Additionally, the literature review examined implementation frameworks from other EU-funded projects dealing with transport emissions, including initiatives under Horizon 2020 and CIVITAS. These case studies offered valuable lessons on replication, monitoring, and stakeholder coordination.

Finally, project deliverables and interim reports from related EU programs were also consulted, providing complementary data on exposure modeling, PM monitoring, and cost-benefit assessments. This convergence of literature and field data ensured that the guidelines were both theoretically sound and empirically validated.

In sum, the methodology adopted for developing the guidelines was underpinned by a comprehensive data ecosystem. Project-generated data provided a unique opportunity to develop protocols grounded in European urban contexts, while the literature review ensured alignment with scientific consensus and emerging regulatory trajectories. This combination has resulted in a set of guidelines that are technically robust, operationally feasible, and adaptable to evolving policy requirements.

3.2 Stakeholder Engagement and Consultation Process

The formulation of technically credible and practically applicable guidelines for non-exhaust emissions required close attention to stakeholder insights. Recognizing the multi-dimensional nature of the issue—spanning engineering, urban planning, environmental science, and public policy—the development process incorporated a range of perspectives across the project lifecycle.

Rather than relying on a formal public consultation framework, the project’s stakeholder engagement strategy emphasized continuous and iterative interaction with domain experts, institutional partners, and practitioners who possess first-hand knowledge of both the technical systems and the policy landscapes in which they operate. This approach was especially valuable in ensuring that the guidelines remained realistic, feasible, and responsive to operational constraints.

Engagement began during the early phases of the LIFE RE-BREATH project, particularly within the design and planning activities of WP2 and WP3. Manufacturers, vehicle operators, and municipal authorities worked closely to define use cases, select test sites, and design monitoring campaigns. These collaborative processes created a feedback loop in which data collection activities were directly

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

informed by on-the-ground insights. For example, the selection of demonstration routes and sampling locations reflected not only scientific objectives but also the lived experience of transport planners and maintenance crews.

During the analytical phases, especially in WP4, technical experts from the research community and private sector partners contributed to the interpretation of chemical and morphological data. Workshops and internal briefings allowed for the exchange of methodological perspectives, particularly on the application of SEM-EDS analysis, elemental fingerprinting, and exposure modelling. This collaborative review process helped ensure the robustness of the empirical findings that underpin the guideline recommendations.

As the guidelines began to take shape under WP5, additional rounds of consultation were held within the project consortium and with selected external experts from the mobility, environmental, and regulatory sectors. These interactions focused on the clarity, applicability, and scalability of the proposed measures. Draft guidelines were presented in internal review sessions that allowed for critique and refinement. The emphasis was placed on identifying gaps in usability, potential conflicts with existing practices, and opportunities for alignment with emerging standards.

Although not structured as a formal public consultation, this targeted and context-sensitive engagement process ensured that the guidelines reflect the practical realities of implementation. The iterative nature of this engagement allowed for real-time adjustments and reinforced the credibility of the resulting recommendations. Moreover, the reliance on networks of professionals with deep sectoral knowledge—rather than generalized stakeholder outreach—allowed the project to anchor its proposals in operational expertise.

The stakeholder engagement process thus functioned as a critical mechanism for co-producing knowledge. It enhanced the legitimacy of the guidelines, fostered alignment among project partners, and helped anticipate the needs and constraints of potential adopters. This collaborative model provides a useful template for future initiatives seeking to combine scientific rigor with practical relevance in the development of environmental policy tools.

3.3 Approach to Developing the Guidelines

The process of developing the technical and policy guidelines on non-exhaust emissions followed a structured, iterative, and evidence-based approach designed to ensure both scientific rigor and practical applicability. It was guided by the core objective of translating empirical insights and technological advances into actionable recommendations that could inform regulatory development and operational practice.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

The approach began with the systematic aggregation of data from multiple work packages of the LIFE RE-BREATH project. Laboratory results from WP2 were reviewed to understand the performance and wear characteristics of various brake material formulations. Field measurements from WP3 and analytical outputs from WP4 were synthesized to identify patterns in particulate emissions under real-world conditions. These datasets formed the empirical backbone of the guidelines, providing both the justification for intervention and the parameters for technical recommendations.

Parallel to this data consolidation effort, a comprehensive literature review was undertaken to map the broader landscape of scientific understanding and regulatory evolution concerning brake wear emissions. This review informed the selection of performance indicators, monitoring methods, and implementation strategies. It also ensured that the guidelines were aligned with emerging standards and reflected international best practices.

To facilitate usability and adaptability, the guidelines were organized into three core sections, each corresponding to a key domain of intervention: emission reduction practices, innovation standards for braking systems, and measurement protocols. This modular structure was chosen to accommodate a variety of audiences and application contexts, from manufacturers and transport operators to urban policymakers and environmental regulators.

Drafts of the guidelines were subjected to multiple rounds of internal review within the project consortium. These reviews focused on validating the technical accuracy, evaluating the clarity of presentation, and assessing the feasibility of proposed measures. Revisions were made to reflect operational constraints, institutional capacities, and technological readiness levels across different urban and transport systems.

The finalization phase involved contextual testing of the guidelines through discussion with sectoral experts and the examination of potential replication scenarios. These exercises highlighted the importance of maintaining a degree of flexibility within the recommendations, allowing users to adapt procedures based on local infrastructure, policy frameworks, and resource availability. While the core technical content was anchored in project data, its presentation was deliberately shaped to support broader applicability and policy translation.

Throughout the process, attention was paid to maintaining a balance between prescriptive detail and general guidance. Where appropriate, the guidelines include references to standardized methodologies and regulatory texts. At the same time, they avoid over-specification that could limit their relevance in differing contexts or discourage innovation.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

In summary, the approach to guideline development was one of methodological integration and iterative refinement. It combined empirical rigor with stakeholder validation and policy foresight. The result is a set of recommendations that are not only scientifically robust but also positioned to inform real-world decisions and future regulatory frameworks on non-exhaust vehicular emissions.

4 Technical Guidelines

4.1 Best Practices for Brake Emission Reduction: Updated Guidelines for Designing Friction Materials

The design of friction materials has undergone significant evolution in recent years, driven by advancements in technical, regulatory, and environmental requirements. This transformation reflects not only the adaptation to growing global market demands but also the need to address stricter regulations and emerging technologies, particularly with the rise of electric mobility.

Initially, friction material design focused almost exclusively on functional performance. Key parameters included braking efficiency, thermal stability, and resistance to fading, all aimed at ensuring reliable and consistent performance under demanding operating conditions such as high temperatures or repeated braking.

Over time, durability emerged as a critical aspect. Material wear became a key factor to ensure not only vehicle safety but also the economic and functional sustainability of braking systems in the long term. Specific tests were introduced to assess abrasion resistance, performance stability over time, and the ability of the material to maintain its characteristics after extended use.

The advent of electric vehicles further reshaped the landscape. Regenerative braking reduced reliance on mechanical brakes, thus lowering overall wear. However, the increased vehicle weight, primarily due to batteries, maintained high stress on braking systems, making it more challenging to balance performance and durability. Modern design must address these contrasting demands, ensuring efficiency under heavier loads and variable usage scenarios.

Another crucial aspect that has gained prominence is NVH (Noise, Vibration, Harshness). In increasingly quiet vehicles, particularly electric ones, acoustic and vibrational comfort has become a distinctive feature of the driving experience. Reducing unwanted noises, squeals, and vibrations is now a priority. This has led to optimized formulations, the introduction of specific underlayers, and advanced

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

simulation and testing techniques to improve the vibroacoustic behavior of braking systems.

Environmental sustainability has also become one of the main drivers of development. Recent regulations, such as Euro 7, impose strict limits on particulate emissions generated during braking. Friction materials must now be designed not only to deliver high performance and longevity, but also to minimize environmental impact. This has spurred research into innovative formulations free of copper and other potentially polluting components to meet regulatory requirements without compromising system efficiency.

At the same time, adopting an integrated approach between the disc and the friction material has become essential. This design synergy allows for the optimization of braking system performance while significantly reducing environmental impact. The pairing of the disc and friction material must be engineered to ensure all aspects of comfort and safety, such as minimizing vibrations, unwanted noise, and wear, without compromising the system's durability and efficiency.

This evolution has significantly influenced the production process. Processing parameters directly affect emissions and material performance. Production has become an integral part of the design process, requiring a holistic approach that considers the entire product's lifecycle. Life Cycle Assessment (LCA) is now integrated into development to evaluate the environmental impact of raw materials, production phases, and product disposal. This approach, known as Eco-Design, guides design choices towards more sustainable and responsible solutions.

Today, integrating performance, wear, NVH, emissions, and the production process represents the standard for friction material design. Every new formulation must be assessed not only for technical performance but also for its environmental impact and compatibility with existing production processes. Only through a multidisciplinary and integrated approach can solutions be developed to meet the current and future challenges of the automotive sector.

4.2 Standards for Innovative Braking Systems: Insights from the Re-Breath Project

The RE-BREATH project focused on evaluating brake emissions from buses operating in urban and extra-urban environments. At the project's inception, no standardized procedures or dedicated dynamometer benches for heavy-duty vehicles were available to perform such tests. Consequently, an innovative approach was adopted using the dynamometer bench available at the Brembo facility. The bench used was compliant with GTR24 recommendations for Light Duty Vehicles (LDV). The approach used in LIFE RE-BREATH introduces a methodology to scale HDV brake system to an equivalent LDV brake. The details of this methodology are

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

thoroughly described in the paper presented at EuroBrake 2024, reported below in the deliverable.
To ensure the test cycle was representative of real-world bus operation, a city bus in Bergamo was equipped with external data logger and sensors. Data collected from its actual route were used to construct a custom dynamometer cycle. The development and of this cycle are also documented in the aforementioned paper.
Using this adapted testing protocol, materials developed within the RE-BREATH project were evaluated. The results demonstrated an approximate 10% reduction in brake emissions. While the EuroBrake 2024 paper reported preliminary values, these were later revised to reflect final measurements, Fig.2:

- Original Equipment (OE): 25.2 mg/km/wheel
- Best performing solutions developed in RE-BREATH: 22.7 mg/km/wheel

In the latter phase of the project, a heavy-duty dynamometer bench became available and was used to validate the procedure. The results obtained from the Re-Breath material were consistent with those from the rescaled light-duty setup, which suggests that the approach might be reliable, Fig.3. A comparative graph illustrating these results is included.
Future work should expand the study to include a broader range of bus routes and different materials. Additionally, it will be valuable to compare the RE-BREATH methodology with the standardized procedure currently under development by the TF5 working group. Notably, RE-BREATH contributed to this effort by presenting its rescaling approach during the first TF5 meeting.

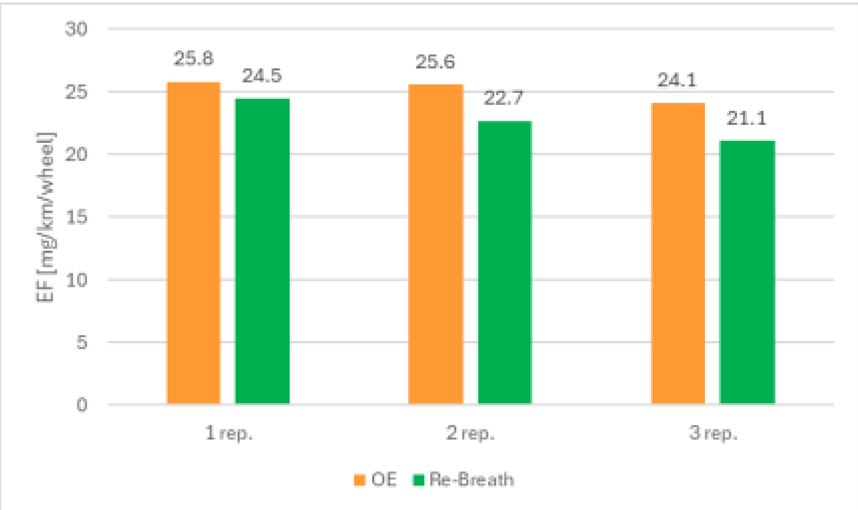


Figure 2. Brake emissions (PM_{10}) measurement of Re-breath material vs OE in different repetition of the cycle.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

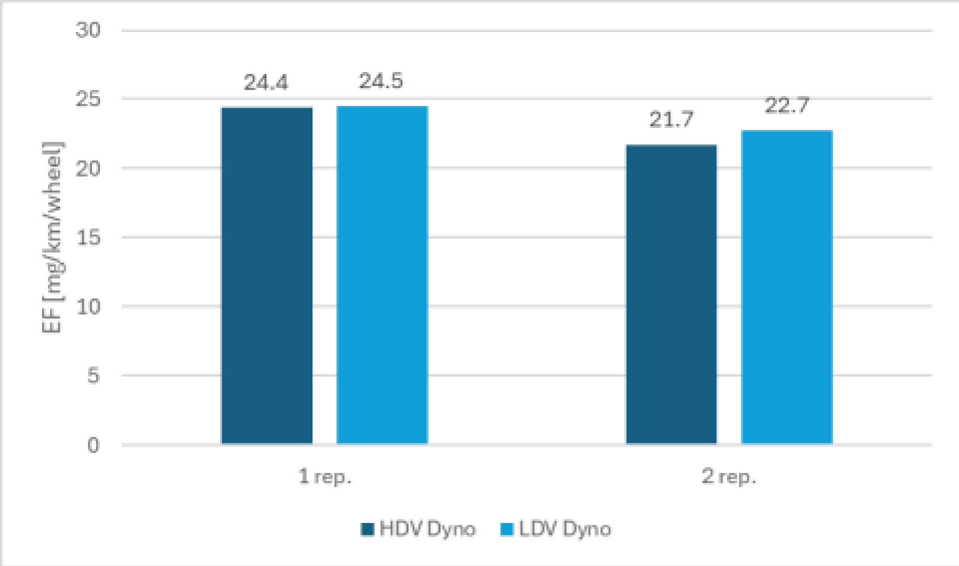


Figure 3. Brake emissions measurement of Re-breath material in HDV Dyno vs LDV Dyno in different repetition of the cycle.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

SUBMISSION NUMBER (EB2024-EFA-015)

Heavy Duty Vehicles brake testing: a novel scaling methodology for PM10 emission measurement

Michele Pagnoni *[1], Mara Leonardi[1], Riccardo Perucca[1], Maurizio Besana[1], Alessandro Santini[1], Matteo Redaelli[1], Stefano Belotti[1], Cristina Ghezzi[1], Guido Perricone[1]

[1]Brembo S.p.A., Via Brembo 25, 24035 Curno, Italy

DOI: https://doi.org/10.46720/EB2024-EFA-015

ABSTRACT: While research on Light-Duty-Vehicles (LDVs) non-exhaust brake emissions is extensive and there is already a measurement protocol, there is a lack of focus on Heavy-Duty Vehicles (HDVs) brake emissions. Key challenges in HDV brake systems testing include pneumatic brake calipers, brake system size, life span of the components and vehicle inertia. To overcome these challenges, the present study introduces a methodology to scale HDV brake system to an equivalent LDV brake. This has enabled testing on a LDV dynamometric bench to assess PM10 emissions from HDVs under a mission profile representative of real-world usage. The study comprises four distinct phases, outlined as follows: instrumentation and data acquisition on an HDV; analysis of mission profiles and generation of a representative dynamometric bench procedure; brake system scaling to match an equivalent LDV brake; experimental testing on the scaled system. The resulting emission factor was determined to be 9.1 mg/km/wheel on the reference materials, and 8.3 mg/km/wheel on an alternative materials coupling. Limitations of the study include pending PM10 tests on HDV brake systems and the necessity for a more diverse dataset to replicate realistic scenarios, underscoring avenues for further research and refinement.

KEY WORDS: brake emission, scaling procedure, heavy-duty vehicles, bus

1. Introduction

he Euro 7 regulation establishes rules to reduce road vehicle emissions, for the first time also from brakes and tyres. The final text of the agreement includes limits for braking emissions: for Light-Duty Vehicles (LDVs) specific limits for the PM10 are indicated, while further limits, also for Heavy-Duty Vehicles (HDVs), will be set by the end of 2027. The Particle Measurement Program (PMP), group of the United Nations Working Party on Pollution and Energy (GRPE), has developed a standardized laboratory measurement procedure to evaluate the brake emissions of LDVs [1], while for HDVs a dedicated task force (TF5) was created in December 2023 to investigate the topic and prepare a dedicated testing protocol.

The scientific literature extensively addresses research on passenger car brake emissions, their correlation with pad wear, and strategies for mitigation [2-5]. However, there is a notable scarcity of studies focusing on HDVs brake emissions. While certain findings regarding the correlation between brake particle emission and wear, as well as relationships between dust generation and brake parameters (velocity, temperature, energy, etc.), may still be applicable [6-8], an evaluation of HDVs emissions is hindered by the absence of standardized norms and testing protocols. Key challenges in HDVs brake systems testing include the definition of a cycle that can be suitable for the different vehicle missions, brake system size, life span of the components and vehicle inertia, assessment of engine and non-friction braking. At the PMP meeting in June 2023, data collected within the framework of a project were presented [9]. In the activities, a few aspects like the driving cycles and the test setup were investigated, some brake particle emission factors were also reported.

The study presented herein aims at introducing a novel methodology aimed at facilitating brake particle emission tests on HDVs. Specifically, a scaling procedure is proposed whereby the original brake system (HDV) is downscaled onto a second system suitable for testing on Light-Duty Vehicle (LDV) emission setup, utilizing an appropriate scale factor. Subsequently, the findings derived from the scaled system can be extrapolated to the original HDV through the previously defined scale factor.

The methodology has been adopted in the framework of Re-Breath, a project founded by European commission’s LIFE Programme aimed at reducing the PM10 emissions related to the braking systems of a bus. Tests on dynamometric benches are needed to speed up the development, however a test protocol is not yet defined for HDVs brake emissions. Thus, a specific brake procedure has been generated starting from vehicle acquisitions on a representative route.

2. Scaling methodology

One of the primary challenges in heavy-duty vehicle brake testing is the availability of suitable test benches; this issue is further compounded when considering particulate emissions. Consequently, a scaling methodology has been developed to replicate the emissions of a heavy-duty vehicle braking system by conducting tests on a downscaled system. The linear dimensions ratio between the downscaled braking system and the full-scale system, henceforth referred to as the scaling factor (f), serves as the basis for defining all other parameters of the testing procedure; to achieve behavior analogous to that of the full-scale system, the testing parameters of the scaled system must be accordingly scaled.

The scaling of various quantities with respect to the scaling factor arises from the following fundamental relationships:

- Braking energy is proportional to mass;
- Conservation of pad/disc contact pressure between the scaled system and the full-scale system;
- Conservation of the sliding velocity of the pad/disc contact between the scaled system and the full-scale system.

In Table 1 are reported the scale factors for some of the principal physical quantities.

Table 1: Scale factors

Physical quantity	Scale factor	Scale factor value
Length	f	0.67
Mass	f^3	0.301
Time	f	0.67
Speed	1	1
Acceleration	f^{-1}	1.493
Inertia	f^5	0.135

As a consequence of this scaling system, the average temperatures of the disc and pads are faithfully reproduced. As a final step, to obtain the full-scale test results from the downscaled test, it is necessary to use the mass scaling factor to adjust particulate emissions, as per the following equation

$$EF_{FullScale} = EF_{DownScaled} * \frac{1}{f^3} \qquad (1)$$

The scaling factor used in this study is chosen to match an existing LDV braking systems. The dimensions of the full-scale and the downscaled brake systems are reported in Table 2:

Table 2: Parameters comparison

	Full-sized	Downscaled
Tyre rolling radius [mm]	465	312
Braked inertia [kg*m2]	973	59
Max procedure speed [km/h]	80	80
Max procedure deceleration [g]	0.3	0.5
Disc diameter [mm]	434	300

Disc thickness [mm]	45	32
Effective radius [mm]	167	120

It is worth noting that the braked inertia value has decreased from 973 to 59 kg*m^2, making it possible to perform the test on a LDV test bench.

3. Vehicle instrumentation and data acquisition

The development of a testing protocol for brake particle emission measurement typically relies on vehicle data, as the test procedure must accurately reflect real-world driving conditions. In this particular instance, no data were accessible at the outset of the project, thus one of the initial tasks was the strategic planning of vehicle acquisition to procure the essential mission profile information.

The project target vehicle was equipped with external data logger and sensor. The external sensors concerns GPS, vehicle speed, IMU and brake thermocouples. Other signals, marked as internal, were acquired via CAN-bus following SAE J1939 protocol.

All signals were acquired by the commercial data logger 2D Datarecoding. Additional details on channels and sample rate are presented in Table 3.

Table 3: Experimental data logging, signals list

Channel name	Description	Type	Sample rate [Hz]
V_Sat	Vehicle speed	Extern al	25
Altitude	GPS Altitude	Extern al	25
Longitude	GPS Longitude	Extern al	25
Latitude	GPS Latitude	Extern al	25
ACC_X	IMU longitudinal	Extern al	200
ACC_Y	IMU lateral	Extern al	200
TF1	Front left disc temperature 1	Extern al	25
TF2	Front left disc temperature 2	Extern al	25
TR1	Rear left disc temperature 1	Extern al	25
TR2	Rear left disc temperature 2	Extern al	25
J1939	CAN bus channels	Intern al	As standard

Temperatures have been logged from rubbing thermocouples on the brake disc external cheek, located on two different radii, in order to account for any inhomogeneity on temperature distribution.

4. Vehicle data analysis

After logging the vehicle data, postprocessing was required to generate the testing protocol. The aim of this section is to outline the data analysis process employed to develop the dyno testing procedure based on road data acquisition. Establishing a representative procedure is crucial due to the impact of test conditions, such as brake temperature, speed and deceleration, on emitted particulate matter.

4.1. Datasets overview

Six datasets, all corresponding to the same route spanning from Bergamo city center to Piazza Brembana, were utilized. This route consists of approximately 30% urban and 70% extra-urban conditions. All the datasets included CAN channel recordings, offering insights into engine speed, engine torque, and retarder torque, these information facilitate the examination of energy dissipation by auxiliary brakes in comparison to the dissipative brake load.

All datasets underwent a standardized post-processing workflow, including signal trimming to eliminate initial and final standstill periods, data cleaning via moving median or low-pass filters, GPS data correction in case of signal loss scenarios (e.g., tunnels), brake event identification and CAN data analysis.

With reference to one of the datasets investigated, relevant information concerns the time history of speed and temperatures, as reported in Figure 1.

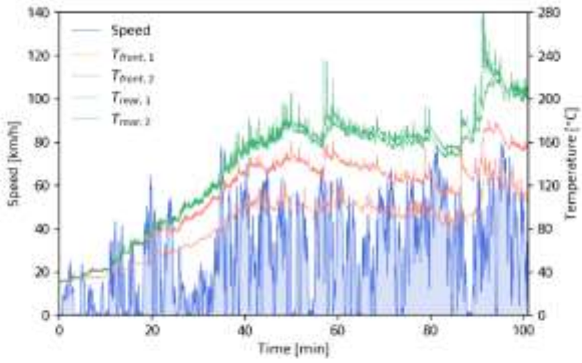


Figure 4: Vehicle speed and brake temperature

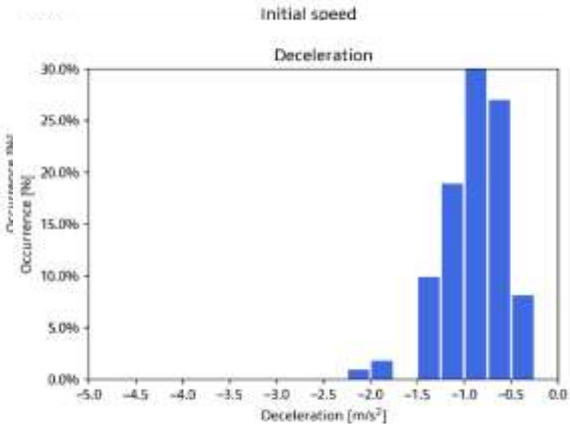
Vehicle speed is limited at 80km/h and, on average, the vehicle moves at ~50km/h. The first part of trip, up to 40-50min, present a constant rate of temperature increase, corresponding to lower vehicle speed in the urban section of the route. Concerning brake temperature, it was observed to range, on average, between 100 and 170°C, depending on the trip considered.

Brake events have been identified through thresholds applied to vehicle deceleration and speed. Specifically, a brake event initiates if both of the following conditions are met: brake deceleration ≥ 0.5 m/s² and vehicle speed ≥ 10 km/h. Subsequently, a brake event concludes when either of the following conditions is satisfied: brake deceleration ≤ 0.3 m/s² or vehicle speed ≤ 5 km/h. Brake events lasting less than 2 seconds were excluded from subsequent analyses.

After splitting the trip in individual brake events, histograms of the main features have been generated. It appears how the initial brake speed is almost uniformly distributed between 25-60 km/h, while decelerations are very low, for the majority of cases in the range between 0 and -1.5 m/s², lower than the common values for passenger cars. Examples of brake initial speed and deceleration distributions are reported in Figure 2 and Figure 3.

Figure 5: Initial brake speed distribution

By the analysis of CAN data, especially of



retarder torque, presented in Figure 4, it is derived that at low speed (<25km/h) the whole deceleration is due to the friction brake, so urban conditions are potentially more critical in terms of PM emissions and brake temperature due to the most frequent use of dissipative brake

For each brake event, the contribution of retarder torque has been removed from the energy dissipated by brakes.

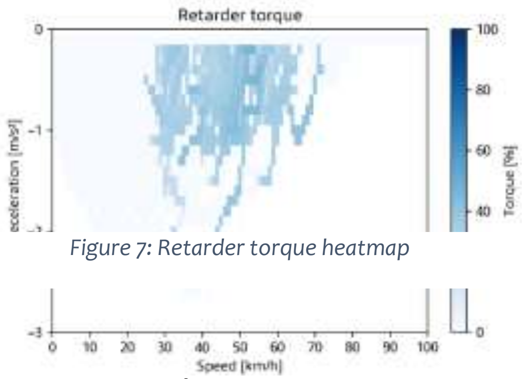


Figure 7: Retarder torque heatmap

4.2. Test protocol generation

The test protocol for emission tests have been generated from three vehicle acquisition out of the six available. The datasets used are those without significative GPS signal losses. A total of 345 brakes compose a brake procedure that spaces the speed, deceleration and temperature conditions of road tests. All these parameters are scaled to the target LDV system by means of the methodology presented in section 2.

The use of consecutive brake parameters from vehicle acquisitions allows for not needing brake heat-up, so that no fictitious brake has been introduced in the testing protocol.

Figure 6: Average brake deceleration distribution

Brake conditions are close to those of the reference procedure for LVDs emission testing, WLTP-brake, in terms of average speed and deceleration, but the brake initial speed never overcomes 70km/h. An extended comparison is reported in Table 4.

Table 4: Test protocol comparison

	WLTP brake	Vehicle cycle
Events [-]	303	345
Brake start speed [km/h]	min 7 avg 42 max 100	min 13 avg 38 max 70
Deceleration [m/s²]	min 0.5 avg 0.97 max 2.1	min 0.4 avg 0.95 max 2.1

Differently from WLTP-brake, the procedure based on vehicle cycles should not be intended as representative of the target HDV mission in the whole, since it's limited by the availability of datasets on a single route.

A visualization of the main features of the proposed test protocol, brake initial and final speed, deceleration and initial disc temperature, is presented in Figure 5.

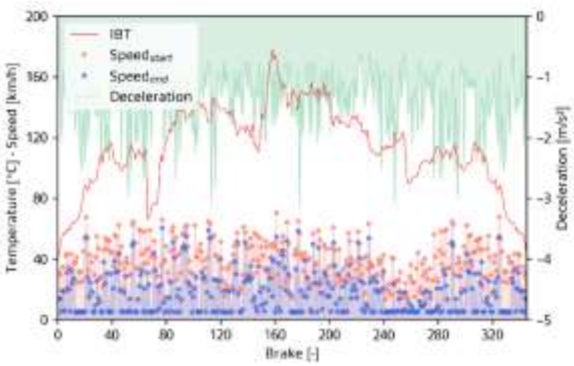


Figure 8: Test procedure representation

5. Emission tests

Following the definition of the testing protocol, the particle measurement tests were setup. As mentioned, the test were performed on a LDV brake system, under the hypothesis of the scaling methodology presented in section 2. Two distinct materials combinations for brake pad and brake disc were examined to verify whether the Aftermarket (AM) proposal ensures a notable reduction in PM10 compared to the Original Equipment (OE).

5.1. Dynamometric bench setup

The scaled brake system is rigidly mounted on the bench: the caliper is fixed using a stiff holder, while the disc is constrained to the bench spindle via the drive flange. In accordance with current regulations [10], the caliper is mounted horizontally in a 12-o'clock position, as illustrated in Figure 6, irrespective of the mounting position at the vehicle.

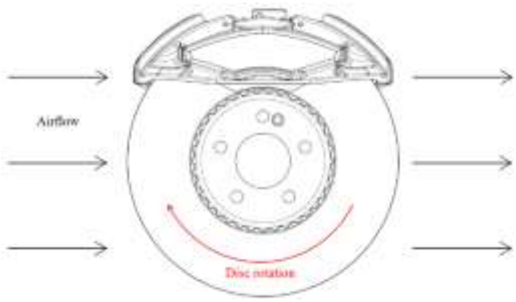


Figure 9: Brake caliper position

Before of starting the test schedule, it is verified that the pads are not in contact with the disc and that the disc runout is less than 0.1 mm. During the tests, air temperature and humidity are controlled so that these values comply with current regulations (T=23±2 °C, HR=50±5 %).

The instrumentation for measuring particulate emissions consists of sampling probes placed in the straight section of the tunnel. On the tip of each particulate matter (PM) sampling probes is installed an appropriate nozzle to ensure isokinetic sampling. A cyclone is applied as PM separation device, then a sampling line transfer the aerosol from the cyclone to the filter holder, where the emitted PM is collected on a PTFE filter. At the end of each test cycle, the filter is weighed. In Figure 7 a schema of the sampling unit is reported.

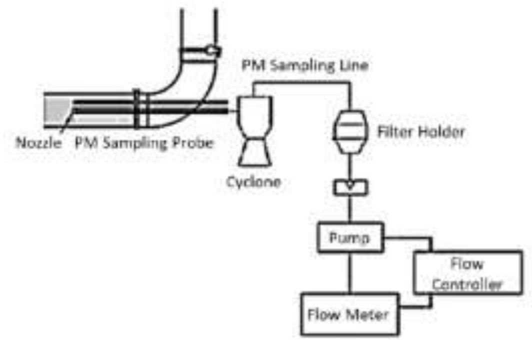


Figure 10: Sampling unit schema from "UN Global Technical Regulation No. 24, Laboratory Measurement of Brake Emissions for Light-Duty Vehicles"

5.2. Test schedule

The tests conducted involve comparing the emissions of two material couples: AM and OE. The test cycle was characterized, for each brake, by the following parameters: initial brake velocity, final brake velocity, brake deceleration, initial disc temperature, acceleration time. After each braking event, the bench accelerates to the target speed for the following brake and waits for the initial disc temperature to be reached. The bench ventilation was calibrated to be consistent with that of the scaled vehicle.

Following the tests, the accuracy of the set ventilation was evaluated against the vehicle cycle logs in terms of brake disc temperature profile.

Five repetition of the procedure cycle were executed as bedding on the new brake components, followed by three measurement cycles for particulate emissions. New filters for PM collection were installed at the end of the bedding and after each measurement cycle.

5.3. Test Outcomes

From the values of PM mass collected by filters, emission factors (EFs) are computed through the following formula:

$$PM_{10}EF = PE_{(10)} * 10^3 * \frac{NQ}{60} * \frac{1}{NQ_{PM10}} * \frac{1}{d} \qquad (2)$$

Where:

- $PM_{10}EF$ is the reference PM10 emission factor for the tested brake in mass per distance driven in [mg/km]
- $PE_{(10)}$ is the PM10 filter mass load in [mg]
- NQ is the average normalized airflow in the sampling tunnel in [m³/h]
- NQ_{PM10} is the average normalized airflow in the PM10 sampling nozzle in [l/min]
- d is the total distance driven during the cycle in [km]

The outcoming EFs, extrapolated to the original HDV through the previously defined scale factor, are summarized in Table 5.

Table 5: Emission Factors [mg/km/wheel]

	1st cycle	2nd cycle	3rd cycle
Original Equipment	9.3	9.2	8.7
Aftermarket	8.9	8.3	7.7

The difference between the two materials tested is limited, but the Aftermarket proposal highlights, on average, a reduction of the emitted PM10 of -9%.

6. Conclusion

The study proposes a method to scale a HDV brake systems to an equivalent LDV brake, facilitating particle emission tests on dynamometric benches. The test procedure was generated from experimental data acquired from an interurban bus. Analysis of acquired data revealed limited longitudinal deceleration during braking. Experimental tests on a dynamometer bench have confirmed the congruence of initial temperatures and enabled the computation of emission factors.

The study's main limitations pertain to validating the proposed scaling methodology. While several hypotheses were verified through FEM analysis and dynamometer bench results, a conclusive back-to-back PM10 test on the HDV brake system remains pending.

In addition, the test procedure, derived from a limited dataset on a single route, could benefit from more diverse data to replicate statistically relevant conditions faced by vehicles of the same class in real-world usage.

ACKNOWLEDGEMENT

The present study was conducted within the funded project Re-Breath ([101074269] — [RE-BREATH] — [LIFE21-ENV-IT-RE-BREATH]). We would like to express our gratitude to Arriva Italia S.r.l. for their support on the project and for providing buses from their fleet to enable the acquisition of experimental vehicle log.

REFERENCES

Type the contents of the section here. Type the contents of the section here. Type the contents of the section here.

[1] Economic Commission for Europe Inland Transport Committee, 'Proposal for a New UN GTR on Laboratory Measurement of Brake Emissions for Light-Duty Vehicles: ECE/TRANS/WP.29/2023/79' Geneve, June 20-22, 2023.

[2] Mathissen, M. Grochowicz, J. Schmidt, C. Vogt, R. Farwick zum Hagen, F.H. Grabiec, T. Steven, H. Grigoratos, T. A Novel Real-World Braking Cycle for Studying Brake Wear Particle Emissions. Wear 2018, 414–415, 219–226.

[3] Grigoratos, T. Martini, G. Brake Wear Particle Emissions: A Review. Environ. Sci. Pollut. Res. 2015, 22, 2491–2504.

[4] Perricone, G. Alemani, M. Wahlström, J., Olofsson, U. A Proposed Driving Cycle for Brake Emissions Investigation for Test Stand. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 2020, 234, 122–135.

[5] Giechaskiel, B. Grigoratos, T. Panagiota, D. Karageorgiou, T. Ntziachristos, L. Samaras, Z. Light-Duty Vehicle Brake Emission Factors. Atmosphere 2024, 15(1), 97.

[6] Candeo, S. Leonardi, M. Gialanella, S. Straffelini, G. Influence of contact pressure and velocity on the brake behaviour and particulate matter emissions. Wear 514-515 (2023) 204579.

[7] Liu, Y. Chen, H. Yin, C., Federici, M. Perricone G. Li, Y. Margaritis, D. Shen, Y. Guo, J. Wei, T. PM10 prediction for brake wear of passenger car during different test driving cycles. Chemosphere 305 (2022) 135481.

[8] Alemani, M. Wahlstrom, J., Olofsson, U. On the influence of car brake system parameters on particulate matter emissions. Wear vol. 396-397, 2018, p 67-74.

[9] Caltrans, ERG, Link. New Research on Brake Wear Particulate Matter Emissions from Several Heavy Truck Vocations in California. State of California report CA21-3232. Update to UNECE/GRPE/PMP-IWG 29 June, 2023.

[10] UN Global Technical Regulation No. 24, Laboratory Measurement of Brake Emissions for Light-Duty Vehicles

4.3 Measurement and Monitoring Protocols for Non-Exhaust Emissions

A. Purpose and Scope

This section outlines standardized protocols for the measurement and monitoring of non-exhaust emissions (NEEs), with a primary focus on particulate matter (PM) generated by brake wear in urban environments. Non-exhaust emissions are an increasingly significant contributor to air pollution, particularly as tailpipe emissions decrease due to regulatory and technological advancements. The purpose of this section is to provide technical guidance for environmental engineers, public authorities, researchers, and transport fleet operators to reliably quantify, analyse, and assess these emissions. The protocols presented here aim to ensure data comparability, reproducibility, and relevance for air quality policy and mitigation planning.

B. Conceptual Framework

Non-exhaust emissions encompass all airborne pollutants released from vehicles excluding tailpipe exhaust. These emissions include brake wear, tire wear, road surface abrasion, and the resuspension of previously deposited road dust. Among these, brake wear is one of the most localized and compositionally distinct sources, often contributing significantly to PM10 and PM2.5 concentrations in areas with frequent deceleration, such as intersections and public transport stops.

PM generated by brake wear originates from friction between brake pads and discs, leading to the release of fine particles enriched in metals such as copper (Cu), zinc (Zn), iron (Fe), antimony (Sb), barium (Ba), and others. These particles can vary in size, morphology, and composition, and often possess unique signatures useful for source apportionment. Their impact is magnified by proximity to human exposure points, especially in dense urban environments.

Monitoring these emissions requires a multi-tiered approach integrating environmental sampling, chemical and morphological analysis, and data interpretation frameworks. Effective protocols must consider ambient PM concentrations, their elemental composition, and meteorological parameters that influence dispersion and deposition. Standardizing these methodologies is essential for supporting emission inventories, validating mitigation strategies, and shaping future regulatory frameworks.

The complexity of NEE characterization stems from the variety of contributing sources and the interaction of emitted particles with ambient environmental conditions. Brake wear emissions often co-occur with other particulate sources, necessitating the development of robust analytical markers and advanced sampling strategies to isolate their specific contribution. Furthermore, the dynamic

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

nature of urban environments demands flexibility in protocol design, allowing adaptation to differing traffic patterns, climate conditions, and site constraints.

Critical components of a comprehensive monitoring strategy include:

- Selection of representative sampling locations reflecting both emission intensity and population exposure.
- Deployment of high-precision equipment capable of capturing and preserving particle integrity.
- Integration of meteorological monitoring to contextualize PM data.
- Analytical techniques tailored to quantify elemental composition and morphological features associated with brake wear.
- Temporal resolution sufficient to differentiate between traffic-related and background pollution levels.

Standardizing the measurement and monitoring of non-exhaust emissions is not merely a technical endeavor but a public health imperative. By establishing reliable data streams and analytical benchmarks, cities and regulatory bodies can make informed decisions regarding vehicle technology, urban planning, and exposure mitigation. These protocols will also facilitate cross-comparative assessments across geographic regions, vehicle fleets, and policy regimes, enabling a coordinated and evidence-based response to the growing challenge of non-exhaust vehicular pollution.

C. Measurement Strategy Overview

The development of a robust measurement strategy for non-exhaust emissions requires a coordinated framework that balances scientific rigor with practical feasibility. The strategy must provide reliable, reproducible, and spatially relevant data on particulate matter concentrations and composition, particularly in areas where human exposure is high.

The core objective of a measurement strategy is to assess the contribution of non-exhaust emissions to ambient particulate matter levels, particularly PM10. This is achieved by combining in-situ monitoring with advanced analytical techniques, enabling both quantitative and qualitative evaluation of emissions. The monitoring campaigns should be designed to capture temporal variations in emissions due to changes in traffic volume, meteorological conditions, and braking behavior.

The measurement strategy comprises the following stages:

1. **Preliminary Site Assessment and Planning**
    - Conduct a scoping analysis to identify suitable monitoring locations based on expected emission intensity and human exposure.
    - Evaluate site-specific constraints such as power availability, safety, accessibility, and interference from other PM sources.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

- Define monitoring periods to capture seasonal variability and peak traffic patterns.

2. **Deployment of Sampling Equipment**
   - Install high-volume air samplers equipped with PM10 inlets at selected locations.
   - Ensure the installation setup minimizes artifacts, protects instruments from environmental damage, and does not obstruct pedestrian pathways.
   - Connect samplers to meteorological stations capable of recording temperature, humidity, wind speed and direction, and solar radiation.
3. **Sampling Duration and Frequency**
   - Plan for multiple sampling periods, including at least one during winter and one during summer to account for meteorological influences on dispersion and particle formation.
   - Collect 24-hour integrated samples over a minimum of five consecutive days for each campaign.
   - Apply consistent timing across locations to enable inter-site comparisons.
4. **Quality Assurance and Calibration**
   - Pre-calibrate all instruments according to manufacturer specifications and international standards.
   - Include duplicate samplers or co-located instruments at a subset of sites to validate data consistency.
   - Use field blanks and standard operating procedures to ensure data integrity.
5. **Sample Collection and Preservation**
   - Use quartz or Teflon filters suitable for gravimetric and elemental analysis.
   - Store samples in clean, sealed containers and refrigerate or freeze during transport to prevent contamination and degradation.
   - Maintain a chain-of-custody protocol to track each sample from field to laboratory.
6. **Data Logging and Documentation**
   - Record metadata for each sampling event, including sampler ID, flow rate, filter type, start/end times, weather conditions, and any anomalies observed.
   - Use digital data loggers and cloud-based storage systems where possible to prevent data loss.

This measurement strategy provides a structured and adaptable approach for reliably assessing brake wear-related non-exhaust emissions. The integration of high-resolution temporal and spatial data allows for fine-grained analysis and facilitates the development of targeted mitigation strategies.

D. Site Selection Criteria

Effective measurement of non-exhaust emissions requires strategic selection of monitoring locations. Site selection should be guided by a combination of scientific, logistical, and policy-oriented considerations to ensure that the data collected is both technically robust and practically relevant.

Key criteria for selecting appropriate monitoring sites include:

1. **Proximity to Emission Sources**
   - Choose locations near known braking zones such as intersections, downhill roads, or public transport stops.
   - Ensure that the site captures real-world driving conditions and representative braking patterns.
2. **Human Exposure Relevance**
   - Prioritize locations where people are likely to be exposed to emissions, such as sidewalks, bus shelters, schools, and commercial areas.
   - Consider both pedestrian and vehicular density to assess exposure risk accurately.
3. **Background Pollution Levels**
   - Include at least one background site away from major roads or urban activities to distinguish local emissions from regional or long-range transported pollution.
   - Use background data for source apportionment and model calibration.
4. **Infrastructure and Accessibility**
   - Ensure the availability of power supply for continuous operation of high-volume samplers and meteorological stations.
   - Assess safety, ease of equipment maintenance, and access for field personnel.
5. **Environmental and Physical Constraints**
   - Avoid locations with obstructive buildings or vegetation that may artificially alter wind flow and dispersion.
   - Take into account prevailing wind direction and urban topography.
6. **Regulatory and Community Considerations**

- Coordinate with local authorities to obtain permissions and inform the public about the purpose of the monitoring activities.
- Avoid disruption to local traffic or pedestrian flow.

7. **Replicability and Comparability**
    - Select sites that allow for replication in other cities or transport contexts to ensure generalizability of the results.
    - Document selection criteria and site characteristics comprehensively.

By adhering to these criteria, monitoring campaigns can produce high-quality, policy-relevant data that informs urban air quality management and vehicle emission control strategies. Site selection plays a foundational role in the reliability and credibility of the entire measurement protocol.

E. Instrumentation and Setup

The choice and deployment of instrumentation are critical to obtaining accurate and reproducible measurements of non-exhaust emissions, particularly particulate matter from brake wear. The recommended instrumentation setup must be capable of capturing PM10 mass concentrations, preserving particulate integrity for chemical analysis, and ensuring continuous and reliable operation in urban environments.

Key instrumentation components include:

1. **High-Volume PM10 Air Samplers**
    - Use samplers compliant with EN 12341:2014 or equivalent standards.
    - Equip with size-selective inlets to ensure only PM10 is collected.
    - Maintain flow rates typically between 1 and 1.4 m3/min.
    - Operate under ambient outdoor conditions with adequate shielding from rain and wind.
2. **Filter Media**
    - Employ quartz filters for gravimetric analysis and elemental detection.
    - Use PTFE or Teflon filters where chemical compatibility is required.
    - Pre-condition and pre-weigh filters in a controlled laboratory environment.
3. **Meteorological Monitoring Station**
    - Integrate sensors to measure temperature, relative humidity, wind speed and direction, and solar radiation.
    - Mount sensors on telescopic masts or buildings near the sampling location to minimize shading and turbulence.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

4. **Power Supply**
    - Secure a stable 220V, 50Hz power source using either street lighting infrastructure or portable battery packs for short-term campaigns.
    - Include surge protection and weatherproof housings to ensure uninterrupted operation.
5. **Data Acquisition and Control Systems**
    - Use digital controllers to manage sampler functions and log real-time flow rate and operational status.
    - Store data locally with remote access options where feasible.
6. **Site Layout and Installation**
    - Place samplers at a height of 1.5 to 3 meters above ground level.
    - Ensure a minimum clearance radius of 1 meter around the inlet to avoid sampling interferences.
    - Use fixed mounting frames or ballast-secured tripods depending on the permanence of the installation.

Instrument deployment should follow a detailed checklist and be documented with site photos, GIS coordinates, and a full inventory of equipment used. Routine inspection, flow rate calibration, and maintenance logs are necessary to ensure continuous data quality and operational stability.

F. Pollutants and Parameters Monitored

The primary focus of non-exhaust emissions monitoring is the assessment of particulate matter (PM10) attributable to brake wear. Accurate characterization of these emissions involves both quantitative measurements of mass concentration and qualitative assessments of chemical and morphological properties.

Key parameters include:

1. **PM10 Mass Concentration**
    - Gravimetric analysis is performed on pre-weighed filters to determine the mass of particulate matter collected over a known sampling period.
    - Results are expressed in µg/m3 and corrected for field blanks and environmental conditions.
2. **Elemental Composition of PM10**
    - Brake wear emissions are characterized by elevated concentrations of metals including Cu, Zn, Fe, Sb, Ba, Mn, and sometimes Pb and Sn.
    - Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or Atomic Emission Spectroscopy (ICP-AES) can be used to quantify these elements.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

- Comparison with reference material or background levels helps identify source-specific enrichment.

3. **Morphology and Microstructure**
   - Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDS) is employed to analyze the shape, size, and surface features of particles.
   - Detection of spherical or flake-like metal-rich particles supports the identification of brake-related sources.
4. **Temporal and Spatial Variation**
   - Time-stamped data allows for correlation with traffic flow, braking frequency, and meteorological shifts.
   - Spatial mapping of concentrations provides insight into exposure gradients and pollutant dispersion.
5. **Meteorological Parameters**
   - Temperature, humidity, wind speed/direction, and solar radiation data are used to interpret pollutant dispersion, deposition, and transformation.

Together, these parameters provide a comprehensive view of the magnitude, composition, and potential sources of non-exhaust particulate matter. They also enable the development of chemical fingerprints for brake wear emissions, which are essential for regulatory monitoring and model validation.

G. Sampling Protocols

Sampling protocols define the procedures and schedules necessary to ensure consistent and valid collection of particulate matter samples for non-exhaust emissions analysis.

1. **Sampling Duration**
   - Conduct 24-hour continuous sampling to align with air quality standards and ensure sufficient mass loading.
   - Consider multiple consecutive days for temporal resolution and weather variability.
2. **Sampling Frequency**
   - Perform seasonal sampling (e.g., summer and winter) to account for meteorological influences on particle behavior.
   - Repeat sampling across weekdays and weekends to capture variations in traffic patterns.
3. **Filter Handling**
   - Use pre-weighed, conditioned filters and record tare mass.
   - Seal filters in labeled, airtight containers immediately after retrieval.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

- Store in refrigerated conditions prior to laboratory transfer.

4. **Operational Procedures**
    - Log flow rates, ambient conditions, and anomalies in a dedicated field journal.
    - Use consistent start and stop times across monitoring sites.

By standardizing sampling protocols, the reliability and comparability of PM10 data across locations and campaigns are significantly enhanced.

H. Laboratory Analysis Protocols

Robust laboratory procedures are essential for deriving meaningful insights from collected PM10 samples. These protocols encompass gravimetric, chemical, and morphological analyses that together provide a comprehensive assessment of non-exhaust emissions.

1. **Gravimetric Analysis**
    - Pre- and post-weigh filters in a temperature- and humidity-controlled environment (20°C, 50% RH).
    - Use a high-precision microbalance (0.1 µg resolution).
    - Apply correction factors for field blanks and filter handling artifacts.
2. **Elemental Analysis**
    - Digest filters using acid mixtures (e.g., HNO3/HF) in closed-vessel microwave systems.
    - Quantify metal content via ICP-MS or ICP-AES.
    - Include calibration standards and replicate analyses for quality control.
3. **Morphological Analysis**
    - Mount filter fragments onto SEM stubs and coat with a conductive layer (e.g., gold or carbon).
    - Perform EDS to obtain elemental maps and spectra.
    - Analyze at least 20 representative particles per sample to establish statistical relevance.
4. **Data Management**
    - Enter results into a centralized database with metadata linking laboratory IDs to field samples.
    - Include QA/QC flags and uncertainty estimates.
5. **Reporting**
    - Provide summary statistics (mean, standard deviation, detection limits).

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

  - Include visual documentation such as SEM images and elemental spectra.

These protocols enable high-fidelity analysis of brake wear contributions to urban PM10 levels and support both scientific research and policy decision-making.

I. Quality Assurance and Calibration

To ensure data accuracy and reliability, rigorous quality assurance and calibration procedures must be followed throughout the monitoring and analysis process.

1. **Instrument Calibration**
   - Calibrate flow rates of air samplers before and after each sampling campaign using certified flow calibrators.
   - Check meteorological sensors against reference instruments.
2. **Field Quality Control**
   - Use duplicate samplers at select locations to evaluate variability.
   - Deploy field blanks to detect contamination from transport, storage, or handling.
3. **Laboratory QA/QC**
   - Include reagent blanks, replicate samples, and certified reference materials.
   - Participate in inter-laboratory comparisons if available.
4. **Documentation and Traceability**
   - Maintain detailed records of calibration certificates, equipment settings, sample custody, and analytical procedures.
   - Store raw and processed data in secure, backed-up databases.

By integrating these measures, the protocol ensures confidence in the resulting emission estimates and supports reproducibility across monitoring campaigns.

J. Data Interpretation and Source Apportionment

The interpretation of data collected through monitoring campaigns enables source-specific assessments and supports regulatory and planning decisions.

1. **Chemical Fingerprinting**
   - Use enrichment factors and metal ratios (e.g., Cu/Zn, Sb/Ba) to identify brake wear signatures.
   - Compare observed profiles with known emission factors from literature or controlled testing.
2. **Source Apportionment Models**
   - Apply receptor models such as Positive Matrix Factorization (PMF) or Chemical Mass Balance (CMB) to deconvolute source contributions.
   - Incorporate meteorological data to refine estimates.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

3. **Comparative Analysis**
   - Assess differences between sites, time periods, and traffic conditions.
   - Evaluate the impact of mitigation measures or technology upgrades.
4. **Integration with Dispersion Modeling**
   - Feed empirical data into atmospheric models to predict population exposure and support air quality planning.

These interpretive tools transform raw data into actionable knowledge and underpin efforts to reduce the public health burden of non-exhaust emissions.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

5 Implementation Recommendations

5.1 Steps for Adoption by Industry

To promote the adoption of the Guidelines by industry actors—including brake system manufacturers, vehicle OEMs, and suppliers—a combination of dissemination, facilitation, and alignment activities should be pursued. These steps aim to ensure that the recommendations formulated in Section 4 become a credible point of reference for the sector, both in anticipation of evolving regulations and in response to increasing attention to non-exhaust emissions.

The first step involves information sharing and awareness raising within industrial and technical communities. This can be pursued through targeted communication activities, including technical workshops, participation in industry forums, and collaboration with sectoral associations. These efforts should highlight the relevance of brake wear emissions, the emerging regulatory landscape (e.g. Euro 7, UNECE TF5), and the practical tools offered by the Guidelines—particularly in relation to material selection, emission testing, and eco-design. Project partners, leveraging their existing networks, can contribute to this dissemination, while encouraging uptake among early adopters and innovation leaders.

A second step is the promotion of dialogue with industry stakeholders to support knowledge transfer and stimulate interest in guideline-aligned practices. This may include informal technical exchanges, contributions to standardization initiatives, or engagement with industry clusters at national or European level. Such exchanges could also help refine specific elements of the Guidelines to enhance their usability across different vehicle platforms or production contexts.

A third recommended action is to support the integration of the Guidelines into voluntary schemes, pilot initiatives, and public procurement criteria, where feasible. While the Guidelines are not intended to be prescriptive, their alignment with anticipated regulatory requirements and environmental goals makes them suitable as a reference for green innovation programs, local fleet renewal strategies, or sectoral sustainability roadmaps. The European Commission and relevant national authorities may be encouraged to consider their incorporation in funding calls, research agendas, or best practice repositories.

Additionally, monitoring the evolution of regulatory and technical standards—and maintaining alignment between the Guidelines and these frameworks—will be important to safeguard their relevance over time. Project partners and interested stakeholders can contribute to this process through knowledge exchange and strategic positioning within relevant expert groups, without requiring formal commitments post-project.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

Finally, encouraging replication and visibility through European networks—including those active in clean mobility, urban air quality, and industrial innovation—will help increase the reach and credibility of the Guidelines. Sharing results with Horizon Europe, LIFE, and EIT Urban Mobility communities, as well as with national transport or environment ministries, will further support adoption, while leaving open the opportunity for future cooperation, refinement, or expansion of the Guidelines in subsequent initiatives.

5.2 Steps for Adoption by Public Authorities

Directive (EU) 2024/2881 on ambient air quality and cleaner air for Europe entered into force on the 10th of December 2024. The recently approved directive is a recast of the previous legislation, updating the common rules and criteria to assess air quality and setting new limit values for the main air pollutants, in order to take into consideration, the latest recommendations of the World Health Organization (WHO, 2021). According to such recommendations, it is necessary to reduce the levels of PM10 to 15 μg/m^3 as an annual average and 45 μg/m^3 as a daily average and the levels of PM2.5 to 5 μg/m^3 as an annual average and to 15 μg/m^3 as a daily average. WHO recommends also monitoring the levels of Black Carbon, ultrafine particles and metals in order to collect all the necessary information to reduce harmful effects of these substances on human health.

Objectives set by the air quality directive are pursued through the reduction of the emissions coming from the main sectors responsible of air pollution. Competent Public Authorities, at national and local level, have to assess the levels of pollutants in their territory, determine which are the main sources of pollution and take all the necessary measures that can reduce pollution.

As previously mentioned, there is a partial awareness of the role that non-exhaust emissions play to determine the contribution of Transport sector on the levels of some pollutants.

The levels of particulate matter in urban areas are determined by different sectors and the relative contributions can vary significantly in different cities. According to the 2023 report "Urban PM2.5 Atlas, Air Quality in European Cities"[1], road transport is one of the relevant sources of PM; in the 150 urban areas examined in the study, the average contribution is 15%, rising to 27% in some cities. Such contribution includes non-exhaust PM emissions due to road abrasion of tires and brake wear, as well as from the off-road emissions sector.

[1] Thunis, P., Pisoni, E., Zauli Sajani, S., Monforti-Ferrario, F., Bessagnet, B., Vignati, E. and De Meij, A., Urban PM2.5 Atlas, Air Quality in European Cities, 2023 Report, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/63641, JRC134950

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union

Non-exhaust emissions are becoming more relevant with the reduction of exhaust and evaporative emissions due to the technological changes promoted by sectoral legislation, and the percentage contribution of them is increasing in recent years. The increase is also due to the circulation of many bigger and heavier vehicles, also in urban areas, that determine an increased amount of particles due to abrasion.

Taking into account the need to reduce significantly PM concentrations in order to reach the new limit values established by directive 2024/2881 and going towards the achievement of the WHO recommended values, reducing this kind of emissions becomes to be more relevant than in past years.

It is important therefore to increase the awareness on this component that has to be taken into account whenever dealing with air pollution, especially in urban areas.

Having in mind the objective of promoting the adoption of the Guidelines by Public Authorities, the following steps should be taken:

1. **Information sharing with policy makers**

   Organizing meetings with policy makers in order to share with them information on the contribution of non-exhaust emissions and illustrate the content of the Guidelines.

   It will be useful to explore the situation of each area and give information on the share of different contributions to total PM coming from different sectors; easily readable data on the possibilities to reduce PM levels acting on a reduction of the non-exhaust component will be really useful to promote actions on this source, integrated by information of the related social and economic costs of the measures.

   Practical suggestions on how to reduce emissions and monitor the progress of implemented actions will be useful to verify the success of the initiatives over the time.

2. **Awareness raising of the population**

   Raising citizens' awareness on this issue will also be helpful in order to reduce the social impact of the reduction measures and to direct people behaviours towards more sustainable and green choices.

   Information campaigns can be designed and implemented to explain in an easy and effective way the impact of personal choices on the level of pollution, always associated to the messages on health impacts of PM and heavy metals concentration in air.

3. **Updating of emission factors and source apportionment**

   Public Authorities, at different levels, have the responsibility to protect their citizens from the negative impacts of air pollutants. Since, according to the

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

recommendation of WHO, the levels of PM should be reduced a lot to reach concentrations that correspond to a minimum risk for human health, it is important that policy makers have at their disposal all the necessary information to implement the right actions.

It will be therefore useful to give them a set of updated and precise emission factors and a clear description of the situation of the area they administrate in order to make the right choices. Cooperation with the science community will represent a key asset in this regard and will give solid basis to the policy strategies.

5.3 Integration into Urban Air Quality Management Plans

Depending on the structure of each urban area, sectoral contributions to the concentrations of particulate matter can vary but, in any case, there will be a percentage of PM coming from road transport. Depending on the average composition of the vehicles fleet circulating in the city, the impact of abrasion to the final amount of PM will have a different weight.

It will be therefore essential to determine the precise contribution of this emission source in the city, during the preliminary technical assessment of any urban air quality plan. The assessment should include also the evaluation of the contribution of traffic routes and the share of local mobility and vehicles coming from outside the Municipality.

Whenever such emission source represents a relevant factor, it will be necessary to consider it in the planning activities and chose the proper actions to reduce its contribution.

The main actions to be taken into account when establishing a urban air quality management plan can include:

1. changes in the fleet used by public authorities, substituting vehicles/brake systems with less polluting ones;
2. changes in the public transport fleet, substituting vehicles/brake systems with less polluting ones;
3. information campaigns to inform citizens on the different impacts of different kind of brake systems;
4. incentives for brake systems change;
5. ban of circulation of polluting vehicles in the low emission zones.

The evaluation of the different possible measures to be adopted and implemented has to include, of course, an evaluation of the efficiency of each solution, including the assessment of the related social and economic impacts.

Considering that primary PM produced by the braking systems contains also heavy metals, such an evaluation should consider also the health impacts of this component and the associated costs of inaction.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.
Co-funded by the European Union

From a general point of view, facilitating the involvement of stakeholders and population in the urban mobility planning can be essential for a successful implementation of the plan.

Exchange of information on implemented best practices between cities and national or international experts and policymakers can be also useful with a view of determining the most effective actions.

6 Conclusions

The LIFE REBREATH project provides a timely and rigorous response to the emerging challenge of non-exhaust emissions in urban mobility, particularly brake wear particles, which are becoming increasingly significant as exhaust emissions decline. Through a multidisciplinary approach that integrates material science, urban air quality monitoring, exposure modelling, and regulatory foresight, the project has produced a set of actionable and science-based guidelines to inform policy, support industry, and protect public health.

One of the main contributions of the project is the demonstration that technological innovation in braking systems—especially in friction material design—can meaningfully reduce PM emissions. The adoption of these technologies is not only technically feasible but also increasingly necessary in light of the revised EU air quality standards and upcoming vehicle emission regulations under Euro 7. Equally important is the development of harmonized methodologies for measuring and monitoring brake wear emissions, ensuring data comparability and supporting enforcement across Europe.

The guidelines presented in this deliverable serve as a foundational tool for cities, manufacturers, and regulators. For public authorities, the recommendations enable the integration of brake emissions into air quality plans and mobility policies, while enhancing their ability to meet the new WHO-aligned PM thresholds. For industry, the roadmap anticipates regulatory evolution and market trends, offering pathways to compliance and environmental leadership.

This project has received funds by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Co-funded by the European Union