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Systematic Review for Brake, Tire, and Road Wear for On-road Light- and Heavy-Duty Vehicles

Final Report

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COORDINATING RESEARCH COUNCIL, INC.

1 CONCOURSE PARKWAY • SUITE 800 • ATLANTA, GA 30328

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Project Title	**Systematic Review of Brake, Tire, and Road Wear Emissions for On-Road Light- and Heavy-Duty Vehicles**
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Prepared for	Coordinating Research Council (CRC), 1 Concourse Parkway, Suite 800 Atlanta, GA 30328, USA
Prepared by	Link Engineering Company and University of California, Riverside – CE-CERT
Project Managers	Carlos Agudelo (LINK)) Zisimos Toumasatos (UCR CE-CERT)
Authors	Carlos Agudelo, Zisimos Toumasatos, Zixuan Gong
Summary	Friction brakes and tires are integral systems or components that are crucial during normal driving and emergency maneuvers [1]. Brakes and tires work together to deliver multiple functions and features, providing safe, comfortable, and cost-effective driving to occupants while protecting vulnerable road users, its cargo, and the vehicle's integrity. Besides providing safe deceleration and holding the car stationary (on demand), friction brakes also perform other functions during driving. E.g., providing full (or partial as part of regenerative braking) decelerating torque, wheel-slip control on dry, wet or icy surfaces; acting during driving (including transverse) dynamics for the Electronic Stability Control (ESC) and Traction Control System (TCS); supplemental transverse dynamics during enhanced understeer control, rollover prevention, or trailer sway mitigation; special driving dynamics for commercial vehicles including directional stability for combination vehicles, and reducing risk of overturning (for single or combination vehicles) during quasi-stationary and dynamic vehicle maneuvers; and automatic brake system operation including pneumatic or hydraulic brake assist, automatic brake pressure increase at the rear wheels, automatic brake pressure increase with forceful brake pedal input, brake disc wiper, automatic prefill, electromechanical parking brake (EPB), hill-hold control, hill descent control, Automatic Emergency Braking (AEB), and active brake application during Automatic Cruise Control (ACC). Tires are the only components that connect the vehicle to the road, providing active safety through the vehicle's power transmission during normal driving and steering, as well as during braking with ABS, ESC, and TCS. Tires also perform multiple functions during driving. E.g., cushion, dampen, brake, accelerate, hold stationary, steer, and transmit vehicle dynamic forces in three directions - simultaneously. Tires can operate on various surfaces, including dry or wet roads, snow, mud, ice, asphalt, concrete, gravel, or dirt roads. Tires need to absorb overloads, roll straight, provide precise intended steering, absorb road irregularities and impacts, and deliver vibration damping and comfort as part of the suspension system. During their life in the vehicle, the contact (intentional or not) between the friction material and its mating disc or drum, and between the tire and the road, friction brakes, tires, and the road itself wear (through highly dynamic and complex mechanisms), releasing wear debris, particulate matter, and gaseous organic and volatile compounds into the road, soil, runoff water, and the atmosphere. To gain a deeper, more comprehensive understanding of non-exhaust particulate matter from brakes, tires, and road surfaces, this report presents a systematic review of over 300 studies, with a focus on recent work. The review evaluates emission factors, test methods, chemical composition, and mitigation strategies, as well as regulatory development, such as Euro 7. The review emphasizes harmonized testing (e.g., GTR 24, CBDC, and UNR[XXX] for C1 tires), identifies key influencing factors, and research gaps for future studies. Although the main methods for brake emissions and tire abrasion have matured significantly over the past several years, a substantial percentage of brake systems and tires sold in the European market today require redesign or reformulation before pursuing type approval in the next decade, as Euro 7 is implemented and comes into force. Test cycles for light vehicles (brakes and tires) have matured into draft European regulations with corresponding limits. Laboratory methods for brake testing cycles for commercial vehicles, as well as laboratory (indoor) or open-road testing, along with the corresponding limits (for brake emissions or tire abrasion index), are on the agenda of multiple working, advisory, or negotiating groups over the next 10 years. Even though testing methods and laboratory setups are well developed for several test cases and applications, the lack of the proper documentation or standard methods, insufficient validation protocols, higher-than-expected or nonexplainable measurement variability, low repeatability / Reproducibility, or absence of recent

	experimental results using realistic test cycles, hinder the ability of researchers (and other stakeholders) to compare among different technical solutions, testing methods, results, and propose limits that both aligned with the objectives of the European Union and other regions, and are achievable by individual vehicle or component manufacturers, including the aftermarket segments. At the time of this report, other countries (e.g., South Korea and China) are considering adopting Euro 7-related limits and regulations, with timelines varying by country. The United States does not have any public announcement related to state or federal proposed rulemaking about non-exhaust emissions from on-road vehicles at the time of this report. Also on tires (except for the ongoing work under the auspices of the United Nations and a few projects in California) it became obvious during the preparation of this report the lack of a new (publicly available) body of knowledge (also more traceable and using standardized methods and reports) on tire abrasion or emissions to quantify the impact of new tire and vehicle technology. Another dimension of developments portrayed in this report includes technologies to mitigate particulate matter generation, ranging from disc coatings to regenerative braking, as well as new brake formulations. New tire compounds or designs and their impact on tire abrasion or tire emissions have not found their way into the world of journal publications at the time of completing this report. Two salient topics related to both brake and tire emissions are the increased interest in measuring volatile organic compounds to account for secondary emissions and more advanced simulations to estimate the transport and fate of particulate matter into natural receptors (e.g., soil, water, air, and ice-covered regions). Lastly, the authors present a series of possible research projects or topics the industry can consider in the future, along with a list of main entities leading research, development, or regulatory work on non-exhaust emissions. This report is not intended to be comprehensive of all studies about non-exhaust emissions. Rather, it highlights important or pivotal studies and encourages the reader to follow closely the development and dynamics of upcoming regulatory work in the European Union, as well as to monitor the development of similar mandates or regulations in other regions over the coming decade. Lastly, with the abundance of research papers and publications, the reader must stay up to date by subscribing to notifications from major scientific journals and actively attending industry events.
Keywords	Brake wear, tire abrasion, non-exhaust emissions, PM_{10}, $PM_{2.5}$, particle number, Euro 7, GTR 24, UNR 117, WLTP, CBDC, LCA, microplastics
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Prepared by	Carlos Agudelo (LINK), Zisimos Toumasatos (UCR CE-CERT)

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Notes

On the use of British/American English language

This report retains British spelling (e.g., tyre, programme, harmonised) when it is part of the original name, study title, or a regulation title. Otherwise, when part of the main discourse, this review report uses the American English spelling (e.g., tire, program, harmonized).

On the use of (...) and [...]

This report uses (…) to denote numerical ranges, examples, or to provide further clarification. […] denotes numbered references or values proposed as part of a regulation at the time of this report.

1 Contents

2 Abbreviations and acronyms

Abbreviation	Description
…/B	Emission factor per brake corner
…/S	Emission factor per stop
…/V	Emission factor per vehicle
3h-LACT	Los Angeles City Traffic Dynamometer Test with a 3-hour duration
3PMSF	Three-Peak Mountain and Snowflake Tire Design for severe snow conditions
ADAC	Allgemeiner Deutscher Automobil-Club (literally 'General German Automobile Club')
AEB	Automatic Emergency Braking
ANOVA	Analysis of Variance
APS®	Aerodynamic Particle Sizer
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems (EU Project)
ATR	Attenuated Total Reflection
BEV	Battery Electric Vehicle
BR	Butadiene Rubber
BSL	Brake Systems Laboratory (formerly a General Motors acronym)
BW	Brake wear

Abbreviation	Description
BWI	Brake Wear Index
BWP	Brake Wear Particles
BWPM	Brake Wear Particulate Matter
C	Friction Brake Share Coefficient for GTR 24; Carbon chemical element
C1	Tires in conformance with UNECE Regulation No. 30 for light vehicles
C1…C21	Straight-chain alkanes for different numbers of C (carbon) atoms
C2	Tires in conformance with UNECE Regulation No. 30 for light vehicles
C3	Tires in conformance with UNECE Regulation No. 54 for light commercial vehicles
CARB	California Air Resources Board
CBDC	California Brake Dynamometer Cycle
CC	Carbon Ceramic
CED	Cumulative Energy Demand
CEM	Conceptual Exposure Model
CFR	Code of Federal Regulations
CMTT	Cryo-milled tire tread
CO	Carbon Monoxide
CoF	Coefficient of Friction
CoV	Coefficient of Variance
C_p	Total torque over brake pressure ratio during chassis dynamometer test
CPC	Condensated Particle Counter
C_r	Rolling Resistance Coefficient
CSO	Combined Sewer Overflow
CVS	Constant Volume Sampling
d_{50}	Particle size corresponding to the cumulative frequency of 50 % (median)
$d_{e.}^{mob}$	Electrical mobility diameter of a particle
d_i	Internal duct diameter
DCE	Danish Centre for Environment and Energy
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPMFA	Dynamic Probabilistic Material Flow Analysis
DQIS	Data Quality Indicator Source
EC	Elemental Carbon (refer to the context)
EC	European Commission (refer to the context)
ECE	Economic Commission for Europe
ECE	Generic term for metallic friction formulations designed for the ECE market
ECEotp	ECE formulation optimized for brake emissions
EDS	Electron Dispersion Spectroscopy
EDX-RF	Energy-dispersive X-ray fluorescence spectrometry
EEA	Environmental European Agency
EEPS®	Engine Exhaust Particle Sizer
EF	Emission factor
ELPI®, ELPI+®	Electrical Low-Pressure Impactor
ELT	End-of-Life Tires
EMFAC	EMission FACtor model
EPB	Electromechanical Parking Brake
ESC	Electronic Stability Control
ESM	Environmental Scanning Electron Microscope
ETH	Equivalent Test Weight
ETRTO	European Tire and Rim Technical Organization
ER	Energy Recovery
FA	Front Axle
FA/RA	Front to Rear axle brake work or test inertia split

Abbreviation	Description
FAST/KIT	Institute of Vehicle System Technology (translated) at the Karlsruhe Institute of Technology
FR	Friedrichstrasse (location in Berlin, Germany)
FTP	Federal Test Procedure
FTIR	Fourier transform infrared spectroscopy.
GAD	Gaseous Analytical Detector
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies Model
GAM	Generalized Additive Model
GBM	Gradient-Boosting Machines
GCI	Grey cast iron
GC-MS	Gas chromatography-mass spectrometry
GHG	Greenhouse Gases
GNSS	Global navigation satellite system
GPS	Global positioning system
GRBP	United Nations Working Party on Noise and Tires
GRPE	United Nations Working Party on Pollution and Energy
GTR	Global Technical Regulation
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
HCN	Hydrogen Cyanide
HDV	Heavy-Duty Vehicle
HD-HS	Highly Dispersible – High Surface area
H_e, H_s	Dimension for sampling tunnel (see GTR 24)
HEPA	High Efficiency Particulate Air (filter)
HEV	Hybrid Electric Vehicle
HLW	Heavily Loaded Weight
HMC	Hard Metal-coated disc
HNCO	Isocyanic Acid
H-PEM	Harvard Personal Environmental Monitor
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicles
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ILS	Interlaboratory (accuracy or variability) Study
IMU	Inertial Measurement Unit
IN	Industrial Roadside
ISO	International Organization for Standardization
JASIC	Japan Automobile Standards Internationalization Center
JASO	Japanese Automobile Standards Organization
JATMA	Japanese Automotive Tire Manufacturers Association
JRC	Joint Research Centre
KD	Kottbusser Damm (location in Berlin, Germany)
LCA	Life Cycle Assessment
LC/MS	Liquid chromatography-mass spectrometry
LCS	Low-Cost Sensors
LDV	Light Duty Vehicle
LOD	Level of Detection
LO-U	Level 0- Universal Fixture for testing according to GTR 24
LO-P	Level 0- Post Style fixture for testing according to GTR 24
Low-met	Low metallic friction material
M_1	Passenger transport car with no more than eight seats in addition to the driver's seat, and has a maximum mass not exceeding 3500 kg
ML	Machine Learning
MMDPI	Multidisciplinary Digital Publishing Institute

Abbreviation	Description
MFC	Mass flow controller
MP	Microplastics
MOUDI™	Micro Orifice Uniform-Deposit Impactors
MOVES	Motor Vehicle Emission Simulator
N_1	Good transport motor vehicles with a gross vehicle weight not exceeding 3,500 kg (3.5 tons)
NAEI	The UK National Atmospheric Emissions Inventory
NAO	Non-Asbestos Organic friction material
NEDC	New European Driving Cycle
NHTSA	National Highway Traffic Safety Administration
NO	Nitric oxide, nitrogen oxide, or nitrogen monoxide
NOAA	National Oceanic and Atmospheric Administration (United States)
NO_2	Nitrogen Dioxide
NOx	shorthand for nitric oxide (NO) and nitrogen dioxide (NO_2)
NR	Natural Rubber
OBD	Onboard diagnostics unit
OC	Organic Carbon
OES	Original equipment service part
OPC	Optical Particle Counter
OPS	Optical Particle Sizer
PAM	Potential Aerosol Mass
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PCA	Principal Component Analysis
PCH	Phenylcyclohexene
PM	Particulate matter
PM_{10}	Particulate matter with an average aerodynamic diameter not exceeding 10 µm
$PM_{2.5}$	Particulate matter with an average aerodynamic diameter not exceeding 2.5 µm
PM_1	Particulate matter with an average aerodynamic diameter not exceeding 1 µm
$PM_{0.12}$	Particulate matter with an average aerodynamic diameter not exceeding 10 µm
PMF	Positive Matrix Factorization
PMP-IWG	Particulate Measurement Programme – Informal Working Group
PN	Particle Number
PSD	Particle size distribution
PTFE	Polytetrafluoroethylene
PTR-MS	Proton-transfer-reaction mass spectrometry
py-GC-MS	Pyrolysis GC-MS
QCM®	Quartz Crystal Microbalance
Q_{max}, Q_{min}, Q_{set}	Cooling airflow levels during the GTR 24 test
Q_{out}, P_{out}, T_{out}	Outputs values for airflow, airflow pressure, and airflow temperature during the GTR 24 test
RA	Rear Axle
RD	Road dust
RDE	Real-world Driving Emissions
RRTP	Runoff Treatment Plant
RS	Residential Roadside
RTWP	road- and tire-wear particles
SAE	Society of Automotive Engineers
SBR	Styrene Butadiene Rubber
SEM	Scanning Electron Microscopy
SF-ICP-MS	Magnetic-Sector Inductively Coupled Plasma Mass-Spectroscopy
SFW	Specific friction work
SIA	Secondary Inorganic Aerosol
SL	Silt Loading
SMPS®	Scanning Mobility Particle Sizer

Abbreviation	Description
SPA	Single Particle Analysis
SPN10	Solid particle number with a lower cutoff diameter of 10 nm
S_Q, S_P, S_T, S_{RH}	Output signals for airflow, air pressure, air temperature, and air relative humidity during the GTR 24 test
StdDev, STD	Standard Deviation
STA	Simultaneous Thermal Analyzer
STEM	Scanning Transmission Electron Microscope
SUV	Sport Utility Vehicle
SVM	Support Vector Machines
TARTA	Toxic-metal Aerosol Real Time Analyzer
TCS	Traction Control System
TCWB	Taiwan Central Weather Bureau
TEM/ SEM	Transmission/scanning electron microscope
TF TA	Task Force on Tyre Abrasion within the UN GRBP
TfL-UIP	Transport for London, Urban Inter-Peak drive cycles
TGA	Thermogravimetric analysis
TOC	Total Organic Carbon
ToF-SIMS	Time-of-flight Secondary Ion Mass Spectrometry
TP	Transformation products
TPN10	Total particle number with a lower cutoff diameter of 10 nm
TPN23	Total particle number with a lower cutoff diameter of 23 nm
TRWP	Tire And Road Wear Particles
TSP	Total Suspended Particles
TSS	Total Suspended Solids
TT	Tire tread
TWP	Tire Wear Particles
UB	Urban Background
UCBR	Upper Colorado River Basin
UFP	Ultrafine Particles
UNECE	United Nations Economic Commission for Europe
UPLC-HRMS	Ultra-Performance Liquid Chromatography – High-Resolution Mass Spectrometry
UTQG	Uniform tire quality grading
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
VPR	Volatile Particle Remover
WAS	Whole Air Sampler
WIP	Waste Incineration Plant
WL/DM	Wheel Load/Disc Mass ratio
WLTC	Worldwide Harmonized Light-duty vehicles Test Cycles
WLTP-B	Worldwide Harmonized Light Vehicle Test Procedure
WWTP	Waste Water Treatment Plant
XRF	X-Ray Fluorescence

3 High-level findings

In the face of upcoming or potential rulemaking, the field of non-exhaust emissions research and measurement has experienced significant growth over the past decade. Some of the main findings from this systematic review include the following for Research Questions 1-7 (see Chapter 6). There are multiple nuances and specifics to the different studies covered by this report, so it is important to gain a deeper understanding before drawing hard conclusions:

Brakes	Tires
RQ1: Magnitude of non-tailpipe PM emissions	
Overall, PM_{10} using laboratory testing is about 8.9 mg/km/Brake, and $PM_{2.5}$ is 5.6 mg/km/Brake	Overall, PM_{10} using laboratory testing is about 5 mg/km/Tire, and $PM_{2.5}$ is 1.6 mg/km/Tire
Recent interlaboratory testing using harmonized setups per GTR 24, PM_{10} is about (1.4 to 8.7) mg/km/Brake, and $PM_{2.5}$ is (0.7 to 3) mg/km/Brake	Median TRWP can be (20 to 30) mg/km per tire, and (53 to 1500) mg/km/V, considering from passenger cars to heavy-duty trucks
Front brakes can generate three or more times more PM_{10} than rear brakes	
RQ2: Test methods to generate non-tailpipe PM	
The prevailing method to generate brake emissions is to use inertia dynamometer test setups, conducting cycles to recreate normal vehicle driving, as a function of the vehicle's vocation	The main method to generate tire abrasion is to drive the vehicle on public roads to recreate normal vehicle driving, or to conduct an engineered cycle using an indoor drum test setup
Overall, testing under the current GTR 24 proposal, approximately half of the friction formulation in the market for light vehicles would exceed the Euro 7 limit for PM_{10}	Overall, approximately 30 to 40% % of C1 tires could be removed from the market for non-compliance with the proposed abrasion index limits
Overall, as much as 60 % of light vehicle brakes may need redesign, reformulation, or regenerative braking to comply with the Euro 7 limits	
RQ3: Characterization of non-tailpipe PM	
Particle size distribution tends to exhibit a multimodal distribution, with main peaks at (10 to 12) nm, (50 to 80) nm, and (1 to 2) µm	In general, PM_{10} is assumed to be (2 to 10) % of total tire abrasion, and $PM_{2.5}$ is 1.6 %
Carbon, Magnesium, Chromium, Iron, and Phosphorus exhibit a positive correlation with brake wear and particulate mass generation. Sodium, Calcium, Barium, Oxygen, Potassium, and Titanium exhibit negative correlations	Chemical composition, morphology, and particle size distribution focused on rubber compounds, volatile organic compounds, and tracer elements to correlate with the tire under testing
Chemical analysis can detect over 20 elements using a GTR 24 test setup	Most analysis methods demand extensive and highly specialized techniques
There is a positive association (or trend) between an increase in brake wear and PM emissions	There is a negative association (or trend) between decreasing tire tread wear and tire mileage durability
RQ4: Test methods (measurements) to characterize non-tailpipe PM emissions	

Brakes	Tires
Gravimetric sampling for particle mass and particle counters provide sampling systems for brake emissions within the scope of European regulations	The primary measurement for tire abrasion within the scope of European regulations relies on tire mass loss during the test
Other instruments utilized during non-regulatory testing (benchmarking, research, or product development) also rely on particle size distribution systems, volatile compound analyzers, airborne metal detection, and extensive post-test chemical speciation analysis	Basic measurement or sampling instruments for tire emissions are similar to those used for brake testing. Chemical analysis requires specialized methods depending on the objective of the study (e.g., environmental sampling; road, sediment, water deposition; air sampling; morphology)
Most test setups are migrating towards fully enclosed sampling systems	Background emissions remain a challenge during the design and validation of laboratory or road measurements for tire emissions
On-road measurement campaigns are increasing, with no methodology available for peer-reviewed validation of sampling and transport efficiency	

RQ5: Strengths or weaknesses of test and measurement methods

Particulate matter from the friction material does not occur independently, without pristine friction material found available in the environment	Particulate matter from the tire does not occur independently, without pristine tire wear particles found in the environment
The use of the GTR 24 and the CBDC test has provided an industry or agency-endorsed test cycle, respectively, for light-duty vehicles	The lack of harmonization for tire emissions nomenclature and reporting metrics may lead to misunderstanding or incorrect results, and create challenges in comparing results
With proper instrumentation and measurements, brake temperatures during dynamometer testing can be within 20 °C compared to proving ground measurements for ICE vehicles, and within 10 °C for Hybrid or BEV vehicles	Development is needed for standard methods targeted by the type of evaluation (by environmental compartment and bulk/single particle)
Current brake dynamometer controls allow the recreation of regenerative braking in real-time during emissions testing	Future projects can generate specific and systematic data on the chemical composition of current and future tires
	Published emissions estimates are traced to a few studies, half of them over 50 years old, and sometimes applied incorrectly to official emission inventories

RQ6: distribution of non-tailpipe PM from their point of source

Brake abrasion (wear) can account for approximately 50% of airborne emissions from transport systems, with unknown amounts attributed to wheels and chassis, road surfaces, soil, or water. Other studies show that brakes can contribute up to 18 %	Some studies show that road dust can account for up to 33 %, and tires for up to 11 %
	Tire contribution to PM_{10} can be (0.3 to 4.5) % overall, and (5 to 31) % to road transport, with road transport being (10 to 15) % of total PM_{10}
	Global MP emissions can range from 800 to 3000 kt/year, and tire contribution to MP emissions can be (47 to 62) %

Brakes	Tires
TQ7: factors known to control or influence non-tailpipe PM emissions	
Real-time particle count increases linearly (in the log-log scale) with kinetic energy Regenerative braking can reduce PM_{10} by (60 to 98) %, while changing from LM to NAO can reduce PM_{10} by up to 80 %, and adopting hard-coated discs can reduce PM_{10} by about 75 % PM_{10} Front-to-rear can be up to 3.5:1; GCI disc with ECE friction, to HMC with Hybrid friction that can be up to 3.8:1	Tire construction and structure, road surface (micro- and macrotexture), and lateral acceleration contribute most to tire abrasion. Type of tire (summer, winter, studded), treadwear resistance, tire load, toe angle, road material/binder, longitudinal acceleration, and braking are the next group of influencing factors So far, the work within the European Commission still exhibits some differences between on-road convoy and indoor tire abrasion testing results, both using a reference tire

This systematic review, instead of presenting the entire body of research over the past 20+ years, focused on the main studies and recent developments that can support the implementation of upcoming rulemaking, the rollout of new technologies and designs to mitigate anthropogenic emissions, and the deepening of the science behind particle formation, emission, dispersion, and ultimately transport into earth systems (air, water, and soil).

3.1 Overall emission factors for brake and tire wear

As shown in Figure 1, data from multiple studies [2] and emissions inventories [3] confirm the anecdotal evidence that a large portion of current friction couples (brake pads and discs, brake shoes and drums) need reformulation, redesign, electrification, or a combination to ensure compliance with Euro 7 [4]. Similarly, under the current proposal for tire abrasion limits, approximately 30% of the tires offered in the market will be removed. The Total Suspended Particles (TSP) values (including but not limited to PM_{10} and $PM_{2.5}$) for brake and tires, shown in Figure 1, were derived using the Tier 2 methodology from [2] including the speed-dependency of tire and brake wear, based on the “detailed Methodology” from the previous version of the [2] Guidebook. The values shown report the average and the 95% confidence interval computed from [5].

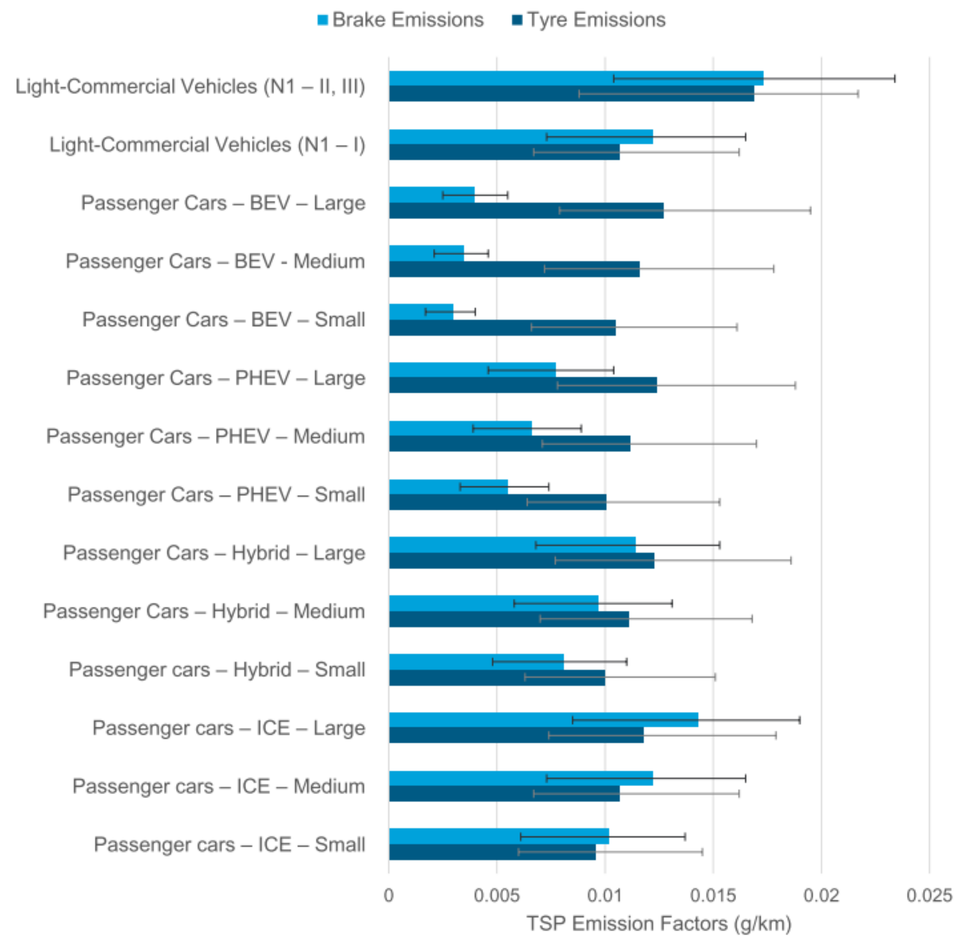

Figure 1 – Emission factors from tire and brake wear for light-duty vehicles from [3]

In addition to the actual levels, the combined variability of test results (e.g., vehicle type, brake or tire design, composition, testing or measurement process, tribology, actual particle generation mechanisms, manufacturing process) increases the risk of non-compliance for emissions factors (brakes), or abrasion index (tires).

3.2 Emission factors for brake particulate matter and tire abrasion

Main test methods for brake emissions measurements

Nevertheless, the industry has coalesced around a few core methods and measurement systems to characterize non-exhaust emissions, bringing the test methods closer to road conditions and reducing the variability (particulate mass emissions for light vehicle brakes) and enhancing the correlation between on-road and laboratory (indoor) testing (abrasion index for light vehicle tires). The laboratory method from GTR 24[1] (UN regulation that defines a standardized laboratory procedure for measuring brake particle emissions from light-duty vehicles) [6] and the CBDC (California Brake Driving Cycle is a dynamometer-based test cycle designed to replicate real-world braking behavior observed in California driving conditions) [7] for light vehicles' brakes, and the proposed development of a new UN Regulation (derived from UNR 117 [8]) for C1 tires[2] have emerged as the primary industry test protocols. In both GTR 24 and CBDC test procedures, the brake assembly is mounted on an enclosed brake dynamometer and subjected to a controlled test cycle. For the GTR 24, a 4-hour WLTP brake cycle with approximately 300 braking events is used to simulate real-world

[1] GTR 24 is a foundational standard for the Euro 7 regulation, which incorporates its methodology to regulate brake emissions starting in 2025

[2] A C1 tire refers to a passenger car tire under the EU tire classification system. According to Regulation (EU) 2020/740, which came into effect on May 1, 2021, tires are categorized into three classes: C1: Passenger car tires, C2: Light commercial vehicle tires, C3: Heavy-duty vehicle tires (e.g., trucks and buses).

driving conditions. In the CBDC, the cycle is tailored to reflect typical urban and suburban driving patterns in California. Conditioned air, filtered and regulated for temperature and humidity, is supplied at a specified flow rate during the sampling process. This air stream carries brake wear particles downstream to a sampling system, where emissions are measured for particulate mass (PM_{10}/$PM_{2.5}$) and particle number (PN) using instruments such as gravimetric filters, condensation particle counters (CPCs), and optical particle sizers (OPS). Test methods for commercial vehicles (including trailers, the effect of retarders, and methods to determine worst-casing for laboratory tests), deeper understanding of the effects of different powertrain capabilities and configurations, convoy and laboratory test methods for commercial vehicles' tires, better understanding of the relationships between tire abrasion and tire emissions, and repeatable and reproducible on-vehicle brake and tire emissions measurements remain open questions for the industry, researchers, environmental agencies, and regulators. It is also evident that many studies could benefit from more rigorous data reporting, using standardized metrics and greater transparency. This approach would enable more accurate statistical assessments and potentially reduce the industry's overall testing burden. This systematic review highlights the expertise already developed in multiple collaborative initiatives amongst industry, academia, and regulatory agencies. CRC could serve as a platform for industry to liaise with and coordinate with various stakeholders' joint efforts to experimentally address some of the most pressing industry needs as part of an overall effort to reduce non-exhaust particulate emissions from on-road vehicles.

When comparing emission factors (EFs) across studies, a notable discrepancy arises between values reported in emissions inventories and those measured in modern, fully enclosed laboratory systems. Specifically, brake wear EFs from inventories are often at least twice as high as those obtained from controlled tests using the WLTP-Brake (WLTP-B) cycle. This overestimation is likely due to the continued reliance on legacy data derived from high-energy test cycles and older friction formulations, which do not reflect current vehicle technologies or regulatory test procedures. Similarly, for tires, only a small fraction of total abrasion contributes to airborne particulate matter: PM_{10} emissions typically account for only 2–10% of total tire mass loss. These findings underscore the importance of updating emission inventories with data from harmonized, modern test methods to ensure accurate representation of non-exhaust sources in regulatory and environmental assessments. Regarding wear studies for tire wear particle emissions, a recent study [9] found that only 12% of country-based emissions calculations use direct experimental data, while most (63%) rely on reviews. Additionally, many studies relied on multiple levels of reviews instead of the original data. Beyond the 1970s, only three studies (circa 1997, 2004, and 2021) report experiments on passenger card driving under real-world field conditions. Not until the kickoff of the Task Force on Tyre Abrasion (TF TA) within the Working Party on Noise and Tyres (GRBP) of the United Nations, has the industry been able to accrue a large set of field data on tire abrasion under controlled conditions and with extensive peer review.

Economic impact and cost-benefit analysis

One dimension related to reducing brake emissions and tire abrasion concerns the economic impact and overall cost-benefit of addressing non-exhaust emissions under the upcoming Euro 7 regulation. In 2022, the European Union completed and published an extensive impact assessment study [10]. The study addresses upcoming regulations related to exhaust emissions, battery-electric vehicles, and non-exhaust emissions. The analysis considers three policy options from different perspectives (effectiveness, efficiency, coherence, and proportionality). Further assessments by industry groups[11], [12] have looked at the Euro 7 regarding topics such as:

- Productive or counterproductive for the environment?
- Helping or hindering decarbonization?
- Cheap or expensive?
- Easy or complicated?
- More or less stringent than other global standards?
- Realistic or unrealistic timings?
- Good or bad for industry competitiveness?

And concluded that the proposed Euro 7 emissions regulations (including all aspects affected by them) would lead to a direct cost increase of between four and ten times higher than those estimated by the European Commission.[3]

Measurements and assessment beyond regulatory compliance

Recent studies have significantly advanced the characterization of non-exhaust particulate matter (PM) from both brake and tire wear. These efforts include detailed analyses of particle size distributions (PM_{10}, $PM_{2.5}$, and ultrafine particles), morphology, chemical composition (e.g., metals such as Fe, Cu, and Zn, as well as organic compounds), and volatility. Techniques such as electron microscopy, thermal-optical analysis, and real-time particle counters have been employed in both laboratory and on-road settings, enabling differentiation between source types and supporting the development of regulatory tests.

In terms of dispersion, research has shown that particle size and environmental conditions critically influence the fate of emitted PM. Ultrafine and fine particles can remain airborne for extended periods and travel considerable distances, contributing to near-road and regional air quality impacts. Modeling studies and field measurements confirm that larger particles tend to deposit near the source. At the same time, finer fractions disperse more broadly, with vehicle aerodynamics, road type, and meteorology playing key roles in transport and deposition patterns.

Lastly, as the research from several studies shows, the laboratory and field measurement of chemical speciation, volatiles, and semi-volatiles compounds (for brakes and tires), and electrical charge opens new research avenues to gain a deeper understanding of submicron particle formation and fate, and to better explain the complex tribological and temporal behavior of non-exhaust emissions.

High-level influencing factors

As for influencing factors to brake emissions, *ceteris paribus* [13], the main ones include. Unfortunately, the study does not provide relative rankings because the rankings are not fixed across the different factors due to confounding effects and interactions. E.g., certain friction formulations, when new, can exhibit higher emissions when mounted on the rear axle of vehicles loaded to their gross axle rating:

- **Friction couple design and formulation:** metallic-based formulations increase particle emissions
- **Brake type:** disc brakes increase particle emissions
- **Axle position:** front brakes increase particulate emissions
- **Test or driving mass:** heavier vehicles increase particle emissions
- **Friction couple conditioning:** non-burnished (new or green) brakes increase particle emissions
- **Test cycle or real-world driving:** high-speed, mountain descent, elevated temperatures, or aggressive driving increase particle emissions

And, some factors influencing tire abrasion, *ceteris paribus* [14]:

- **Topography:** mountainous regions increase tire abrasion
- **Driving surface:** a concrete surface, compared to an asphalt surface, increases tire abrasion
- **Weather conditions:** wet road surfaces cause higher tire abrasion[4]

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[3] Anecdotal information from a medium-sized European manufacturer of light duty passenger and cargo vehicle, indicated that the direct cost of developing a new friction formulation (while keeping the same brake design and sizing) can cost between half-million and one million euros, with testing (including but not limited to brake emissions limits) accounting for approximately 250,000 euros. Such a process could take from 18 to 24 months. These figures do not consider significant changes to the brake disc design or material, or multiple iterations to comply with other applicable requirements related to noise, stopping distance, durability, comfort, corrosion protection, or production readiness.

[4] Generally, tires tend to wear less on wet surfaces compared to dry surfaces, assuming normal driving conditions and no excessive slipping due to reduced friction and lower temperature. However, there are important caveats (a) Slippage/Skidding: If the tires lose traction and slip or hydroplane on a wet surface (due to excessive speed, worn tread, or sudden maneuvers), this will cause very rapid and uneven wear. While the overall friction is lower, the localized friction during a slip can be intense; (b) Road Contaminants: Rain can mix with oil, dirt, and other debris on the road, creating a slippery film that can still contribute to wear, especially if it leads to more frequent minor slips; (c) Driving Style: Aggressive driving (hard braking, rapid acceleration, sharp turns) will always increase tire wear, regardless of whether the surface is wet or dry. If a driver compensates for wet conditions by driving more cautiously, this can further contribute to

- **Air temperature:** average driving temperature influences different tires in different ways
- **Vehicle weight:** the higher the vehicle weight, the higher the tire abrasion
- **Axle geometry:** sporty chassis setup increases tire abrasion
- **Engine (powertrain) characteristics:** higher torque increases tire abrasion
- **Driving speed:** higher speed causes higher tire abrasion
- **Driving style:** proactive, fuel-efficient driving reduces tire abrasion

3.3 Current development to implement type approval for brake emission and tire abrasion in Europe

The European Union is working towards imposing limits on brake emissions and tire abrasion, effective from late November 2026 for light vehicles and until 2036 for all tires put on the market for heavy commercial vehicles. Under the Euro 7 emission regulation, the European Union has introduced brake particulate matter (PM_{10}) emission limits for light-duty vehicles to address non-exhaust emissions. Methods and future limitations applicable to medium- and heavy-duty vehicles are currently under discussion. Additionally, Euro 7 includes provisions to limit tire abrasion index during the 2026-2036 period to achieve net-zero emissions by 2050.

The limits and timelines for non-exhaust emissions or abrasion limits are ultimately agreed upon through a “trialogue” among the European Commission, the European Parliament, and the European Council. The input to the exchange comes from multiple stakeholders and is documented on the Terms of Reference [15] . The main non-governmental stakeholders include:

- The Advisory Group on Vehicle Emission Standards (AGVES); no website
- European Automobile Manufacturers’ Association / Association des Constructeurs Européens d'Automobiles (ACEA) ACEA - European Automobile Manufacturers' Association
- European Association of Automotive Suppliers (CLEPA) CLEPA | European Association of Automotive Suppliers
- European Tyre & Rim Technical Organisation (ETRTO) https://www.etrto.org/
- FuelsEurope FuelsEurope - European Fuel Manufacturers Association - FuelsEurope
- Gmobility, formerly Natural Gas Vehicle Industry (NGVA) NGVA Europe becomes Gmobility - LNG Prime
- International Road Transport Union (IRU) IRU | World Road Transport Organisation
- International Organization of Motor Vehicle Manufacturers / Organisation Internationale des Constructeurs d'Automobiles (OICA) www.oica.net
- Association of the German Automotive Industry / Verband der Automobilindustrie (VDA) https://www.vda.de/de

The current limits for brake emissions are shown in Table 1 below are the different vehicle categories for passenger cars, buses, and trucks. Task Force 3 and Task Force 5 (TF3 and TF5) within the UNECE/PMP/GRPE are working on Amendment 3 of the GTR 24 (including a transition to a UN Regulation) and on defining the test setup, test cycle, and brake families for commercial vehicles, respectively.

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reduced wear; and (d)Tire Type and Design: Tires designed for wet conditions (e.g., winter tires, some all-season tires) have specific tread patterns and rubber compounds to optimize water displacement and grip. These tires are built to handle wet conditions, but their overall wear characteristics can still vary.

Table 1 – Euro 7 limits and timeline for brake emissions

Date	Application	Powertrain Type	Limit per Vehicle M_1 – passenger cars. M_2 – medium buses. M_3 – heavy buses. N_1 – light trucks. N_2 – medium trucks. N_3 – heavy trucks			
			Type	M_1/N_1 Class I & II	N_1 Class III	M_2/N_2 and M_3/N_3
From: 29 November 2026	• New vehicle types • Components and systems for type-approved vehicles	Battery Electric Vehicles	PM_{10}	3 mg/km	5 mg/km	none
			PN	none	none	none
		Others (hybrid, fuel cell, and ICE)	PM_{10}	7 mg/km	11 mg/km	none
			PN	none	none	none
From: 29 November 2027	• New vehicles • Components and systems for those vehicles	Battery Electric Vehicles	PM_{10}	3 mg/km	5 mg/km	none
			PN	none	none	none
		Others (hybrid, fuel cell, and ICE)	PM_{10}	7 mg/km	11 mg/km	none
			PN	none	none	none
From: 1 January 2030 to 31 December 2034	• New vehicles • Components and systems for those vehicles	Battery Electric Vehicles	PM_{10}	tbd	tbd	tbd
			PN	tbd	tbd	tbd
		Others (hybrid, fuel cell, and ICE)	PM_{10}	tbd	tbd	tbd
			PN	tbd	tbd	tbd
From: 1 January 2035	• All vehicles • All components and systems	All Powertrain Technologies	PM_{10}	3 mg/km	3 mg/km	tbd
			PN	tbd	tbd	tbd

None = not applicable
tbd = to be defined
Timeline for replacement (aftermarket) not included

Table 2 shows the target limits for the abrasion index, including the abrasion margin allowance to account for the complexity of the abrasion level measurement methods and special characteristics of special tire groups. The allowances [0.15 and 0.20] are under discussion at the time of this report.

Table 2 – Euro 7 limits and timeline for tire abrasion

Vehicle category	Effective date and limits for each type of tire		
	New type approvals	All tires on new vehicles	All tires put on the market
C1 tires (cars and light commercial vehicles)	1 July 2028 AICT Normal tire [1.00] AICT Snow tire [1.00] AICT Special-use tire [not defined]	1 July 2030 Normal tire [1.00] Snow tire [1.00] Special-use tire [not defined]	1 July 2032 Normal tire [1.00] Snow tire [1.00] Special-use tire [not defined]
C2 tires (medium load heavy-duty vehicles)	1 April 2030	1 April 2032	1 April 2034
C3 tires (high-load, heavy-duty vehicles)	1 April 2032	1 April 2034	1 April 2036

"*Abrasion index" (AICT)* means the dimensionless value for expressing the tire abrasion level of a candidate tire relative to that of the applicable Standardized Reference Test Tire (SRTT).

4 Overview

4.1 This systematic review

This work is a systematic review that consolidates knowledge on emission factors, physical and chemical characterization, measurement technologies, contributing factors, and strategies for mitigating particulate matter emissions from brakes, tires, and roads for light and heavy vehicles.

As tailpipe Particulate Matter (PM) emissions from light-duty (LD) vehicles declined, other PM emissions became more critical. LD vehicles emit at least 5 types of PM: tailpipe emissions, brake wear, tire wear, road wear, and resuspended road dust. Although measurement methods are still in development, total combined PM emissions for brakes, tires, and road wear are estimated at 30 mg/mi. This magnitude exceeds the tailpipe PM regulatory limit of 3 mg/mi on the Federal Test Procedure (FTP) and the state of California's 1 mg/mi limit on the FTP. Battery Electric Vehicles (BEVs) emit four of the five PM types, except for tailpipe PM. Government regulatory agencies, including the EPA and the California Air Resources Board, have studied certain types of non-tailpipe PM, including PM from brake and tire wear reported by [16], [17]. Although it is unclear when or if U.S. regulatory limits will be proposed for vehicle non-tailpipe PM emissions, we aim to increase understanding of this topic.

The questions addressed by this systematic review included the magnitude of non-tailpipe emissions; test methods to generate particulate matter; main physical properties and chemical composition; methods to characterize non-tailpipe emissions; strengths and weaknesses of the different test and measurement methods; distribution and fate of particulate matter from brakes and tires; and factors that influence the non-tailpipe emissions (e.g., design and composition, vehicle mass, powertrain).

The main boundary conditions for selecting the included studies are: work published no earlier than 2008; studies with numerical results to substantiate their findings; and publications released or presented by the main industry working groups researching or developing technology to measure and mitigate non-tailpipe emissions.

With a few exceptions, the cutoff date for the main literature searches was April 1, 2025. The methods used to assess the risk of bias included the date of publication, single-brake or single-tire studies, one-time circuits without feasibility for repeatability, and subjective ratings without numerical evidence. To synthesize the results and findings, the review primarily focused on assessments supported by data from leading authors (with known contributions to developing knowledge on non-exhaust emissions), technical experts with active industry engagement, reputable academic institutions, government entities, or environmental agencies. The research team preparing this systematic review leveraged their direct involvement in non-exhaust measurements, research, testing, and contributions to working groups as an additional perspective for curating studies and reports.

The primary methods for sourcing included curated web resources and publicly available studies presented to industry working groups on non-tailpipe emissions.

Some salient factors that can introduce risk of bias or uncertainty include the use of dated test methods, retired vehicle applications or product designs (such as brakes or tires) or formulations, one-time studies with insufficient details to replicate them, or reliance on older databases and simulation tools. Research questions organize the presentation of results throughout the systematic review, as agreed upon with the CRC Panel. This prioritizes findings and numerical results from recent large studies on brake and tire emissions, consolidates numerical findings that substantiate the conclusions, and provides evidence traceable to other studies and specific measurement or testing campaigns. The entire database includes 286 studies. The main database selected for assessment contains 140 studies (50 on tires and 90 on brakes) organized by indexing number, DOI identifier, first author, article title, source, year, vehicle type (light or heavy), and specific entries to address the research questions.

The studies are broadly split into three main categories:

1. Systematic reviews about specific topics (e.g., brake or tire emission factors for different types of vehicles)

2. Targeted studies (e.g., effects of propulsion systems on brake emission factors, or chemical speciation of particulate matter, emission factors for different friction materials and vehicle types under specific test cycles)
3. Reports and proposals to industry working groups with experimental evidence (e.g., tire abrasion rates for different tire designs, variability of tire abrasion for different test methods, results from interlaboratory studies)

4.2 Aggregated emission factors for particulate matter for brakes and tires

Comparing (and normalizing to vehicle-level emission factors) two datasets from the studies reviewed (both combining different vehicles and friction materials, and average vehicle test mass of 1860 kg with covariance of 25 %), set 1 with 68 tests with multiple test setups and test cycles, and set 2 with 90 tests using the GTR 24 test setup and cycle:

- PM_{10} increases by about 35% from set 1 to set 2
- $PM_{2.5}$ increases by almost 60 % from set 1 to set 2

From a detailed assessment of a subset of studies (90 for brakes and 50 for tires), 75% of measurements for brakes used a fully enclosed sampling system, while 62% used an open system for tires. This reflects the different maturity levels of methods and systems for measuring non-exhaust particulate emissions from brakes and tires, as well as the varying emphasis on measuring brake emissions, in contrast to the focus on measuring abrasion levels for tires. The difference also reflects how the Euro 7 intends to limit non-exhaust particulate matter.

The values reported reflect confounding effects related to differences in (a) test cycles, (b) brakes or tires under testing, and (c) sampling systems. Regarding particulate matter with a mean aerodynamic diameter of 10 µm or less (PM_{10}), Table 3 summarizes emission factors for distance-based average (mg/km). Values for the coefficient of variance exceeding 100% are valid in the statistical sense and do not imply *negative* emission factors in the data.

Table 3 – Average PM_{10} emission factors ±stdv (in mg/km) for single brake and single tire; values in parentheses show the coefficient of variance

Sampling Method	Brake Wear	Tire Wear
Fully Enclosed	8.9 ± 6.4 (CoV: 72.0%)	—
Semi-Enclosed	10.84 ± 14.9 (CoV: 137.5%)	4.9 ± 7.9 (CoV: 159.3.4%)
Single Probe	—	—
On-Road	—	6.24 ± 4.1 (CoV: 65.3%)

Table 4 shows emission factors for particulate matter with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$). Since PM_{10} includes a wider particle size range, the coefficient of variation (CoV)[5] For PM10 under fully enclosed sampling conditions, results are slightly lower, indicating greater consistency than for $PM_{2.5}$.

Table 4 – Average $PM_{2.5}$ emission factors ±stdv (in mg/km) for single brake and single tire; values in parentheses show the coefficient of variance

Sampling Method	Brake Wear	Tire Wear
Fully Enclosed	3.12 ± 2.4 (CoV: 76.5%)	—
Semi-Enclosed	3.83 ± 5.8 (CoV: 152.5%)	1.56 ± 7.9 (CoV: 504.3%)
Single Probe	6.1 ± 7.6 (CoV: 124.6%)	—
On-Road	—	3.30 ± 4.1 (CoV: 72.8%)

The results mentioned above are based on the general literature review, and further detailed analysis will follow in the next pages. However, the aggregated values in Table 5 reveal general trends in the repeatability of $PM_{2.5}$ and PM_{10} emission testing across the different sampling system methodologies (fully enclosed, semi-enclosed, and single probe). Hence, CoV values (a metric of variance) for both $PM_{2.5}$ and PM_{10} are lower under fully enclosed sampling systems than

[5] CoV = (Standard Deviation ÷ Mean) × 100. Higher CoV indicates greater variability in test results.

under semi-enclosed ones. The latter suggests higher reproducibility of the testing procedure under the fully enclosed sampling system setup.

Table 5 summarizes values for particle number concentration (PN). One should notice that CoV values under fully enclosed and semi-enclosed sampling systems are different from the findings derived from Table 10 and Table 11. PN concentration heavily depends on the sampling system architecture and is prone to particle losses in most cases. Hence, a higher variation can be identified. More information can be found in Research Question 1 (RQ1).

Table 5 – Average PN emission factors for brakes and tires

PN concentration (#/cm³)				
Brake wear			**Tire Wear**	
Fully-enclosure	Semi-enclosure	Single probe	On-road	Lab
Average				
3.34E+05	7.17E+04	6.00E+04	2.52E+06	6.33E+04
Standard Deviation				
4.04E+05	3.88E+04		4.32E+06	5.68E+04
CoV (StdDev/Mean)				
120.8%	54.1%		171.8%	89.7%
EF PN #/km				
Brake wear			**Tire Wear**	
Fully-enclosure	Semi-enclosure	Single probe	On-road	Lab
Average				
5.81E+12	1.25E+12		3.00E+13	1.16E+12
Standard Deviation				
1.40E+13	2.16E+12			5.60E+11
CoV (StdDev/Mean)				
240.1%	172.9%			48.3%

Aggregate chemical speciation

Figure 2 summarizes common chemical elements and their corresponding percentage by weight in the formulations available for this study. Several elements present in both brakes and tires have percentages by weight in the same order of magnitude, necessitating proper separation at the time of sampling (on the vehicle or chassis dynamometers) to prevent cross-contamination, especially when the study requires chemical analysis.

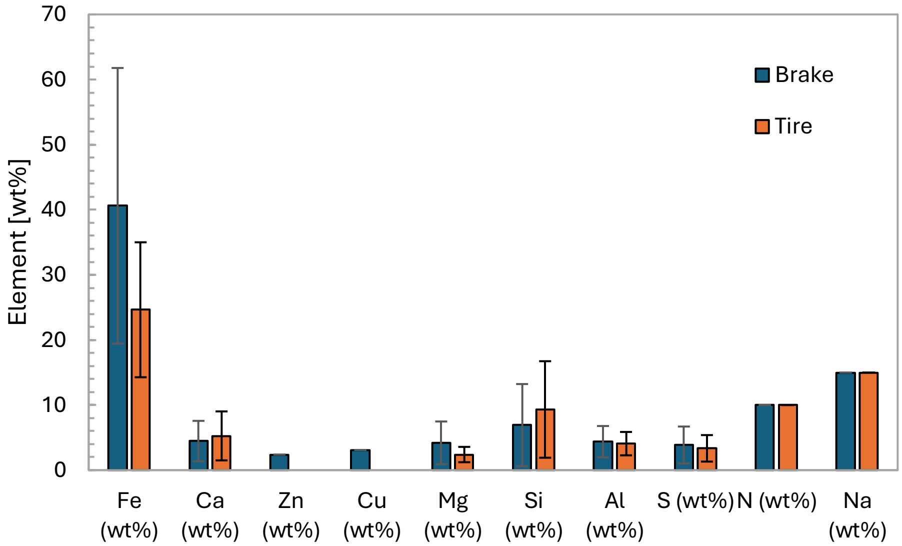

Figure 2 – Brake and tire chemical speciation based on the aggregated values derived from the literature review, general matrix

Figure 3 shows the emission rates for brakes and tires from the subset of studies that include only research papers on fully enclosed and semi-enclosed sampling systems. While the emissions factors remain within the same order of magnitude, there are nuances in the data that may have different effects on the test results, such as:

a) Unknown confounding, correlated, or independent effects due to the lack of standard information from the studies to allow a more rigorous comparison (e.g., brake formulation or tire composition, brake or tire type, loading condition, axle position, test setup for sample extraction, and sampling system)
b) Differences due to the first measurement principle used to collect PM (gravimetric filter holders, cascade impactors, electrodynamic), and the effect of separating cyclones used, and the cutoff response
c) Semi-enclosed brake testing can have more interactions with the test environment around the brake (on-vehicle) and varying levels of transport losses, hence increasing variability
d) Semi-enclosed brake testing was commonly used with low-metallic, semi-metallic, or ECE-type friction materials, all of which have metal matrix compositions. This may introduce bias in the results, as these materials tend to emit more particles, potentially skewing comparisons with fully enclosed systems that may use a broader range of formulations.
e) Higher on-road tire emissions due to the ability to combine longitudinal and lateral loading using normal driving cycles with longitudinal and lateral loading
f) Lab testing for tires can include a series of artificial loading or accelerated testing on surfaces with different friction, while Figure 3 aggregates data from various studies and sampling methods (including both fully and semi-enclosed systems) and aims to illustrate general trends in emission factors (EF) across vehicle classes and brake pad types. However, due to heterogeneous test setups and legacy data, the variability is high, and error bars are large, limiting the ability to draw definitive conclusions about smaller variables, such as vehicle-to-vehicle differences or specific brake formulations.

To address this limitation, the report includes a focused analysis using only GTR-24-compliant tests (see Table 10 And Figures 17–23). In that subset:

Vehicle-to-vehicle differences become discernible due to standardized test mass, brake work, and inertia settings.

The effects of brake pad formulation are statistically significant. For example, NAO pads consistently show lower PM_{10} and $PM_{2.5}$ emissions than ECE or low-metallic pads.

Error bars are narrower, with intra-lab CoV values often below 15–25%, enabling meaningful comparisons.

Thus, while Figure 3 provides a high-level overview, the GTR-24-only analysis confirms that smaller variables can be reliably distinguished when test conditions are harmonized and variability is controlled.

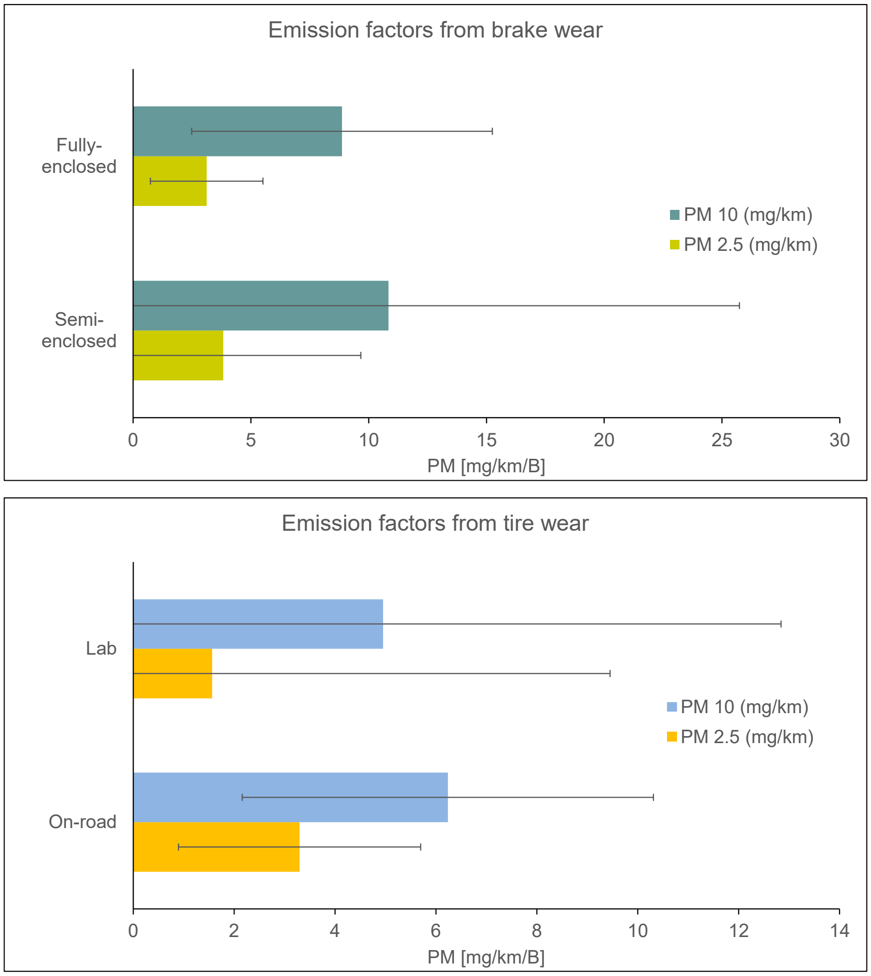

Figure 3 – (Upper panel) for brake and (lower panel) for tire emission factors based on the aggregated values derived from the literature review general matrix

Other aspects of [18] on the contributions of road vehicle tires to microplastics include the following:

- There are two main methods to estimate particle emissions: a) use tire wear or PM emissions factors multiplied by the total distance driven, and b) determine the mass loss per tire during its lifetime, multiplied by the consumption of the tire
- Most studies rely on previous data, mostly collected before 2000, with estimates from 3.2 million to 9 million tonnes being emitted globally in 2017
- The European Union (EU) is working towards reducing the intentional (e.g., cosmetics and detergents) and unintentional (tire wear, textiles, road markings) release of microplastics
- "Tire wear particles" (TWP) and "tire–road wear particles" (TRWP) have an ambiguous usage thus far. Instead, "tire wear particles" is more accurate in referring to the tread particles encrusted and mixed with foreign materials from the road, dust, brakes, and soil. The term "tire abrasion particles" or "tire particles" should be used to refer only to the tread part emitted to the environment (even if other materials are encrusted). Tread particles (TPs) usually refer to the tread rubber particles produced by shaving and crushing the tire tread or using a rotating abrader, rasp, or grinder, to conduct special studies and analysis
- Tire life exhibits a large spread due to multiple factors (e.g., size, tread pattern, composition, loading, axle position, weather, driving style). C1 tires fitted on light vehicles can last 37,000 ± 6,000 km on the front and 64,000 ± 8,500 km on the rear. C2 tires for light- and medium-sized commercial vehicles can last 40,000-70,000 km. And C3 tires

mounted on large commercial vehicles can last on average 220 000 km, extending their life to 600 000 km with retreading

- An average tire sheds 10 % of its mass for passenger cars and 18 % for heavy-duty vehicles over the useful tread life of the tire (retreaded tires excluded).
- The contribution of passenger cars to microplastics from road transport varies greatly, depending on the region. In the EU, it is about 66 %; in northern Europe 62 % to 71 %; Japan, China, and Brazil are 47 %; India and South Korea are About 20 %. Microplastics from road transport may also come from other sources, such as resuspension from traffic, road-deposited debris, or runoff water.
- Because several studies and emissions inventories rely on legacy data (in some cases dating back 30 years), [19] reanalyzed primary and secondary research for emission factors for light-duty vehicles. The study found that, after excluding road wear and resuspension, the mean tire wear PM_{10} emissions were 1.1 mg/km/V (median 0.2 mg/km/V). In contrast, the mean emissions were 2.7 mg/km/V (median 1.1 mg/km/V) when studies including resuspended tire wear were included. Instead, the mean is 6.5 mg/km/V and the median is 6.1 mg/km/V, both substantially higher than those reported in the secondary literature and cited frequently. The significant differences are attributed to misunderstandings, misquotation, obsolescence of studies dating back to 1995, or selection bias in multiple studies. These factors have prompted revisions or challenges to mass-based emission factors from the U.S. Environmental Protection Agency and the European Environment Agency.

This systematic review focuses on studies that include results from various sources, including simulations, laboratory tests, proving grounds, and on-road measurements. From the subset of 140 studies in the database with data extraction for summaries (from a total of 307 studies in the database). This statistic does not reflect the ongoing market assessment from the UNECE/GRBP/TF TA for tires fitted on light vehicles (C1 tires):

- For brake wear and emissions, 13 test campaigns used semi-enclosed systems, and 40 used fully-enclosed ones, reflecting the GTR 24 setup
- For tire wear, 12 studies relied upon laboratory tests, while 19 used on-road testing. The study is evaluating 30 3PMSF tires and 70 normal tires.

5 Rationale for the review in the context of existing knowledge

As tailpipe Particulate Matter (PM) emissions from light-duty (LD) vehicles declined, other PM emissions became more critical. LD vehicles emit at least five types of PM: tailpipe emissions, brake wear, tire wear, road wear, and resuspended road dust. Although measurement methods are still in development, total combined PM emissions for brakes, tires, and road wear are estimated at 30 mg/mi. This magnitude exceeds the tailpipe PM regulatory limit of 3 mg/mi. Battery Electric Vehicles (BEVs) emit four of the five PM types, except for tailpipe PM. Government regulatory agencies, including the EPA and the California Dept of Transportation, have studied certain types of non-tailpipe PM, including PM from brake and tire wear. Although it is unclear when, or if, U.S. regulatory limits on non-tailpipe PM emissions from vehicles will be proposed, we want to understand this topic better.

The rapid pace of research and measurement campaigns in other regions, led by the Euro 7 initiative on brake emissions and tire abrasion, as well as research in Japan and the U.S., has generated a body of literature that warrants careful consideration. Both developments (brake emissions and tire abrasion) include LD and Heavy-Duty (HD) vehicles, presented to Task Forces 3 and 5 (TF3 and TF5) of the Particulate Measurement Programme (PMP) of the European Commission (EC), the Tire Abrasion Task Force of the EC, the German Association of Automotive Industry (VDA), and ISO Working Group 13 within the Technical Committee 31. The development of the California Brake Dynamometer Cycle (CBDC) and the Worldwide Harmonised Light Vehicle Test Procedure (WLTP-Brake cycle), along with driving circuits and laboratory tests for tire abrasion, and on-road measurement campaigns, provides a robust set of methods to assess the principal factors influencing non-exhaust emissions and tire abrasion.

Unlike previous systematic reviews, this project combines peer-reviewed studies with input from various stakeholders (including government-mandated working groups) actively drafting rulemaking and developing and validating measurement methods (laboratory and field-based) for non-exhaust particulate emissions from brakes, tires, and roads.

6 Objectives

The scope of the systematic review, as directed by the CRC Panel, is to provide insight into the following research questions:

1. **RQ1: Magnitude of non-tailpipe PM emissions**, preferably expressed in units like mg/mi, to allow comparison with tailpipe PM emissions levels and regulatory standards (including brake wear, tire wear, road wear, resuspended road dust, etc.)
2. **RQ2: Test methods to generate non-tailpipe PM**. Compare and contrast test methods (if possible) to identify the potential influence of the method on measurement results, including methods to discriminate PM from various sources (e.g., component bench tests, full vehicle laboratory tests, on-road tests)
3. **RQ3: Characterization of non-tailpipe PM**, including chemical composition, morphology, particle density, and particle size distribution.
4. **RQ4: Test methods to characterize non-tailpipe PM emissions** related to measurement instruments.
5. **RQ5: Strengths or weaknesses of test or measurement methods** based on findings from research questions 2, 3, and 4
6. **RQ6: Information about the distribution of non-tailpipe PM from the point source**. For example, residence time, half-life, dispersion distance, or other metrics characterizing how long non-tailpipe PM stays suspended in the atmosphere, and dispersion characteristics from the source of origin. Mine safety and health agencies worked on this topic in the 1990s.
7. **RQ7: Factors known to control or affect the magnitude or type of non-tailpipe PM emissions**. For example, vehicle weight may affect tire wear, while brake pad material or disc coating may affect brake wear, and the chemical composition can influence tire abrasion. Electric vehicles have been reported to experience faster tire wear than comparable conventional ICE vehicles, possibly due to a combination of higher vehicle weight and higher launch torque (acceleration). Include methods proposed to control or reduce LD vehicle non-tailpipe PM emissions.

7 Eligibility criteria

The criteria for identifying and selecting the different studies to include in this systematic review include the following:

1. Literature published after 2008 (except for prior seminal work), prioritizing review of newer studies
2. Test cycles using WLTP-B or CBDC for brakes (circa 2018)
3. Driving circuits based on real-world driving for tires
4. Numerical analysis with comparative results
5. Literature referenced in other recent Literature Review papers (brakes and tires)
6. Publications from recognized online Journals (e.g., MDPI, Environmental Science & Technology), industry conferences (e.g., SAE Brake Colloquium, EuroBrake, ETH, CRC)
7. Public presentation and documents from and working groups (e.g., United Nations Particulate Matter Programme, United Nations Working Party on Noise and Tires – GRBP, United Nations Working Party on Pollution and Energy - GRPE)

The criteria for exclusion of studies and documents include:

a) Test cycles not based on real-world driving (e.g., SAE J2522 – AK Master)
b) Studies using sampling systems before 2018, not following PMP or CARB requirements or guidelines, which were developed by extensive peer-review and experimental validation (for PMP), and adapting best practices from laboratory emissions and aerosol engineering (for CBDC)
c) Studies without experimental validation
d) Research with normalized results without reporting the measurand units
e) Studies beyond the 120 total count after prioritizing using the inclusion criteria.

8 Information sources

The primary sources of studies and reports include the following:

- Legacy online scientific databases (e.g., Google Scholar, MDPI)
- AI-supported searches for high-level summaries to guide the findings (Openread.academy, Connectedpapers.com)
- UNECE wiki pages (GRBP and GRPE) and trusted websites (e.g., CRC, SAE)
- Conference proceedings

9 Search strategy

The search strategy used multiple paths, depending on the database or website. Table 6 Shows the main steps for the different types of searches:

Table 6 – Study Search Strategies

Item	Web Search	Literature Review Studies	Databases and Conferences
Sources	– Google Scholar – MDPI	– Google Scholar – MDPI – Business intelligence – Citations from recent systematic review studies – Openread.academy – connectedpapers.com	– internal LINK and UCR electronic libraries – EuroBrake Conference – SAE Brake Colloquium Conference – CRC Conference – UNECE GRPE and GRBP wiki pages
Filters and limits	– English language only – Title, author, abstract, and conclusions or proposals – Studies with numerical values different from subjective ratings or simple non-dimensional ranking – Up to 120 total studies and documents to review and extract information – Publication date: not earlier than 2008 – Prioritize: • recent publication with direct citation of main studies • studies and documents published in 2018 or later (post-CARB cycle development and first version of GRPE-81-40) • publications from Government agencies and working groups (e.g., UNECE GRPE on brakes and UNECE GRBP on tires) and active participants (academia, industry stakeholders, or individual researchers) in development and testing (lab and measurements) for non-exhaust emissions for brakes and tires • studies cited in large systematic reviews for non-exhaust brake, tire, and road emissions		

Item	Web Search	Literature Review Studies	Databases and Conferences
Keywords or search questions	– non-exhaust emissions – non-exhaust emissions factors – non-exhaust emissions rates – brake emissions – tire emissions – road emissions – tire abrasion – non-exhaust emissions laboratory methods – non-exhaust emission field measurements – non-exhaust emissions for electric vehicles – non-exhaust emissions for light vehicles – non-exhaust emissions for heavy vehicles – physical and chemical composition of non-exhaust emissions	– Read recent (circa 2020 and newer) systematic review studies to extract manually findings and data to answer the seven research questions – Extraction using Openread.academy and connectedpapers.com outputs	– non-exhaust emissions – non-exhaust emissions factors – non-exhaust emissions rates – brake emissions – tire emissions – road emissions – tire abrasion – non-exhaust emissions laboratory methods – non-exhaust emission field measurements – non-exhaust emissions for electric vehicles – non-exhaust emissions for light vehicles – non-exhaust emissions for heavy vehicles – physical and chemical composition of non-exhaust emissions
Main search strategies	– Individual search by PIs – Focus on studies with numerical results comparing relevant factors	– Individual read by PIs – Line-by-line reading searching for findings, data, and citations related to the research questions – Compilation into a summary document for peer review for findings and data entry	– Individual read by PIs to search for presentations, studies, and proposals related to the research questions – Extraction of findings and numerical results

Note: Business intelligence refers to information available to the PI and Co-PIs from their business and technical liaisons or their internal work on non-exhaust emissions

The above criteria produced a database of 307 studies. The count does not include reports and presentations from the working groups within the European Commission on brake emissions and tire abrasion, as they were retrieved in the last few weeks near the end of the preparation of this review. The pace of publications produced more than 50 % of the studies in 2020 or later, as shown in Figure 4, coinciding with the publication of the drafts of brake emissions regulations as part of the Euro 7 initiative.

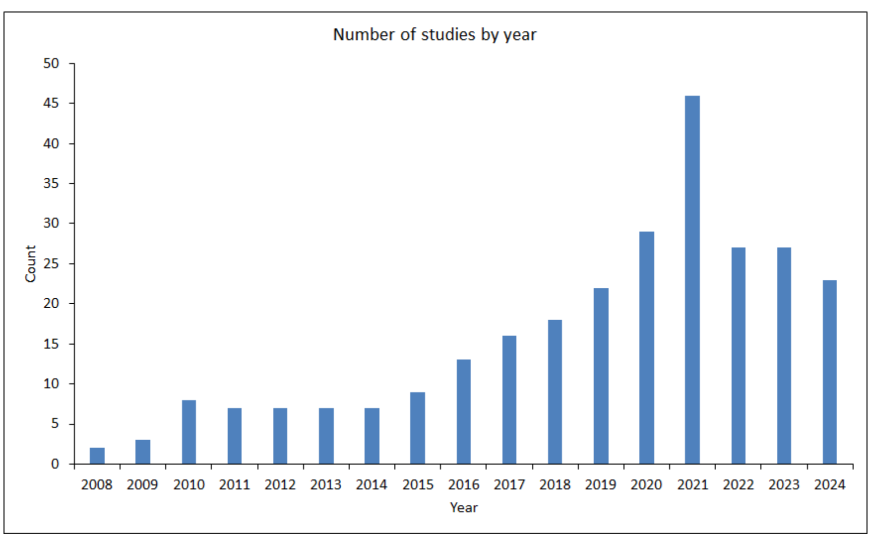

Figure 4 – Number of studies per year included in the database

Table 7 Shows a census of studies on specific items within each research question.

Table 7 – Items included in the compilation of initial findings

Item	Count
RQ1: Non-tailpipe PM emissions	
$PM_{2.5}$ mg/km or mg/km/V	35
PM_{10} mg/km or mg/km/V	41
PM_1 mg/km/V	5
PM mg/km/ton	0
PM_{10} mg/test	2
PN p/km or p/km/B	16
PN #/cm	17
$PM_{2.5}$ µg/m³	9
PM_{10} µg/m³	16
PM_{10} p/km	2
Fe (ng/m³)	2
Fe (wt%)	14
Ca (ng/m³)	1
Ca (wt%)	8
Zn (ng/m³)	0
Zn (wt%)	2
Cu (ng/m³)	0
Cu (wt%)	2
Mg (wt%)	5
Si (ng/m³)	1
Si (wt%)	10
Al (ng/m³)	1
Al (wt%)	9
S (wt%)	8
N (wt%)	1
Na (wt%)	1
RQ2: Test methods to generate non-tailpipe PM	
Brake Wear	89
Tire Wear	65
Road Wear	33
Resuspension of Road dust	28
comparisons	27
test influencing factors	119
Test setup: Fully enclosed	13
test setup	106
test conditions	111
measurements	50
test cycle(s)	67
RQ3: Characterization of non-tailpipe PM	
chemical composition	56
morphology	25
particle density	3

Item	Count
particle size distribution (PSD)	83
Particle Mass (PM)	51
Particle Number (PN)	68
Physical: size distribution, morphology, density, porosity, optical properties, light scattering, and light absorption)	84
Chemical Characterization: Inorganic Ions, Elemental Carbon, Organic Carbon, Polycyclic Aromatic Hydrocarbons (PAHs, Volatile Organic Compounds (VOCs)	14
Source Apportionment: Chemical Mass Balance (CMB), Positive Matrix Factorization (PMF), Receptor Modeling	0
Thermal Properties: Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC)	5
Electrical Properties: conductivity, dielectric constant	0
Hygroscopicity for Water Uptake	0
RQ4: Test methods to characterize non-tailpipe PM emissions (see RQ4 & 5)	
CPC based	28
GCMS	9
TSI DustTrak	34
TSI OPS	2
EEPS	21
11-D Grimm	7
APS	26
Dekati ELPI+	28
PM_{10}	34
$PM_{2.5}$	32
PM_{1}	5
$PM_{0.12}$	1
Solid particle number	16
Total particle number	50
RQ5: Strengths or weaknesses	
Actual test	102
Calculations based on ML tools	12
Numerical simulations	8
RQ6: Information about the distribution of non-tailpipe PM	
Fate	3
dispersion time and distance	1
residence and half-life times	2
RQ7: Factor known to control or affect the magnitude or type of non-tailpipe PM emission	
vehicle mass	19
Vehicle type	2
propulsion system	2
Brake temperature	2
Velocity	1
Brake energy	1
brake or tire materials	62
Driving dynamics (Number of braking events, level of acceleration, deceleration, cornering, etc.)	77
Tire pressure	9
Road type	28

Item	Count
Hybrid mode	23
Materials and composition	64
Driving controls	70
Propulsion systems	10
Electric propulsion	4
Ambient conditions	12
Vehicle type (electric cars or combustion cars)	13
Traffic management	11

10 Selection process

The selection of studies and findings to bring into this systematic review involved the following steps:

1. Does it meet the search criteria?
2. Does the study include reference values from other studies or sensitivity to specific factors relevant to the research question?
3. Do at least two PIs agree on the finding and the content to bring into the systematic review?
4. Subsequent joint review of whether the finding from a given study is compatible with others and if there is sufficient evidence to retain the finding, even if contradicting or significantly different from other studies

11 Data collection process

The PIs conducted individual searches on databases, websites, and conferences and combined them into a single database with sufficient details (e.g., doi numbers, author, title, year of publication). The database provided a list of studies to download from relevant scientific journals and online technical libraries (e.g., MDPI, SAE, UNECE GRPE wiki sites, and GRBP). Subsequently, the PIs used tools such as Mendeley to characterize the topics, relevance, and coverage of the seven research questions. All available studies were uploaded to a shared online repository. This database also serves as the basis for the library section of the final report for all open-access studies used in the analysis.

The reviewers worked independently with periodic alignment and update meetings to review the studies added to the shared web folder for literature and statistical analysis. The PI combined studies from various sources, emphasizing recent studies that adhered to the latest testing methods (e.g., GTR 24 for brakes and UNR 117 for tires). The reviewers conducted a thorough review of approximately 35 papers, extracting and combining findings relevant to the research questions. The findings are further categorized into brakes, tires, and roads, where applicable.

12 Data items

From all studies included in this systematic review, the main extraction included the following and was assigned to specific research questions:

- emission factors for particle mass and particle count
- abrasion or wear rates
- chemical composition
- concentration levels per the test or measurement reported
- scope of the measurement (physical, chemical, dispersion)

- method(s) used to test, sampling system, and measurement devices and instruments (e.g., particulate matter, size distribution, wear)
- key findings from the study and validation or comparisons to other studies
- sources of uncertainty on the values reported
- potential for future research

Not all studies provided sufficient information to extract all the items above.

13 Study risk of bias assessment

The UCR and LINK PIs conducted a joint review of the findings and prioritized studies with high scientific value and alignment with this systematic review. The joint review primarily considered studies with metrics and methods aligned with GTR 24 for brakes and UNR 117 for tires, published by a multidisciplinary group of authors (including academia, industry, and regulatory or environmental agencies). To avoid time bias, the systematic review prioritized recent studies to guide the assessment of the research questions.

14 Synthesis methods

The first level of synthesis involved a detailed reading of the study or report to identify applicable content —background, analysis, statements, and findings —for each data item. The second level involved extracting numerical results into tables with metrics or data items supporting the research and properly segmenting the results (e.g., single probe near the test article, semi-enclosed, fully enclosed; non-GTR 24, GTR 24 test cycles). Figure 5 shows the first 10 rows of studies with the import details.

Basic details	Import details										
Index	DOI Identifier	First author	Study title	Source (journal, report series, …)	Year	Imported by (partner ID)	UCR selection B:BRAKES, T:Tires, BT: Brakes and Tires	LINK selection B:BRAKES, T:Tires, BT: Brakes and Tires	Import date	Vehicle type Light-Duty	Vehicle type Heavy-duty
1	https://doi.org/10.1016/j.scitotenv.2010.06.011	Aatmeeyata, & Sharma, M.	Polycyclic aromatic hydrocarbons, elemental and organic carbon emissions from tire-wear.	Science of the Total Environment	2010	UCR			08/16/2024	1	
2	https://doi.org/10.1007/s10661-016-5377-1	Adamiec E. Jarosz-Krzeminska E. & Wieszala R.	Heavy metals from non-exhaust vehicle emissions in urban and motorway road dusts. Environmental Monitoring and	Environmental Monitoring and Assessment	2016	UCR			08/16/2024	1	1
3	https://doi.org/10.4271/2020-01-1637	Agudelo C. Vedula R. T. Collier & Stanard A.	Brake particulate matter emissions measurements for six light-duty vehicles using inertia dynamometer testing.	SAE Technical Papers	2020	UCR	B	B	08/16/2024	1	
4		Allen J. O. Alexandrova P. E. O. & Kaloush K. E.	Tire Wear Emissions for Asphalt Rubber and Portland Cement Concrete Pavement Surfaces	Arizona Department of Transportation Contract KR-04-0720-TRN Final Report.	2006	UCR			08/16/2024	1	1
5	https://doi.org/10.1016/j.atmosres.2021.105557	Alves C. Evtyugina M. Vicente A. Conca **E.** & Amato F.	Organic profiles of brake wear particles.	Atmospheric Research	2021	UCR			08/16/2024	1	
6	https://doi.org/10.1016/j.chemosphere.2023.139874	Asma Beji, Karine Deboudt, Bogdan Muresan, Salah Khardi, Pascal Flament, Marc Fourmentin, Laurence	Physical and chemical characteristics of particles emitted by a passenger vehicle at the tire-road contact	Chemosphere	2023	UCR			8/22/2024	1	
7	https://doi.org/10.1007/978-3-658-26435-2_55	Augsburg K. Wenzel F. & Gramstat S.	Methodology for the measurement of tire wear particles	10th International Munich Chassis Symposium 2019	2019	UCR			08/16/2024	1	
8	https://doi.org/10.3390/atmos14030488	Bondorf L. Kohler L. Grein T. Epple F. Philipps F. Aigner M. & Schripp T.	Airborne Brake Wear Emissions from a Battery Electric Vehicle.	Atmosphere	2023	UCR	B	B	08/16/2024	1	
9	https://doi.org/10.1016/j.scitotenv.2022.160853	Charbouillot T. Janet D. C. Schaal P. Beynier I. et al.	Methodology for the direct measurement of tire emission factors	Science of the Total Environment	2023	UCR			08/16/2024	1	
10	https://doi.org/10.1007/s40825-018-0105-7	Chasapidis L. Grigoratos T. Zygogianni et al.	Study of brake wear particle emissions of a minivan on a chassis dynamometer.	Emission Control Science and Technology	2018	UCR			08/16/2024	1	

Figure 5 – First ten rows of the main database

The systematic review reports values in their native units of measurement or reporting to avoid skewing the results or presenting findings that are sensitive to unvalidated assumptions by the co-PIs (e.g., assuming a sampling airflow to estimate an emission factor).

15 Reporting bias assessment

The vast number of studies on non-exhaust emissions, microplastics, and their environmental fate does not allow for an all-inclusive report, as on average, up to 3 new studies or industry reports are published weekly. The co-PI approach used the main database to select 140 studies for data extraction and numerical analysis, and to select 35 studies or reports for extracting findings, progress, recommendations, and current issues related to non-exhaust emissions. The CRC Project Panel is encouraged to read individual studies to gain a fuller understanding of specific topics of interest and to monitor publications and reports (e.g., European Commission regulatory work, European Union-funded projects, and environmental research in the United States).

16 Certainty assessment

The diversity in scope, resources, test setups, reporting methods, and details disclosed across the studies significantly hindered the ability to assess confidence statistically. Few studies include multiple measurements across several samples, and many report average values without recording standard deviations or the number of samples.

17 Results of syntheses

17.1 Magnitude of non-tailpipe PM emissions

17.1.1 Brakes

Emission factors studied by the European Commission

As part of the development of the GTR 24 proposal, the Informal Working Group of the Particulate Measurement Programme of the European Commission has coordinated and reported three Interlaboratory Studies (ILS1, ILS2, and ILS3), all of which used brake dynamometer testing. The early work on applying statistical tools for repeatability and Reproducibility during brake inertia dynamometer testing was studied by [20], [21]. Subsequent applications to the brake emissions initiative within the UNECE PMP were documented by [22], [23], [24], [25], [26] in preparation for releasing GTR 24 as the testing method for non-exhaust brake emissions within the proposed Euro 7 [27]. ILS1 focused on the WLTP-B cycle without emissions measurements. ILS2 studied several brakes (including disc and drum brakes, NAO and low-met vehicles, and M1 and N1 vehicles). And ILS3 included two phases, each with three different brakes under test.

ILS1[6] for validation of testing capabilities, involved eight laboratories and produced results for 13 measurands (e.g., braking speed, average deceleration, brake torque, coefficient of friction, initial brake temperature, average cooling air temperature) using robust algorithms for heterogeneous materials following [28]. Figure 6 depicts the workflow for the ILS1 reported by [29]

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6 https://www.bing.com/ck/a?!&&p=bf76dbc234356cf2d19b38c6b4cda739ac2a4c522c5175a5d1f0033c255666ceJmltdHM9MTc0MzM3OTIwMA&ptn=3&ver=2&hsh=4&fclid=0d9d122f-5990-6986-354d-07b058146883&psq=pmp+interlaboratory+accuracy+study+report&u=a1aHR0cHM6Ly93aWtpLnVuZWNlLm9yZy9kb3dubG9hZC9hdHRhY2htZW50cy8xMjg0MjEzMzUvUE1QJTIwVEYxJTIwSW50ZXJsYWIlMjBTdHVkeSUyMC0lMjBTdGF0cyUyMHJlcG9ydCUyMC0lMjAxNUpVTDIwMjEucGRmP2FwaT12Mg&ntb=1

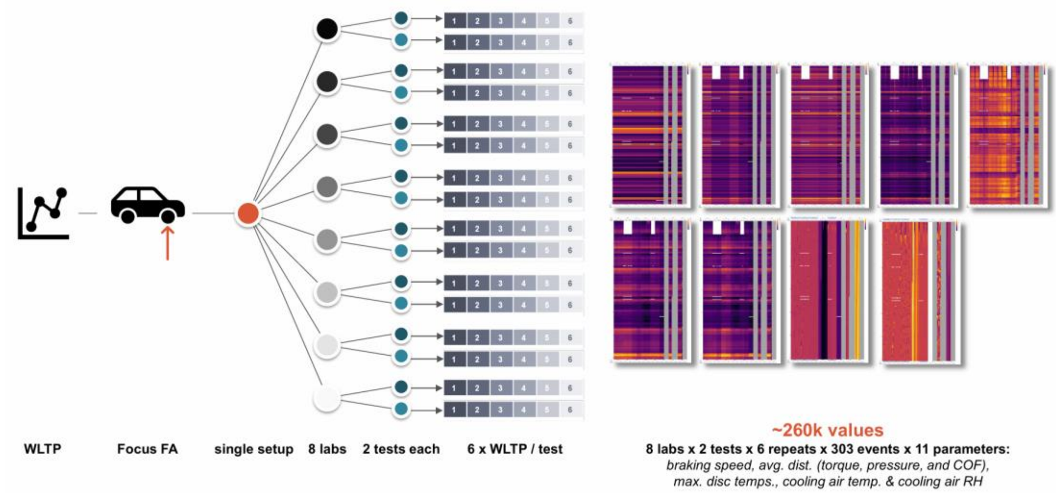


Figure 6 – Workflow for interlaboratory accuracy study for the WLTP-B cycle

The report provides details of the statistical treatment, accompanied by numerical examples and data visualization. The results of the analysis show the standard deviations for repeatability (within the test), sample effect (between tests), lab effect (between labs), and total reproducibility. The variability levels were satisfactory, giving the EC the confidence to develop the draft document, including the PM and PN measurement systems. The variability of the coefficient of friction (COF), shown in Figure 7 for all labs, with two tests per lab and six repeats per test, exemplifies the need for using statistical methods for heterogeneous materials and robust algorithms for averaging and standard deviation.

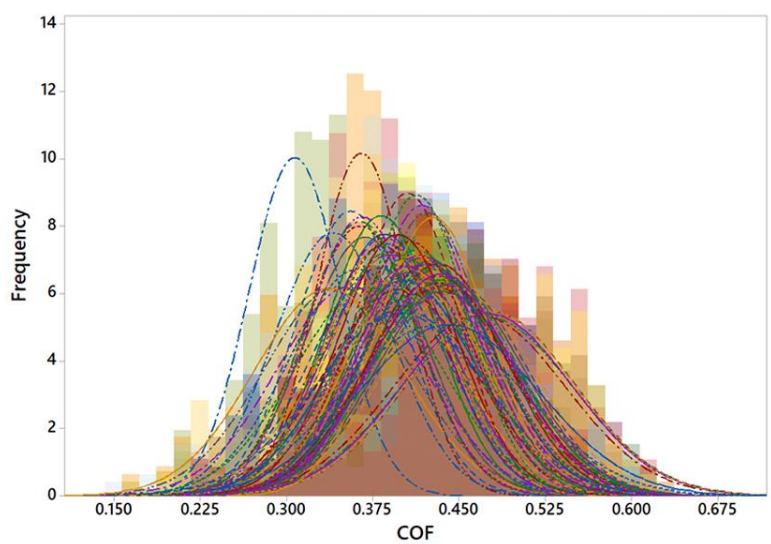


Figure 7 – Histograms for the coefficient of friction for eight labs with two tests and six repeats on each test

A second interlab study (ILS2) reported by [23], [24], [25], [26] includes brake emissions measurements for seven brake assemblies from five vehicle applications (two sedan, SUV, compact as M1, and one cargo van as N1), with ECE (low-met) and NAO friction materials, vehicle test mass (1250 to 3390) kg, test inertia 16…118 kg·m², and wheel load-to-disc mass ratio (WL/DM), from 45:1 to 122:1. The study applied all the criteria and elements from the GTR 24 along with checklists to validate the test setups and test results. Not all labs conducted all tests on seven brakes. Data visualization per [30] Early on during the assessment, we detected labs with deviations from the GTR 24 requirements for cooling air temperature (Figure 8), cooling air humidity (Figure 9), braking speed (Figure 10), and average brake disc or drum temperature during trip # 10 (Figure 11).

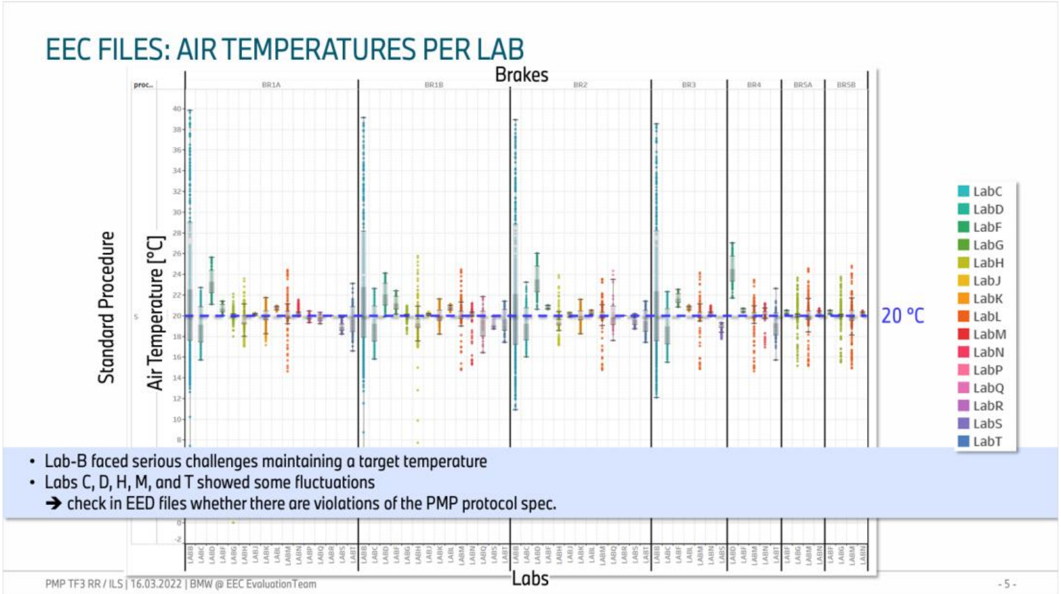


Figure 8 – Boxplots for cooling air temperature during WLTP-B tests for up to seven brakes. The dashed line at 20 °C indicates the target GTR 24 air temperature used for the ILS2

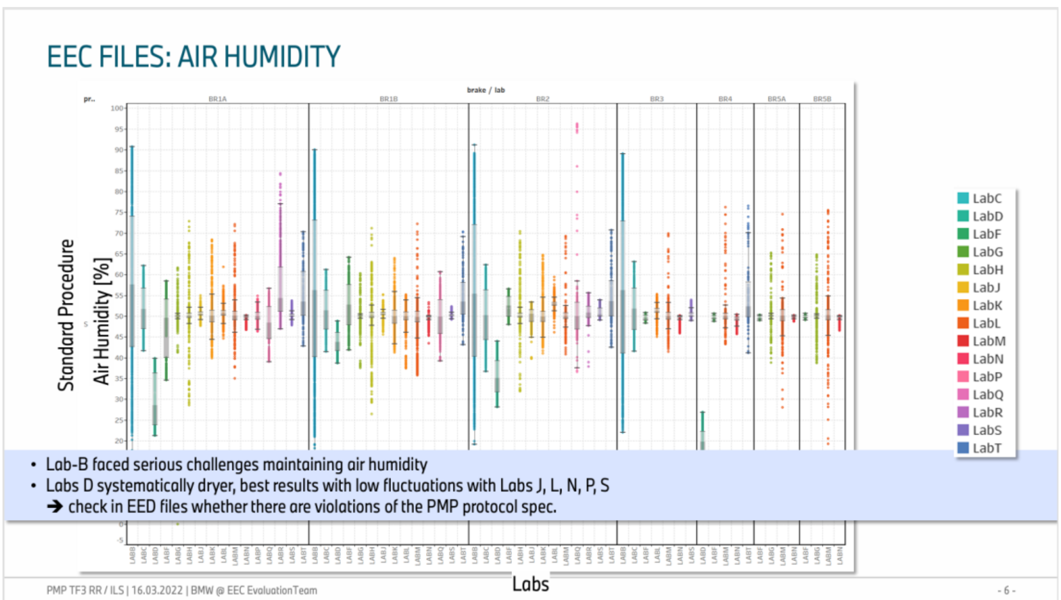


Figure 9 – Boxplots for cooling air humidity during WLTP-B tests for up to seven brakes. the set value for the ILS2 was 50 ± 10 % RH

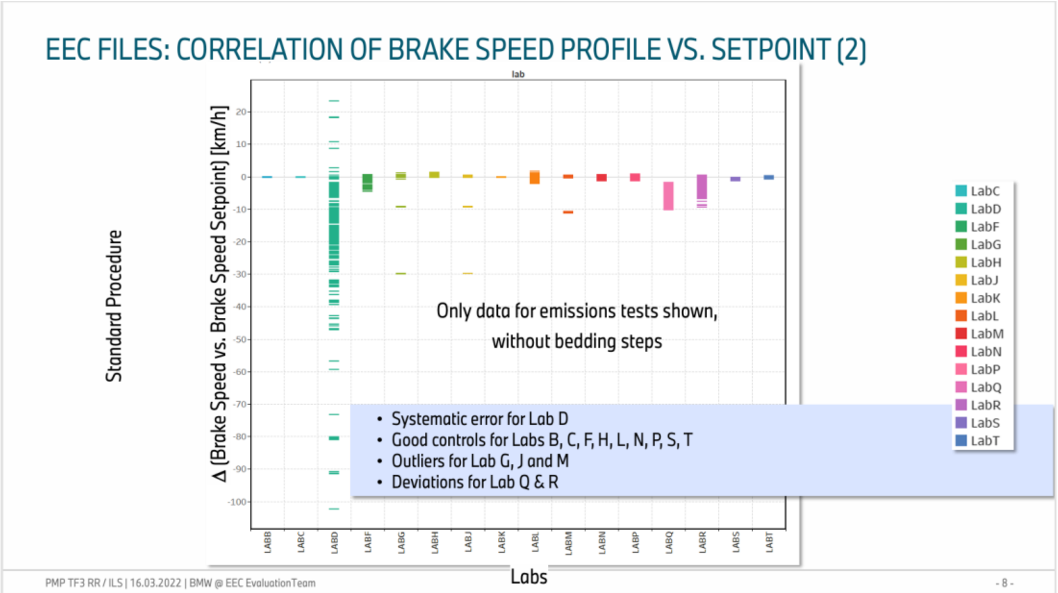


Figure 10 – Bias for braking speed during WLTP-B tests for up to seven brakes

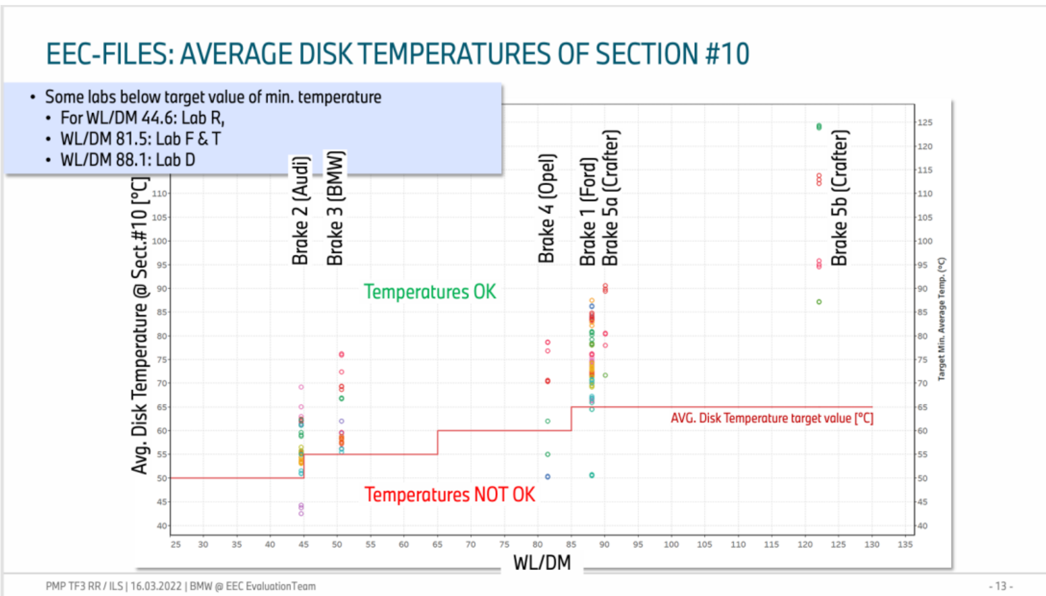


Figure 11 – Bias for the average brake disc temperature during WLTP-B tests for up to seven brakes. The stairstep red line indicates the minimum value as a function of the WL/DM ratio for the brake under testing

Upon technical scrutiny of the test results and exchanges with the individual laboratories, a subset of results (filtered data) concluded that:

- Emission factors[7] for the disc brakes varied between (0.8 to 4.0) mg/km/B and (2.2 to 9.5) mg/km/B per brake for $PM_{2.5}$ and PM_{10}, respectively, depending on the brake type and the applied testing load

[7] Emission factors (EFs) for brake and tire wear are typically reported in one of the following formats:
.../B: Per brake corner (i.e., one wheel's braking system)
.../S: Per braking stop
.../V: Per vehicle (i.e., total emissions from all brake corners)
To estimate total vehicle-level emissions from per-brake-corner values, multiply the .../B value by the number of active brake corners. For example: An 18-wheeler truck with 5 axles and 2 brakes per axle (10 brake corners total) has a measured EF of 3 mg/km/B. The total vehicle-level EF would be:3 mg/km/B×10 brake corners= 30 mg/km/V. This scaling is essential for comparing against regulatory limits or inventory models, which often use .../V units. For light duty

- The drum brake emitted much lower PM (< 1 mg/km/B and 0.5 mg/km/B for PM_{10} and $PM_{2.5}$, respectively) due to its enclosed nature and the smallest WL/DM ratio
- Almost (37 to 45) % of the emitted PM falls in the fine particle size, with this fraction being higher for the drum brake
- Approximately (50 to 65) % of the total brake mass loss falls in particle sizes larger than 10 µm or gets lost before being measured
- EF for PM_{10} on two brakes compared to previous studies, with an average of 8.7 mg/km/B and 8.9 mg/km/B, corresponding to 25-27 mg/km/V, assuming a scaling factor of 3:1
- Except for one lab, PM's repeatability (expressed as covariance) on the reference brake (using a low-met formulation) was below 5 %. The repeatability of the same reference brake, with an NAO formulation, exhibited lower emissions levels and higher covariance
- The $PM_{2.5}$/PM_{10} ratio and PM_{10}/Mass loss ratio exhibited significant variability among labs, hinting at issues related to transport losses or overestimating PM_{10}. Some labs exhibited systematic bias on either side of the average. Factors inducing variability in the ratios include transport losses (recirculation zones and long residence times inside the brake enclosure; gravitational or inertial losses in the tunnel while particles are transferred from the enclosure's exit to the sampling probe's inlet; possible anisokinetic and/or anisoaxial sampling while entering the sampling probe (noting that it could also lead to overestimating and not only underestimating emissions); isokinetic ratio (with most labs within 0.9-1.15); and variability in airflow control and airflow measurement methods
- The reproducibility (between-lab variance), after removing labs with significant deviations, for PM_{10} was close to 20 % for most cases (ranging from 17 % to 62 %), while $PM_{2.5}$ was higher (close to 30 %) and ranging from 28…47 %, indicating the need to harmonize further and restrict some options in the GTR 24 test method. Focusing the analysis on the labs that tested the van vehicle applications, which also exhibited a low count of non-compliance, the reproducibility is further reduced to 23 % (compared to 35 % with all labs included).
- Even though it exhibited low emission factors, the drum brake application exhibited a reproducibility comparable to all other brakes, building confidence in the ability of the GTR 24 method to work for low-emitting brakes
- Labs reporting $PM_{2.5}$ emission factors twice as high as the average used inertia impactors, perhaps overestimating $PM_{2.5}$ due to bouncing and inducing larger particles to settle on the $PM_{2.5}$ impaction stage. To eliminate this possible source of variability, GTR 24 deprecates the use of inertia impactors.
- A special case occurred with a small sedan with NAO friction material with two distinct groups of results for emission factors and mass loss, behaving as if there were two different brakes. The latter is not a plausible explanation, as all the brakes came from the same batch and were assigned randomly to the labs. The low-loss group with three labs reported a mass loss of 1.8 ± 0.2 mg/km/B compared to 6.5 ± 0.9 mg/km/B for the high-loss group with six labs; PM_{10} and $PM_{2.5}$ were approximately three to five times lower than the emission factors of the high-loss group.

The ILS3 results reported by [31] from the same working group looked at three brakes in two steps. This initiative included 16 labs from vehicle manufacturers, brake and friction vendors, research centers, technical services, and test system suppliers from Europe, the United States, and Japan. The team included organization and management (co-chaired by the JRC and BMW as the industry representative), a checklist committee to review the initial data for vetting and curation, and a data processing and analysis team to compile, assess, and detect abnormalities for event-based and time-based data from the different labs. After scrambling and anonymizing the lab identification (for unbiased assessment and to avoid conflicts of interest or inadequate commercial use), the labs conducted two tests: cooling air adjustment, five bedding cycles, and three brake emissions cycles on new brake assemblies. Two labs retracted from the ILS3, so 81 tests (14 labs × 3 brakes × 2 tests per brake – 3 non-compliant tests) were submitted for analysis. Initially, the labs embarked on a round of testing (with new hardware for the BMW X5 front brake) to assess the variation relative to the ILS2 and to allow all labs to validate their internal testing processes and workflow for data submission. The selection of the BMW X5 obeyed the criteria of using a brake known to have a high level of emissions (not meant to be a Euro 7 compliant friction couple) to reduce the uncertainty of having some results close to the level of detection or reporting. From the ILS2 (with five labs and 15 data points) to the ILS3 (with 13 labs and 75 data points), the EF for PM_{10} remained around 9 mg/km/B

vehicles, the accepted scaling factor (unless known from actual testing both axles individually) is using a multiplying factor of 3 to go from mg/km/B on the front axle to mg/km/V. e.g., a front brake with an EF of 2.33 mg/km/B becomes 7 mg/km/V estimated for the entire vehicle.

and 3 mg/km/B for $PM_{2.5}$. The increase of labs and data points and further harmonization could have also improved (by reducing) the spread of results. The 95 % confidence limit for PM_{10} was reduced (own estimation from the original report) from (2 to 14) mg/km/B to (6 to 11.5) mg/km/B, and for $PM_{2.5}$ from (1 to 5) mg/km/B to (1.5 to 4.25) mg/km/B.

Upon confirmation of the validity of the first step of the ILS3, the working group completed tests on two different brakes, a Ford Puma (small sedan) and a Jaguar Land Rover (low-emissions). One important step before detailed data analysis was validating the emission background particle count before and after the test to confirm air cleaning was within the GTR 24 limit (less than 20 #/cm³ as the average during a five-minute measurement). Except for one lab that exceeded the limit and two individual tests that were at the limit, the rest were well within the background limits for clean air supply during the tests.

Regarding emission factors for particle mass, Table 8 shows the PM_{10} and $PM_{2.5}$ average, standard deviation, and covariance (standard deviation as a percent of the average) for the three brakes under testing. The results confirm the GTR 24's ability to differentiate performance among friction couples.

The within-lab repeatability (as covariance) for PM_{10} on the BMW X5 and the Ford Puma was 3 % on average and about five times higher for the JLR (NAO). For $PM_{2.5}$, the covariance was about 4 % for the BMW X5 and Ford Puma, and five times higher for the JLR (NAO) brake.

Table 8 – PM results from PMP ILS3

Parameter	**PM_{10}**			**$PM_{2.5}$**		
Brake	BMW X5	Ford Puma	JLR (NAO)	BMW X5	Ford Puma	JLR (NAO)
Labs	13	14	14	13	14	14
Results (1)	75	82	79	75	82	79
PM_{10} [mg/km/B]	8.7	4.7	1.4	—	—	—
$PM_{2.5}$ [mg/km/B]	—	—	—	3.0	1.4	0.7
Std. Dev. [mg/km/B]	1.4	0.45	0.4	0.8	0.35	0.2
Intra-lab covariance	15.8 %	9.4 %	27.7 %	26.2 %	25.2 %	27.9 %

(1) After removing cycles, self-declared as invalid by three labs

The ILS3 also measured particle number (TPN10 and SPN10) as a standard output from the tests for total (as sampled) and solid (after removing volatiles using a catalytic stripper). Table 9 shows the TPN10 and SPN10 expressed as #/km, their corresponding standard deviation, and the 95 % confidence interval (CI) for cycle-to-cycle repeatability as a percent of the average for all labs with valid test results. Even though it is customary to express variation as a percent value, grasping the magnitude of the variation when dealing with physical units is more relevant.

Table 9 – PN results from PMP ILS3

Parameter	**TPN10**		**SPN10**	
Brake	Ford Puma	JLR (NAO)	Ford Puma	JLR (NAO)
Labs	14	14	14	14
Results (1)	81	77	81	77
TPN10 [#/km/B]	1.35E+09	1.14E+09	—	—
SPN10 [#/km/B]	—	—	1.50E+09	1.23E+09
± 2 ×Std. Dev. [mg/km/B]	1.14E+09	6.39E+08	1.47E+08	7.99E+08
95 % CI cycle-to-cycle	16.3 %	21.6 %	12.0 %	20.5 %

Emission factors for light vehicles as part of CARB's updates to the EMFAC2021 model

As tailpipe emissions of PM from the light-duty fleet have decreased significantly, non-tailpipe PM emissions, such as brake and tire wear, have become more relevant and may substantially impact air quality near roadways. This research project[8] was conducted to measure and analyze particulate matter (PM) emitted during light-duty vehicle braking to allow

[8] https://ww2.arb.ca.gov/sites/default/files/2021-04/17RD016.pdf

CARB to update emission factors in the Emission Factor inventory model (EMFAC), as well as to better understand the vehicle operational conditions associated with varying levels of brake PM emissions. This study utilized a brake dynamometer (in which the brake components of a single wheel are mounted and operated electronically) to measure PM emissions over a prescribed driving cycle. Figure 12 presents the vehicle-level results for each of the 6 tested models by three pad materials: Original Equipment Service non-asbestos organic (OES NAO), aftermarket NAO, and aftermarket Low-Metallic (LM). Vehicle-level emissions for each pad type are calculated by doubling the average front and rear single-wheel emission rates for each pad material type and then summing them.

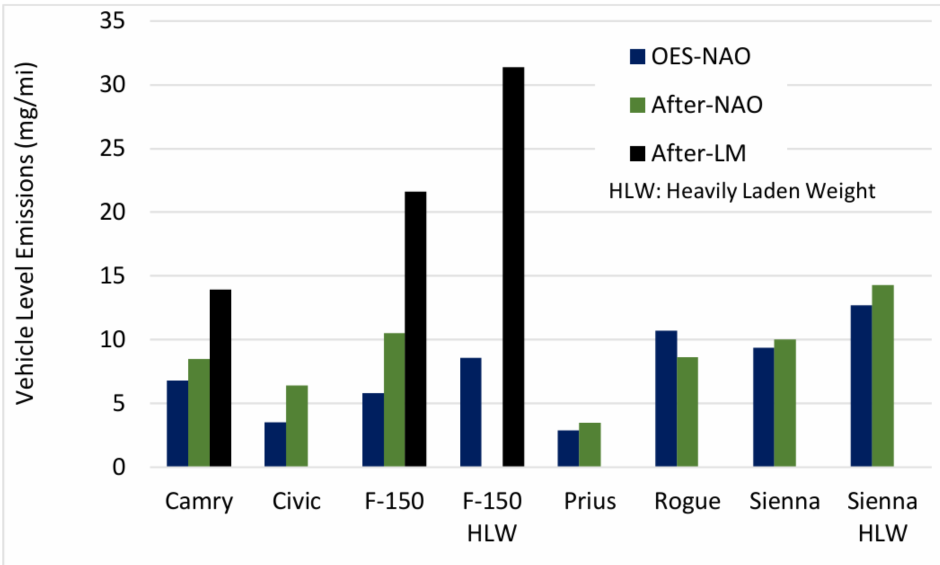


Figure 12 – Vehicle level braking emissions by model and friction material

Vehicle-level emission rates trended with vehicle weight within each pad material type. Figure 13 presents the vehicle level PM mass emission rate against the simulated vehicle test weight. From these results, the OES-NAO fit has the shallowest increase in emissions with weight and the LM fit has the highest increase with weight.

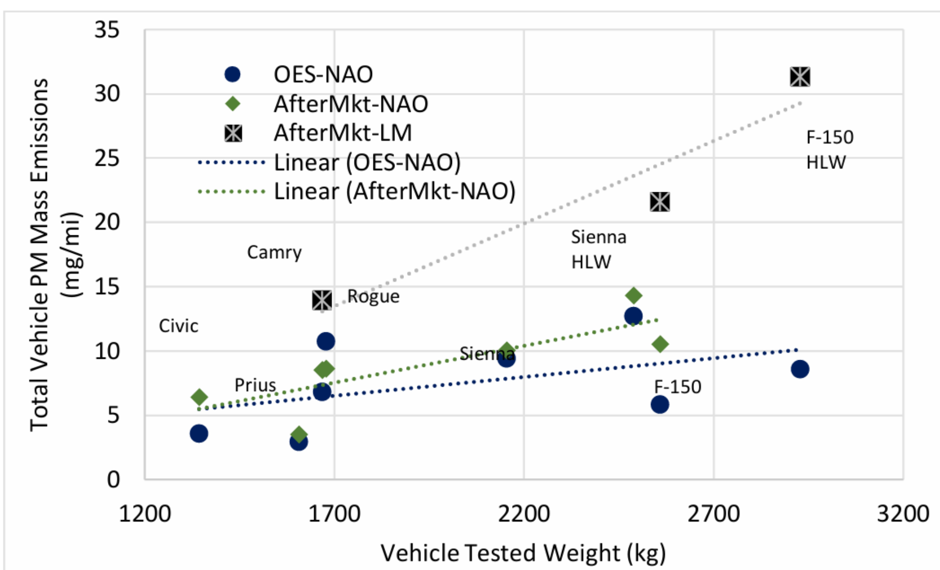


Figure 13 – Vehicle level braking emissions vs. vehicle test weight by friction material type

Emission factors for light vehicles as part of the California Department. of Transport (Caltrans) and updates to the EMFAC2021 model

In 2021, Caltrans reported the results from a study to gather brake particulate matter (PM) data on a range of heavy-duty (HD) trucks and one light-duty (LD) electric vehicle with regenerative braking in [16]. The main objective was to measure brake PM on various (HD) truck classes and brake configurations representing California's truck fleet. Some highlights of the study include the following, when rolled up to full truck emissions:

- Refuse trucks had the highest emission rates at 210 mg/mi (130.5 mg/km/V)
- Class 8 trucks were estimated to produce nearly 150 mg/mi (93.2 mg/km/V) when accounting for the projected 50/50 mix of drum and disc brakes within ten years.
- For individual wheel tests, Class 8-disc brakes on a drive axle under full load and low-speed brake-intensive operation had the highest PM emissions, at nearly 50 mg/mi (31 mg/km/B).
- The Tesla Model 3 exhibited a very aggressive regenerative braking strategy, reducing dependence on the vehicle's disc brakes.
- As a result, the PM_{10} emissions for the Tesla Model 3 were quite low, with a full vehicle estimate of 1.42 mg/mi, which is about 44 percent of the Toyota Prius' full vehicle emissions level. However, the $PM_{2.5}$ fraction based on filter data collected for the Tesla was relatively high, at 70 percent.
- Loading and duty cycles were significant sources of variability in overall PM emissions
- In-use brake temperatures were first characterized with track testing on four HD trucks and one trailer to simulate real-world thermal regimes for dynamometer emissions testing

Figure 14 overviews of PM_{10} EF for the different vehicle, brake, and axle positions.

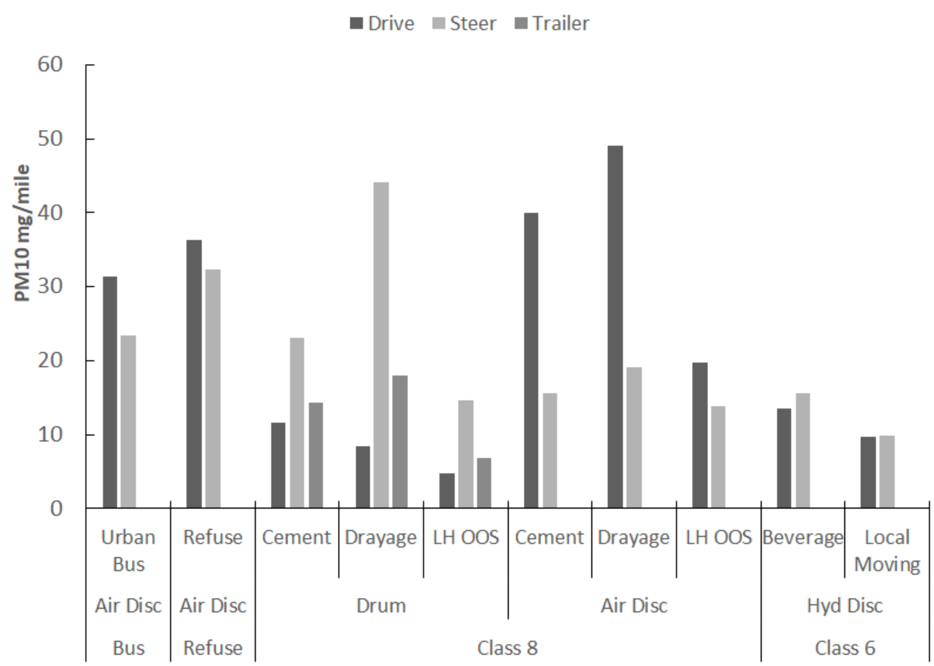


Figure 14 – Emission factors result for Caltrans commercial vehicles

Updates to the EPA's MOVES5

Upon completion of the two campaigns for light—and heavy-duty vehicles, the United States Environmental Protection Agency conducted a systematic update to the emission factors for both vehicle categories, including hybrid and electric powertrains [32], [33]. In summary:

MOVES5 includes updates to brake wear for light- and heavy-duty vehicles for model years 2011 and later, incorporating analysis of new data

• In general, the new $PM_{2.5}$ brake wear rates are:

– Lower for light and medium-duty vehicles, light heavy-duty vehicles, and urban buses

– Higher for other heavy-vehicle classes, most notably for heavy heavy-duty vehicles
• This results in an overall increase in $PM_{2.5}$ emissions from brake wear, compared to MOVES4
• Particle size data from these studies also allowed us to update the $PM_{10}/PM_{2.5}$ ratios in MOVES
– The new data imply lower PM_{10} emission rates for all vehicle classes

Figure 15 shows the effects of the new emission factors on total brake wear modelling through 2050.

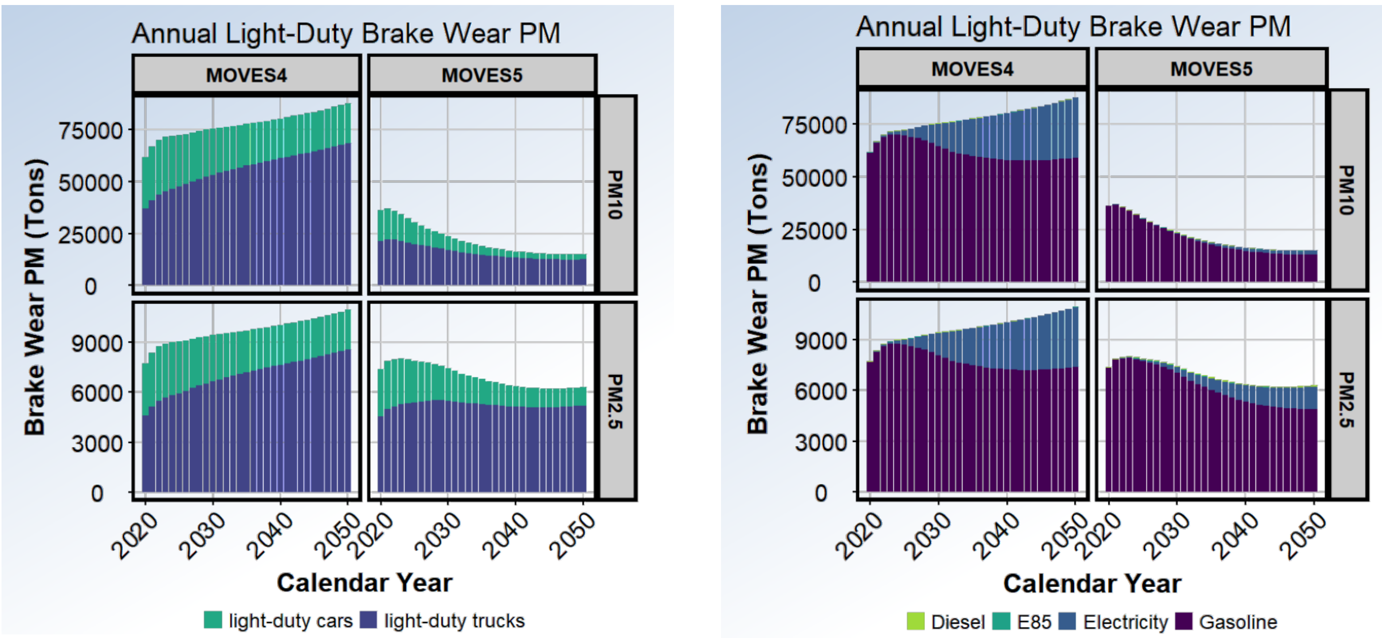


Figure 15 – Effect of new emission factors on brake wear projections within MOVES5. Image released by source

Emission factors using various test cycles

The academia and industry studies on EF for particle mass and particle number have shifted significantly towards conducting laboratory-based measurements after publication of the GRPE-81-40 using the WLTP-B cycle and the subsequent GTR 24 from April 24, 2024 [6]. Some studies use the CDBC, also developed as a laboratory dynamometer test using an enclosed brake with conditioned and clean air, and isokinetic sampling on a constant volume sampling tunnel [7]. Previous studies relied on wear vs. temperature cycles and city driving simulation [34], both exhibiting limitations due to reflecting high-energy or aggressive driving or lack of equivalent driving distance. The latter precluded the EC from reporting the EF as mg or particle count per unit distance, as mandated in the proposed Euro 7 regulation to enter into effect in November 2026. [35][36][7], [35], [36]Table 10 shows the data for the statistical assessment that follows.

The statistical analysis initially evaluated the hypothesis that PM_{10} emission rates per brake pad material are (statistically) significantly different. The data entry includes summary results from 68 studies with varying conditions, including different test setups and test cycles.

Table 10 – Emission factors (EF) of full friction brakes at vehicle level for particulate mass (mg/km/V) or particle number (#/km/V)

Index	Year	Source	Powertrain	Axle	Type	Pad	Vehicle or Test Mass kg	PM_{10} mg/km/V average	$PM_{2.5}$ mg/km/V average
1	2000	[35]	ICE	n/a	D	SM	1600	4.15	2.3
2	2000	[35]	ICE	n/a	D + Drum	SM	PT	7.5	5.5
3	2002	[35]	ICE	n/a	n/a	n/a	n/a	7	-
4	2003	[35]	ICE	F	D	LM	1600	24.6	-
5	2003	[35]	ICE	F	D	SM	1600	6	-

Index	Year	Source	Powertrain	Axle	Type	Pad	Vehicle or Test Mass kg	PM_{10} mg/km/V average	$PM_{2.5}$ mg/km/V average
6	2003	[35]	ICE	F	D	NAO	2100	5.4	-
7	2004	[35]	ICE	n/a	D	n/a	1600	1.8	-
8	2004	[35]	ICE	n/a	D + Drum	n/a	1600	12.6	-
9	2008	[35]	ICE	n/a	n/a	NAO	2000	17.4	-
10	2015	[35]	ICE	n/a	D	NAO	1600	0.67	0.53
11	2015	[35]	ICE	n/a	D	NAO	1600	1.38	1
12	2016	[35]	ICE	n/a	Drum	NAO	1600	0.16	0.11
13	2017	[35]	ICE	n/a	D	NAO	1500	26.55	
14	2017	[35]	ICE	n/a	D	LM	1500	30	-
15	2019	[35]	ICE	F	D + HMC	LM	1600	5	-
16	2019	[35]	ICE	F	D + HMC	proto	1600	-	-
17	2019	[35]	ICE	n/a	D	n/a	2286	-	-
18	2021	[35]	ICE	n/a	D	n/a	1840	-	-
19	2020	[35]	ICE	n/a	D	LM	n/a	2.5	-
20	2020	[35]	ICE	n/a	D	NM	n/a	1.25	-
21	2021	[35]	ICE	n/a	D	LM	n/a	14	-
22	2021	[35]	ICE	n/a	D	NM	n/a	3.25	-
23	2021	[35]	ICE	n/a	D	LM	1600	7.4	-
24	2022	[35]	ICE	n/a	D	LM	1300	17.1	6.3
25	2022	[35]	ICE	n/a	D	NAO	1300	3.3	2.3
26	2022	[35]	ICE	n/a	D	LM	1400	7	
27	2022	[35]	ICE	F	D	ECE	2310	3.5	
28	2023	[35]	ICE	F	D	ECE	1800	10.2	3.1
29	2023	[35]	ICE	n/a	D	SM	n/a	12.3	2.75
30	2023	[35]	ICE	n/a	D	Ceramic	n/a	3.1	0.7
31	2020	[37]	ICE	F	D	ECE	1300		
32	2019	[38]	ICE	F	D	ECE	1719	5.4	
33	2019	[38]	ICE	F	D	SM	1719	4.5	
34	2020	[7]	ICE	R	D	NAO	2617	6	2.55
35	2020	[7]	ICE	R	D	NAO	2695	5.4	1.35
36	2020	[7]	ICE	R	D	LM	2617	5.7	1.44
37	2020	[7]	ICE	R	D	LM	2695	5.85	1.44
38	2020	[7]	ICE	F	D	NAO	2617	5.25	1.35
39	2020	[7]	ICE	F	D	NAO	2695	4.95	1.77
40	2020	[7]	ICE	F	D	LM	2617	15.3	5.55
41	2020	[7]	ICE	F	D	LM	2695	24	6.6
42	2020	[7]	ICE	R	D	LM	1665	5.7	1.17
43	2020	[7]	ICE	R	D	NAO	1665	2.55	0.9
44	2020	[7]	ICE	F	D	LM	1665	6.6	0.96
45	2020	[7]	ICE	F	D	NAO	1665	5.25	1.65
46	2020	[7]	HEV	R	D	NAO	1592	0.6	0.3
47	2020	[7]	HEV	F	D	LM	1592	2.55	1.35
48	2020	[39]	ICE	F	D	LM	n/a	7.5	
49	2020	[39]	ICE	F	D	NM	n/a	4.5	
50	2021	[40]	ICE	n/a	D	NAO	n/a	0.882	0.618
51	2021	[40]	ICE	n/a	D	NAO	n/a	0.663	0.216
52	2021	[40]	ICE	n/a	D	NAO	n/a	0.483	0.294
53	2021	[40]	ICE	n/a	D	NAO	n/a	0.753	0.348
54	2021	[40]	ICE	n/a	D	NAO	n/a	0.339	0.147
55	2019	[41]	ICE	F	D	ECE	1600		
56	2019	[40]	ICE	F	D	ECE	1600		

Index	Year	Source	Powertrain	Axle	Type	Pad	Vehicle or Test Mass kg	PM_{10} mg/km/V average	$PM_{2.5}$ mg/km/V average
57	2024	[42]	ICE	F	D	ECE	n/a	39	12
58	2024	[42]	ICE	F	D	ECE	n/a	42.6	6.6
59	2024	[42]	ICE	F	D	Ceramic	n/a	21	6.3
60	2024	[42]	ICE	R	D	ECE	n/a	18	4.5
61	2024	[42]	ICE	R	D	ECE	n/a	33	5.1
62	2024	[42]	ICE	R	D	Ceramic	n/a	6	2.4
63	2024	[42]	ICE	F	D	ECE	n/a	63	12
64	2024	[42]	ICE	F	D	ECE	n/a	29.4	4.5
65	2024	[42]	ICE	F	D	Ceramic	n/a	4.5	1.8
66	2024	[42]	ICE	R	D	ECE	n/a	13.5	3
67	2024	[42]	ICE	R	D	ECE	n/a	18	2.7
68	2024	[42]	ICE	R	D	Ceramic	n/a	3	2.55

Table 10 – continued

Index	TPN #/km/V average	Sampling system	Instrument	Test setup	Test cycle	Comments
1	-	n/a	Mass loss	Mass loss		Estimate
2	-	n/a	Mass loss	Mass loss		Estimate
3	-	n/a	Mass loss	Mass loss		Estimate
4	-	Single probe	PM	On-road	RDE	-
5	-	Single probe	PM	Dyno	RDE	Wind tunnel, urban driving
6	-	Single probe	PM	On-road	RDE	-
7	-	n/a	Mass loss	Mass loss (Motorway)	RDE	On-road
8	-	n/a	Mass loss	Mass loss (Urban – Motorway)	RDE	On-road
9	-	FE	PM	Dyno	Accel-Decel	Estimate
10	-	FE	PM	Dyno	JC08	Dyno, JC08 cycle
11	-	FE	PM	Dyno	JC08	
12	-	FE	PM	Dyno	RDE	Dyno, RDE
13	1.53E+12	FE	PM,PN	Dyno	SAE J2707	Dyno, SAE J2707
14	4.95E+11	FE	PM,PN	Dyno	SAE J2707	Dyno, SAE J2707
15	7.40E+11	FE	PM,PN	On-road	LACT	On road, LACT
16	1.00E+10	FE	SPN	Dyno	LACT	Dyno, LACT
17	1.20E+10	FE	PM,PN	On-road	RDE	On-road
18	3.00E+10	FE	PM,PN	Dyno	WLTP-B	Dyno, WLTP-B
19	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E, OPC
20	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
21	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
22	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
23	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
24	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
25	-	FE	PM,PN	Dyno	WLTC	Dyno, WLTP-E
26	-	FE	PM,PN	Dyno	WLTP-B	Dyno, WLTP-B
27	-	FE	PM,PN	Dyno	RDE	Dyno, RDE
28	3.70E+10	FE	PM,PN	On-road	RDE	On road RDE
29		FE	PM	Dyno	RDE	Dyno, RDE
30		FE	PM	Dyno	RDE	Dyno, RDE
31	1.20E+10	FE	PM,PN	On-road	RDE	On road RDE
32	2.10E+14	FE	PM,PN	On-road	RDE	On road RDE

Index	TPN #/km/V average	Sampling system	Instrument	Test setup	Test cycle	Comments
33	6.00E+13	FE	PM,PN	On-road	RDE	On road RDE
34	3.00E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
35	2.55E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
36	2.64E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
37	3.30E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
38	4.50E+08	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
39	3.00E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
40	7.20E+10	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
41	8.40E+10	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
42	4.50E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
43	1.50E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
44	3.30E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
45	2.55E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
46	1.35E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
47	1.47E+09	FE	PM,PN	Dyno	CBDC	Dyno, CBDC
48	9.60E+09	FE	PM,PN	Dyno	WLTC	Brake Dyno, WLTC
49	3.20E+09	FE	PM,PN	Dyno	WLTC	Brake Dyno, WLTC
50	1.38E+05	FE	PM,PN,FMPS	Dyno	WLTC	Brake Dyno, WLTC
51	1.02E+05	FE	PM,PN,FMPS	Dyno	NEDC	Brake Dyno, NDEC
52	1.26E+05	FE	PM,PN,FMPS	Dyno	FTP	Brake Dyno, FTP
53	6.90E+04	FE	PM,PN,FMPS	Dyno	LACT	Brake Dyno, LACT
54	6.60E+04	FE	PM,PN,FMPS	Dyno	WLTP-B	Brake Dyno, WLTP-B
55	2.10E+10	FE	PN	Dyno	LACT	Brake Dyno, LACT
56		FE	SPN	Dyno	LACT	Brake Dyno, LACT
57		FE	PM,PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
58		FE	PM,PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
59		FE	PM,PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
60		FE	PM,PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
61		FE	PM,PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
62		FE	PM, PN	Dyno	WLTP-B	Brake Dyno, WLTP-B
63		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE
64		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE
65		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE
66		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE
67		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE
68		FE	PM,PN	Dyno	RDE	Brake Dyno, RDE

Using the data from Table 10 and focusing on fully enclosed brake sampling systems, the one-way ANOVA analysis for PM_{10} revealed a significant difference between population means at a 0.05 significance level.

Descriptive Statistics					
	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
NAO	8	0	2.46875	2.60726	0.92181
LM	13	0	3.81154	2.73484	0.75851
NM	3	0	1	0.54645	0.31549
ECE	9	1	9.62963	5.99712	1.99904
Ceramic	4	0	2.875	2.78014	1.39007

Overall ANOVA					
	DF	Sum of Squares	Mean Square	F Value	Prob > F

Model	4	322.87469	80.71867	5.75477	0.00132
Error	32	448.8445	14.02639		
Total	36	771.71919			
Null Hypothesis: The means of all levels are equal Alternative Hypothesis: The means of one or more levels are different **At the 0.05 level, the population means are significantly different**					

Fit Statistics				
	R-Square	Coeff Var	Root MSE	Data Mean
	0.41838	0.8129	3.74518	4.60721

After converting the WLTP-B kinetic energy of 15,980 J/kg of vehicle mass, assuming an average vehicle mass of 2000 kg and a nominal test duration of 4.3 h (7433 kJ/h = 0.21 bhp-hr), Figure 16 indicates that [43] while exhibiting a large variation, most of the fleet's current brake systems would exceed California's particle mass (PM) and Euro 7 particle count (SPN10) tailpipe regulatory limits. Working the calculation backward yields a maximum PM_{10} of 2.1 mg/km/V. Brake emissions vary significantly compared to exhaust emissions, depending on the brake disk temperature (driving aggressiveness) and brake pad chemistry. Most of the non-exhaust results are in Region II, where PN and PM regulation limits are violated. Non-exhaust emissions can vary from 10^9 to 10^{13} p/km and 10 to 100 mg/km for PN and PM_{10}, respectively, in most cases.

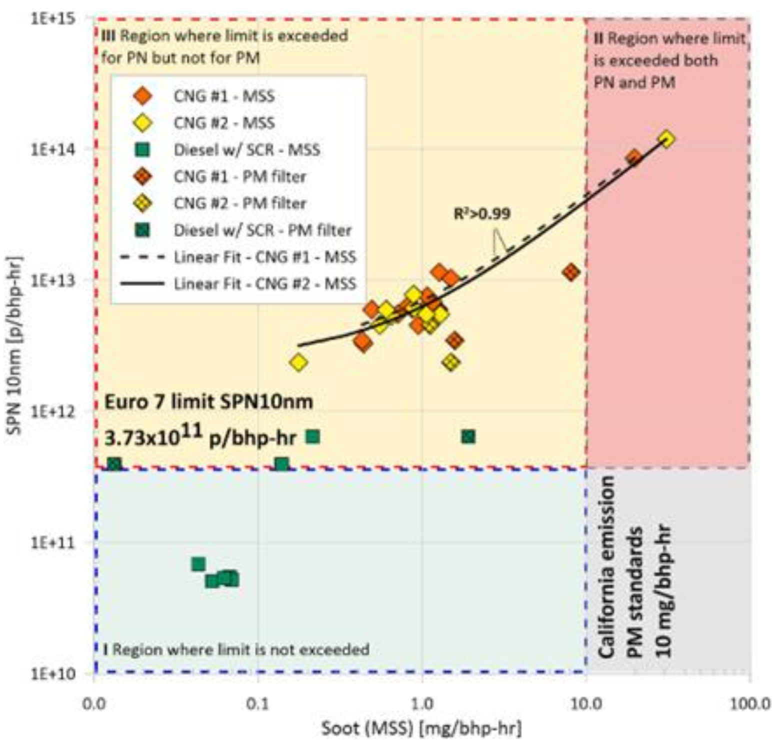


Figure 16 – SPN10 vs. PM mass (soot) emissions concerning Euro 7 PN and California PM mass standard; The horizontal axis shows PM mass (soot) and the vertical axis the SPN10 emissions; Each color represents a different vehicle. Image from open source [40]

Figure 17 and Figure 18 show the results primarily from laboratory tests using the GTR 24 test method, which is the basis for future product development, type approval, conformity of production, and market surveillance. Some results will reflect EF from previous test cycles and be marked accordingly. In the graphs that follow, emission factors are for full brake assemblies for various vehicle classes, brake systems, and friction couple designs. Laboratory brake assemblies or OEM brake systems were tested in an enclosure sampling system, using a brake dynamometer, and following the WLTP-B (brake) cycle. Sampling from a tunnel using cyclonic separators is followed by filters for PM and condensation particle counters

(CPC) for PN. PN refers to total PN > 10 nm, but only when the measured values were close to the solid PN. The initial screening suggests higher ECE PM_{10} emission rates for heavier vehicle classes, while there is no clear trend for the other brake pad types. Lastly, Figure 17 shows lower emissions rates for the NAO brake types, aligning with findings from other studies [7], [35], [36]. For $PM_{2.5}$ EF, the initial screening suggests higher emission rates of ECE and LM $PM_{2.5}$ under heavier vehicle classes, no clear trend for the other brake pad types, and Lower emissions rates for the NAO brake types. Figure 18 illustrates the EF PM_{10} and EF $PM_{2.5}$ as a function of vehicle weight class and type of friction material. The emission factors for PM exhibit marked differences between emission inventories, studies with semi-enclosed systems, and studies with fully enclosed testing. The EF from emissions inventories is at least twice as high as measurements with a fully enclosed system. One explanation for this is that several inventories still use data from legacy studies that rely on high-energy cycles and older formulations, whereas newer tests use the WLTP-B cycle and current or newer friction formulations. Figures 17 to 20 show box plots of emission factors categorized by different factors or criteria.

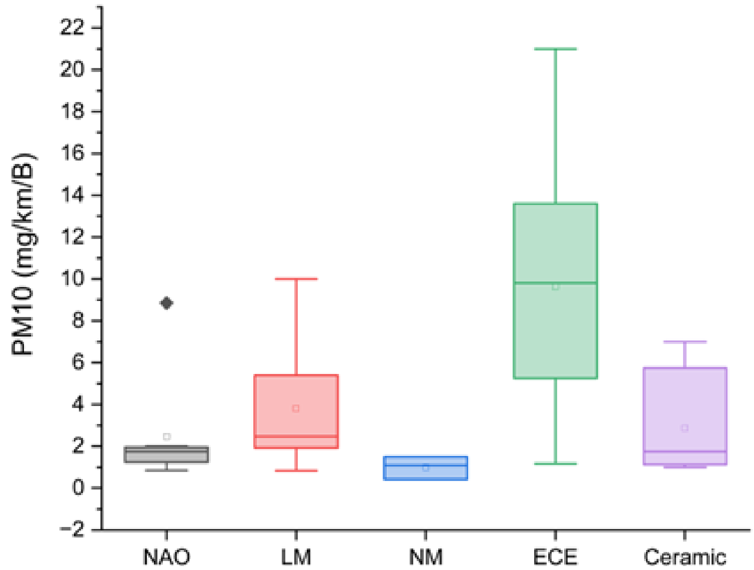
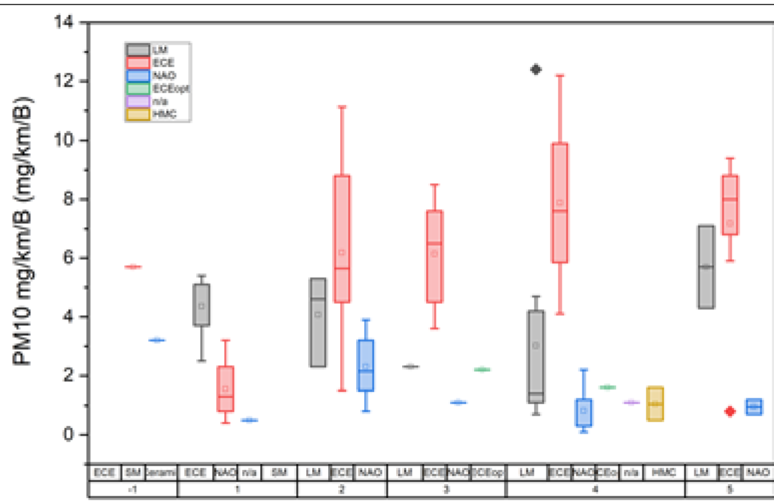
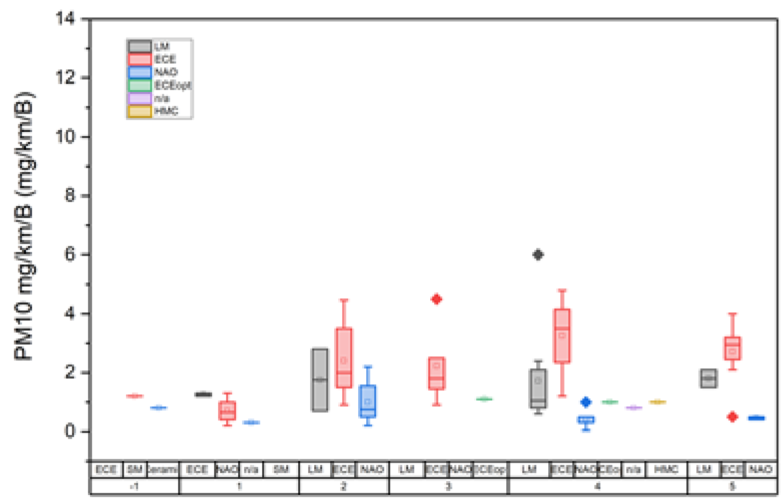


Figure 17 – PM_{10} emission rates based on Table 10, which includes fully enclosed brake sampling systems



(a) PM_{10} emission factor per brake

Weight ranges [kg]	Weight class
<1100	1
1100-1500	2
1500-1700	3
1700-2000	4
2000-2500	5
2500-3000	6



(b) PM2.5 emission factor per brake

Figure 18 – PM_{10} and $PM_{2.5}$ per GTR 24 for different vehicle weight classes and friction material types

The relationship between fine ($PM_{2.5}$) and coarse (PM_{10}) particles is also important for further characterizing the friction couple or comparing the behavior of different sampling systems. Figure 18**Error! Reference source not found.** and Figure 19**Error! Reference source not found.** show the results for the entire dataset, including multiple independent studies across various vehicle classes, brake systems, and friction couple designs. PM_{10} emissions on a mg/km/B basis suggest that ECE brake pads have higher emission rates under heavier vehicle classes, while there is no clear trend for the other brake pad types. Lastly, Figure 18 – PM10 and PM2.5 per GTR 24 for different vehicle weight classes and friction material types suggests that the lower emissions rates are presented for the NAO brake types.

Regarding the $PM_{2.5}$ fraction, Figure 19 shows that higher ratio values suggest a larger fraction of coarse-mode (>$PM_{2.5}$) particulates, with no clear trend across the different weight classes. High average $PM_{2.5}/PM_{10}$ values were identified under NAO brake pads for the heavier vehicle classes. The large variation in the ratio also points to the need (as stated in GTR 24) to measure the two fractions separately, as there are no clear trends or ratios that allow estimating one EF from the other. From the data analyzed, as shown in Figure 20, brake discs with non-traditional surfaces (HMC or CC) can exhibit a larger $PM_{2.5}$ fraction than other formulations included in the analysis.

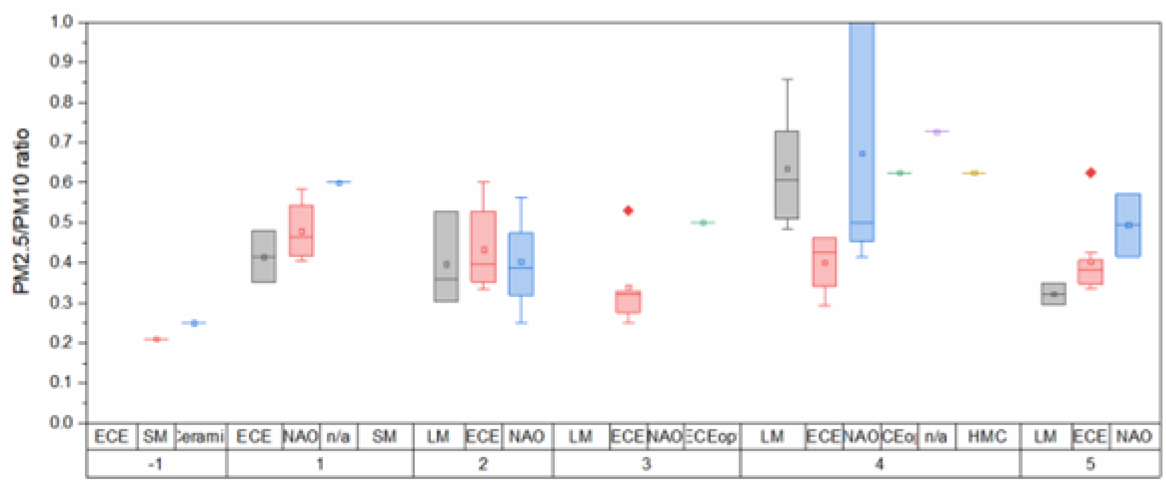


Figure 19 - $PM_{2.5}$ / PM_{10} ratio for several studies on different vehicles, brakes, and friction couples

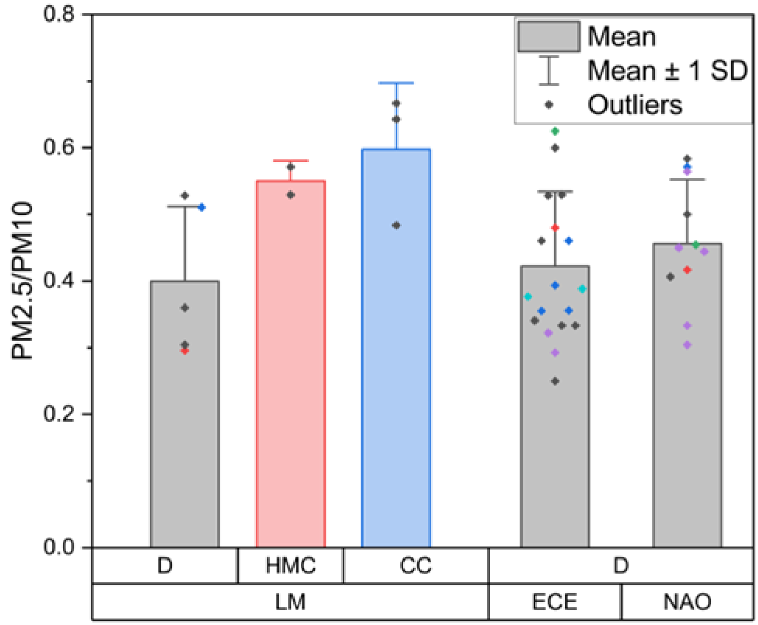


Figure 20 – $PM_{2.5}$ / PM_{10} per brake pad and brake disk material with data from Table 11, which includes $PM_{2.5}$ and PM_{10} using GTR 24 tests. Brake Disk: D = disc (gray cast iron or GCI); HMC = hard metal coated; CC = carbon ceramic. Brake Pad: LM = low metallic; ECE = Economic Commission for Europe; NAO = non-asbestos organic

Correlations between main metrics for PM and PN

When multiple studies are involved and several factors (e.g., vehicle test mass, vehicle type, friction couple design) are present, scatter plot analysis can reveal associations or correlations that explain trends in EF. Figure 21 illustrates the pairwise correlations among PM_{10}, $PM_{2.5}$, PN, and vehicle test weight, with data grouped by friction material formulation type. The graphs include scatter plots at each intersection and histograms showing the distribution of results for each factor.

Figure 21 indicates the following findings:

a. When taking the entire set of results, there is a strong correlation between $PM_{2.5}$ and PM_{10}
b. PN EF exhibits a broad trend to increase as $PM_{2.5}$ or PM_{10} increases
c. Due to the confounding of multiple factors without proper segregation within the studies, vehicle weight alone does not provide a useful prediction of PM or PN EFs, beyond indicating that when one measurand increases, the others tend to increase as well.

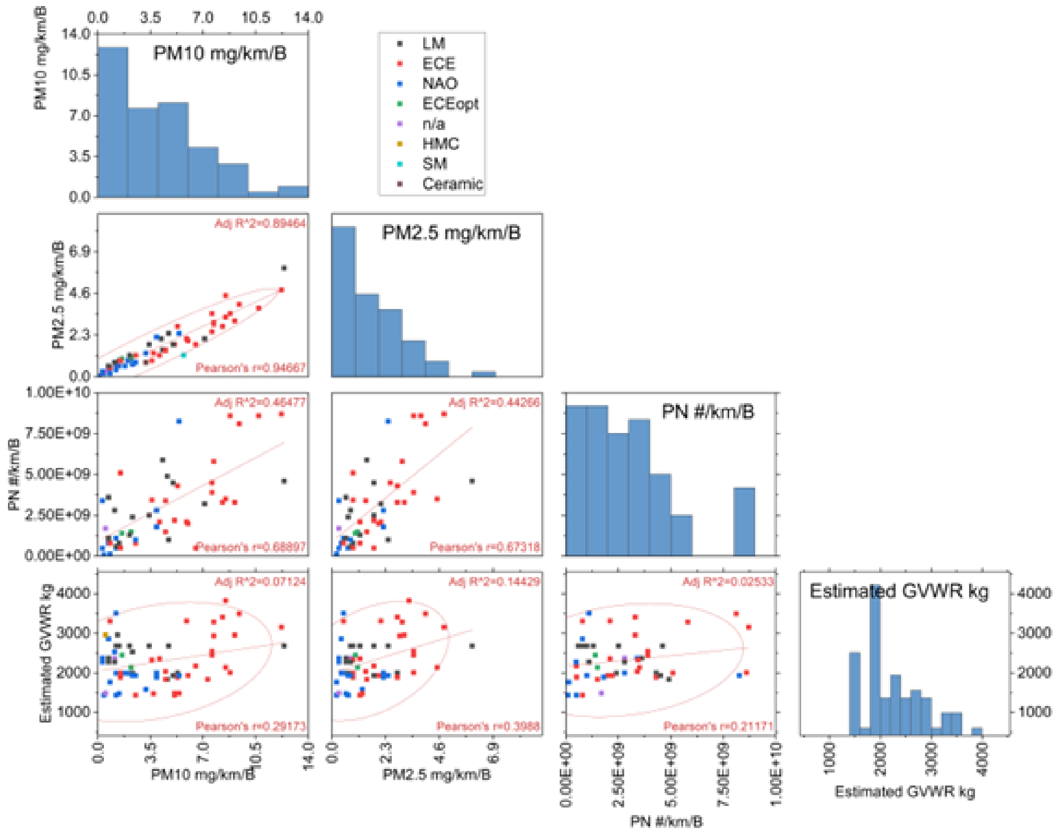


Figure 21 – Pairwise correlation between PM_{10} / $PM_{2.5}$ for several studies on different vehicles, brake types, and friction couples formulations

Figure 22 depicts the behavior of isolating ECE brake pads. While most correlations exhibit similar behavior compared to the entire set of studies, the correlation is higher for ECE with vehicle weight than all formulations combined. Pearson's r^2 for EF PM_{10} v estimated GVWR increases from 0.25 for all formulations to 0.42 for ECE pads. For EF $PM_{2.5}$, Pearson's r^2 remains about 0.37, and for EF PN, Pearson's r^2 increases from 0.4 to 0.62.

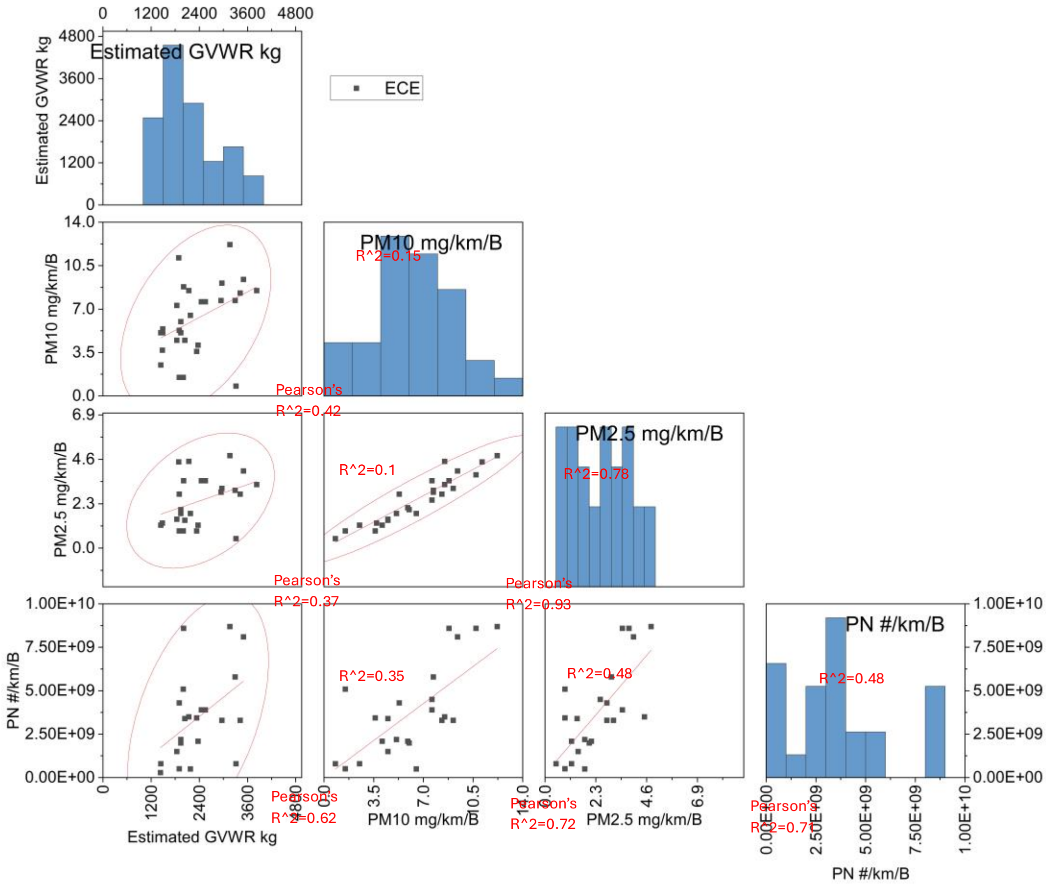


Figure 22 – Pairwise correlation between PM_{10} / $PM_{2.5}$ for several studies on different vehicles, brake types, and friction couples with ECE brake pad formulations

Principal component analysis (PCA)

PCA [44]is another tool for assessing the source of variation and the relation among factors. PCA aims to determine the minimum set of variables that explain most of the variation. Typical PCA uses two principal components to account for at least 80% of the variation. In this study, principal component 1 explains 69 %, and principal component 2 explains 21 %, corresponding to 90 % of the variation. PCA can help identify correlations between variables. ECE and NAO brake pads seem to follow PC2, which is mostly related to vehicle load. LM brake pads are strongly associated with PC1. This suggests that the emission performance of these higher friction pads is more closely associated with the generation of ultrafine particles during braking rather than the brake power itself. This finding aligns with studies showing that high-friction brake pads, such as LM pads, produce many ultrafine particles due to their abrasive content and high-temperature performance. [7], [45], [46], [47]. The length of the vectors for the different variables indicates their respective contribution to total variance, with EF PM_{10} and EF $PM_{2.5}$ exhibiting equal contribution and a strong correlation (as the vector directions and magnitude are almost identical). This effect is also visible in the scatter plots in Figure 21 and Figure 22. Figure 23 shows the results of the PCA assessment. The eccentricity (deviation from the circular shape) of the different ellipses for the various materials also indicates how sensitive the given formulation is to the estimated GVWR for the vehicle. E.g., in this compilation, the LM materials (in green) have a larger scatter in emission factors (more eccentric) and are less sensitive to GVWR (low alignment between the major axis and the GVWR loading vector, comparted to the ECE materials (in red). The wide range of test setups, test conditions, and brake under testing, can also contribute to the scatter in test results. We found at least two studies [48], [49] applying the PCA approach to a systematic set of results, including the application of PCA to predict $PM_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region.

6

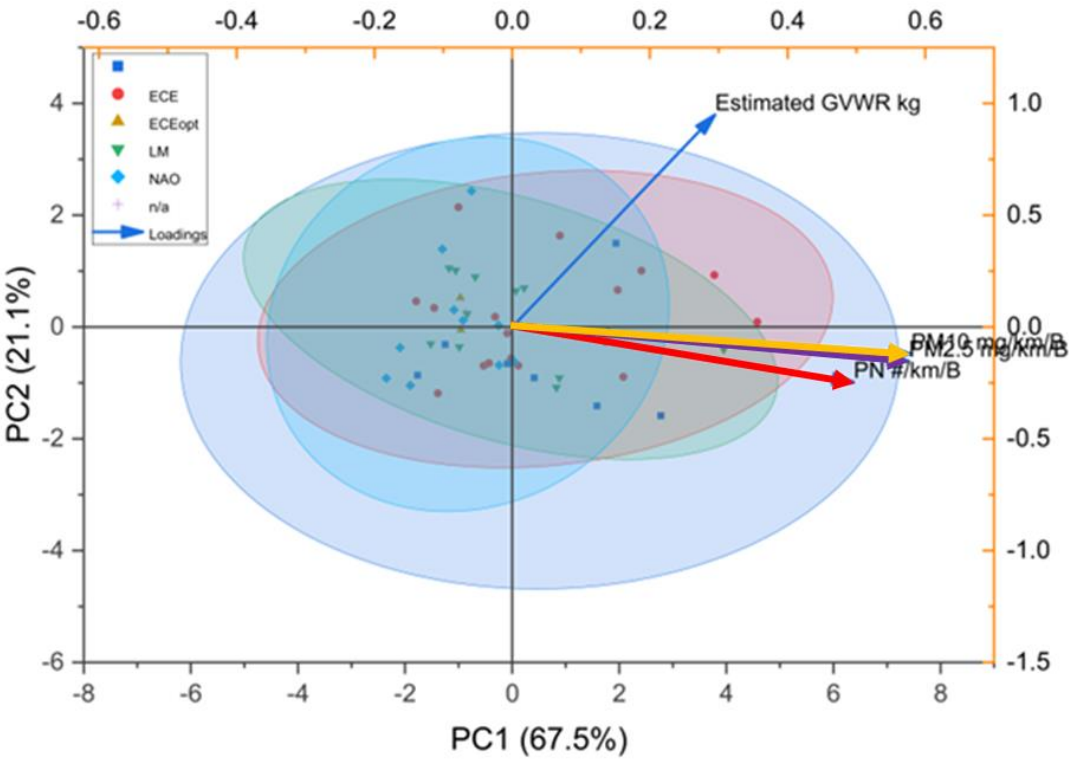


Figure 23 – Biplots from Principal Component Analysis (PCA) for several studies on vehicles, brake types, and friction couples' formulations based on Table 11 using GTR 24 tests. Orange vector for PM_{10}; purple for $PM_{2.5}$, and red for PN

In Circa 2018, the industry was able to commence testing with the first iterations of the current GTR 24 test setup. Testing a brake assembly in an enclosure, using a brake dynamometer, and following the WLTP-B (brake) cycle. Sampling from a tunnel using cyclonic separators is followed by filters for PM and condensation particle counters (CPC) for PN. PN refers to total PN > 10 nm, but only when the measured values were close to the solid PN.

Table 11 from [35] show emission factors of full friction brakes for mass (mg/km/B or mg/km/V) or particle number (#/km/B or #/km/V) measured according to the Brakes GTR 24 for light-duty vehicles, i.e., with the WLTP-B (worldwide harmonized light vehicles test procedure brake cycle), unless otherwise specified. Values in *italics* were calculated based on the vehicle classification and the default loading conditions from the GTR 24 and common payloads for the different vehicle classifications

Table 11 – Emission factors measured during GTR 24 tests

Index	**Year**	**Source**	**Vehicle type**	**Axle**	**Type**	**Pad**	**Test Mass kg**	**Estimated GVWR kg**	**US CFR**	**EU LDV**	**Comments**
1	2019	[35]		F	D	LM	1500	*1840*	*C*	C	Mid-sized, LACT cycle
2	2019	[35]		F	D	ECE	1500	*1840*	*C*	C	Mid-size
3	2019	[35]		F	D	ECE	1200	*1440*	*B*	B	City car
4	2019	[35]		F	D	NAO	1200	*1440*	*B*	B	City car
5	2019	[35]		F	D	NAO	1200	*1440*	*B*	B	City car

Index	Year	Source	Vehicle type	Axle	Type	Pad	Test Mass kg	Estimated GVWR kg	US CFR	EU LDV	Comments
6	2020	[35]		F	D	ECE	1750	*1990*	*C*		
7	2020	[35]		F	D	ECE	2150	*3250*	*E*		8% payload
8	2020	[35]	ICE	F	D	NAO	2500	*3600*	*F*		8% payload
9	2020	[35]	ICE	F	D	NAO	2500	*3600*	*E*		67% payload
10	2020	[35]	ICE	F	D	ECE	2950	*4050*	*F*		67% payload
11	2020	[35]	ICE	F	D	LM	2500	*3600*	*E*		
12	2020	[35]	ICE	F	D	LM	2950	*4050*	*F*		67% payload
13	2020	[35]	ICE	F	D	NAO	2182	*3280*	*D*	M	Mini van
14	2020	[35]	ICE	F	D	NAO	1651	*1990*	*C*	C	Medium car
15	2020	[35]	ICE	F	D	NAO	1655	*1995*	*C*	C	Medium car
16	2020	[35]	ICE	F	D	NAO	1655	*1995*	*C*	C	Medium car
17	2020	[35]	ICE	F	D	LM	1655	*1995*	*C*	C	Medium car
18	2020	[35]	ICE	F	D	NAO	1347	*1585*	*B*	B	City car
19	2020	[35]		F	D	ECE					
20	2020	[35]		F	D	NAO	2000	*2240*	*C*		
21	2021	[35]		F	D	ECE	1700	*2140*	*C*	C	Mid-size
22	2021	[35]		F	D	ECEopt	1700	*2140*	*C*	C	Mid-size
23	2021	[35]		F	D	LM	2250	*2690*	*D*	J	SUV
24	2021	[35]		F	HMC	LM	2250	*2690*	*D*	J	SUV
25	2021	[35]		F	CC	LM	2250	*2690*	*D*	J	SUV
26	2021	[35]		F	CC	LM	2250	*2690*	*D*	J	SUV
27	2021	[35]		F	HMC	LM	2250	*2690*	*D*	J	SUV
28	2021	[35]		F	CC	LM	2250	*2690*	*D*	J	SUV
29	2022	[35]		F	D	ECE	1800	*2040*	*C*	F	Luxury sedan
30	2022	[35]		F	D	LM	2000	*2240*	*C*		
31	2022	[35]		F	D	NAO	2000	*2240*	*C*		
32	2023	[35]		F	D	ECE	1600	*1940*	*C*	C	Medium car
33	2023	[35]		F	D	NAO	1600	*1940*	*C*	C	Medium car
34	2023	[35]		F	D	ECE	1660	*2000*	*C*	J	SUV
35	2023	[35]		F	D	ECE	2623	*2960*	*E*	C	Mid-size
36	2023	[35]		R	Drum	n/a	1253	*1490*	*B*	A	Super mini
37	2023	[35]		F	D	ECE	2500	*3600*	*F*		LCV 28% payload
38	2023	[35]		F	D	ECE	3390	*4490*	*F*		LCV 90% payload
39	2023	[35]		F	D	LM	1660	*2000*	*C*	C	Mid-size
40	2023	[35]		F	D	NAO	1660	*2000*	*C*	C	Mid-size
41	2023	[35]		F	D	ECE	1660	*2000*	*C*	C	Mid-size
42	2023	[35]		R	Drum	n/a	2041	*2380*	*D*	C	Mid-size
43	2023	[35]		R	Drum	LM	2041	*2380*	*D*	C	Mid-size
44	2023	[35]		R	Drum	NAO	2041	*2380*	*D*	C	Mid-size
45	2023	[35]		F	D	ECE	2113	*2450*	*D*	C	Mid-size
46	2023	[35]		F	HMC	ECEopt	2113	*2450*	*D*	C	Mid-size
47	2023	[35]		F	D	ECE	2027	*2365*	*D*	F	Luxury sedan
48	2023	[35]		F	D	ECE	1840	*2180*	*C*		Japanese market
49	2023	[35]		F	D	LM	1820	*2920*	*D*		*
50	2023	[35]		F	D	NAO	1820	*2920*	*D*		*
51	2023	[35]		F	D	LM	2250	*3350*	*E*		*
52	2023	[35]		F	D	HMC	2250	*3350*	*E*		*
53	2023	[35]		F	D	ECE	1500	*1840*	*C*		Large car
54	2023	[35]		F	D	ECE	1250	*1490*	*B*	B	City car

Index	Year	Source	Vehicle type	Axle	Type	Pad	Test Mass kg	Estimated GVWR kg	US CFR	EU LDV	Comments
55	2023	[35]		F	D	ECE	1200	*1440*	*B*	B	City car
56	2023	[35]		F	D	ECE	1250	*1490*	*B*	B	City car
57	2023	[35]		F	D	SM	n/a				Average
58	2023	[35]		F	D	Ceramic	n/a				Estimated
59	2023	[35]	ICE	F	D	ECE	1240	*1480*	*B*		
60	2023	[35]	ICE	F	D	NAO	1240	*1480*	*B*		
61	2023	[35]	ICE	F	D	NAO	1533	*1770*	*B*		
62	2023	[50]	PHEV	F	D	NAO	1533	*1770*	*B*		
63	2023	[42]	HEV	F	D	ECE	1547	*1885*	*C*	E	Large car
64	2022	[51]	HEV	R	D	ECE	1195	*1435*	*B*	B	City car
65	2022	[51]	HEV	R	D	SM	1195	*1435*	*B*	B	City car
66	2022	[42]		F	D	ECE	1993.5	*2330*	*D*	E	Executive car
67	2021	[42]		F	D	ECE	2524.7	*3315*	*F*		
68	2023	[42]	ICE	F	D	ECE	1659.5	*1895*	*C*	C	Mid-size
69	2023	[42]	ICE	R	D	ECE	1659.5	*1895*	*C*	C	Mid-size
70	2023	[42]	ICE	F	D	NAO	1659.5	*1895*	*C*	C	Mid-size
71	2023	[42]	ICE	F	D	ECE	2112.5	*2550*	*D*	J	SUV
72	2023	[42]	HEV	F	D	HMC	2112.5	*2550*	*D*	J	SUV
73	2023	[42]	ICE	R	Drum	LM	2040.5	*2280*	*C*	C	Mid-size
74	2023	[42]	ICE	R	Drum	LM	2040.5	*2280*	*C*	C	Mid-size
75	2023	[42]	ICE	R	Drum	NAO	2040.5	*2280*	*C*	C	Mid-size
76	2023	[42]	PHEV	Total	D	ECE	1659.5	*1995*	*C*		
77	2023	[42]	BEV	Total	D	ECE	1659.5	*1995*	*C*		
78	2023	[52]	HEV	Total	D	ECE	1500	*1840*	*C*		
79	2020	[53]	HEV	Total	D	NAO	1592	*1930*	*C*		
80	2024	[50]	ICE	Total	D	NAO	1533	*1870*	*C*		
81	2024	[50]	PHEV	Total	D	NAO	1533	*1870*	*C*		
82	2023	[41]	LCV	F	D	ECE	1600	*1940*	*C*		
83	2023	[41]	LCV	F	D	NAO	1600	*1940*	*C*		
84	2023	[41]	LCV	F	D	ECE	1668	*2005*	*C*		
85	2023	[41]	SUV	F	D	ECE	2623	*3415*	*F*		GTR 24 load
86	2023	[41]	LCV	R	Drum		1253	*1590*	*B*		
87	2023	[41]	VAN	F	D	ECE	2500	*2940*	*E*	M	MPV
88	2023	[41]	VAN	F	D	ECE	3390	*3830*	*G*	M	MPV
89	2024	[54]	ICE	F	D	LM	1600	*1940*	*C*	C	Medium car
90	2024	[54]	ICE	F	D	NAO	1600	*1940*	*C*	C	Medium car

*Corrected with ×0.7/2

U.S. CFR:
Class A—Not greater than 1360 kg. (3,000 lbs.) Class B—Greater than 1360 kg. to 1814 kg. (3,001-4,000 lbs.) Class C—Greater than 1814 kg. to 2268 kg. (4,001-5,000 lbs.) Class D—Greater than 2268 kg. to 2722 kg. (5,001-6,000 lbs.) Class E—Greater than 2722 kg. to 3175 kg. (6,001-7,000 lbs.) Class F—Greater than 3175 kg. to 3629 kg. (7,001-8,000 lbs.) Class G—Greater than 3629 kg. to 4082 kg. (8,001-9,000 lbs.) Class H—Greater than 4082 kg. to 4536 kg. (9,001-10,000 lbs.) Class 3—Greater than 4536 kg to 6350 kg. (10,001-14,000 lbs.) Class 4—Greater than 6350 kg to 7257 kg. (14,001-16,000 lbs.) Class 5—Greater than 7257 kg to 8845 kg. (16,001-19,500 lbs.) Class 6—Greater than 8845 kg to 11793 kg. (19,501-26,000 lbs.) Class 7—Greater than 11793 kg to 14968 kg (26,001-33,000 lbs.) Class 8—Greater than 14968 kg. (33,001 lbs. and over) according to [55]

European Commission vehicle segmentation according to [56]

Table 11 – continued

Index	Powertrain or Vehicle type	Axle	Type	Pad	Test Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN #/km/B	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V
1		F	D	LM	1500	4.6		4.90E+09	13.80	
2		F	D	ECE	1500	4.5	1.5	1.50E+09	13.5	4.5
3		F	D	ECE	1200	2.5	1.2	8.00E+08	7.5	3.6
4		F	D	NAO	1200	1.2	0.7	5.00E+08	3.6	2.1
5		F	D	NAO	1200	0.4	0.2	1.00E+08	1.2	0.6
6		F	D	ECE	1750	7.6	2.5	4.50E+09	22.8	7.5
7		F	D	ECE	2150	12.2	4.8	8.70E+09	36.6	14.4
8	ICE	F	D	NAO	2500	1.2	0.5	1.10E+09	3.6	1.5
9	ICE	F	D	NAO	2500	0.7	0.4	8.00E+08	2.1	1.2
10	ICE	F	D	ECE	2950	0.8	0.5	8.00E+08	2.4	1.5
11	ICE	F	D	LM	2500	4.3	1.5	5.90E+09	12.9	4.5
12	ICE	F	D	LM	2950	7.1	2.1	3.20E+09	21.3	6.3
13	ICE	F	D	NAO	2182	2.2	1		6.6	3
14	ICE	F	D	NAO	1651	2	0.9		6	2.7
15	ICE	F	D	NAO	1655	1.8	0.6		5.4	1.8
16	ICE	F	D	NAO	1655	1.2	0.4		3.6	1.2
17	ICE	F	D	LM	1655	2.3	0.7	2.40E+09	6.9	2.1
18	ICE	F	D	NAO	1347	3.2	1.3		9.6	3.9
19		F	D	ECE						
20		F	D	NAO	2000	0.1	0.05		0.3	0.15
21		F	D	ECE	1700	8.5	4.5	3.50E+09	25.5	13.5
22		F	D	ECEopt	1700	2.2	1.1	1.50E+09	6.6	3.3
23		F	D	LM	2250	4.7	2.4	1.00E+09	14.1	7.2
24		F	HMC	LM	2250	2.1	1.2	1.30E+09	6.3	3.6
25		F	CC	LM	2250	1.4	0.9	8.00E+08	4.2	2.7
26		F	CC	LM	2250	12.4	6	4.60E+09	37.2	18
27		F	HMC	LM	2250	3.4	1.8	2.50E+09	10.2	5.4
28		F	CC	LM	2250	1.2	0.8	6.00E+08	3.6	2.4
29		F	D	ECE	1800	4.5	1.45	3.40E+09	13.5	4.35
30		F	D	LM	2000	4.2	2.1		12.6	6.3
31		F	D	NAO	2000	1.2	0.5		3.6	1.5
32		F	D	ECE	1600	6	2	2.00E+09	18	6
33		F	D	NAO	1600	2.3	0.7		6.9	2.1
34		F	D	ECE	1660	10.7	3.8	8.60E+09	32.1	11.4
35		F	D	ECE	2623	9.1	3.1	3.30E+09	27.3	9.3
36		R	Drum	n/a	1253	0.5	0.3	1.70E+09		
37		F	D	ECE	2500	7.7	3	5.80E+09	23.1	9
38		F	D	ECE	3390	9.4	4	8.10E+09	28.2	12
39		F	D	LM	1660	5.3	2.8	4.30E+09	15.9	8.4
40		F	D	NAO	1660	3.9	2.2	2.80E+09	11.7	6.6
41		F	D	ECE	1660	1.5	0.9	5.10E+09	4.5	2.7
42		R	Drum	n/a	2041	1.1	0.8	2.80E+09		
43		R	Drum	LM	2041	0.7	0.6	3.60E+09		
44		R	Drum	NAO	2041	0.3	0.3	3.40E+09		
45		F	D	ECE	2113	7.6	3.5	3.90E+09	22.8	10.5
46		F	HMC	ECEopt	2113	1.6	1	1.40E+09	4.8	3
47		F	D	ECE	2027	4.1	1.2	2.10E+09	12.3	3.6
48		F	D	ECE	1840	6.5	1.8	5.00E+08	19.5	5.4
49		F	D	LM	1820	2.3			6.9	
50		F	D	NAO	1820	1.1			3.3	

Index	Powertrain or Vehicle type	Axle	Type	Pad	Test Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN #/km/B	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V
51		F	D	LM	2250	1.3			3.9	
52		F	D	HMC	2250	0.5			1.5	
53		F	D	ECE	1500	7.3			21.9	
54		F	D	ECE	1250	5.4			16.2	
55		F	D	ECE	1200	5.1			15.3	
56		F	D	ECE	1250	5.1			15.3	
57		F	D	SM	n/a	5.7	1.2		17.1	3.6
58		F	D	Ceramic	n/a	3.2	0.8		9.6	2.4
59	ICE	F	D	ECE	1240	3.7	1.3		11.1	3.9
60	ICE	F	D	NAO	1240	1.4	0.6		4.2	1.8
61	ICE	F	D	NAO	1533	0.8	0.2	1.40E+08	2.4	0.6
62	PHEV	F	D	NAO	1533	0.095	0.045	1.00E+08	0.285	0.135
63	HEV	F	D	ECE	1547	11.13	4.47	5.48E+10	33.39	13.41
64	HEV	R	D	ECE	1195			2.92E+08		
65	HEV	R	D	SM	1195			2.18E+08		
66		F	D	ECE	1993.5	3.6	0.9	3.44E+09	10.8	2.7
67		F	D	ECE	2524.7	5.9	2.1	2.10E+09	17.7	6.3
68	ICE	F	D	ECE	1659.5	5.3	2.8	4.30E+09	15.9	8.4
69	ICE	R	D	ECE	1659.5	1.5	0.9	5.10E+08		
70	ICE	F	D	NAO	1659.5	3.9	2.2	1.80E+09	11.7	6.6
71	ICE	F	D	ECE	2112.5	7.6	3.5	3.90E+09	22.8	10.5
72	HEV	F	D	HMC	2112.5	1.6	1	1.40E+09	4.8	3
73	ICE	R	Drum	LM	2040.5	1.1	0.8	2.80E+09		
74	ICE	R	Drum	LM	2040.5	0.7	0.6	1.10E+09		
75	ICE	R	Drum	NAO	2040.5	0.3	0.3	4.90E+08		
76	PHEV	Total	D	ECE	1659.5				6	3.6
77	BEV	Total	D	ECE	1659.5				3.3	2.4
78	HEV	Total	D	ECE	1500				11.13	4.74
79	HEV	Total	D	NAO	1592				2	0.9
80	ICE	Total	D	NAO	1533				1.92	0.58
81	PHEV	Total	D	NAO	1533				0.28	0.13
82	LCV	F	D	ECE	1600	5.1	1.8	2.20E+09	15.3	5.4
83	LCV	F	D	NAO	1600	2.5	0.8	1.00E+09	7.5	2.4
84	LCV	F	D	ECE	1668	8.8	3.5	8.60E+09	26.4	10.5
85	SUV	F	D	ECE	2623	8.3	2.8	3.30E+09	24.9	8.4
86	LCV	R	Drum		1253	1.2	0.2	1.70E+09		
87	VAN	F	D	ECE	2500	7.7	2.9		23.1	8.7
88	VAN	F	D	ECE	3390	8.5	3.3		25.5	9.9
89	ICE	F	D	LM	1600	5	1.8	4.50E+09	15	5.4
90	ICE	F	D	NAO	1600	5.4	2.4	8.26E+09	16.2	7.2

* Divided by 2.83 to convert from vehicle to brake corner. B = brake; CC = carbon ceramic; D = disc (GCI); ECE = Economic Commission for Europe; GCI = gray cast iron; HMC = hard metal coated discs; LACT = Los Angeles City Traffic; LCV = light-commercial vehicle; LM = low metallic; NAO = non-asbestos organic; SUV = sports utility vehicle

Table 12 from [35] list the main emissions inventories currently in place and their respective limits for PM.

Table 12 – Light-duty vehicles' brake emissions are based on emission inventories (mg/km/V)

Year	PM_{10}	$PM_{2.5}$	Source
2022	12	4.8	EEA, COPERT (PC ICE)
2022	9.5	3.8	EEA, COPERT (PC HEV)
2022	6.5	2.6	EEA, COPERT (PC PHEV)
2022	3.3	1.3	EEA, COPERT (PC BEV)
2022	12	4.8	EEA, COPERT (LCV N1-I)
2022	17	6.7	EEA, COPERT (LCV N1-II/III)
2020	8.4	3.3	NAEI UK (PC)
2020	13.1	5.1	NAEI UK (LCV)
2020	6.2	2.4	Australia, COPERT Australia (ICE)
2020	4.3	1.6	Australia, COPERT Australia (BEV)
2020	13.8	1.7	US EPA, MOVES3 (PC)
2020	15.3	1.9	US EPA, MOVES3 (LCV)
2021	3–10	1–3	CARB, EMFAC (PC)
2021	14	4.5	CARB, EMFAC (LCV)
2021	9.1	3.6	DCE, (PC)
2021	10	-	PBL NL (PC)

The emission factors for PM exhibit significant differences between emission inventories, studies using semi-enclosed systems, and studies employing fully enclosed testing. The EF from emissions inventories is at least twice as high as measurements with a fully enclosed system. One explanation for this is that several inventories still use data from legacy studies that rely on high-energy cycles and older formulations, compared to newer tests using the WLTP-B cycle and current or recent formulas. [34], [41], [45], [50], [57], [58], [59].

17.1.2 Tires

On contributions to microplastics from road transport tires

A recent review study [18] relied on about 300 measurements, indicating a mean abrasion of 110 mg/km/V or 68 mg/km/tonne for passenger cars. To assess the abrasion rate experimentally by tire mass loss, the vehicle (typically on a convoy with one vehicle fitted with a reference tire) is driven between 5000 km and 15,000 km. Tires fitted on the front of the front-wheel-drive (FWD) can account for between 60 % and 85 % of the total tire mass loss for the vehicle. For rear-wheel-drive (RWD), the rear tires can contribute to about 71 % of the total tire loss. Table 13 from the same study summarizes the studies of the abrasion levels and the spread of results. For the tire 205/55 R16, abrasion rates from 25 mg/km up to 227 mg/km have been reported, with most values falling in the (50 to 125) mg/km range. Several studies [60] highlight that, like brakes, tires exhibit higher wear rates during the first few thousand kilometers of driving, decreasing from about 240 mg/km after driving 1000 km to about (44 to 63) mg/km after 7000 km. The same study includes a simplified representation of the main factors and measurements needed to understand the role of tire abrasion on microplastics and pollution from particulate matter.

Table 13 – Abrasion rates of various tires determined from on-road test

Year	No. of Tires × Types of Tires	Vehicle	Abrasion mg/km	Comment
2013	1 × 175/70 R13	n/a	127	
2013	2 × 185/60&70 R14	n/a	132	
2013	1 × 195/65 R15	n/a	149	
2013	4 × 205/60-70 R14&15	n/a	141 (125–154)	Data (per tire) from the Russian Federation, based on mass loss and average travel distance. They were multiplied by four, assuming they were based on both front and rear wheels. The exact number of vehicles is not provided
2013	1 × 215/65 R16	n/a	119	
2004	195/65 R15	FWD	56	36,000 km (motorway), 90–94 km/h

Year	No. of Tires × Types of Tires	Vehicle	Abrasion mg/km	Comment
2004	185/65 R14	FWD	67	40,370 km (motorway), 65–75 km/h
2004	145/80 R13	RWD	86	11,300 km (urban), 43–51 km/h
2004	185/65 R14	FWD	193	3665 km (urban), 60–64 km/h, misaligned wheels
2004	175/70R	FWD	85	15,000 km (rural), 61–66 km/h
2022	Gasoline 1370 kg	-	158	
2022	Diesel 1395 kg	-	168	Based on tread depth loss, a 550 km test track with asphalt concrete (KS F 2349, b19 mm). 50 km/h (3 h), 80 km/h (2 h), and 110 km/h (2 h).
2022	Electric 1665 kg	-	202	
2022	ICEs	-	72 (36–105)	
2022	Hybrids summer	-	53 (26–91)	
2022	Hybrids M + S	-	112 (56–175)	Based on tread depth loss, 76 taxis in Rome (Italy) and Athens (Greece). Hybrids (Toyota-Auris) and ICEs (Škoda Octavia) had a similar curb mass.
2022	Hybrids winter	-	160 (109–180)	
2022	18 × (models)	Mercedes C-class [1]	67 (38–161)	5000 km (motorway) in the U.K.
2021	6 × 205/55 R16 91	Peugeot 308	37–63	15,000 km (65% rural, 30% motorway) in France, 71 km/h, LoAS 0.68 m/s², LaAS 0.87 m/s²
2022	2 × 205/55 R16 91	VW T-Roc	217–227	7000 km (39% motorway, 31% rural) in Spain
2021	4 × 205/55 R16 [S]	VW Golf 8	91 (70–115) [2]	France and Germany up to 24,000 km, at temperatures from 7 °C to 25 °C (summer tires) and 4 °C to 16 °C (winter tires).
2021	6 × 205/55 R16 [W]	VW Golf 7	94 (58–163) [2]	
2021	2 × 235/35 R19 [S]	VW Golf 8	92 (59–123) [2]	
2022	14 × 185/65 R15 [S]	VW Polo	89 (58–126)	
2019	16 × 185/65 R15 [S]	VW Polo	93 (59–124)	
2019	16 × 185/65 R15 [W]	VW Polo	109 (85–109)	
2021	15 × 205/65 R16 [S]	VW Golf 7	118 (82–151)	
2020	15 × 205/65 R16 [W]	VW Golf 7	121 (86–149)	15,000 km (55% rural, 40% motorway) in Germany, 85 km/h average speed
2016	7 × 205/65 R16 [M + S]	VW Golf 7	117 (82–152)	
2020	16 × 225/40 R18 [S]	VW Golf 7	130 (115–157)	
2021	16 × 195/65 R15 [W]	VW Golf 7	139 (100–171)	
2023	50 × 205/65 R16 91 [S]	(VW Golf 7)	125 (56–202) [2]	35 on a drum, 19 on-road
2023	5 × 245/45 R19 102 [S]	BMW X1, iX1	171 (134–202) [3]	15,000 km (50% rural, 35% motorway) in France

[1] RWD; [2] assuming 1.6 t vehicle mass; [3] assuming 2.28 t vehicle mass. FWD = front-wheel-drive; ICE = internal combustion engine; LaAS = lateral acceleration standard deviation; LoAS = longitudinal acceleration standard deviation; M + S = mud and snow; RWD = rear-wheel-drive; S = summer; W = winter. Example: 50 × 205/65 R16 91 [S] means 50 summer [S] tires were tested with 205 mm width, a 65% aspect ratio (distance between the wheel and the edge of the tire to the tire width), radial R construction, a 16-inch rim size (internal diameter of tire), and a 91 load index (≈615 kg).

Figure 24 from [18] provides a visualization of the level and spread of abrasion rates for different regions, along with the weighted mean for all studies (on the rightmost bars).

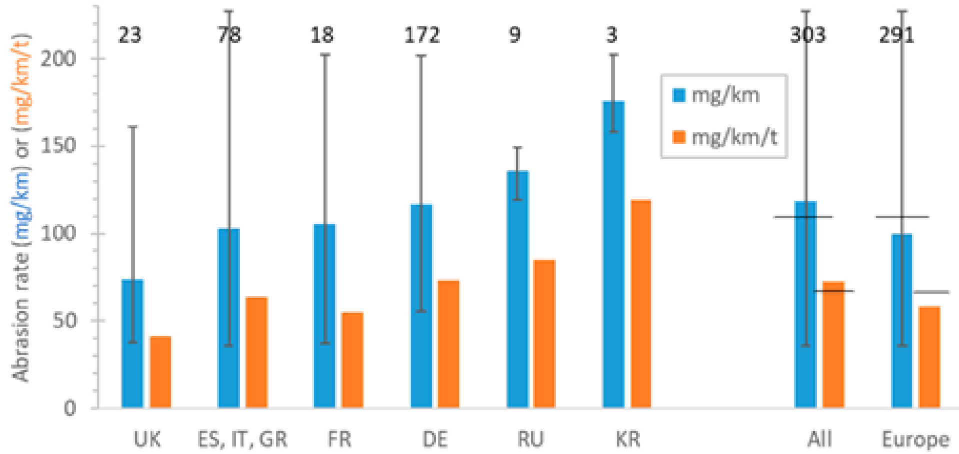


Figure 24 – Summary of tire abrasion rates in various countries. Error bars show min–max. Numbers indicate the number of tires. The small horizontal lines indicate the weighted mean of all studies. Image from open source [15]

No studies with dates after 2000 exist until results from the ongoing market assessments for commercial vehicle tires (C3) are available.

Even though there are limited studies, the PM_{10} emissions were (1.4 to 2.2) mg/km per tire, and particle number emissions were 10^{10} #/km per tire. The ratio of PM_{10} to total abrasion was 2.5% on average, which can be attributed to the sampling system used or the actual behavior of the tire. Lastly, the $PM_{2.5}/PM_{10}$ ratio was estimated to be around 40%. Table 14 shows PM EF for different tires tested under various conditions. A 2014 review concluded that the ratio of PM_{10} to total abrasion is less than 10% [25]. Another recent study reported in [18] argued that this ratio (PM_{10} to total tire abrasion) can be as low as 1.5 % on average, which agrees with recent studies (1.5 % to 3 %). In general, PM_{10} is assumed to be (2 to 10) % of the total tire abrasion. Table 14 provides some percentages reported. The mean value is 2.5%, or 1.9%, weighted by the number of tires tested in each study. For $PM_{2.5}$, the values were 1.6% and 1.0%, respectively.

Table 14 – Particulate matter (PM) values (per tire) and ratios

Year	No. of Tires	PM_{10} mg/km	PM_{10}/ Abrasion	$PM_{2.5}$ mg/km	$PM_{2.5}$/ Abrasion	$PM_{2.5}/PM_{10}$	Comments
2005	2	(9–11)	-	1–2	-	0.11	Road simulator
2010	3 types	{0.9}	-	-	-	-	Up to 350 mg/km[1]
2013	1	-	-	-	-	0.73	On-road
2018	5	-	-	-	-	0.45	Road simulator
2018	4	0.05	1.5 %	0.04	1.20%	0.82	Drum, abrasion 3.4 mg/km
2018	1	0.01	0.3 %	0	0.10%	0.55	Drum, abrasion 3–9000 mg/km
2019	5	-	-	-	-	0.7	Drum
2020	4	1.9	-	-	-	-	Road simulator
2021	1	-	-	-	-	0.25	Abrasion device
2021	1	1.7	3.7 %	1.3	3.30%	0.76	Drum-like
2022	3	2.2	-	0.4	-	0.16	Drum[2]
2022	4	0.9	-	0.2	-	0.23	Drum
2023	3	-	2.4 %[3]	-	0.20%	0.08	On-road
2024	9	0.4	-	0.1	-	0.15	Drum
Average	-	2.2 (1.4)[4]	2.5 %	0.5	1.60%	0.42	-
Weighted average	-	1.9 (1.1)[4]	1.9 %	0.3	1.00%	0.37	-

[1] the value in {…} not considered in the analysis. The value of the summer tire was calculated using a factor of 100 less than the studded tire, based on the graphs of the study and dividing by four; [2] the values reported for vehicles were divided by four; [3] the original study assumed an abrasion rate of 120 mg/km, so the percentages were recalculated using 110 mg/km; [4] the value in parenthesis (…) was calculated without the studies with values in parenthesis (too high or too low PM).

PM emission factors exhibit a large range of values, with emission inventories using values between 5.8 and 11 mg/km.

Using a comprehensive approach to national tire wear emissions

Study [14] tackles the question of tire emissions with two approaches to provide input for environmental assessments. One method uses a mileage approach combining emission factors measured directly for passenger cars and LDV, and emissions factors from literature for HDV for tire wear and vehicle kilometers. The second method validates the process by using tire recycling/sales/material flow statistics. The calculations yielded slightly lower overall emissions than legacy estimates, higher for passenger cars and LDV (more than 50 % of the total), and lower for HDV and motorcycles. This study relies on estimates that tires emit approximately 1.3 million tons of different compounds, microplastics, and particulate matter of varying sizes each year in the EU. The mileage approach enables greater detail for specific vehicle types and traffic activity data, including a split between urban and rural roads and motorways. It assesses the impact of potential regulations and measures on TWP emissions, including the Euro 7 emission standard. However, climate, road topology, and road surface properties influence tire wear; hence, national emission factors are expected to differ. The study relied on direct laboratory measurements for tire wear on light-duty vehicles and adapted literature-based emission factors for HDVs and buses. For a mileage approach, the study combined results or values for the average yearly traveling distance per vehicle, the number of tires in traffic, and the EF. Computation also incorporates factors for the mix of road types and then combines them with the mix of traveling distances to determine an emission factor for a tire type. For the sales approach, the calculation assumes stable tire wear throughout the tire's life. It combines the number of tires replaced (not relying solely on sales figures) in the fleet with the average weight loss during the tire's lifetime. It should be noted that the abrasion rates are much higher during the first 1000 km driven, decreasing slowly or even stabilizing after 5000 km [61]. For passenger cars and LDVs, it is important to account for changes in vehicle miles driven. In Sweden, between 2000 and 2019, the number of LDVs increased by 30 %, and the miles driven doubled. Between 2010 and 2019, the miles driven by passenger cars increased by 1 %, while LDV increased by 23 %. This study includes data and highlights the need to determine emission factors for a given geography (state, county, or region), including at least the following factors to validate the estimates:

- Vehicle mileage, number of vehicles, and tires in traffic (active fleet)
- Number of tires (per type or vocation) yearly replaced, scrapped, and installed in new vehicles (using vehicle registration data instead of vehicles sold)
- Estimates for tire life or replacement rates

Upon computing the estimates, the study suggests that only lifetime, total mass loss over the tire’s lifetime, and total number of tires in use are important for the forecast. This approach offers useful simplifications to compensate for the lack of detailed data in a comprehensive study. Based on this study for Sweden, the tire wear emission factors for summer and the overall average (including non-studded and studded) were reported as:

- Combined EF (mg/tire/km): 22 for summer
- Passenger cars EF (mg/tire/km): 21 for summer and 23 for average
- LDV EF (mg/tire/km): 28 for summer and 29 for average

For heavy-duty vehicles (HDVs), the study considers domestic, international, and foreign transport, combining government data with modeling and surveys, which yields notably different estimates for vehicle mileage: 4.6×10^9 km and 3.6×10^9 km, respectively. The main contributors to total distance were vehicles 60-70 metric tons GVW with 55%, 26-28 metric tons with about 13 %, and vehicles 14-20 metric tons with about 7%. Further subdivisions based on GVW (3.5-16 metric tons, 16-26 metric tons, and above 26 metric tons) and vehicle types (road tractor with trailer, rigid truck with trailer, and rigid trucks). EF (including airborne and larger particles) or tire wear (was (50-61 mg/tire/km) for straight trucks and (38-50 mg/tire/km) for tractor units. The background study did not provide details to explain the differences in the estimates.

Regarding buses (divided into two main categories, those under and over 18 metric tons), the study estimated 9.3×10^8 km driven in 2019, relying on partial data that is publicly available. Unfortunately, this study had to rely on EFs derived before 2000 for their estimates of 170 mg/tire/km. For heavy trucks, the study used primarily tire sales and lifetime wear (from about
600 000 tires in 2018-2019), with 60 kg of average weight for new tires and 10-15 % weight loss during usage. When

combining all the above information and estimates, the study reports that passenger cars, light-duty vehicles, and domestic heavy-duty vehicles account for 91 % of the total tire wear emissions in metric tons per year in Sweden. Buses and foreign heavy-duty vehicles account for 9%, with international heavy-duty vehicles and motorcycles accounting for the remaining 1%.

Figure 25 illustrates the split of tire wear emissions (tonnes/year) by road type and vehicle category for Sweden, using the mileage approach.

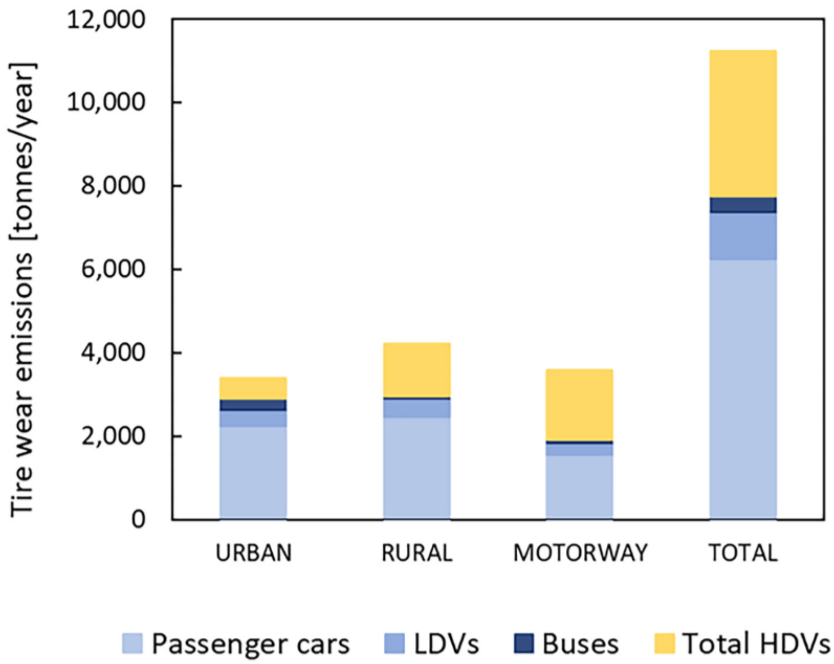
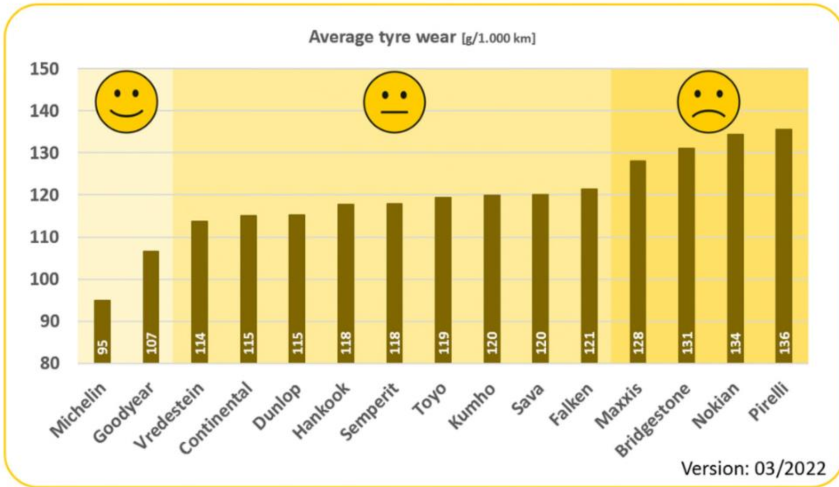


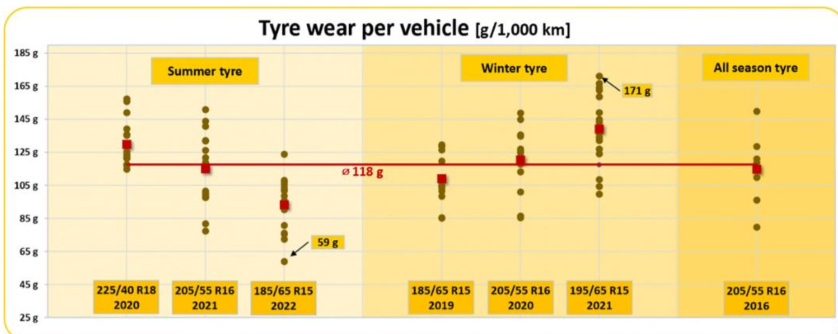
Figure 25 – Total tire wear emissions in metric tons per year by road type and vehicle category in Sweden. Image from open source [12]

Tire wear particles in the environment

According to recent studies, 500,000 tons of tire abrasion are released annually in the EU, accounting for an estimated one-third of all microplastics emitted in Germany alone. ADAC [62] has developed extensive studies and methodologies combining real-life driving and laboratory testing to reach maximum wear limits (based on tread depth). According to this study, the average tire wear per vehicle was 118 g/1000 km, calculated by combining results from summer, winter, and all-season tires across five tire sizes and 15 tire brands. Figure 26 depicts the aggregate values per brand.



(a) Average tire wear per brand



(b) Individual values, average, and dispersion per tire tested

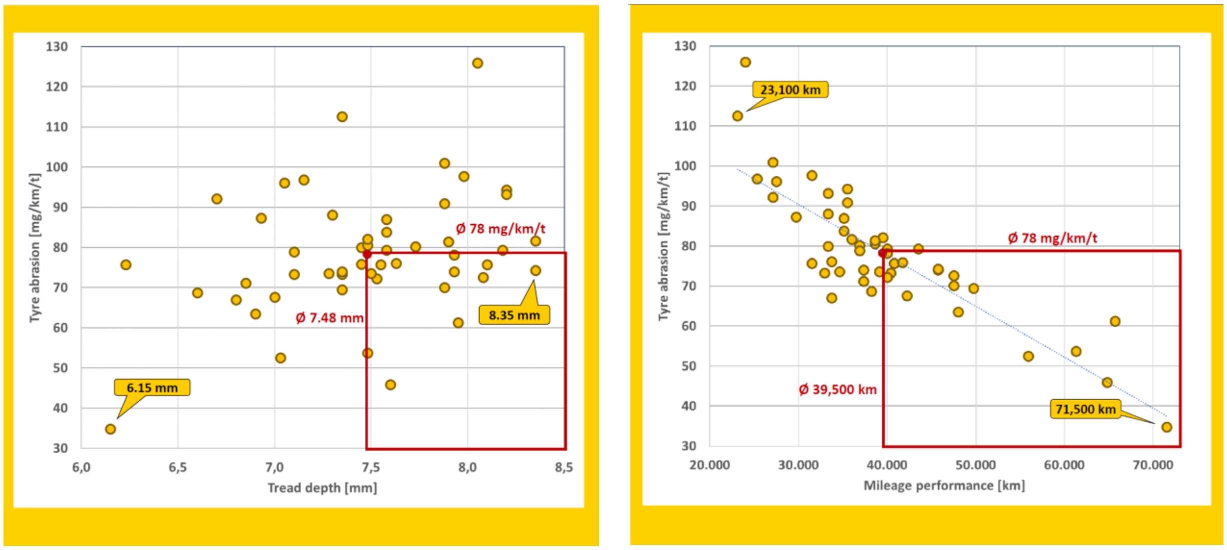
Figure 26 – tire wear for 25 brands and five tire sizes from ADAC 2022

Some of the main findings related to tire wear are the following:

- On average, the tire abrasion of a vehicle is around 120 g/1 000 km.
- There is a tendency for tire abrasion to be slightly lower on summer tires than on comparable winter tire sizes.
- In almost all tire sizes tested, you can find tires that achieve a low tire abrasion of < 100 g/1 000 km.
- One exception is the summer tire size 225/40 R18. In this size, the racing tire models received special attention in the tests, and it was concluded that they all have above-average tire abrasion.
- The summer tire size 195/65 R15 is also conspicuous. Tires designed for compact vehicles and vans typically have very high tire abrasion levels for this size. Whether this tire size has design disadvantages or the manufacturers are using outdated tire technology has not been clarified.
- There are tire models in all sizes with low abrasion and good driving safety.
- Tires with low abrasion do not necessarily lead to an increased risk of aquaplaning, as the aquaplaning features depend entirely on the tread design and depth and not on the rubber compound.
- In the case of winter tires, it is evident that tires with low abrasion tend to provide poorer snow performance. However, some tires effectively reconcile this conflict of objectives while still providing acceptable performance in snow with low abrasion.
- Especially in the case of racing tire sizes and so-called ultra-high-performance tires (UHP), the focus often seems to be placed only on high-performance stability on dry roads. The tire abrasion associated with this is rarely the focus of many manufacturers. However, the above-average tire performance on dry roads provides hardly any additional safety advantages in normal road use since the borderline range is extremely high. At best, these tires are good for racing.

- The 185/65 R15 tire size stands out. In this tire size, which is suitable for small cars, many models produce significantly less than 100 g/1 000 km of tire abrasion, especially among the summer tires

Another study from ADAC [13] reported relationships between abrasion level, tread depth, and mileage, as shown in Figure 27.



(a) Abrasion v tread depth *(b) Abrasion v mileage*

Figure 27 – Abrasion, tire tread, and mileage correlations

17.1.3 Road

From [18] multiple reported values from on-road tests include a significant percentage of road wear particles and resuspension. For several emission inventories, road wear particles are at the same level as tire abrasion in terms of mass [63]. Another review also found similar levels of tire and road wear PM emissions. An on-road study with sampling behind the tire found that tire abrasion particles accounted for less than 27% of the total PN measured and 65% of the mass (including brakes and road resuspension). An analysis of a roadside sample from a bus stop found that asphalt particles were more than tire abrasion particles.

17.2 Test methods to generate non-tailpipe PM

17.2.1 Brakes

The landscape of test methods and setups for brake emissions has undergone significant evolution since the first experiments over 25 years ago. Results in the systematic review are based on laboratory and on-road tests using fully-enclosed, semi-enclosed, and open-probe sampling brake emission techniques. Regarding the test cycles, the study's results presented are based on the test cycles summarized in the following Table 15.

Table 15 – Characteristics of test cycles used worldwide for assessing vehicle emissions

Test cycle	Brake stops	Initial velocity (range) km/h	Deceleration (range) m/s²	Test duration	Driving distance km	Source
SAE J 2707	20	50-100	4	20 min	~8	[64]
ISO 26867	143	80-200	0−1.7	-	-	[65]
3h-LACT	217	9-154.3	0.2-2.88	3 h	150	[66]
SAE J2522	8−18	80-200	0.5-1.7	~12 h	-	[67]
WLTP-B	303	7.58-135.19	0.49-2.18	4 h 24 min	192	[40]
BSL-035	1000	65	2.94	-	-	
WLTC	51	56.5−131	1.05−1.66	30 min	23	[40]
NEDC	18	15-50	0.53	20 min	11	[40]
FTP	45	91.2	0.58	41 min	~18	[40]
ARTEMIS [68]	23	50-120	-	50 min	~51	[69]
CBDC	347	<10-123	0.28-3.3	4 h 9 min	131	[16]

This paragraph focuses on three main test methods: the Global Technical Regulation GTR 24 from the European Union, the California Brake Dynamometer Cycle (CBDC) for light vehicles, and Caltrans cycles for heavy-duty vehicles. The second part of the paragraph provides brief descriptions of R&D setups to measure volatile organic compounds. Other methods, including pin-on-disc, chassis dynamometer, and on-road testing, are described in detail elsewhere [34].

Global Technical Regulation 24 from the European Union for light vehicles

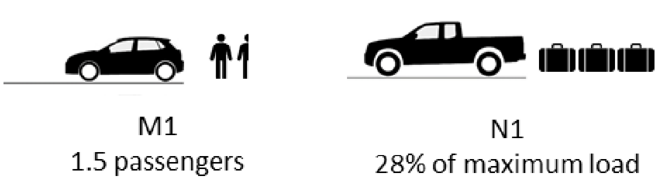
Test setups for brake emissions testing have reached a level of maturity over the past few years since the release of the new GTR 24 [6]. The Second Amendment of the United Nations Global Technical Regulation GTR 24 and the conversion into a United Nations Regulation are under development at the time of completing this systematic review [70]. The latest draft of the intended UN regulation includes updates on type approval process and minimum items to report, computation of emission factors combining results from both brakes (front and rear), sampling devices, sampling probes arrangement, brake drag measurements, kinetic energy calculation, and decimal places, among other updates[71]. This document was published after the completion of this report, so the reader is encouraged to become familiar with the last update to the draft regulation [71].

The actual development and other details (including the 1 Hz time-resolved speed trace) on the WLTP-B cycle were presented in [46].

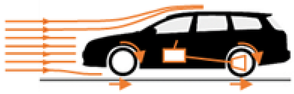
After the statement of technical rationale and justification in paragraph I, paragraph II of the GTR 24 provides the following:

- Paragraph 3 with Definitions for vehicle and brake dynamometer settings, test setup, brake hardware, WLTP-Brake cycle, PM and PN measurement, test system, and non-friction braking. Some important definitions include the following:

  "Vehicle test mass"



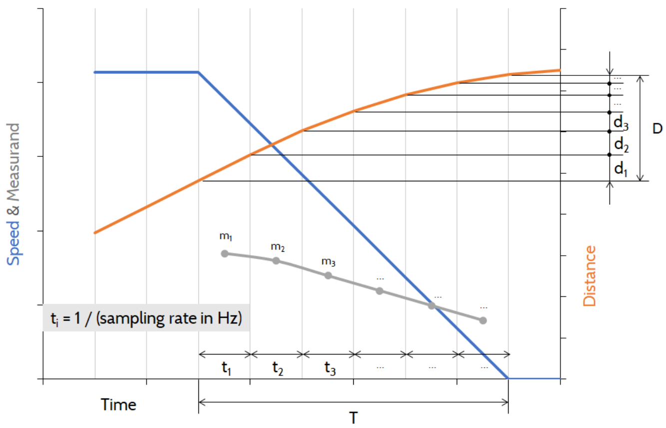
"*Road loads*," fixed as 13 % of the test mass



$$T_L = f_o + f_1 \cdot V + f_2 \cdot V^2 = 13\% \times WL_n$$

"*Average-by-time*" $(m_1 \times t_1 + m_2 \times t_2 + m_3 \times t_3 + \ldots)/T$

:"*Average-by-distance*" $(m_1 \times d_1 + m_2 \times d_2 + m_3 \times d_3 + \ldots)/D$



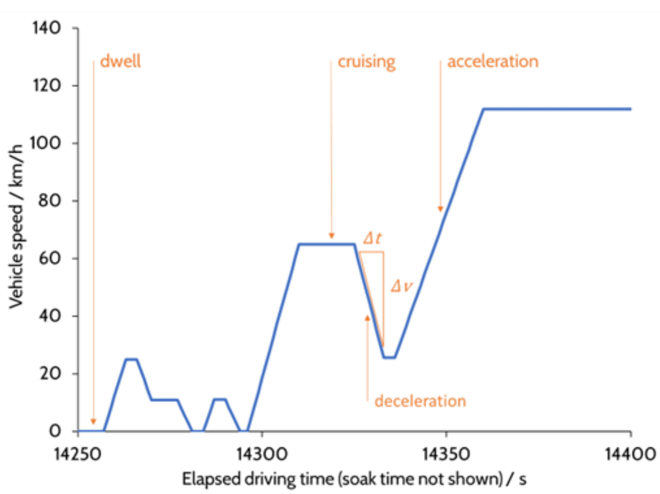
"*Brake acceleration event*" means a measurable period during which the linear speed increases to a predetermined set value at a known rate. This event always precedes a brake-cruising or brake-deceleration event.

"*Brake cruising event*" means a measurable period during which the (non-zero) linear speed is constant.

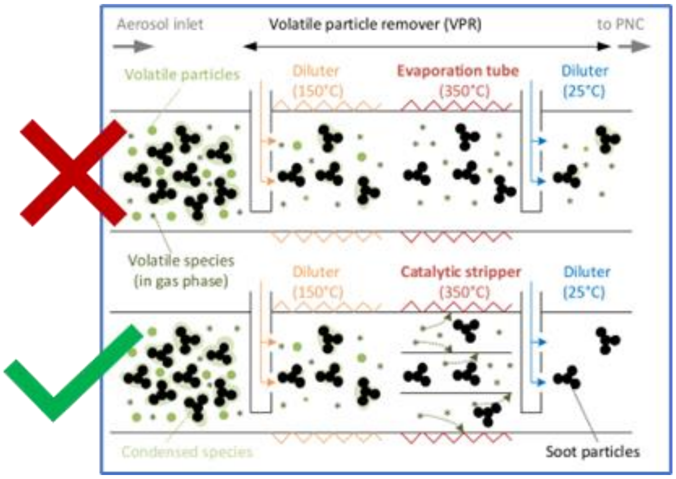
"*Brake dwell event*" means a measurable and predictable brake pause at zero speed during the cycle.

"*Nominal brake deceleration event*" means a measurable period during which the nominal linear speed decreases at a known rate to a predetermined release speed during the cycle. The nominal deceleration event is identified using the fast nominal linear speed signal as per paragraph 9.4.3 (i).

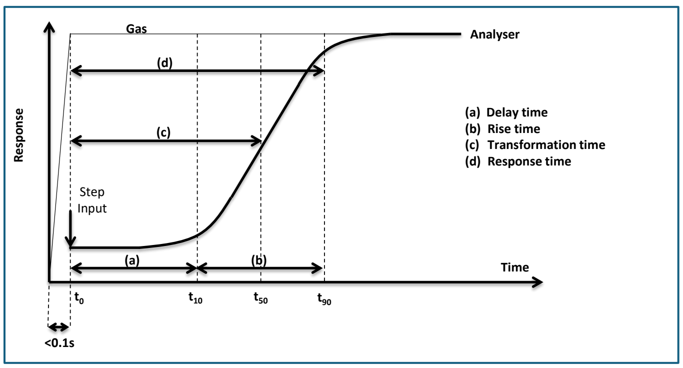
"*Deceleration rate*" means the total rate of reduction in the vehicle's linear speed induced by the application of the service brake, the road loads, and the non-friction torque from the electric machine.



"*Solid particle number emissions*" means the number of solid particles emitted from the brake under testing per [72]



"*Response time*" […] Difference in time from the reference point to the measurement system per [73].

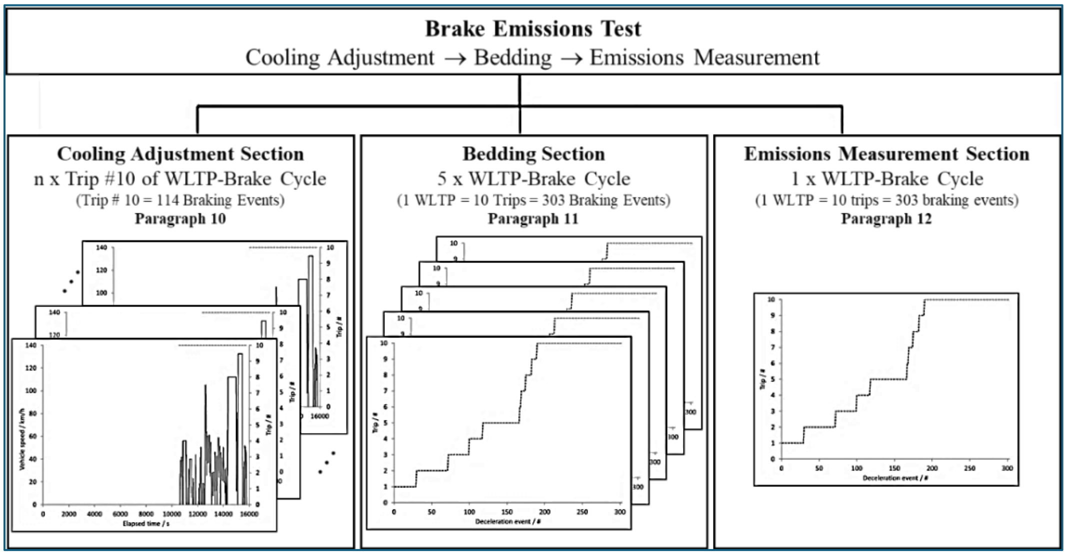


- Paragraph 4 with abbreviations and symbols
- Paragraph 5 has general requirements for brake emissions families for original, identical, and non-original replacement as a function of brake design and vehicle application for disc or drum brakes. In addition, this paragraph provides Table 5.3 with the default friction braking share coefficient for all vehicle types per Table 16.

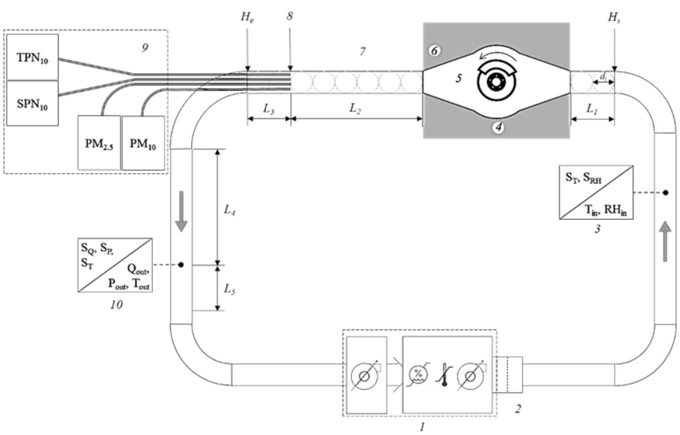
Table 16 – Friction brake share coefficient for all vehicle types per Table 5.3 from GTR 24

Brake type	*Vehicle Electrification Type*	*Friction Braking Share Coefficient (c)*
Full-friction braking	ICE and other vehicle electrification types not covered in the non-friction braking categories in this Table	1.0
Non-friction braking*	NOVC-HEV Cat. 0 **	0.90
	NOVC-HEV Cat. 1	0.72
	NOVC-HEV Cat. 2	0.52
	OVC-HEV	0.34
	PEV	0.17

- Paragraph 6 provides an overview of the test for full-friction braking, including cooling adjustment, brake bedding, and brake emission measurements, as shown below.

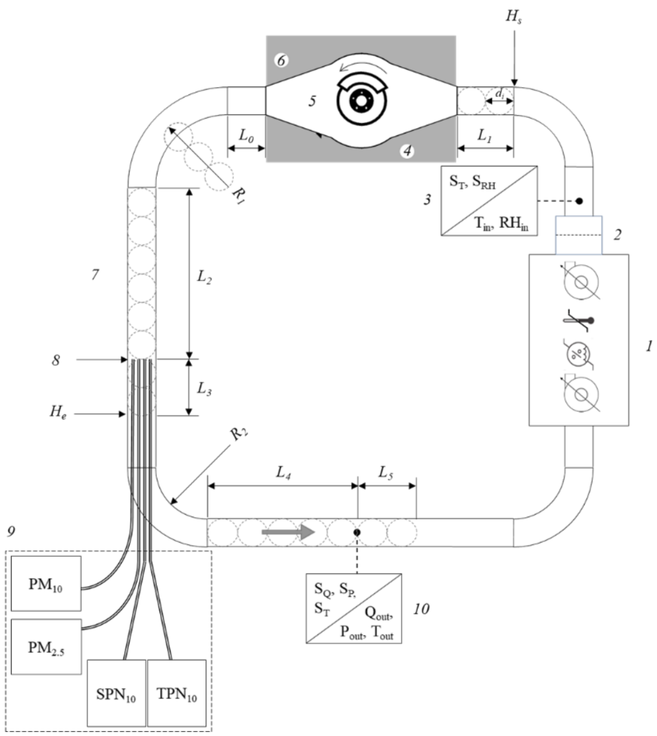


- Paragraph 7 details the test system, providing two indicative layouts without and with a 90° bend in the sampling tunnel downstream from the brake enclosure, as illustrated in Figure 12(a) and 12(b), respectively (of the GTR 24).



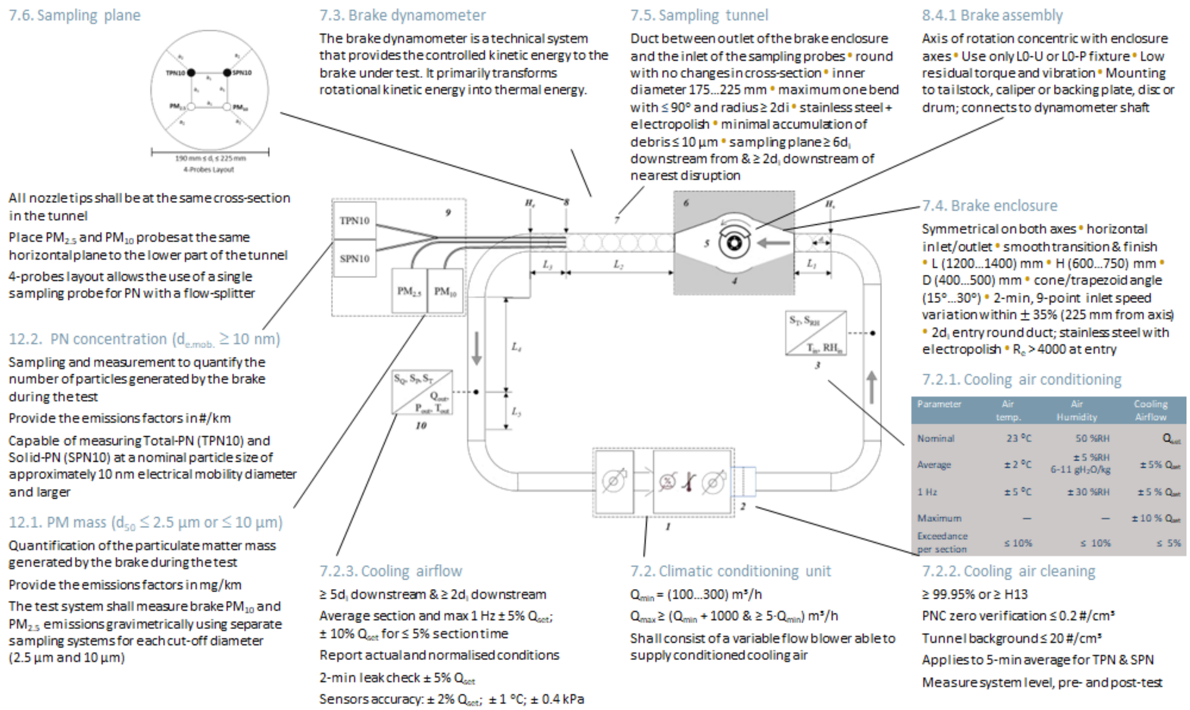
Note: (a) The layout has the sampling tunnel connected directly to the brake enclosure and assumes four sampling probes (a three-sampling probe layout is also feasible). The brake dynamometer is not depicted but only denoted (grey area)

Note: (b) The layout has a bend downstream of the enclosure and upstream of the sampling plane and assumes four sampling probes (a three-sampling probe layout is also feasible). The brake dynamometer is not depicted but only denoted (grey area)



The same paragraph represents the main subsystems of a GTR 24 brake dynamometer setup, with:

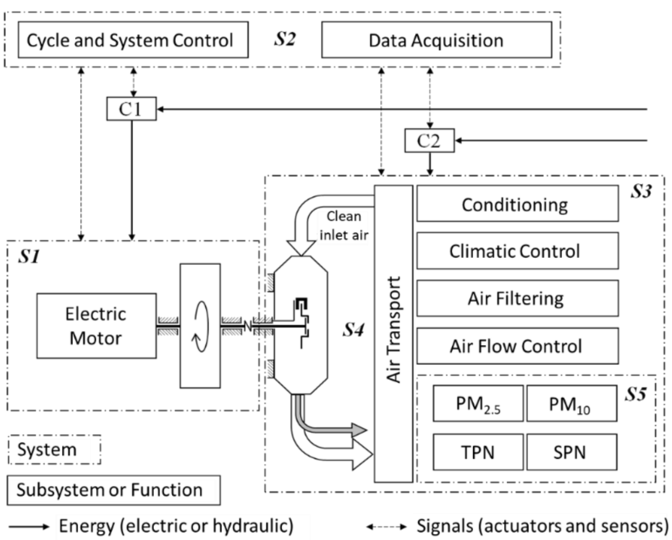
1	Climatic conditioning unit with variable flow blower(s), air temperature, and air humidity control
2	Cooling air filtering medium
3	Cooling air temperature and humidity sensors placed upstream of the brake enclosure
4	Brake enclosure
5	Brake assembly connected to the brake dynamometer
6	Brake dynamometer (not depicted but only denoted in grey)
7	Sampling tunnel
8	Sampling plane with the corresponding PM and PN sampling probes
9	Instruments to collect PM mass and measure PN concentrations
TPN10, SPN10	Systems to control, measure, and output signals of TPN10 and SPN10
$PM_{2.5}$, PM_{10}	Systems to control sampling flow, sample brake particulate matter on filters, and output signals
10	Airflow measurement elements placed downstream of the sampling plane
Symbols	Per GTR 24 [70]



Parameter	Air temp.	Air Humidity	Cooling Airflow
Nominal	23 °C	50 %RH	Q_{set}
Average	± 2 °C	± 5 %RH 6-11 gH_2O/kg	± 5% Q_{set}
1 Hz	± 5 °C	± 30 %RH	± 5 % Q_{set}
Maximum	–	–	± 10 % Q_{set}
Exceedance per section	≤ 10%	≤ 10%	≤ 5%

- The same paragraph 7 classifies all the elements of the test setup into five systems:

S1 – Brake dynamometer
S2 – Automation, control, and data acquisition system
S3 – Climatic conditioning unit
S4 – Brake enclosure and sampling plane
S5 – Emissions measurement system



- Paragraphs 7, 8, and 12, combined, provide the requirements related to:

  Cooling air conditioning level and tolerances per Table 17.

Table 17 – Summary of cooling air temperature, humidity, and airflow requirements

Parameter	Cooling air temperature	Cooling air relative humidity	Cooling airflow
Nominal value	23 ºC	50 %	Set value (Q_{set}) per paragraph 10.
Average value: Maximum permissible tolerance	±2 ºC (21 ºC ≤ T ≤ 25 ºC)	±5 % (45 % ≤ RH ≤ 55 %)	±5 % of Q_{set}
Instantaneous values (1Hz): Maximum permissible tolerance	±5 ºC (18 ºC ≤ T ≤ 28 ºC)	±30 % (20 % ≤ RH ≤ 80 %)	±5 % of Q_{set}
Instantaneous values (1Hz): Permissible deviation beyond the maximum permissible tolerance	Not defined	Not defined	±10 % of Q_{set}
Instantaneous values (1Hz): Maximum time exceeding the maximum permissible tolerance	10 % of each test section's duration	10 % of each test section's duration	5 % of each test section's duration

Climatic conditioning unit with Q_{min} = (100 to 300) m³/h; $Q_{max} \geq (Q_{min} + 1000 \ \& \geq 5 \cdot Q_{min})$ m³/h; Shall consist of a variable flow blower able to supply conditioned cooling air

Cooling air cleaning with efficiency ≥ 99.95% or ≥ HEPA 13 filter; PNC zero verification ≤ 0.2 #/cm³; Tunnel background ≤ 20 #/cm³; applies to 5-min average for TPN & SPN; Measure system level, pre-and post-test

Cooling airflow measurement and control at ≥ 5d_i downstream & ≥ 2d_i downstream; average airflow for the section and maximum airflow at 1 Hz ± 5% Q_{set}; allow ± 10% Q_{set} for ≤ 5% section time; report actual and normalized conditions; 2-min leak check ± 5% Q_{set}; Sensor's accuracy: ± 2% Q_{set}; ± 1 °C; ± 0.4 kPa

The brake dynamometer is a technical system that provides controlled kinetic energy to the brake under test. It primarily transforms rotational kinetic energy into thermal energy.

Brake enclosure being symmetrical on both axes; horizontal inlet/outlet; smooth transition & finish;
L (1200 to 1400) mm; H (600 to 750) mm; D (400 to 500) mm; cone/trapezoid angle (15° to 30°);
2-min measurement, 9-point measurement for inlet speed variation within ± 35% (225 mm from axis); 2d_i entry round duct; stainless steel with electropolish; Re > 4000 at entry

Sampling tunnel with constant diameter duct between the outlet of the brake enclosure and the inlet of the sampling probes; round with no changes in cross-section; inner diameter d_i (175 to 225) mm; maximum one bend with ≤ 90° and radius ≥ 2d_i; stainless steel + electropolish; minimal accumulation of debris ≤ 10 µm; sampling plane ≥ 6d_i downstream from, and ≥ 2d_i downstream of nearest disruption

Sampling plane with all nozzle tips shall be at the same cross-section in the tunnel; $PM_{2.5}$ and PM_{10} probes at the same horizontal plane to the lower part of the tunnel; 4-probes layout allowing the use of a single sampling probe for PN with a flow splitter

Brake assembly with the axis of rotation concentric with enclosure axes; use only L0-U or L0-P fixture; low residual torque and vibration; mounting to tailstock, caliper, or backing plate, disc or drum; connecting to the dynamometer shaft

PM mass measurement system (d_{50} ≤ 2.5 µm or ≤ 10 µm) to quantify the particulate matter mass generated by the brake during the test; provide the emissions factors in mg/km; measure brake PM_{10} and $PM_{2.5}$ emissions gravimetrically using separate sampling systems for each cut-off diameter (2.5 µm and 10 µm)

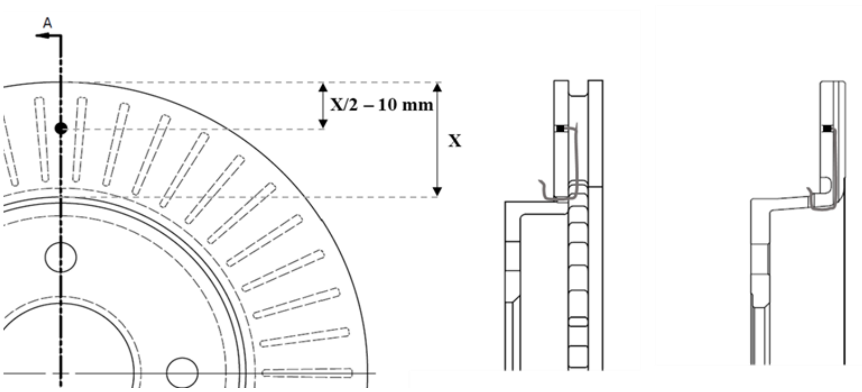
PN concentration measurement system ($d_{e.}^{mob.}$ ≥ 10 nm); sampling and measurement to quantify the number of particles generated by the brake during the test; provide the emissions factors in #/km/B; capable of measuring Total-PN (TPN10) and Solid-PN (SPN10) at a nominal particle size of approximately 10 nm electrical mobility diameter and larger

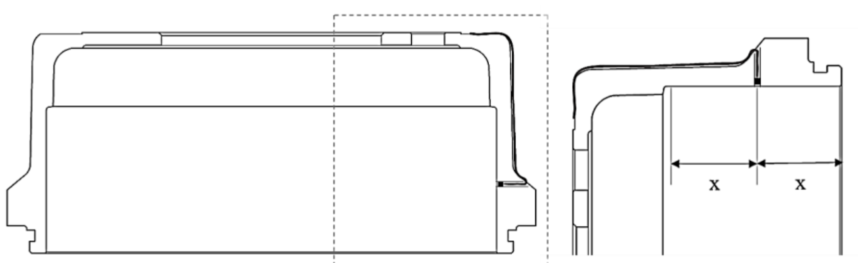
The default brake work distribution of 77 % on the front and 32 % on the rear axle for vehicles category 1 (passenger cars), and 66 % on the front and 39 % on the rear axle for vehicles category 2 (pick-up trucks and SUVs) according to [74]. The per cent distributions represent the (representative) axle portion of maximum vehicle mass, considered individually, hence the total for the vehicle add to more than 100 %.

Test parameters for the vehicle application and the brake under testing

Test setup preparation, including software and test parts measurement, including installation of thermocouples; brake runout ≤ 50 µm; zero level for torque and pressure signals during ≥ 30 s with the brake stationary; brake bleed to remove air from the brake lines 300…3000 kPa; brake drag at three speeds (5, 50, and 135) km/h ≤ 10 N·m; verify data collection, dyno operation, and test inertia; set cooling air to predefined or default value; verify pre-test background emissions (TPN10)

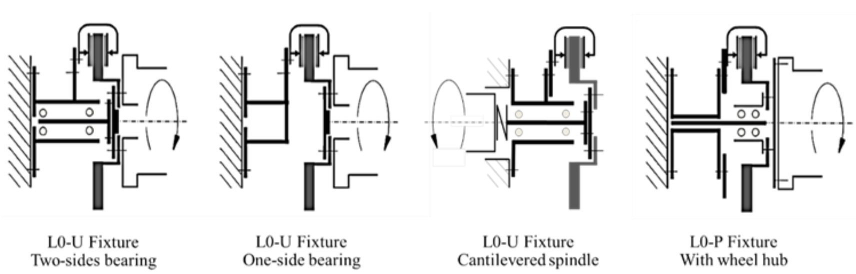
Location and depth of thermocouples installed on the disc or drum

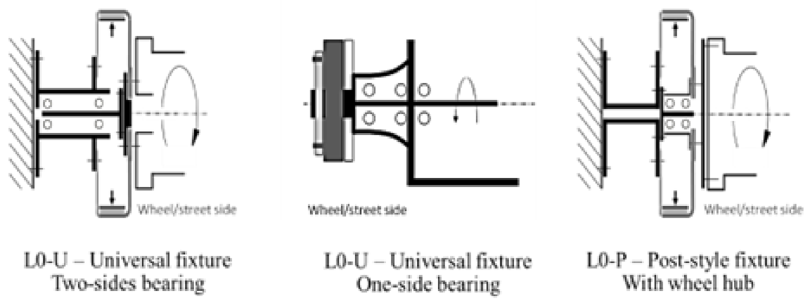




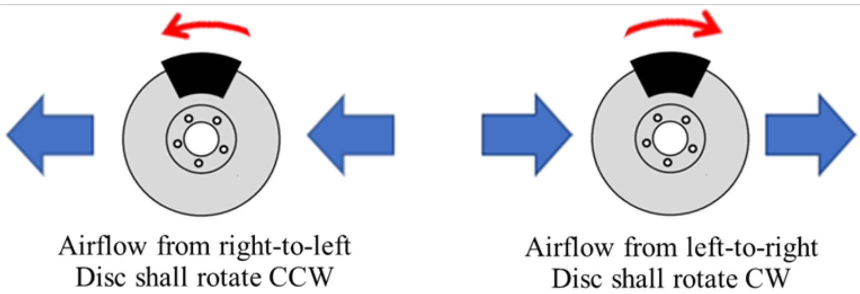
Caliper positioning at the 12 o'clock position

Use of universal or post-style fixtures

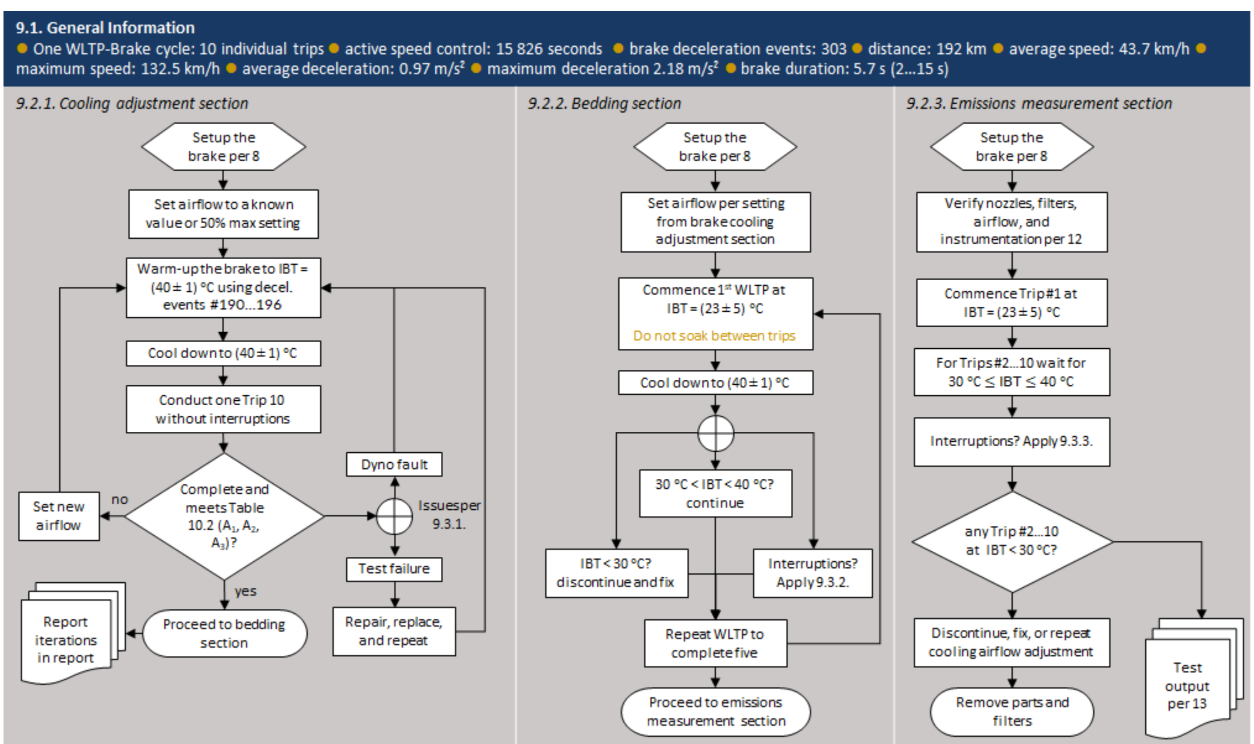




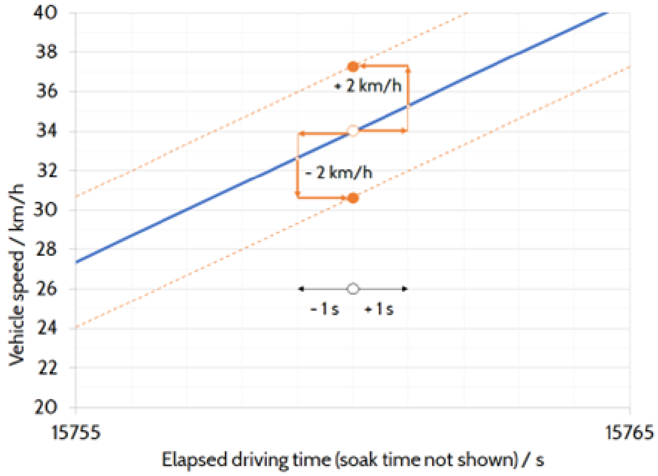
Airflow direction as a function of disc rotation

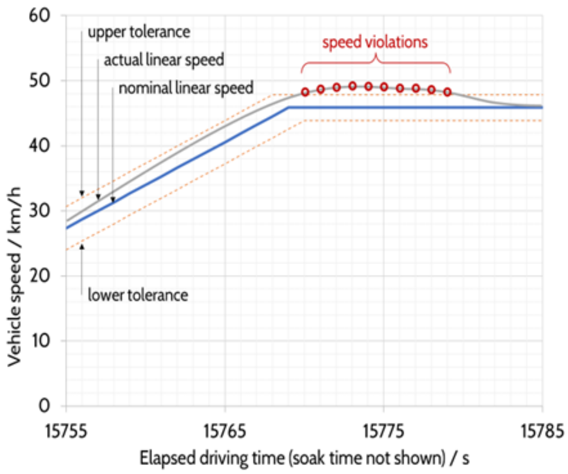


- Paragraph 9 describes the cooling adjustment, the bedding, and the emissions sections with one WLTP-Brake cycle with 10 individual trips each; active speed control: 15 826 seconds; 303 brake deceleration events; nominal test distance: 192 km; average speed of 43.7 km/h; maximum speed of 132.5 km/h; average deceleration: 0.97 m/s²; maximum deceleration 2.18 m/s²; average brake duration of 5.7 s; deceleration event duration 2…15 s.



Paragraph 9 also describes criteria to define speed violations following GTR 15 [75] using an upper limit: nominal speed within ± 1 s of a given point + 2 km/h, and a lower limit: nominal speed within ± 1 s of a given point - 2 km/h





$$speed\ violations = \frac{\#\ outside\ tolerance}{\#\ total} = \frac{10}{31} = 32\%$$

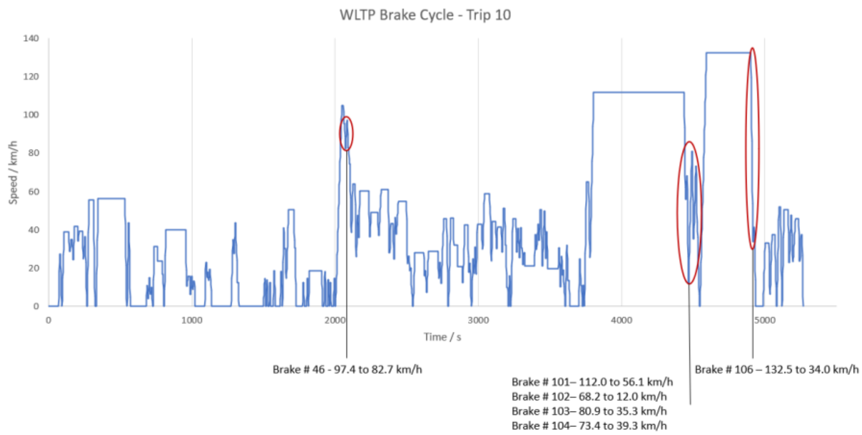
Kinetic energy dissipation during brake deceleration events using the equation:

$$w_{f,n} = \frac{2 \times \pi}{60} \cdot \frac{1}{WL_t} \cdot \int_{t=t_{start,nom,n}-1.0s}^{t_{end,nom,n}+1.0s} f(t) \cdot \tau(t) \cdot dt$$

Where:

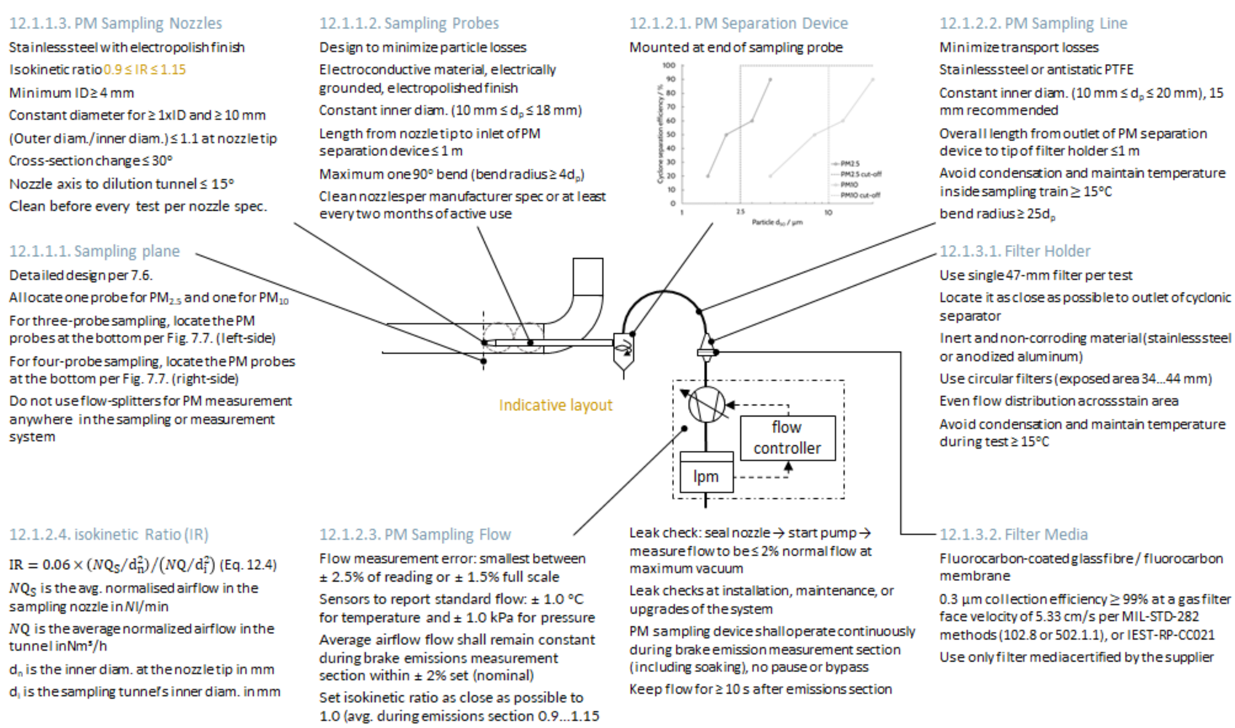
$w_{f,n}$	is the specific friction work of the nth brake deceleration event in J/kg
WL_t	is the test (or applied) wheel load in kg
$t_{start,nom,n}$	is the start time of the nth nominal brake deceleration event in seconds
$t_{end,nom,\ n}$	is the end time of the nth nominal brake deceleration event in s
$f(t)$	is the fast rotational speed signal in 1/min
τ_{brake}	is the fast brake torque signal in Nm

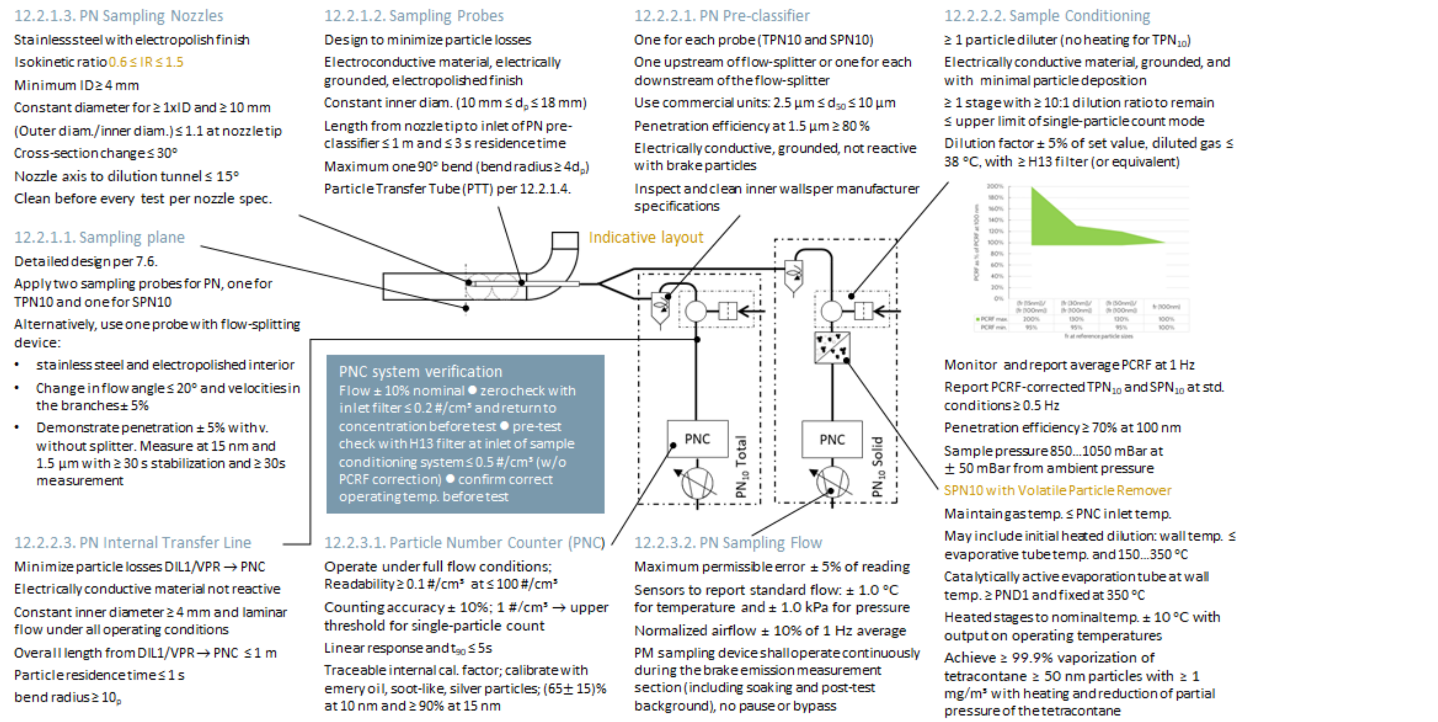
- Paragraph 10 deals with cooling airflow adjustment. The conditioned air (for cleanliness, temperature, and humidity) across the brake under testing serves a dual purpose: to cool the brake and transport particles from the braking surface to the sampling plane. To determine the amount of airflow for a given test, the test facility runs a series of Trip # 10 from the WLTP-B cycle to target the average brake temperature during the trip, along with the initial and final brake temperatures for the six deceleration events (46, 101, 102, 103, 104, and 106) with the highest kinetic energy dissipation.



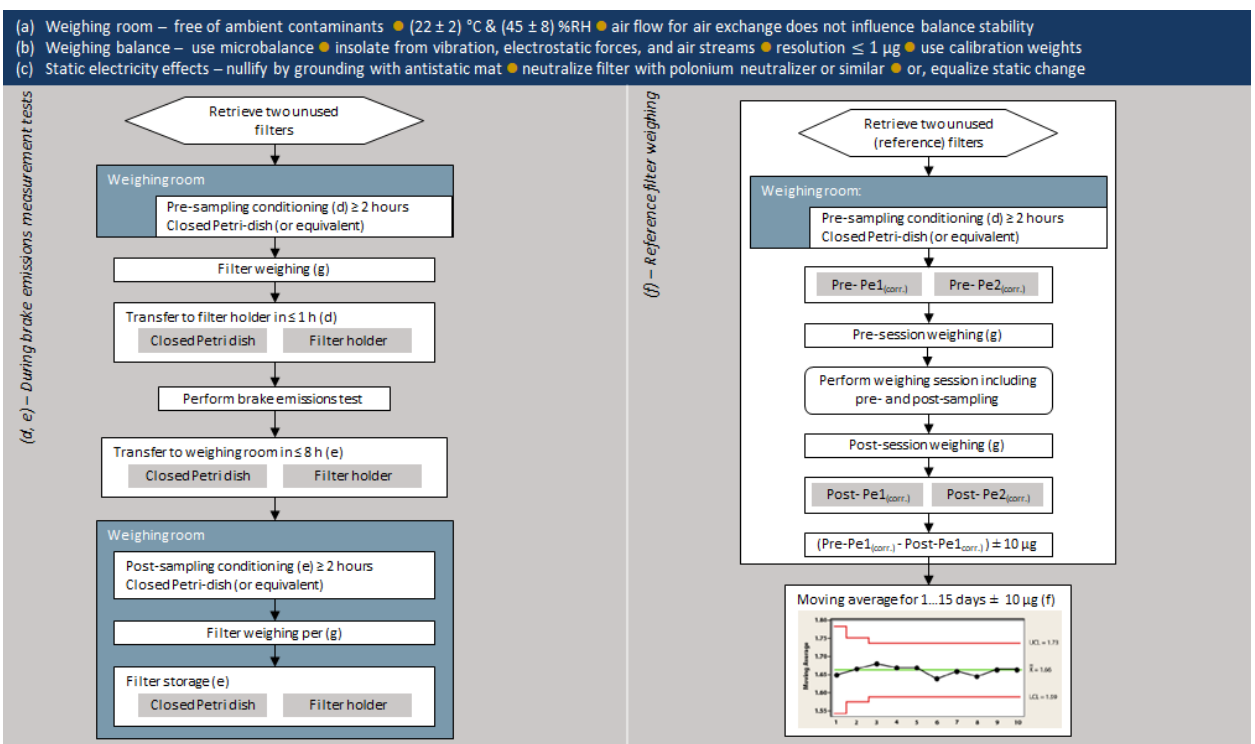
The temperature ranges are a function of the wheel load-to-disc mass ratio. The latest proposed amendment to the GTR 24 [70] This paragraph includes a default airflow of 950 m/h³ when multiple airflows meet the temperature metrics. It also has provisions for carbon ceramic and drum brakes to consider new braking technologies and legacy braking systems.

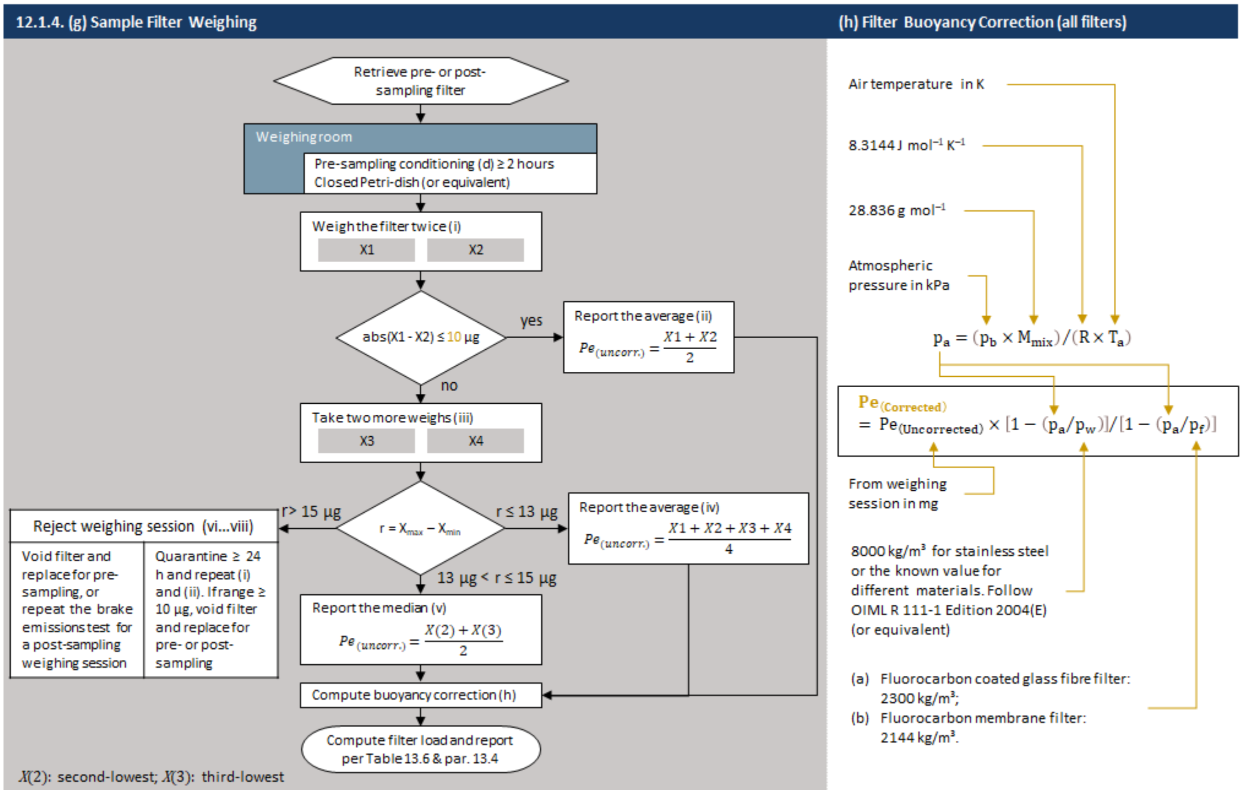
- Paragraph 11 addresses brake bedding by repeating five WLTP-B cycles without soaking in between and without PM or PN emission measurements.
- Paragraph 12 provides technical and embodiment details of the PM mass measurement system for PM_{10}, $PM_{2.5}$ and PN (Total and Solid)

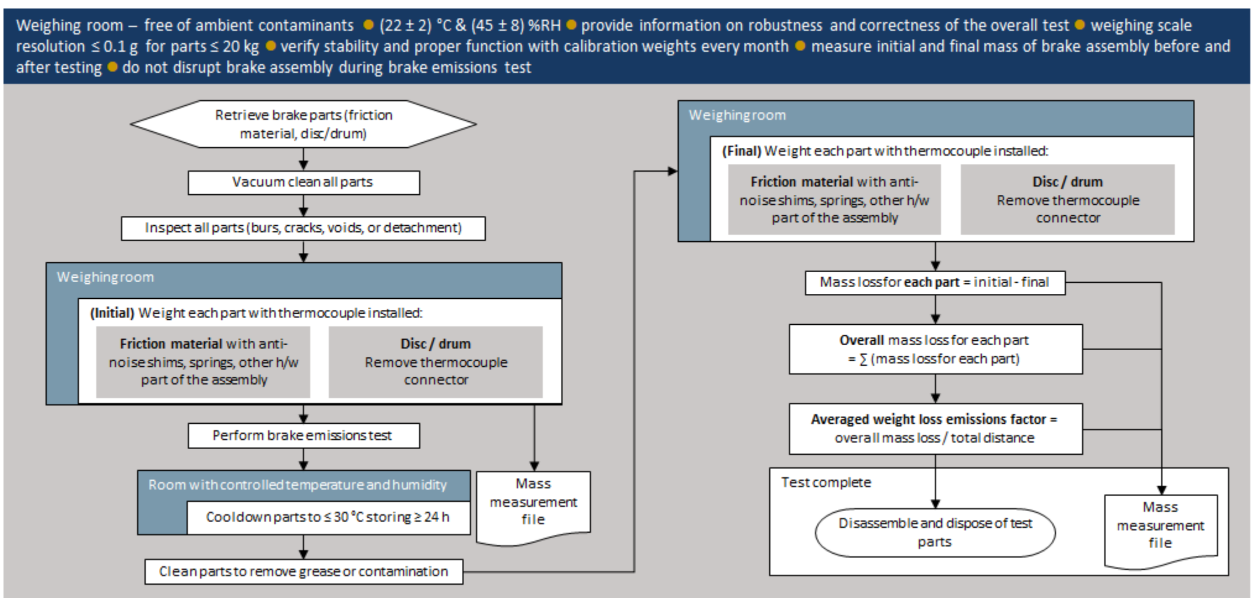




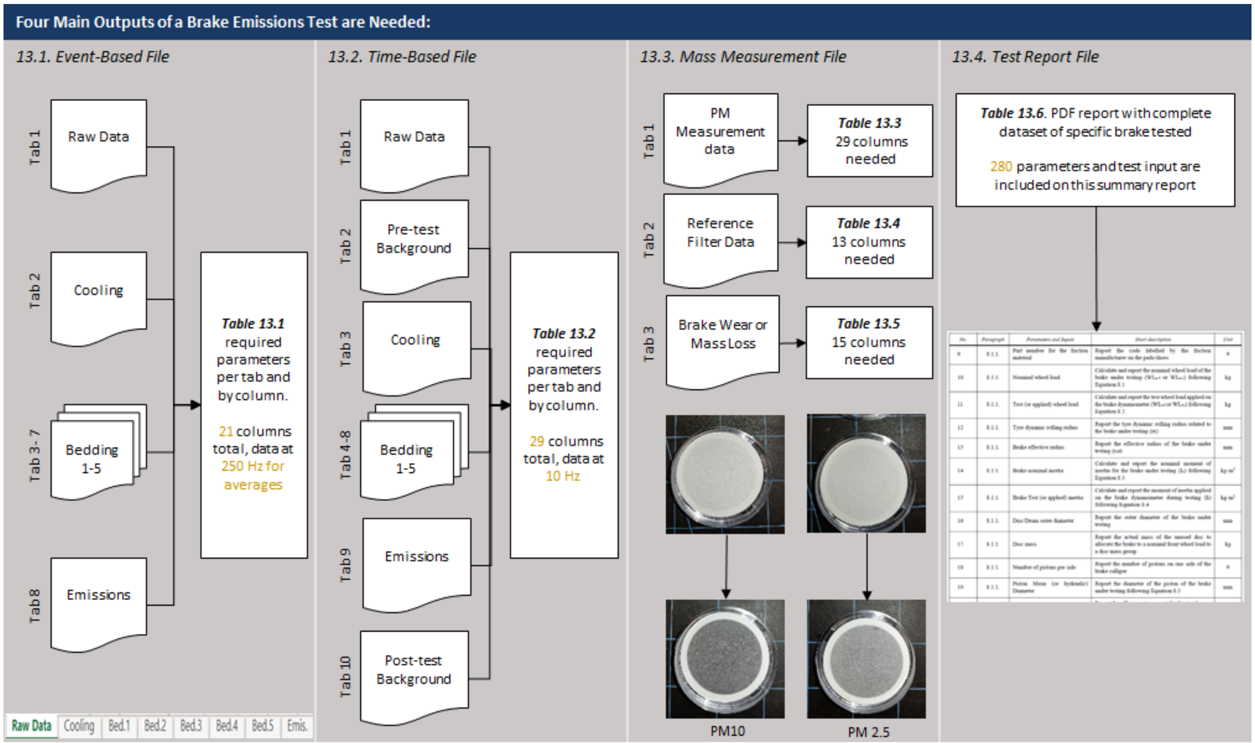
– Paragraph 12 also describes the weighing procedure from the test and the reference filters residing in the weighing room or chamber, along with the buoyancy correction for filter mass reported







- Paragraph 13 addresses one crucial aspect of reproducible measurements: the structure and format of the test report, using several spreadsheets with predefined format, syntax, and units for close to 400 parameters and values.



- Paragraph 14 details aspects related to calibration and ongoing quality controls for all sensors and devices part of the test toolchain (brake dynamometer, cooling air, PM measurement, PN measurement, and weighing systems for filters and test parts). The details include requirements for zero intercept, linearity, standard error, and coefficient of determination for dynamic sensors (e.g., brake speed, torque, pressure, airflow) and weighing balances. This paragraph also details sample treatment, conditioning devices, and particle number counters.
- Annex A includes all events (idle, acceleration, cruise, and deceleration) for the entire WLTP-B. Below is a depiction of the first 100 seconds of the cycle out of the 15,826 seconds total.

Annex A

WLTP-Brake Cycle Events

Event time start [s]	Event time end [s]	Trip [#]	Event Type	Speed at start [km/h]	Speed at end [km/h]
0	4	1	Idle	0.0	0.0
4	10	1	Accel.	0.0	20.7
10	18	1	Cruise	20.7	20.7
18	24	1	Decel.	20.7	0.0
24	27	1	Idle	0.0	0.0
27	46	1	Accel.	0.0	23.1
46	58	1	Cruise	23.1	23.1
58	65	1	Decel.	23.1	5.6
65	68	1	Cruise	5.6	5.6
68	77	1	Accel.	5.6	15.4
77	85	1	Cruise	15.4	15.4
85	89	1	Decel.	15.4	4.4
89	92	1	Cruise	4.4	4.4
92	100	1	Accel.	4.4	25.7

- Annex B lists all 303 brake events, which are divided into 10 trips. Below is a depiction of the first 10 events for trip #1.

Annex B

WLTP-Brake Cycle Brake Events

Trip	Brake Event #	Start time [s]	End time [s]	Event duration [s]	Initial Speed Setpoint [km/h]	Final Speed Setpoint [km/h]	Deceleration Rate [m/s^2]	Event Distance [m]	Specific KE (Decel only) [J/kg]
1	1	18	24	6.0	20.7	0.0	0.958	17.24	16.53
1	2	58	65	7.0	23.1	5.6	0.695	27.88	19.38
1	3	85	89	4.0	15.4	4.4	0.760	11.01	8.40
1	4	103	109	6.0	25.7	7.2	0.857	27.47	23.48
1	5	129	132	3.0	24.8	16.7	0.748	17.28	12.97
1	6	140	149	9.0	18.7	0.0	0.577	23.36	13.49
1	7	177	183	6.0	32.5	0.0	1.506	27.11	40.75
1	8	298	303	5.0	27.5	11.8	0.872	27.31	23.80
1	9	314	320	6.0	29.4	9.7	0.915	32.59	29.72
1	10	341	347	6.0	31.9	9.5	1.037	34.47	35.78

- Annex C describes the main elements and requirements for measuring and calculating vehicle-specific brake share coefficients *c,* conducting only a WLTB-B cycle or Trip #10. The measurement requires the use of a chassis dynamometer compliant with GTR 15 [76].

  Reference method and calculation for vehicle-specific friction braking share coefficient: friction work (including braking power and brake torque using direct, pressure-based, or alternative methods); and determination of the C_p value for the torque-to-pressure ratio

  Testing setup and specifications: vehicle selection; preparation (e.g., torque, pressure); data recording; chassis dynamometer settings; test sequence; chassis dynamometer test quality criteria (driven and target velocity, acceleration, and specific inertial power); root mean squared speed error, inertial work rating for deceleration, inertial power difference work, and inertial power difference rating.

  Equivalency of methods for computation of *c*, including the selection of a vehicle for proof of equivalence, testing of the alternative method, and the equivalency criterion

  Equivalency of the test cycle, allowing the use of only trip # 10 of the WLTP-B cycle

  Test output and allowed offset of the declared friction braking share coefficient (increased by the vehicle manufacturer by up to 50 % of the measured value or 0.05 absolute value, whichever is greater, in coordination with the contracting party.

During the ILS3 of the UNECE PMP-IWG to enhance the GTR 24 document, several aspects were improved, clarified, or corrected.

One important enhancement of Amendment 2 to the [6] is the correction of the computation method for kinetic energy dissipation. The revised calculation relies on the integral of torque × rotational speed to replace the former method, which used simple average torque and revolutions to stop, as described in the initial release of the document. Figure 28 exemplifies the effect of the change in the computation method, thereby avoiding false positives (Labs C, F, K, and M) and false negatives (Labs E and N) in the results.

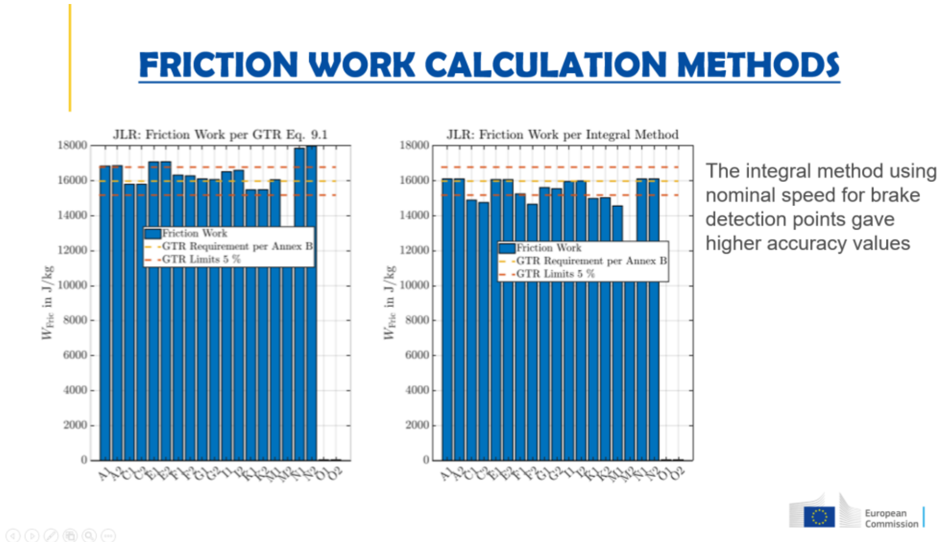


Figure 28 – Comparison of methods to calculate kinetic energy

Other improvements to the document include the following:

- New equation to harmonize the calculation of the nominal torque for a given deceleration event using a threshold deceleration of 0.25 m/s² to determine the start and end of the brake event
- Remove the average-by-time definition for torque, pressure, and coefficient of friction to reflect the vehicle dynamics response better
- Clear definition of time stamps (15 % of target torque) to define the start and end of events

Enhanced definitions for brake effectiveness to account for disc and drum brakes

A comprehensive study was conducted using three different brake enclosures and sampling tunnel setups to approximate the GTR 24 setup, and documented in [36].

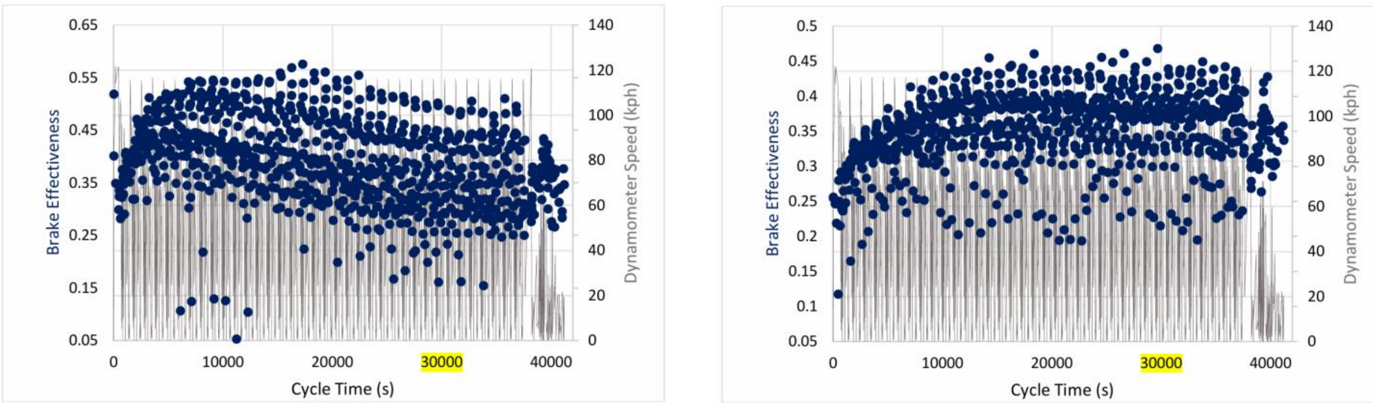
California Brake Dynamometer Cycle CBDC for light vehicles

In 2018, CARB launched a study to update the Emissions Factor Model 2021[9] (EMFAC2021) for automotive brakes by a) conducting a market survey for vehicle and friction material applications, including estimates for wearable mass and replacement rate, b) conducting proving ground measurements using WLTP-B cycles to determine the thermal regimes, and c) conducting laboratory testing using single-ended inertia dynamometers on six vehicles applications, each axle tested separately, and assessing the PM, PN, PSD, and time-based mass for the OES and two leading aftermarket friction couples. The development of the CBDC test cycle provides a 22-hour test v 2.5 days per WLTP-B, and compared to the WLTP-B, it has shorter brake events, lower deceleration rates, slightly higher braking speeds, and a larger percentage of driving time. Defining the CBDC started with analyzing the Caltrans 2010-2012 California Household Survey data from over 14 000 hours of data at 1 Hz (OBD-only, OBD+GPs, and GPS-only) from more than 2000 vehicles in operation.

One important difference between the CBDC and the WLTP-B cycles is that the former uses non-constant decelerations within a given braking event. Like the WLTP-B test per GTR 24, the CBDC setup uses HEPA-filtered air conditioning for temperature (20 ± 5) °C and humidity (50 ± 10) %RH, an electropolished brake enclosure, a constant volume sampling tunnel, and a sampling plane located at least six diameters downstream from the last disturbance, and two diameters upstream from the next disturbance in the sampling tunnel. For quality controls, the CBDC uses speed violations and speed errors according to UN GTR 15 and SAE J2951. For brake bedding, the CBDC includes a series of 35 repeats of high-energy modules from the activity data to condition the friction couple and a short conditioning cycle to transition to the actual emission cycle with active PM, PM, and PSD measurements. To assess the validity of the bedding cycle, the project measured the stabilization of the coefficient of friction (COF) and particle number. As a result of testing the front

[9] https://ww2.arb.ca.gov/sites/default/files/2021-04/17RD016.pdf

brakes on the Ford F150 and Toyota Camry, the COF was stable after 30 000 seconds and 20 000 seconds, respectively, as shown in Figure 29. At this point, the PN had achieved a stable level when using the cumulative particle count on the CPC. The project also considered the adjustment of the cooling airflow for the laboratory test using brake temperatures measured on the proving ground. The laboratory tests exhibited an average disc/drum temperature within 10 °C, an average disc/drum initial temperature for six events with high braking power, and an average disc/drum final temperature within 25 °C, all when compared to the vehicle.

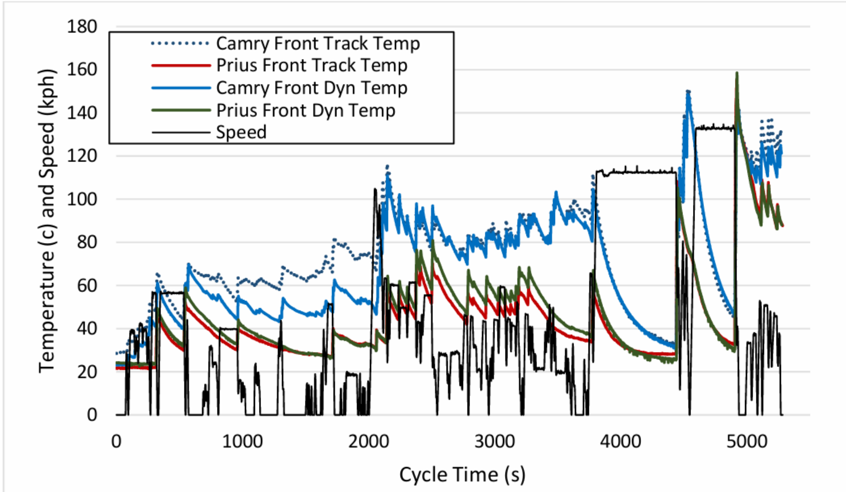


(a) F150 front AM low-met COF

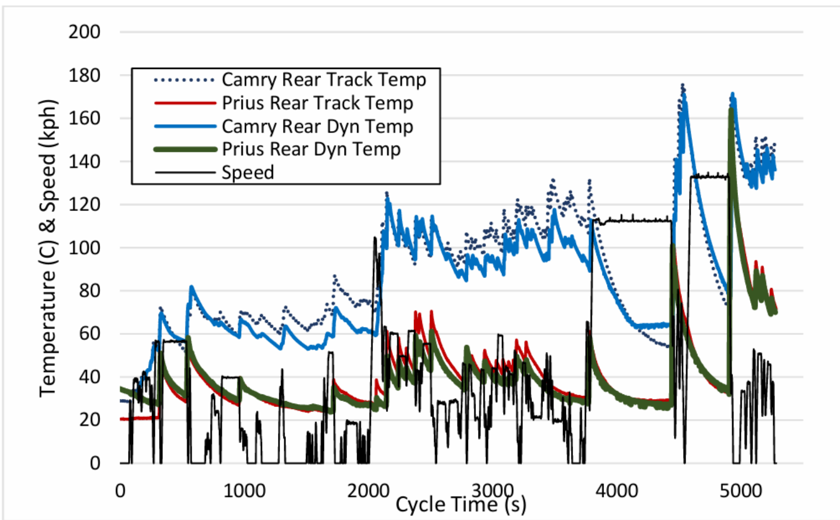
(b) Camry front NAO COF

Figure 29 – Brake effectiveness during CBDC bedding

One important aspect of this study was the ability of the brake dynamometer to recreate the kinetic energy and thermal behavior measured on the proving ground, especially for the Toyota Prius with regenerative braking. Figure 30 shows the time-resolved alignment for brake disc temperatures for the front and rear brakes on the Toyota Camry and Toyota Prius. The comparison is three-fold: a) confirmation of the kinetic energy dissipation as a function of dynamometer control and test inertia, b) cooling airflow adjustment observed as the peak temperatures achieved during high energy events and cooldown periods, and c) regenerative braking on the dynamometers observing the temperature rise during braking for the Toyota Prius.



Front brake



Rear brake

Figure 30 – Example of temperature traces for proving ground and brake dynamometer tests for front (top) and rear (bottom) panels

The cycle developed applied a microtrip approach with a thermal model to define the CBDC test with 14 933 seconds (compared to 15 826 seconds for WLTP-B), three speed ranges (compared to 10 trips for WLTP-B), 347 braking events (compared to 303 events for WLTP-B), and a total test distance of 131.2 km (compared to 192 km for WLTP-B). Table 18 shows the main parameters, and Figure 31 shows the speed trace.

Table 18 – main parameters for CBDC test

Microtrip average speed range	Percent of Caltrans distance traveled	New cycle distance	New cycle represented the distance	New cycle duration
[0, 21] km/h	4 %	6.16 km	4.7 %	2740 s
[21, 69] km/h	38 %	47.31 km	36.0 %	8340 s
> 69 km/h	58 %	77.78 km	59.3 %	3855 s
Total	100 %	131.25 km	100 %	14 933 s

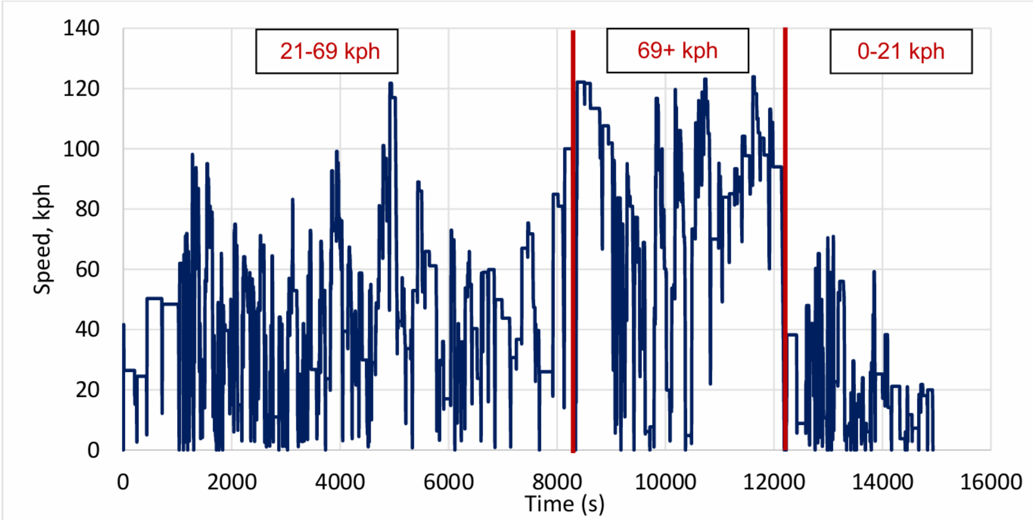


Figure 31 – CBDC speed trace at 1 Hz

The bedding cycle, designed to allow an entire CBDC test to run for 24 hours, includes 32 repeats of a high-energy segment of the CBDC, followed by a low-energy segment for cooldown, before the actual brake emissions measurement cycle. The total kinetic energy dissipated during the bedding is equivalent to five WLTP-B cycles.

The payload during testing is equivalent to the curb weight plus 300 lbs. For SUVs or pickup trucks, the heavily laden weight is calculated as follows:

$$HLW = Curb\ Weight + \frac{2}{3} \times (GVW - Curb\ Weight)$$

During the CARB study [77] a fully enclosed brake inertia dynamometer with climatic conditions, a constant volume sampling tunnel for isokinetic sampling, and an electropolished enclosure following the guidelines shared with the UNECE PMP-IWG were used. QCM 140 and 100S4 measured or collected $PM_{2.5}$; 100S4 and gravimetric sampling provided PM_{10}; CPC and EEPS reported PN, and the APS provided time-resolved PM up to PM_{10}. Figures 31 to 33 depict the dynamometer setup and the sampling system.

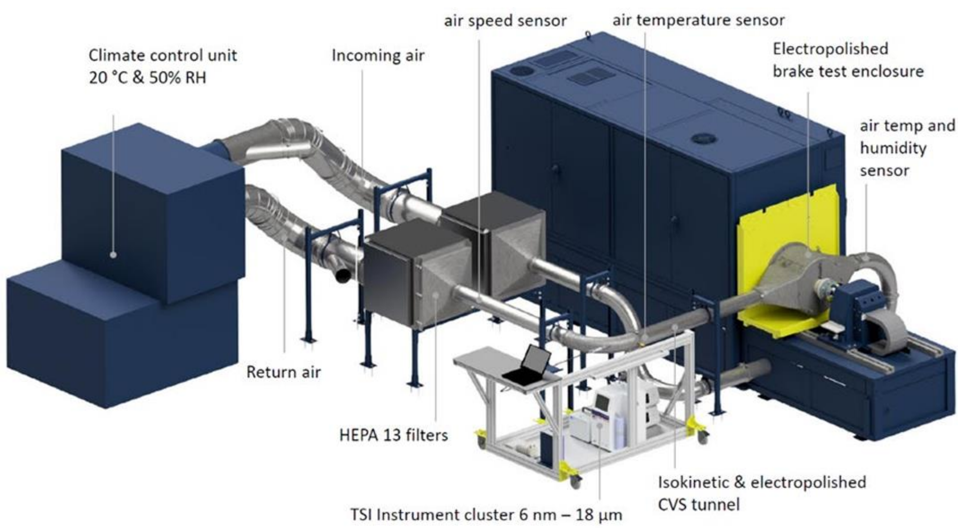


Figure 32 – Dynamometer and sampling system circa 2018

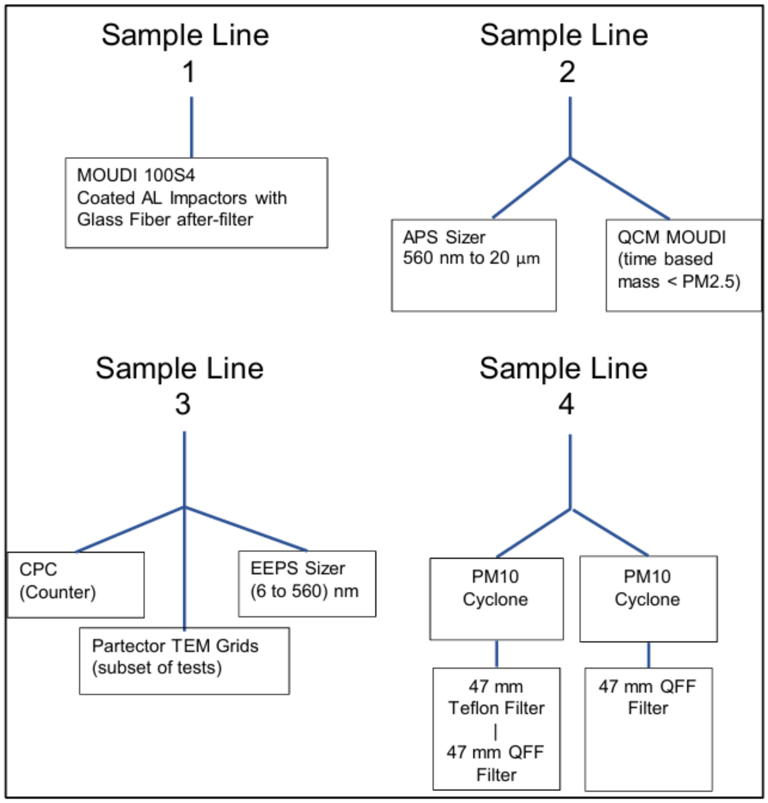


Figure 33 – Block diagram for sampling nozzle assignment circa 2018

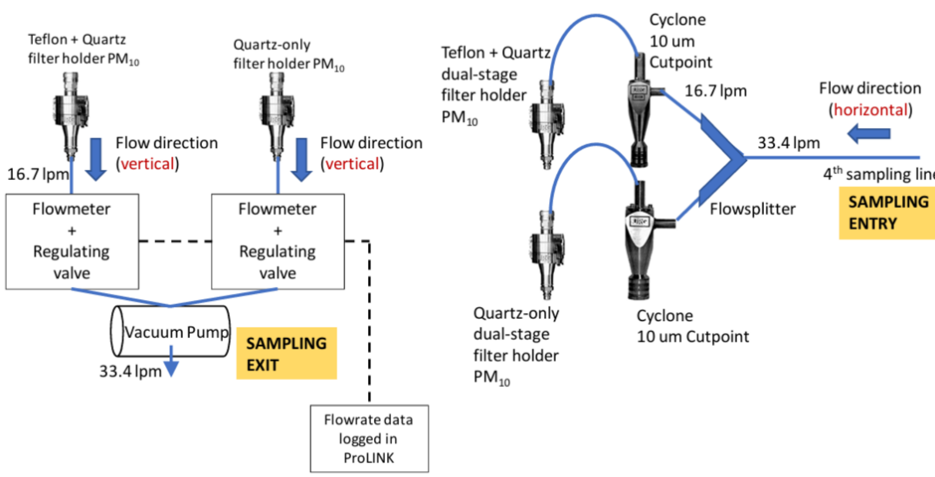


Figure 34 – Arrangement of PM sampling devices circa 2018

The real-time instruments for the light and heavy-duty vehicles were the same and included the following:

- TSI QCM MOUDI 140. The Model 140 Quartz Crystal Microbalance (QCM) MOUDI is designed to perform continuous, real-time size-segregated mass concentration measurements of particles smaller than 2.5 µm. The system uses six cut-point stages at (960, 510, 305, 156, 74, and 45) nm and operates at a 10 L/min inlet flow rate. Based on input from the CARB LD study results, the QCM was improved to report 10-second average results vs. 60-second average results for the heavy-duty study

- TSI CPC. The 3790A Condensation Particle Counter (CPC) is a full-flow design PM particle counter with a particle size lower detection limit[10] of 23 nm. The unit is designed to respond linearly to particle concentrations ranging from 1 to 10,000 particles/cm³ and can operate continuously, taking 10 Hz measurements. TSI indicates a counting accuracy of ± 10%. The PMP has specified using this unit as the baseline for brake particle counting, utilizing a catalytic stripper for the Volatile Particle Remover (VPR) and a dilution stage. No VPR or dilution was used for the CARB or Caltrans studies.
- TSI APS. The 3321 Aerodynamic Particle Sizer (APS) measures the aerodynamic size of particles ranging from 0.5 µm to 20 µm. The system uses time-of-flight aerodynamic sizing to determine the particle's airborne behavior and is unaffected by the index of refraction or Mie scattering. The unit also measures light-scattering intensity in the equivalent optical size range of 0.37 to 20 µm. The system offers continuous sampling at a rate of 1 Hz.
- TSI EEPS. The 3090 Engine Exhaust Particle Sizer (EEPS) spectrometer continuously measures the size distribution of particle emissions from 5.6 to 560 nm at a rate of up to 10 Hz. The EEPS provides outputs of size distribution in the above range and particle number concentrations down to 200 particles/cm³.

Figure 35 shows the dynamic ranges for the real-time instruments.

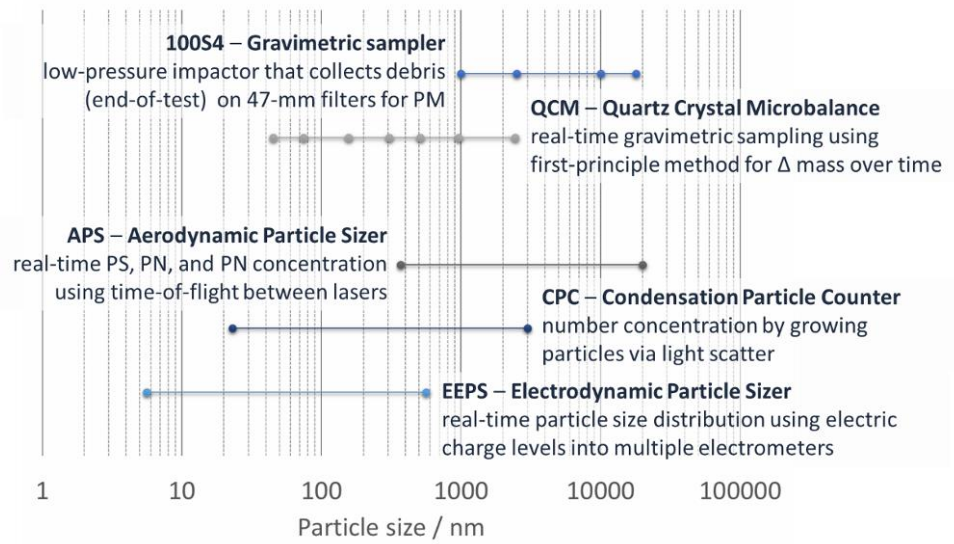


Figure 35 – Dynamic ranges for sampling and measurement devices circa 2018

Parallel to this study, a high-fidelity computational fluid dynamics simulation was compared to experimental measurements, where fine Arizona dust was injected into the sampling nozzles inside the enclosure's brake position to assess transport efficiency (using particle count as the surrogate metric). Figure 36 shows the comparison between the simulation and the laboratory measurements [78].

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[10] Since the completion of this study, the industry has moved on to adopt 10 nm as the low cut-point

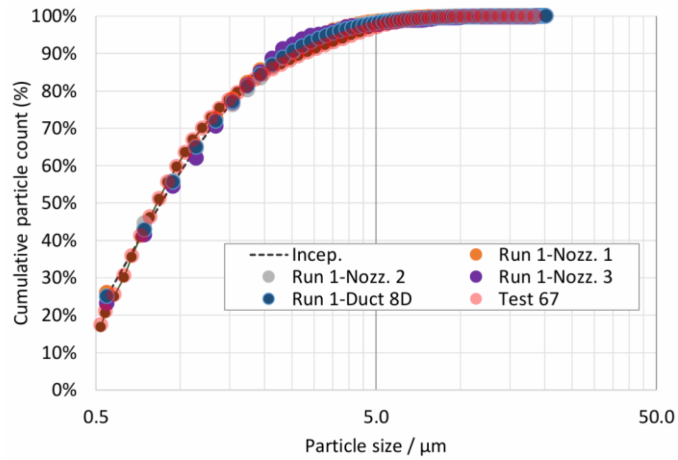


Figure 36 – Cumulative size distribution for high-fidelity simulation. "Runs" denote simulations; "Test" denotes experiments at the physical sampling system

One important parameter to monitor is the thermal regime represented by the average rotor temperature. Figure 37 shows the average and the 95th confidence interval for all the tests on a given vehicle, axle, and loading conditions.

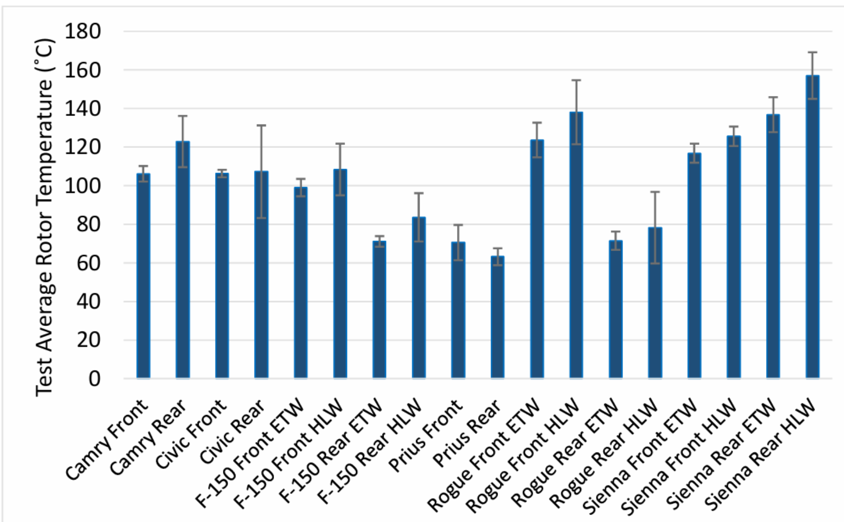


Figure 37 – Average brake temperature and tolerance

For the same project, the weighing process went through a correlation study with 30 untested filters measured in triplicates, comparing the testing laboratory with the EPA Emissions Laboratory in Ann Arbor, MI, as a reference. The filter weights ranged from 385 to 400 mg, and the regression line had a slope of 1.00008 and a zero offset of 0.035 mg.

California Brake Dynamometer Cycles for Caltrans heavy-duty vehicles

The Caltrans study [16] for heavy-duty vehicles focused on commercial vehicles with a gross vehicle weight rating above 10 000 lbs (4536 kg), equipped with air or hydraulic brakes. A second type of test included a Tesla Model 3 tested under the CDBC and with an approximation of the regenerative braking in real-time during testing. Regarding the HD tests:

- The data from the proving ground testing was used to adapt and update a HD brake temperature model first published in the 1980s [79], with good agreement between predicted and observed temperature traces
- Measured and modeled brake temperatures were applied to emissions tests on a HD brake dynamometer with gravimetric and real-time PM sampling on a Constant Volume Sampling tunnel with cooling air condition for cleanliness, temperature, and humidity

This study took two steps before developing a test matrix and plan, both shown in Figure 38:

a) Creating a Brake Wear Index (BWI) to rank and select the vocations for the study using vehicle miles traveled (VMT) statistics for California, nominal brake dimensions, and replacement rates from business intelligence from the industry. Figure 38 shows the calculation for the BWI
b) Using the BWI results to confirm the test plan and secure the test hardware for the study. Figure 37 shows the ranking of the BWI metric for all the vocations analyzed

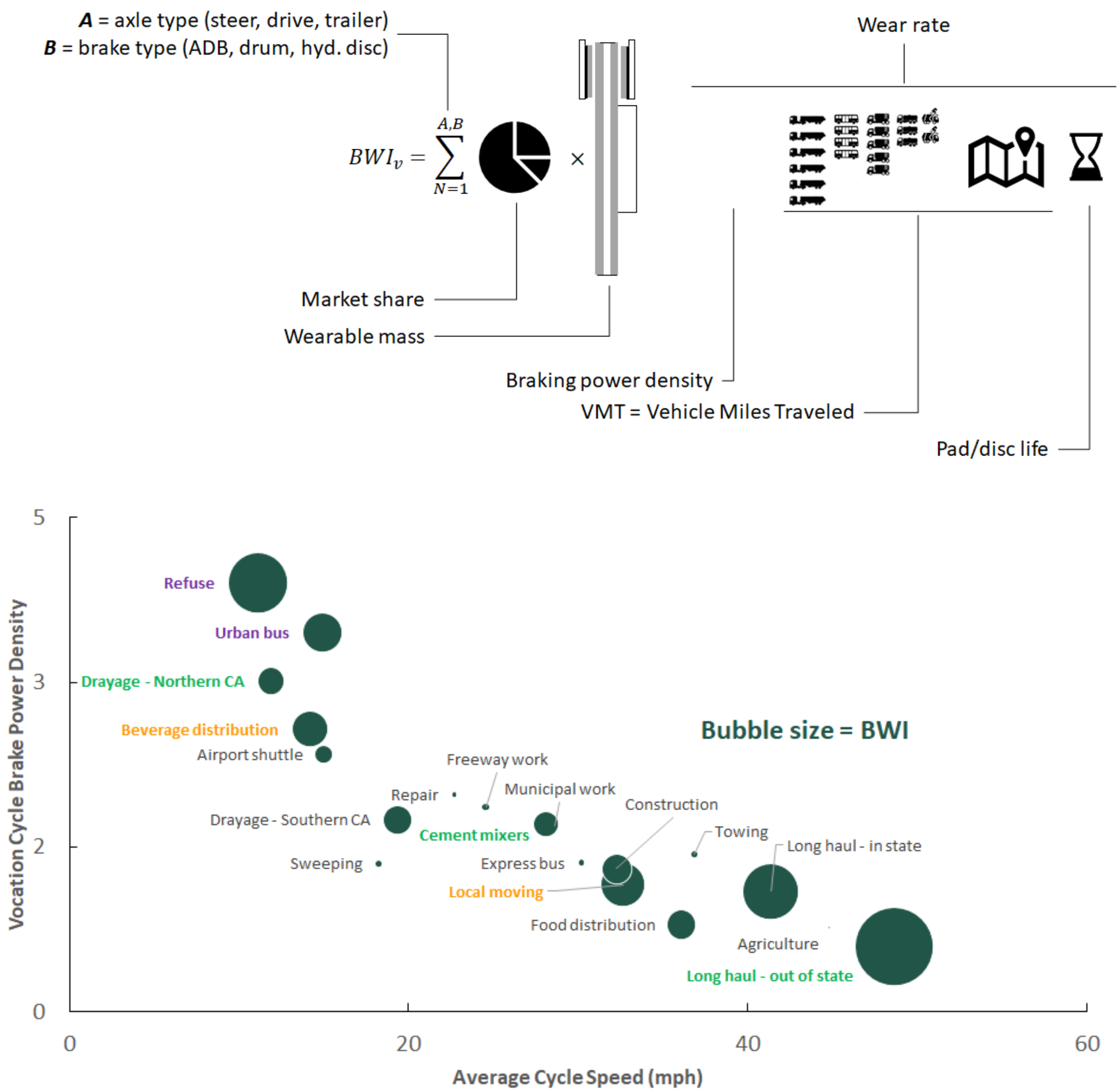


Figure 38 – Upper panel: infographic for Brake Wear Index. Lower panel: application to market survey and fleet

The test matrix was determined from a California brake wear mass balance analysis, accounting for braking activity by truck vocation as shown in Table 19. The test matrix included Class 8 drum, disc, and trailer configurations tested over three vocation cycles and two load points a Class 6 hydraulic disc configuration tested over two vocation cycles. A refuse truck and urban bus tested over representative cycles. Tests were repeated for original equipment and aftermarket brake pads to evaluate potential deterioration in brake emissions over time, though the differences between these equipment types were not statistically significant. Individual wheel PM filter results were then used to update EMFAC HD brake PM emissions based on statewide estimates of loaded/unloaded travel, axles per truck, speed distributions, and brake material replacement intervals.

Table 19 – Overview of Caltrans test matrix

Vehicle	Brake/axle	Cycle 1	Cycle 2	Cycle 3	Load	Repeat	EMFAC class
Class 8	drum steer	Drayage N*	Cement	LH OOS**	1		T7
	drum drive	Drayage N	Cement	LH OOS	2	Yes	
	ADB steer	Drayage N	Cement	LH OOS	2	Yes	
	ADB drive	Drayage N	Cement	LH OOS	1		
Refuse	ADB steer	Refuse			2		Refuse
	ADB drive	Refuse			1		
Urban bus	ADB steer	Urban bus			1		Bus
	ADB drive	Urban bus			1		
Service	Hyd. Disc steer	Beverage	Delivery		1		T6
	Hyd. Disc drive	Beverage	Delivery		1	yes	

*Northern CA Drayage ** Long-Haul Out-of-State

One important aspect of this study was adapting field measurements for short (30-minute) cycles for exhaust emissions, which were readily available for the brake emissions measurements (proving ground for temperatures and brake dynamometer for actual emissions measurements). Figure 39 illustrates the speed trace for different vocations obtained from [80].

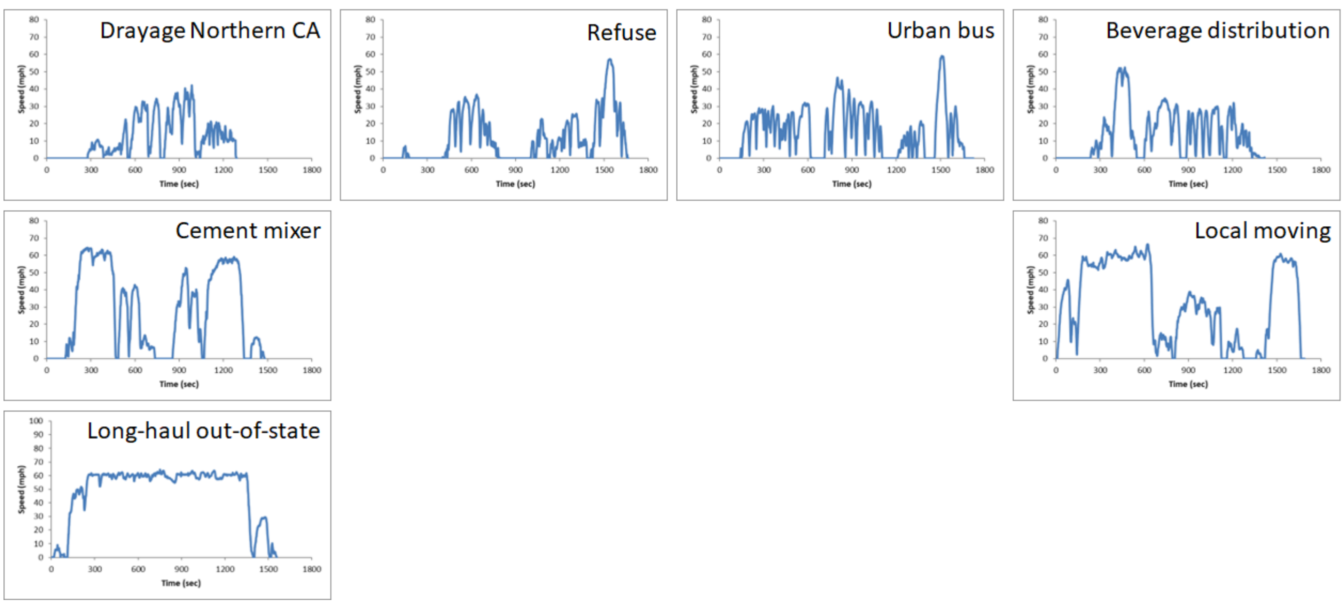


Figure 39 – 1-Hz time-resolved driving cycles

The control system allows the entry of the coastdown coefficients per [81] for the vehicle under test to reflect road loads, enhancing the fidelity of the dynamometer test with parameters shown in Table 20. This approach corrects the dynamic torque demand for friction brakes for road loads. Considering that there is a lack of parameters on how brake retarders interact with friction brakes, that many municipalities in the United States do not allow the use of retarding in populated areas, and the study intended to characterize friction brakes, this study did not attempt to reduce the frictional torque demand in addition to road loads.

Table 20 – Coastdown coefficients applied for the different tests

Vehicle type	A [N]	B [N/(km/h)]	C [N/(km/h)²]	Test mass [kg]
Class 8 loaded	1985.45	21.023	0.2538	36 746
Class 8 unloaded	580.61	15.332	0.2930	13 045
Class 6	687.54	26.387	0.0502	12 603
Refuse	1082.43	28.930	0.0848	20 276
City bus	847.40	25.514	0.1336	16 465

Regarding brake temperature control, this study combined proving ground measurements and an update to a legacy thermal model [79]. Figure 40 shows the overlay between measured and computed results. The actual temperature during the dynamometer tests remained, on average, within ± 25 °C of the target, with the Class 8 trailer axle with drum brakes and the refuse drive axle with disc brake exhibiting the lowest temperatures, even at the lowest cooling airflow setting.

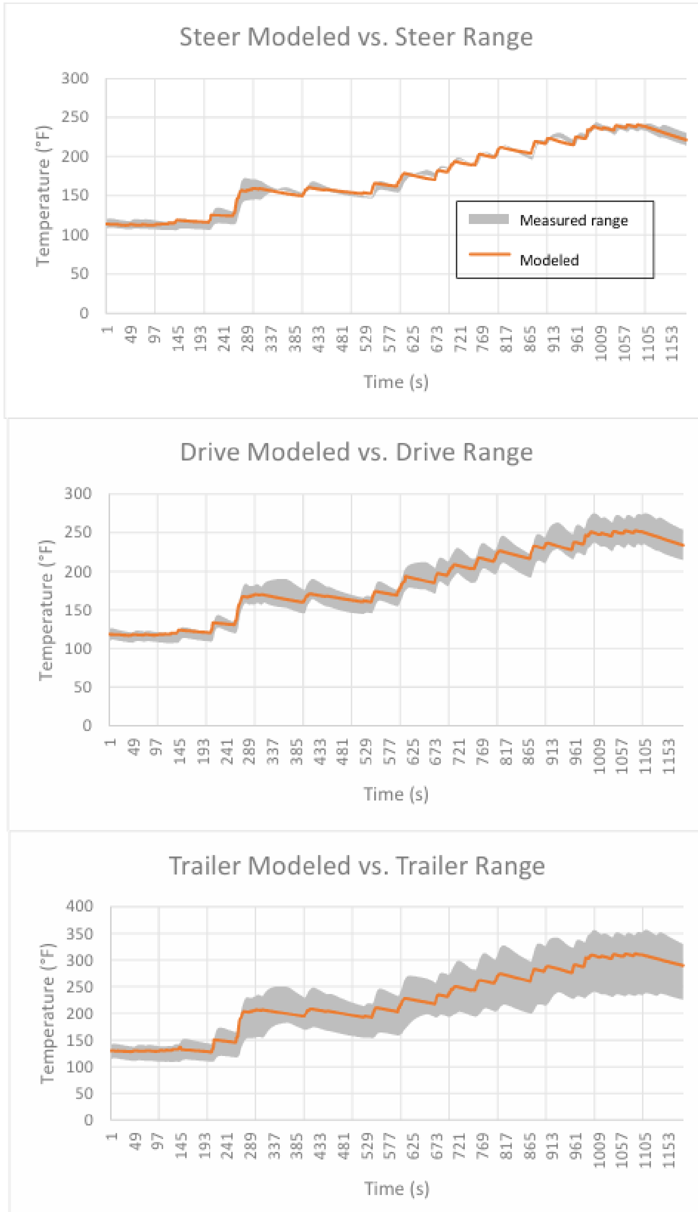


Figure 40 – Simulation of brake temperature vs. dynamometer test results

And, Figure 41 reflects the actual test plan for commercial vehicles.

All tests conducted with original equipment (OE) and aftermarket (AM) friction material

Test Fixture	Cycle 1	Cycle 2	Cycle 3	Loads	Repeat Tests
Class 8 Drum Steer	Drayage N*	Cement	LH OOS**	1	
Class 8 Drum Drive	Drayage N	Cement	LH OOS	2	✓
Class 8 Drum Trailer	Drayage N	Cement	LH OOS	2	✓
Class 8 Disc Steer	Drayage N	Cement	LH OOS	1	
Class 8 Disc Drive	Drayage N	Cement	LH OOS	2	✓
Refuse Truck ADisc Steer	Refuse			1	
Refuse Truck ADisc Drive	Refuse			1	
Urban Bus ADisc Steer	Urban Bus			1	
Urban Bus ADisc Drive	Urban Bus			1	
Hydraulic Disc Steer	Beverage	Local Moving		1	
Hydraulic Disc Drive	Beverage	Local Moving		1	✓

*Northern California Drayage **Long Haul Out-Of-State

Figure 41 – Test plan combining brake types, vocations, and friction materials

The test protocol includes the following steps:

Air disc and drum brakes:

1. Burnish (200 stops at 250 °F and 200 stops at 500 °F)
2. Resink pad/shoe thermocouple
3. Re-run 50 stops at 500 °F
4. Vocation cycles (1 for Bus/Refuse, 3 for Class 8)
5. Intermittent tunnel blank tests

Hydraulic disc brakes:

1. Burnish following SAE J2684 (500 snubs at 393 °F) [82]
2. Resink the brake shoe thermocouple
3. Re-run 50 stops at 500 °F
4. Run vocations (2 for Class 6)
5. Intermittent tunnel blank tests

R&D setups for chassis dynamometers

Chassis dynamometers remain important test systems for different purposes. Besides providing the means to quantify the friction brake share coefficient for future type approval for non-exhaust brakes, it allows detailed investigation of interactions with the vehicle environment. One practical use studied on [52] applied to assessing hybrid light vehicles' particle number and particle mass, using a 13-stage (from 30 nm to 12 µm) low-pressure impactor and Polycarbonate foils as particle carriers for mass-size distribution and electron microscopy studies, depicted in Figure 42. For reference, this study reported PN emission factors (>23 nm) during the WLTC cycle lie at 5.0×10^{10} 1/km/B, PM_{12} EF at 3.71 mg/km/B, and $PM_{2.5}$ of 1.58 mg/km/B. These values need to roughly triple to obtain an estimate for the brake particle emission of all four brakes and wheels of the entire vehicle. The study also reports brake PN emissions factors in the same order of magnitude as the tailpipe PN of a Euro 6 light-duty vehicle equipped with a particle filter. Lastly, differences in brake particle emissions between hybrid and all-electric operating modes have been assessed through a series of specific measurements, showcasing the potential of all-electric vehicle operation in reducing brake particles by a factor of two.

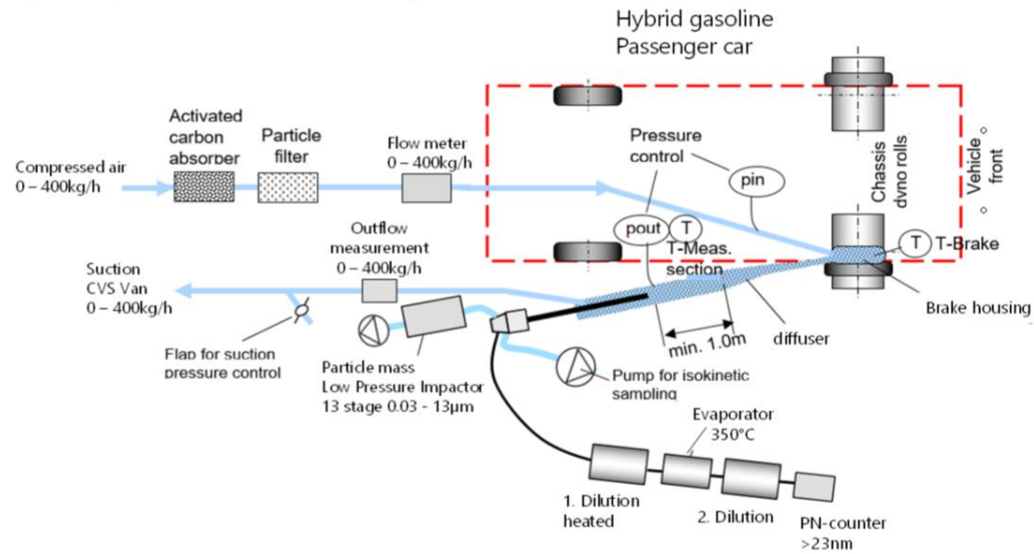


Figure 42 – Experimental setup for measuring brake particles (PN and PM) on a chassis dynamometer. Image from open source [52]

Measurement of organic volatiles as markers for brake wear

Several studies [83], [84] have investigated the identification of volatiles emitted during brake testing with dedicated setups. Besides the phenolic resins used as binders in the friction material, other potential sources of volatile organic compounds include reclaimed rubber (for noise damping), cashew nut oil (as a friction modifier), and graphite (for enhancing friction stability). Figure 43 from the same studies also show a breakdown of different materials for various types of vehicle applications.

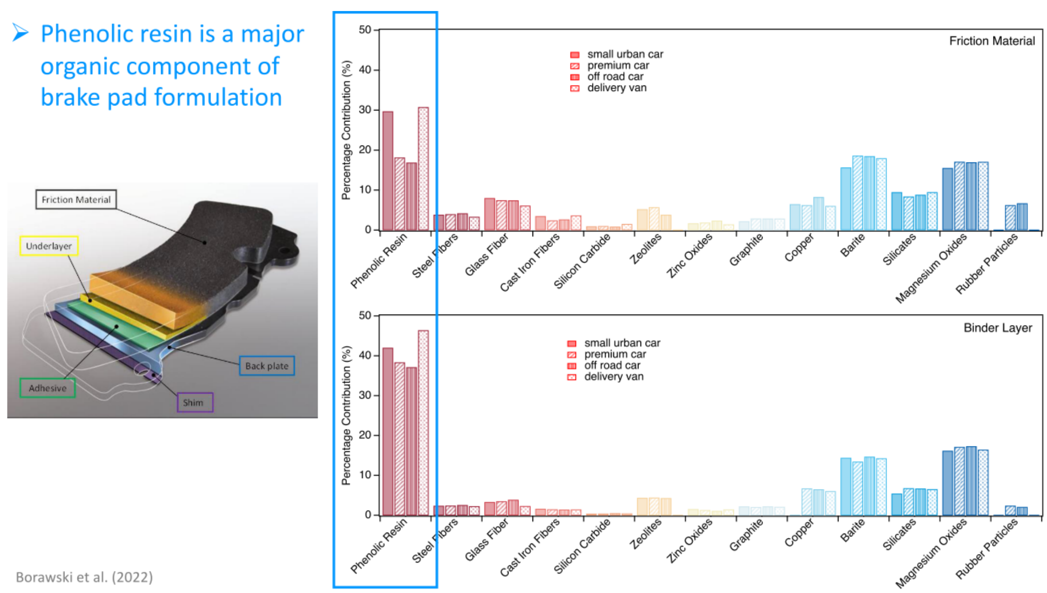


Figure 43 – Percent contribution of phenolic resin to different friction material formulations. Image from open source [83]

In another study [83] with a dedicated adaptation of a lathe to conduct continuous brake applications is shown in Figure 43, depicting the laboratory setup using brake applications (8 to 10) seconds long, at constant speed (~25 km/h), with torque (100 to 270) N·m, inducing temperatures from 86 °C to 360 °C.

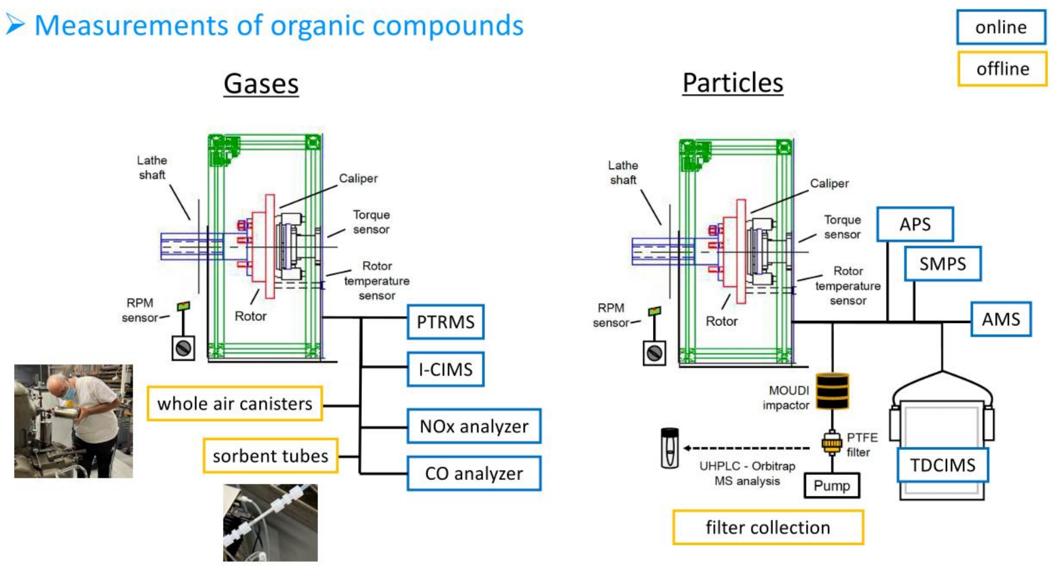


Figure 44 – Diagram of sampling systems for gaseous and particle emissions. Image from open source [83]

17.2.2 Tires

Euro 7 planned regulation to limit tire abrasion to reduce microplastic release

UNR 117 [8] defines two test methods for light vehicles with C1 tires (multi-vehicle convoy or laboratory indoor testing using individual tires). Figure 45 compares some general aspects of brakes and tires side by side based on upcoming EU regulations to limit PM_{10} for the former and abrasion for the latter. To stay informed about progress and changes to the UN Task Force on Tyre Abrasion, follow its wiki page for working documents from each official session.[11]

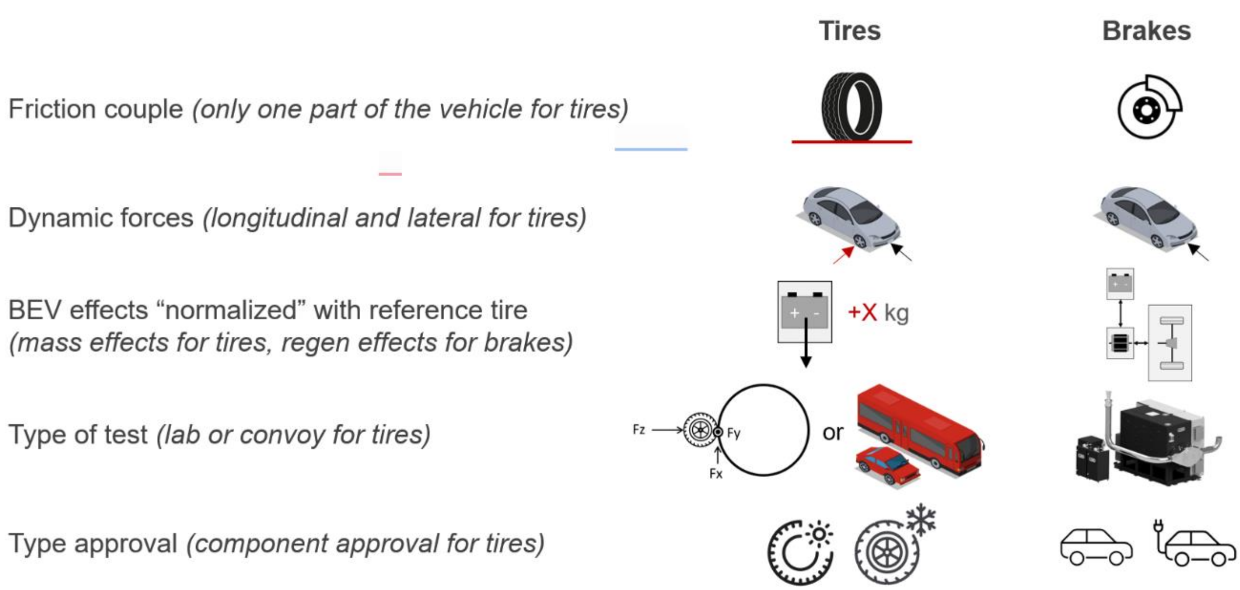


Figure 45 – Infographic for key elements for brake v tire type approval under Euro 7

Figure 46 illustrates a flowchart of the main phases of a convoy test for C1 tires as defined on the draft UNR [XXX].

[11] Task Force on Tyre Abrasion (TF TA) - Transport - Vehicle Regulations - UNECE Wiki

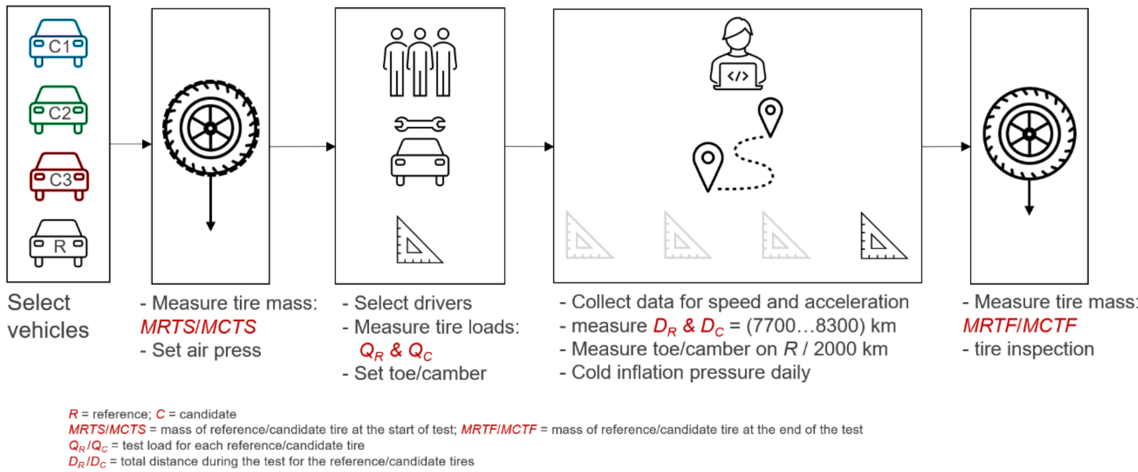


Figure 46 – Infographic for convoy testing process and key measurements

Figure 47 shows the proposed suspension settings for vehicle toe and camber.

Drivetrain	Toe IN/OUT		Camber (+/–)	
Axle position	**Front**	**Rear**	**Front**	**Rear**
FWD				
Reference – R	0° ± 0,05° & |R| ≤ |C|	0,05°…0,15°	–1,2°…0°	–1,9°…–1,6°
Candidate – C	0° ± 0,1°	↑	↑	↑
RWD = AWD				
Reference – R	0° ± 0,05° & |R| ≤ |C|	0° ± 0,1°		
Candidate – C	0° ± 0,1°	↑		
AWD as FWD or RWD				
Reference – R	See above			
Candidate – C	See above			
Not tunable as FWD or RWD (confirm with ≥ 4 vehicles ≤ 2 years of age, from 4 carmakers)				
Set R and C	0° ± 0,1°	|R – C| ≤ 0,1° & |R| < |C|	|R – C| ≤ 0,5° & |R| < |C|	|R – C| ≤ 0,6° & |R| < |C|
Reference – R	0° ± 0,05°	0,05°…0,3°	– 1,7°…0°	–2,7°…0°
Candidate – C	0° ± 0,1°	↑	↑	↑
End of Test	Change from initial tuning ≤ 0,15°		Change from initial tuning ≤ 0,3°	

Figure 47 – Default parameters for suspension tuning. Values in red font indicate proposals at the time of compiling this report

Figure 48 shows four panels of the main requirements for the convoy's vehicle dynamics during circuit development and actual testing according to type approval.

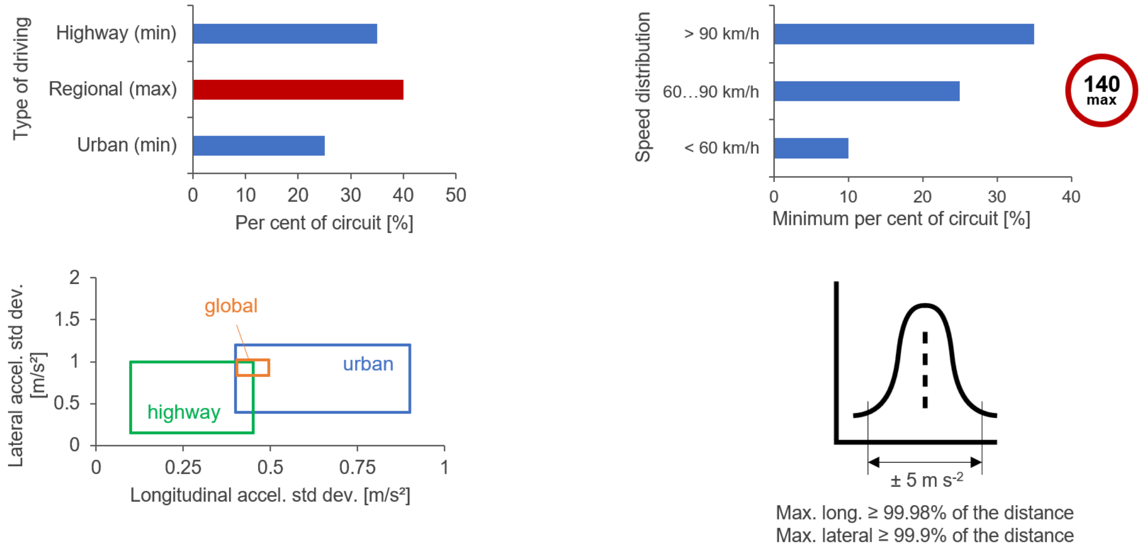


Figure 48 – Infographics for drive mix, speed mix, and vehicle dynamics

Figure 49 shows the ranges for outside temperatures and road conditions during the validation of the test circuit and subsequent testing (including type approval),

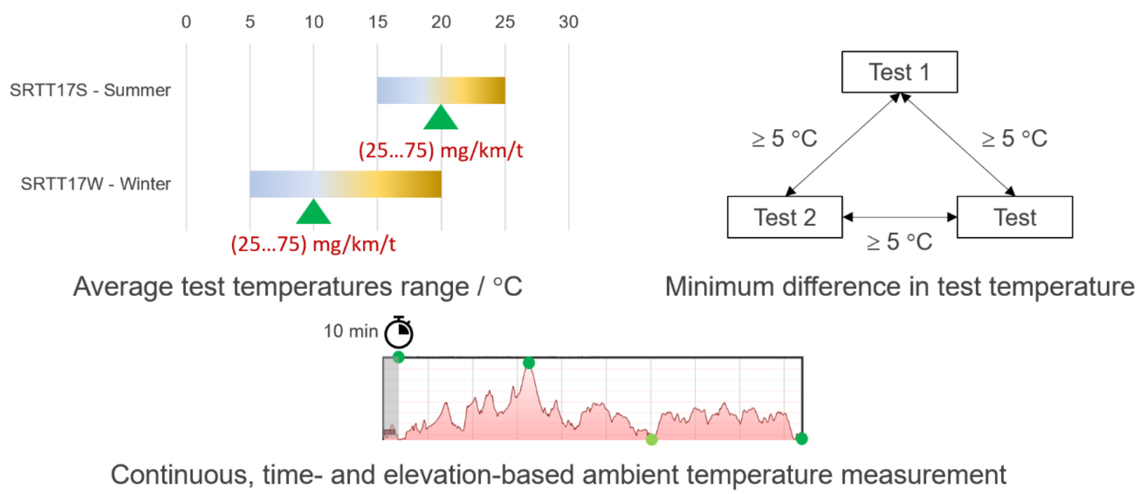


Figure 49 – Criteria for testing and validation of the drive circuit for temperature

Figure 50 illustrates the allowable outside temperatures depending on the type of tire and road surface conditions for wetness and snow.

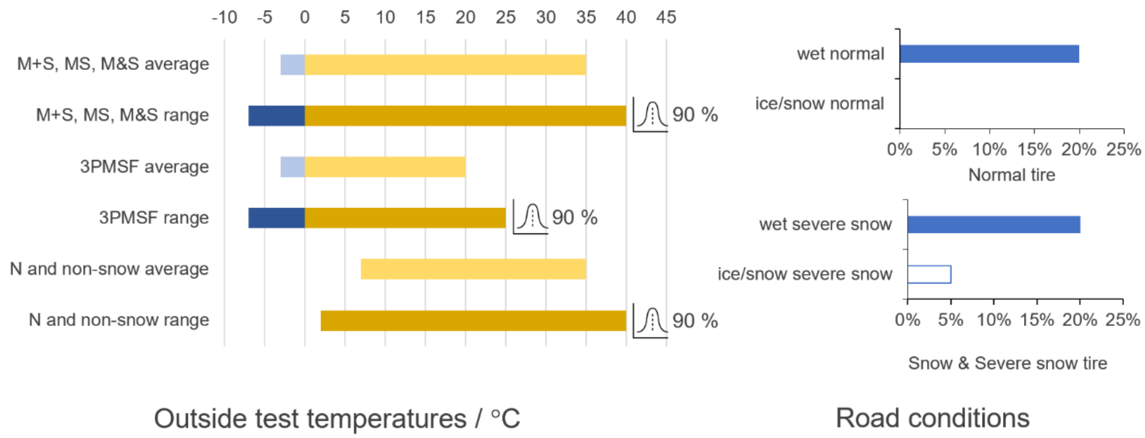


Figure 50 – Allowed outside temperatures and road conditions

A critical aspect of convoy testing involves vehicle preparation, on-road measurements, and driver and vehicle rotation within the convoy during the test. Figure 50 shows this in a graphic format for a 4-vehicle convoy.

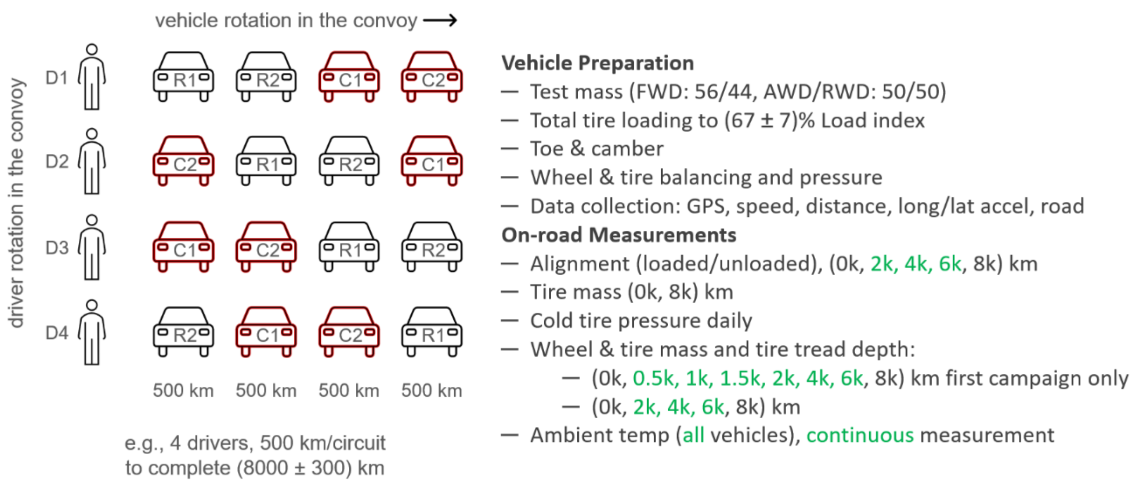


Figure 50 – nominal schedule to rotate drivers and vehicles, including vehicle management

Regarding tire wear, tread depth reduction, and service life

A 2025 study [85] led by the JRC, dives into the associations and possible correlations among tire size, design, position, and tire useful life metrics. From the study of the two main methods in practice today by the industry, the Uniform Tire Quality Grading Standards (UTQGS) method applied in the U.S. by the National Highway Traffic Safety Administration (NHTSA) [86], and the General German Automobile Club (Allgemeiner Deutscher Automobil-Club, ADAC). Compiling several studies from [87], [88], [89] based on the manufacturer's mileage warranty, tire rating, and tread wear, Figure 51 depicts the overall correlation among tire wear, ratings, and life, hinting at the feasibility of a service life index using convoy or laboratory drum tire abrasion tests. From Figure 151(a), even though the scatter is large, the trendline indicates an approximate ratio of 100:1 between the service life and the tire rating. The estimated tire service life using the wear at 15 000 km and extrapolates to the minimum thread depth of 1.6 mm in Germany. The average tire life in Europe of (40 000 ± 10 000) km, based on 50 tires is close to another study from 5000 passenger car tires [90]. Figure 52 illustrates the key tire measurements and nomenclature.

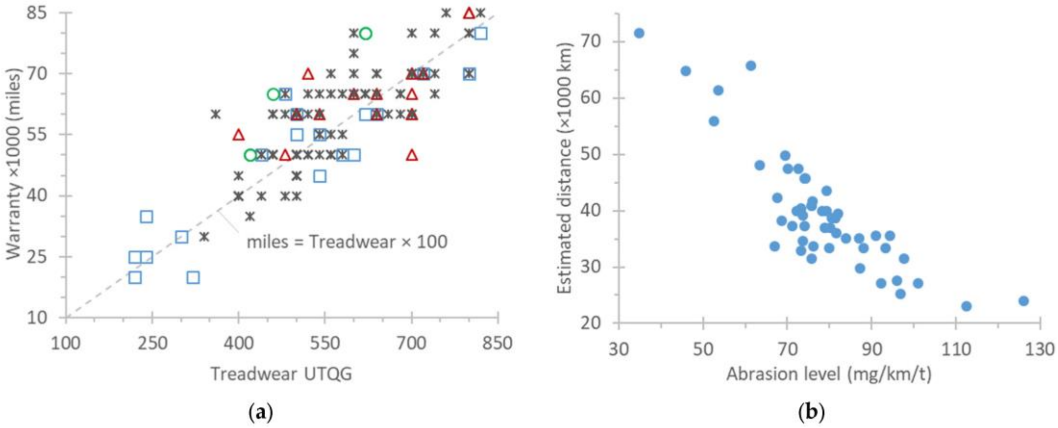


Figure 51 – Estimated tire service life (a) based on tread wear index and reported mileage warranties from tire manufacturers (green circles, blue squares, red triangles, gray asterisks from compilation (see details in actual text); (b) based on reduction in tread of 50 205/55 R16 summer tires tested by ADAC. Image from open source [85]

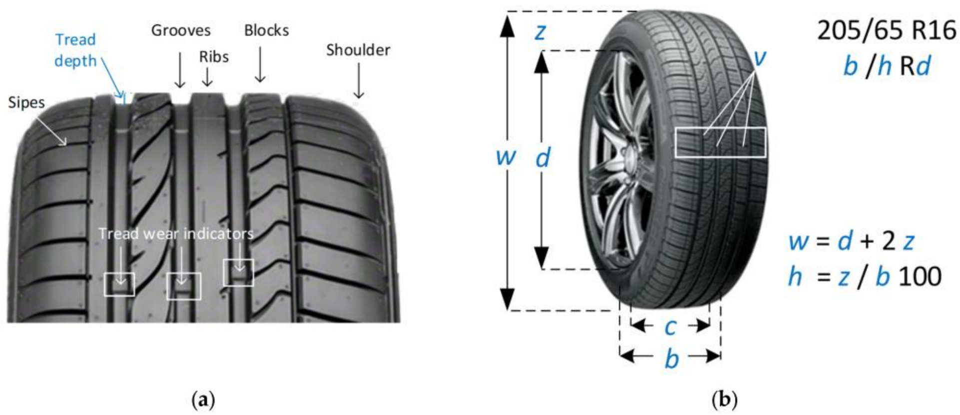


Figure 52 – Terminology and nominal dimensions of C1 tires, where 205/65 R16 is 205: Tire width in millimeters. (mm)/65: Aspect ratio (sidewall height as a percentage of width) and R16: Rim diameter in inches. The dimensions are b = Section width (mm), h = Sidewall height (mm), Rd = Nominal Rim diameter (inches), z = Likely refers to the sidewall height (mm), d = Rim diameter converted to mm, w = Overall tire diameter (mm), h = Aspect ratio (unitless percentage). Image from open source [85]

On the contribution of road vehicle tire wear to microplastics and ambient air pollution

Depending on the objective, the resources, and the logistics for a given study, tire abrasion and tire emission (microplastic release) can be measured using several methods, as explained in [18]. The predominant ones for laboratory measurements are the following:

a) Road simulators, where one or several wheels are run on real pavement materials (e.g., asphalt), either in a carousel setting as in [91] or using an inner drum setting per and shown in Figure 53 explained by [92], [93]

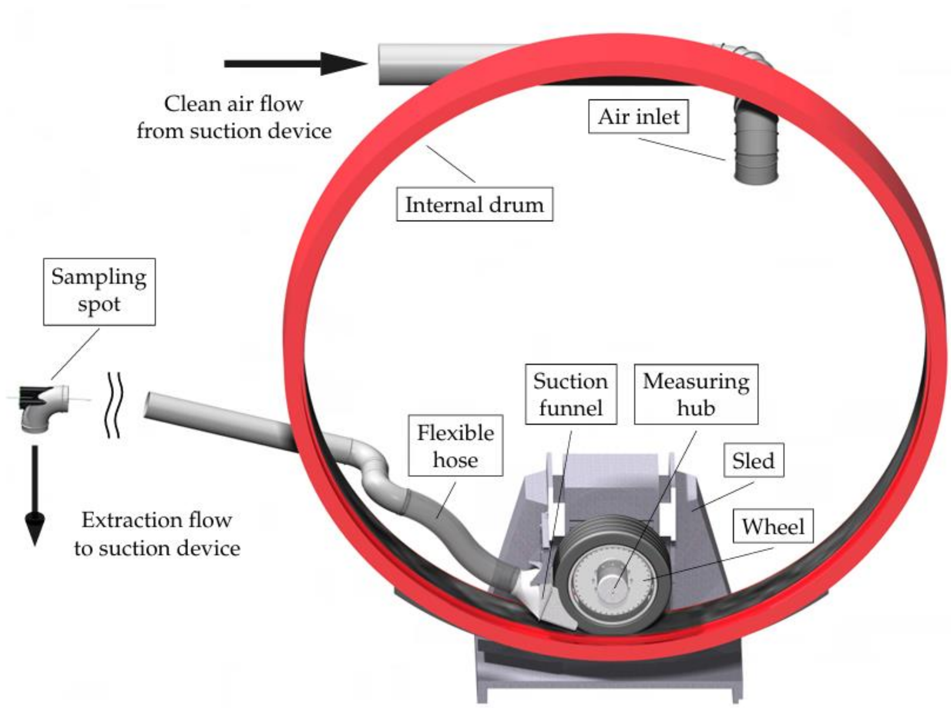


Figure 53 – CAD representation of the internal drum test bench at FAST/KIT with the components extended for measuring tire–road particulate matter. The back panel of the internal drum and the front fairing are not shown to provide better visibility of the elements. Image from open source [93]

b) Outer drum dynamometer, where one or two tires roll on the outer surface of the drum with a wearing countersurface, e.g., sandpaper. This method is the one prescribed in the current proposal for the Euro 7 tire abrasion for laboratory test method per the latest draft ECE Regulation 117 at the time of this review [8]
c) Chassis dynamometer on which the vehicle is driving per [94], [95]. Sampling is usually performed behind one tire in chassis laboratories. Alternatively, the measurement includes tire mass loss or tread depth reduction during the test

When using on-road testing and measurements, the main methods include the following:

a) On-road, near the tires, using portable devices [96], [97] [98], [99], [100], [101] or measuring the tires' mass loss (or tread depth) before and after the test. Figure 54 shows the scope of using dedicated sampling nozzles as studied by [100]

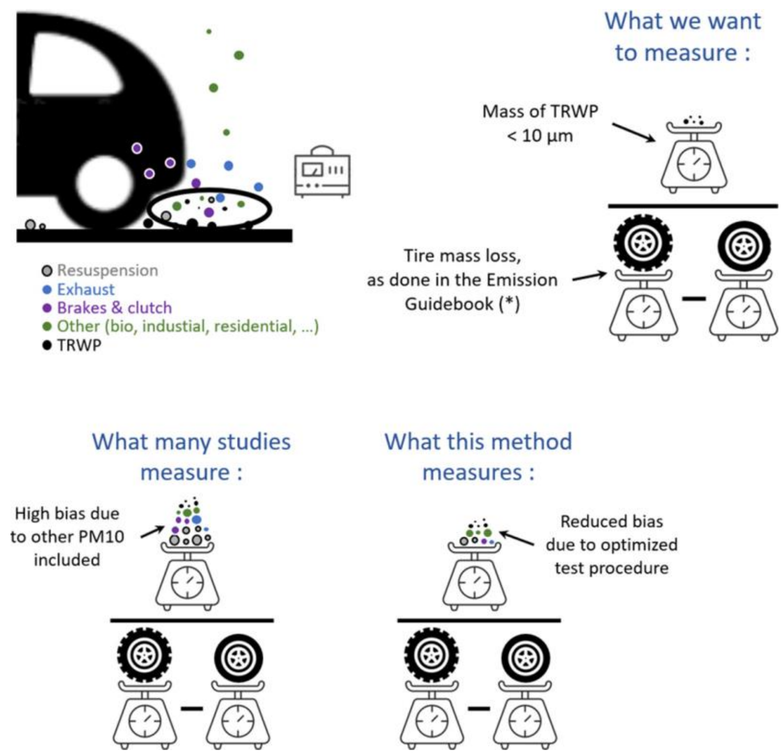


Figure 54 – Visual abstract of on-road measurement. Image from open source [100]

Figure 55 depicts a dedicated sampling nozzle with high sampling efficiency, with the geometry to reduce the bias from extracting non-tire PM during testing. The setup uses isokinetic sampling by an ELPI+ installed in the vehicle.

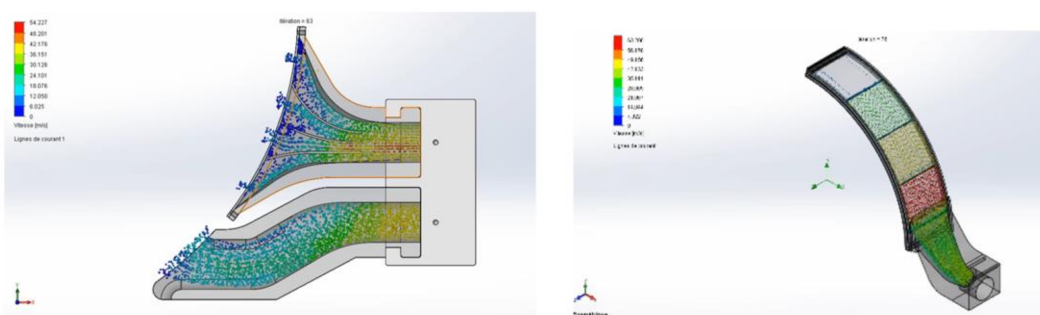


Figure 55 – Air velocity inside the second version of the nozzles. Left: lower and middle nozzles, respectively, nozzle A and B. Right: upper nozzle named nozzle C. Image from open source [100]

b) Roadside, through ambient air sampling using real-time instruments or filters via sampling and analysis [102].
c) Directly from road runoff, soil, or water samples [102], [103], [104], [105]

17.2.3 Road

One of the main aspects of characterizing road dust is the location of the measurement relative to the road or even the lane and the tire tracks. See Figure 56 for an example of sampling and analysis for road resuspension.

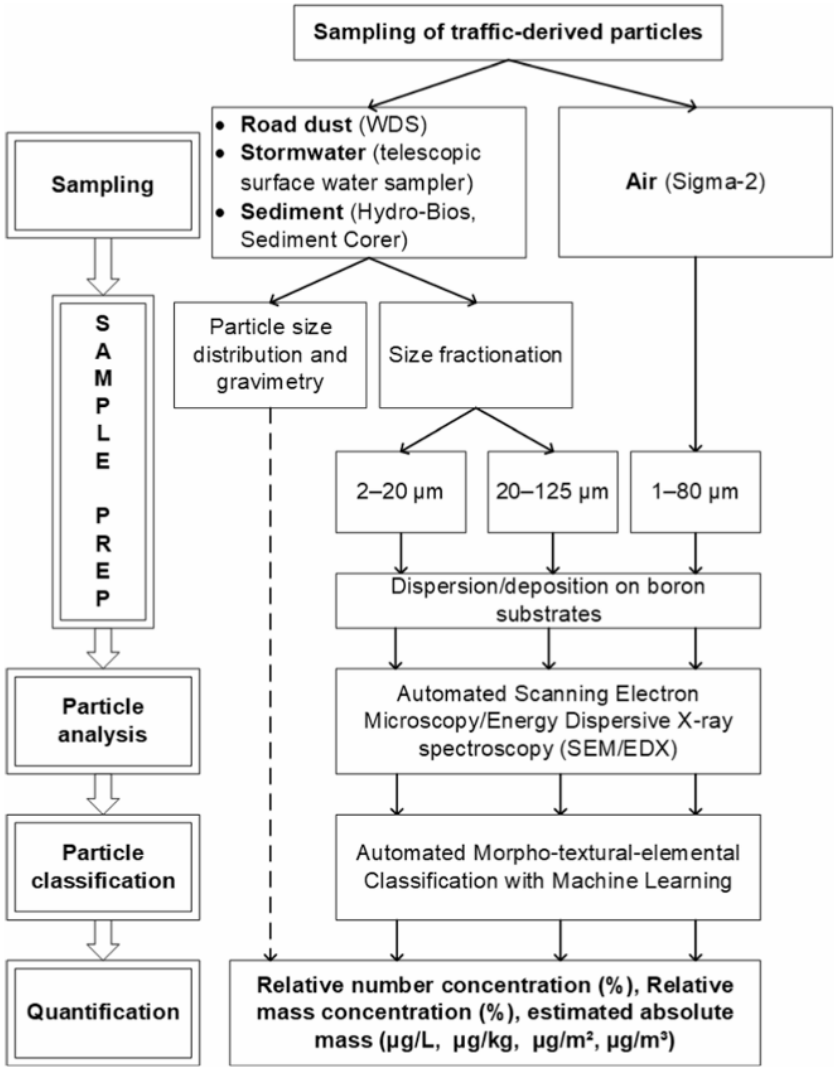


Figure 56 – Workflow for the measurement process for road particles. Image from open source [102]

17.3 Characterization of non-tailpipe PM

The highest level for characterizing non-tailpipe particulate matter is to estimate their presence (or not) in the environment. This highlights areas where traffic is a particularly prevalent source, due to the extensive and complex network of freeways, highways, and surface streets. Despite overall improvements in reducing tailpipe emissions, traffic-related air pollution (TRAP) remains an important source of near-roadway PM exposure in urban areas. [106] points to the fact that Previous studies in Los Angeles have shown that mobile vehicular sources are the largest contributors to PM mass in the quasi-ultrafine size fraction (< 0.25 µm in aerodynamic diameter).p The same study used data from the CHS 'Intra-Community Variation 2′ (ICV2) sampling campaign (Urman et al. 2014), which was conducted in Anaheim (AN), Glendora (GL), Long Beach (LB), Mira Loma (ML), Riverside (RV), San Dimas (SD), Santa Barbara (SB) and Upland (UP) (see Figure 57). These communities range from coastal areas impacted by marine vessel emissions and aerosols (SB and LB) to inland regions affected by traffic, freight, dairy farming, and secondary aerosol formation (AN, UP, GL, SD, ML, and RV). Figure 57 shows the areas of interest on a map.

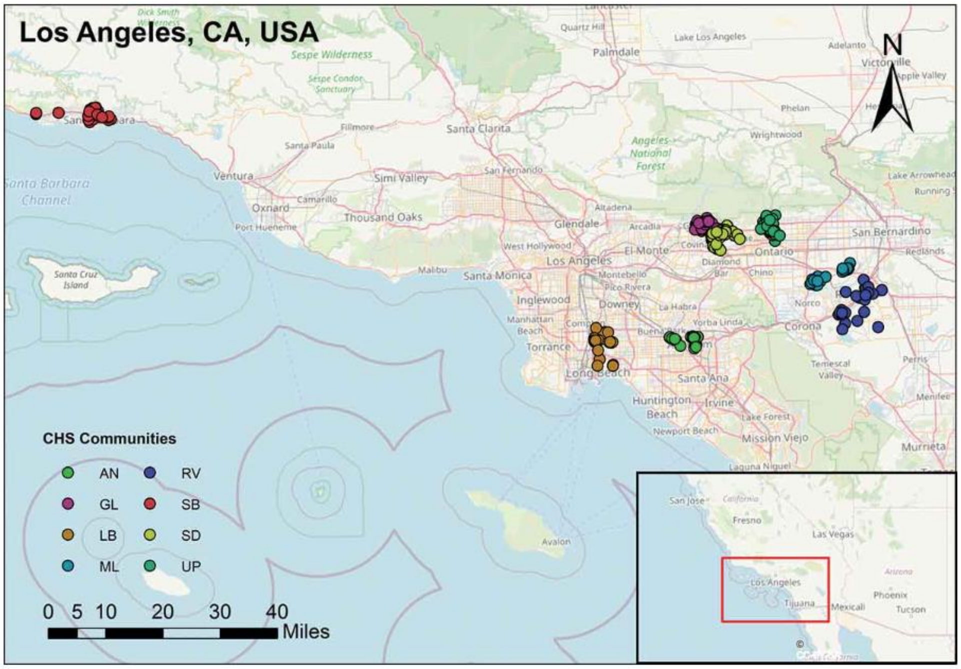


Figure 57 – Map of CHS southern California communities participating in the ICV2 sampling campaign. (AN = Anaheim, GL = Glendora, LB = Long Beach, ML = Mira Loma, RV = Riverside, SB = Santa Barbara, SD = San Dimas, UP = Upland)[12]

The study used modified Harvard Cascade Impactors (0.2, 0.5, 2.5, and 10) µm with Polyurethane foam, PTFE, or quartz filters. Additionally, a Harvard Personal Environmental Monitor (H-PEM) collected $PM_{2.5}$. The concentrations of 48 elements (both total and water-soluble) in each size fraction were determined by magnetic-sector inductively coupled plasma mass-spectroscopy (SF-ICP-MS; Thermo-Fisher Element 2), and our analysis for a subset of elements is shown on the Forest plot in Figure 58.

[12] Contribution of tailpipe and non-tailpipe traffic sources to quasi-ultrafine, fine and coarse particulate matter in southern California

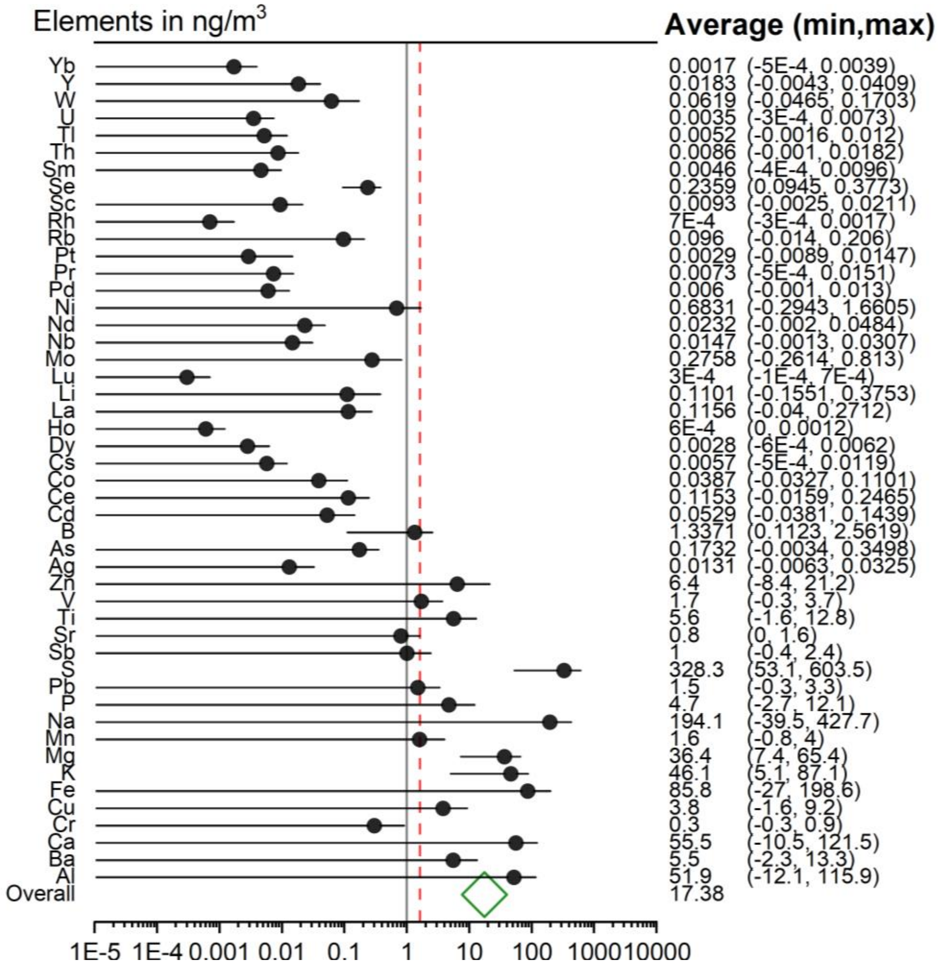


Figure 58 – Near-road chemical composition based on data collection near southern California (Los Angeles) for a subset of elements. The Forest plot uses a log scale to represent the dynamic range of concentrations measured. Negative values in the computation of confidence limits are a statistical artifact without physical meaning

The associations between environmental concentrations and non-exhaust particulate matter are discussed elsewhere and are not part of this review.

17.3.1 Brakes

Measurement of particle size distribution using CARB project with the CBDC testing

The CARB study [77] quantified vehicle levels for particle counts for all six vehicles and the different friction materials. In general, NAO materials emit fewer particles than LM, as Figure 59 illustrates.

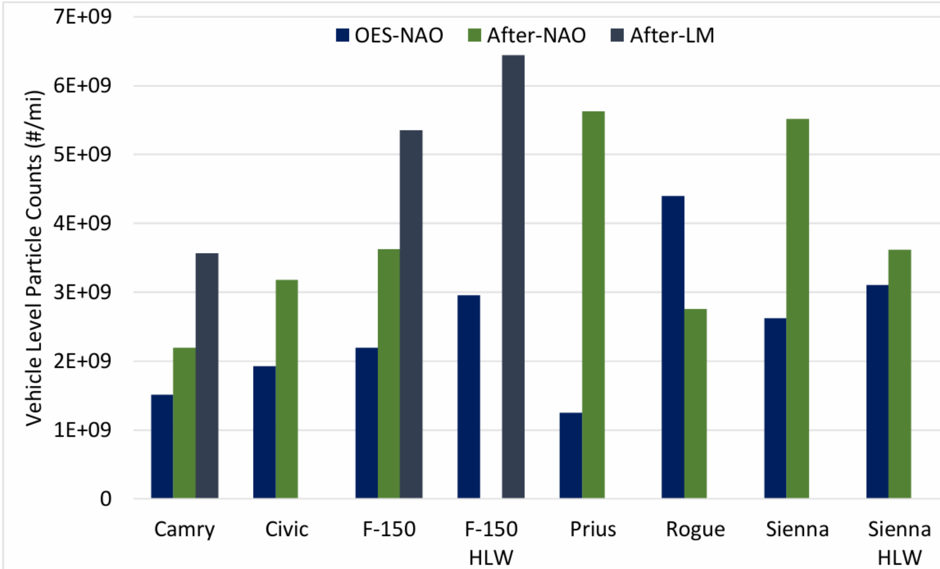


Figure 59 – Particle count for six vehicles during CARB testing

The study also quantified the PSD from over 80 tests. On the submicron range of (5.6 to 560) nm, the average distribution on the front axle for all vehicles (except the LM material on the Toyota Camry) exhibited a bimodal distribution, dominated by nucleation modes at 10-12 nm and 50-60 nm, agreeing with previous studies. Most rear axle brakes, like the front axle and the Toyota Camry, exhibited multimodal behavior, with a distinct mode at (50 to 80) nm. The EEPS results were similar across all tests, with less apparent responsiveness to the test parameters. However, results for all tests indicated a multimodal distribution in which at least one peak was present in the APS size range, and one peak was present in the EEPS size range. Size distributions are presented in graphs by vehicle and axle, and each distribution is color-coded by brake pad material. Note that all distributions in the size distribution figures are normalized to sum to 1. This is to enhance the comparability of particle size without any bias from particle number differences at the test level. Particle number is measured specifically by the CPC, so reporting absolute count was not a necessary function of the particle sizers. Figure 60 shows the normalized size distribution for the APS range (0.54 to 20) µm.

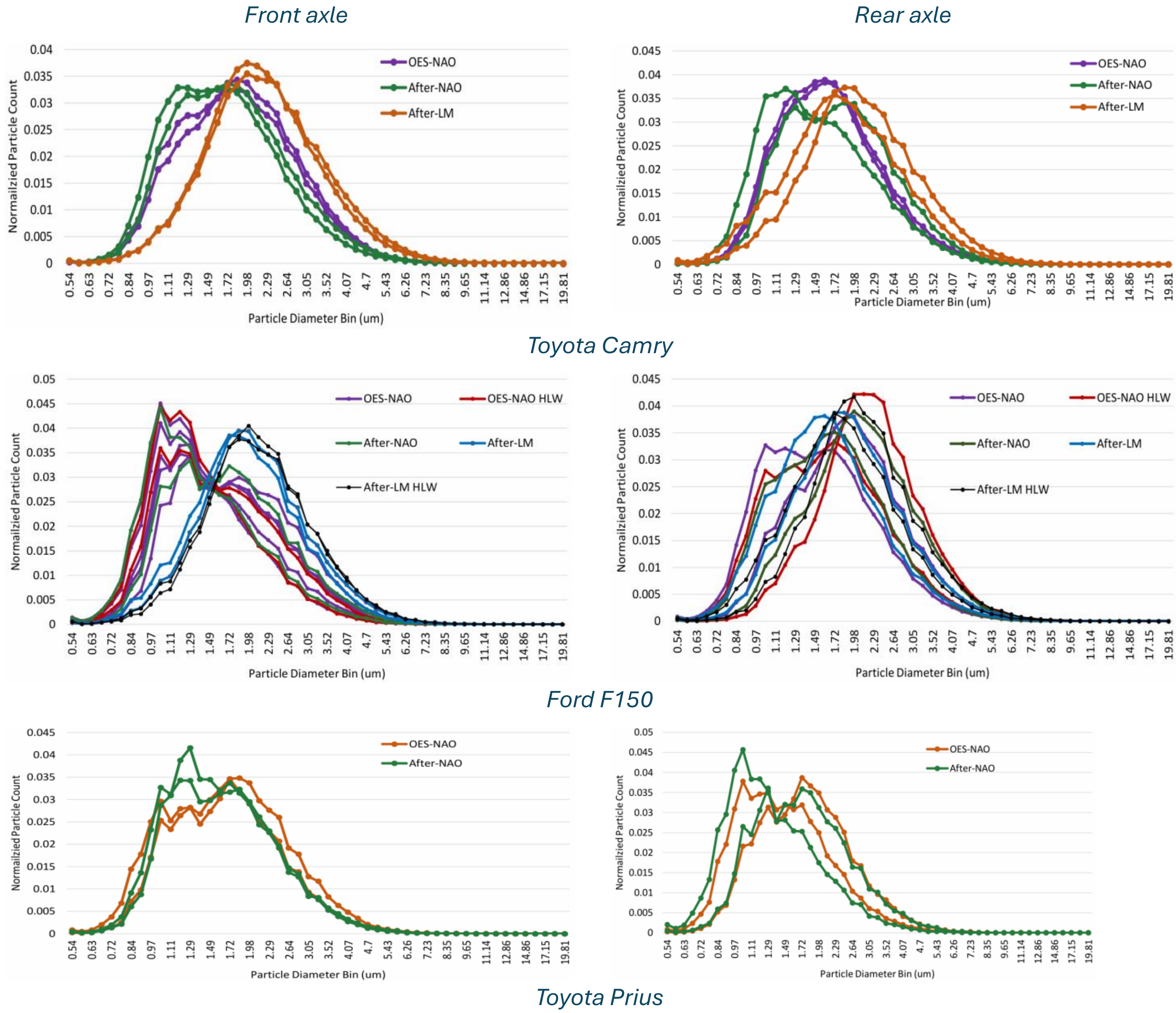


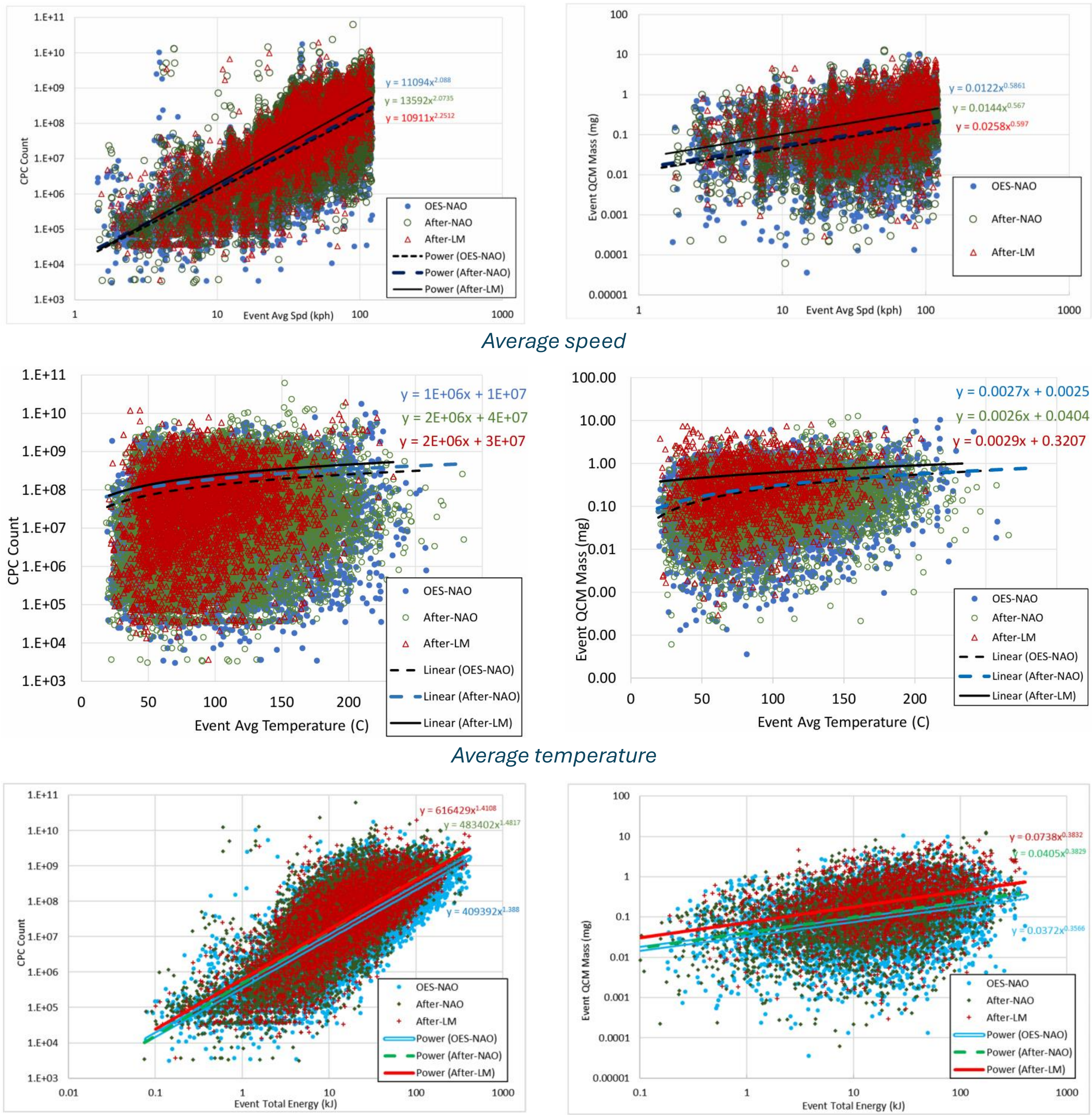
Figure 60 – Particle size distribution for three vehicles on front and rear axles and multiple friction materials

Since this project had available time-resolved (minute-by-minute) mass measurement in the range (0.42 to 2.5) µm and particle count with the CPC for total particle number with a smaller cutoff size of 23 nm. Figure 61 shows the time-resolved (accumulated for the duration of the brake event) results for CPC and QCM as a function of average speed, brake average temperature, and kinetic energy dissipated. Different from other studies [107] , the results for particle count did not exhibit the hockey stick behavior with an obvious transition temperature. This is likely due to the relatively low temperatures used in this study (primarily intended to represent normal on-road use). The gradual uptrends in these plots may also be subjected to the confounding factor that the higher-temperature events are likely to be of higher intensity (since the rotor temperature is driven primarily by braking energy). So, it isn't easy to draw meaningful conclusions about the effect of brake temperatures on on-road PM emission rates.

Particle count (CPC) *Airborne mass (QCM)*

Average speed

Average temperature



Kinetic energy

Figure 61 – Near road chemical composition based on data collection near southern California (Los Angeles) using a log-log scale

For larger particles (0.5 to 20) µm using the APS, PSD behavior was comparable among vehicles with unimodal or bimodal curves with (1 to 2) µm peaks.

This study also considered the correlation between PM_{10} in mg and total brake wear in grams. Even though there was a trend to have higher PM_{10} mass in the filter at higher total wear (friction material and disc or drum), the correlation was weak since the wear measurements included the bedding cycle. In contrast, the PM_{10} included only the emissions cycle. Figure 62 shows the non-linear relationship when considering all friction couples tested in aggregate.

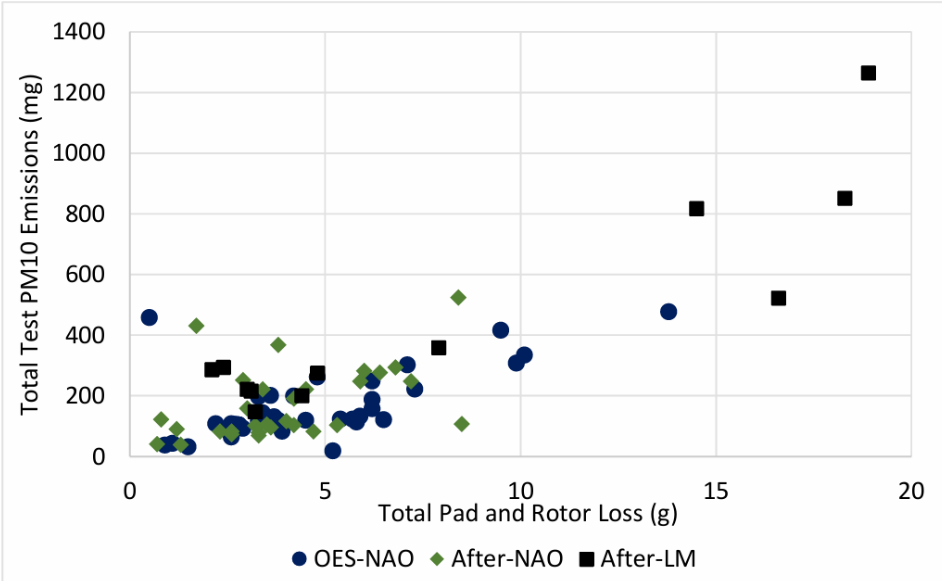


Figure 62 – Correlation graph for total brake wear vs. total test PM_{10}

It is worth mentioning two relevant nuances to the data:

- Most test cycles (also considering the GTR 24) do not allow for disrupting the assembly under testing to perform mass loss measurement on the parts; hence, the mass loss during the bedding is included
- There is no obvious correlation until the total mass loss exceeds about 10 g. In this study, the range includes all the aftermarket NAO and most OES NAO materials

Figure 63 shows the PM_{10} and mass loss for pads and rotors separately.

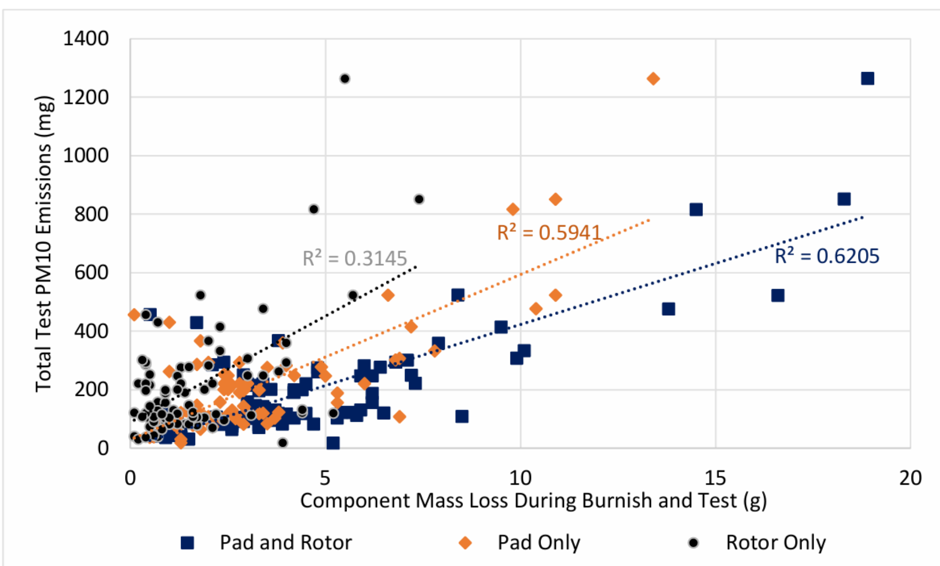


Figure 63 – Correlation between PM_{10} with each wear metric individually

Regarding the relationship between EF $PM_{2.5}$ and EF PM_{10}, this study exhibited the former EF being about 35% of the latter, with a regression R^2 of 0.94. the 0.34 factor has been confirmed by other studies using the GTR 24 cycle. Data in the appendixes of the same study shows scatter graphs for time-based particle count and particle mass as a function of brake speed, kinetic energy dissipated, braking power, and average disc temperature. An interesting study result is the correlation between total PN in #/km/B and total $PM_{2.5}$ in mg/km/B for all results. Lastly, this same study showed a linear increase (in the log-log scale) in PN as a function of $PM_{2.5}$, with a minimum level of 6 x 10^6 #/km/B for the Toyota Prius.

Measurement of particle size distribution, time-resolved particle count, and total mass using Caltrans testing

The heavy-duty study [16], which used the same instrument cluster as the light-duty study, measured particle size distributions between 5.6 nm and 20 µm using a TSI EEPS and an APS, respectively. Figure 64 shows an example from the urban bus test cycle.

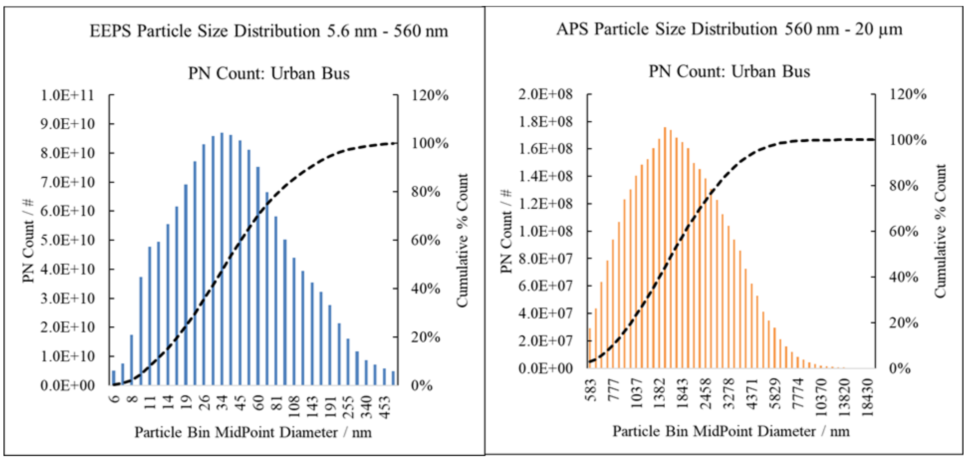


Figure 64 – Particle size distribution for EEPS and APS

Another application of the real-time particle count (TPN23) and particle mass ($PM_{2.5}$) enabled the study to quantify the relationship between these measurements and rotor temperature, kinetic energy, and vehicle speed. Figure 65 depicts an example of the urban bus application.

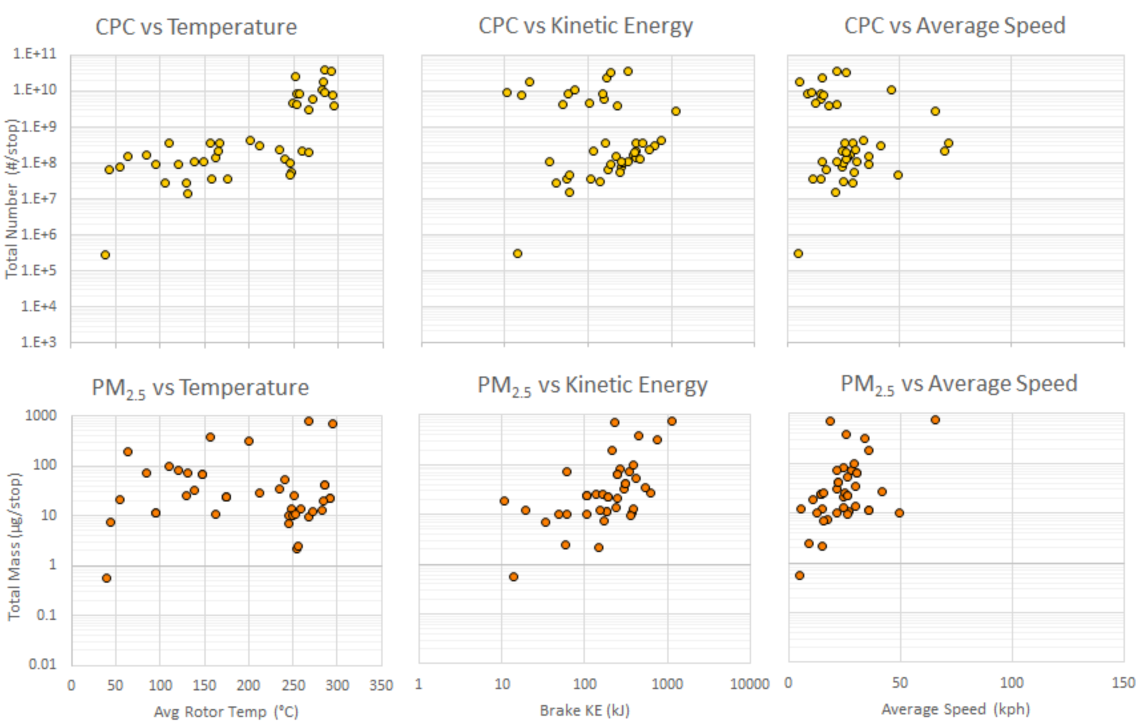


Figure 65 – Time-based mass and particle number vs. brake temperature, kinetic energy, and brake speed

Trace metals and chemical composition of brake wear particulate matter from light-duty vehicles from CARB

One particular study [108] assessed in detail the metal composition of the vehicle applications and friction formulations, using the filter media collected during brake dynamometer tests using the CBDC under the CARB project 17RD016. Figure 66, Figure 67, and Figure 68 depict the data in three dimensions—speciation comparison for brake pad type, axle, and braking system (powertrain).

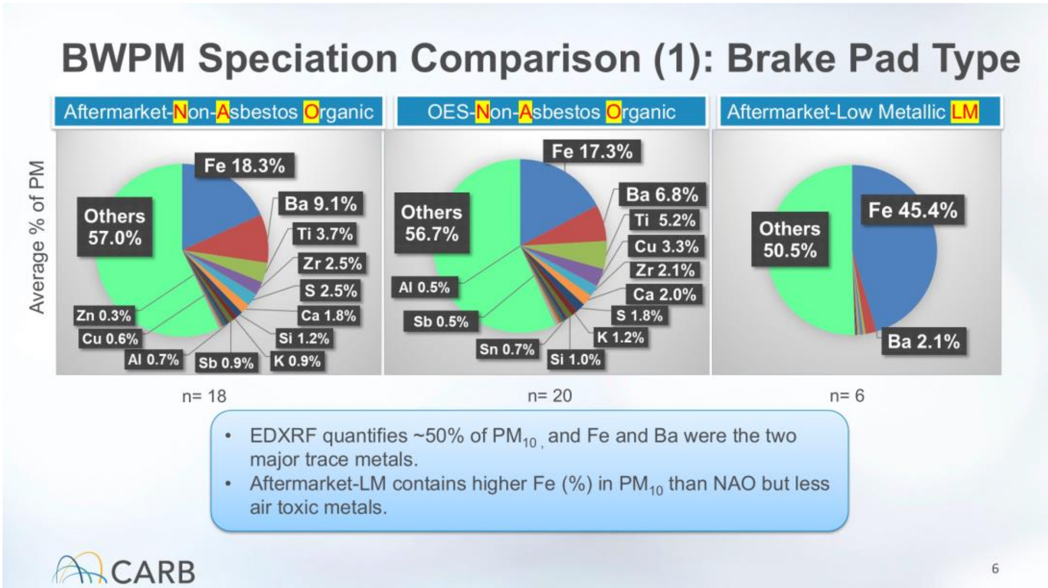


Figure 66 – Chemical composition by brake type

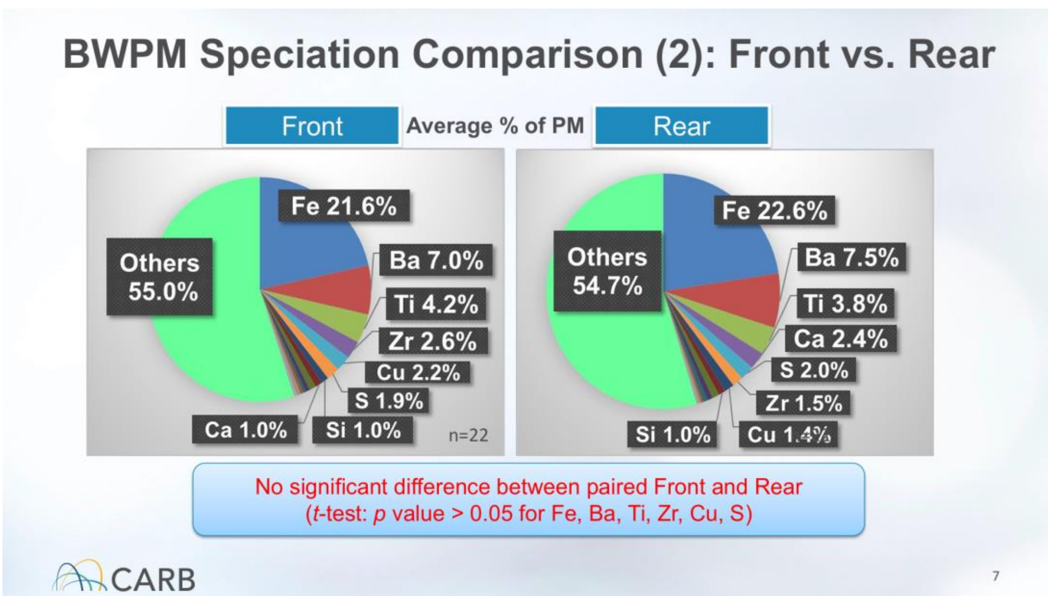


Figure 67 – Chemical composition by axle position

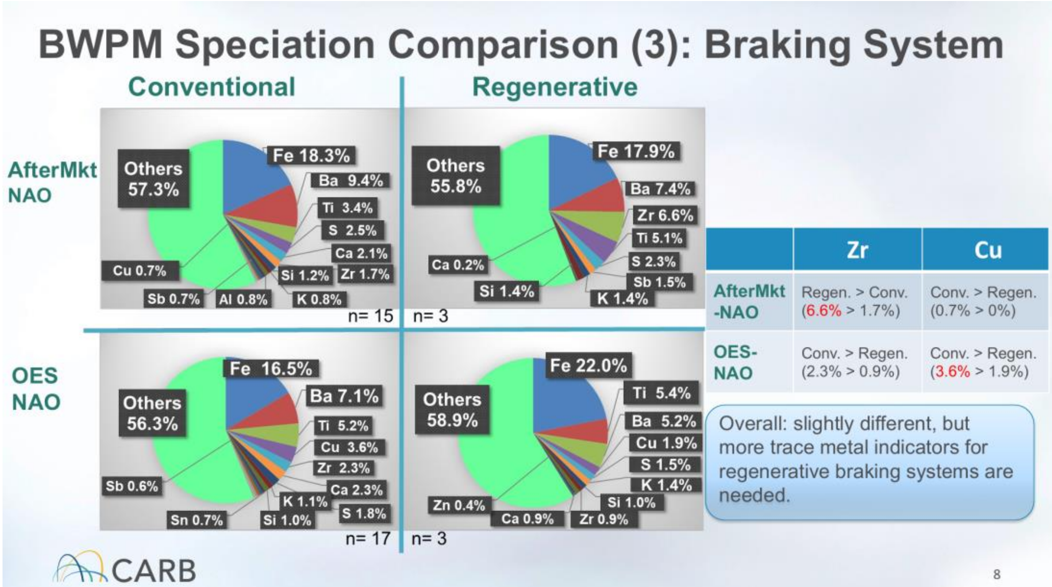


Figure 68 – Chemical composition by powertrain type

The main conclusions from this study include the following:

- EDXRF accounts for ~50% of PM_{10}; Fe and Ba are the two major trace metals; water-soluble ions are negligible in BWPM
- LM vs. NAO: Low Metallic contains higher Fe (%) in PM_{10} than Non-Asbestos Organic
- No significant differences were observed: OES-NAO vs. AfterMkt-NAO / Front vs. Rear
- Regenerative braking with AfterMkt-NAO contains higher Zr (6.6%) than conventional braking.
- Emission rate:
  - AfterMkt-LM: high emission rate is mainly due to Fe contribution
  - Weak or moderate correlation between trace metal emissions and pad/rotor temperature
- Considering metallic elements are present in form of oxides in BWPM, the possible OM + EC + other compounds contribute 29-45% to total PM_{10}, improving the PM mass balance closure.
- Propose a reconstructed PM mass for LD brake wear, adjusting the coefficients for iron, barium, zirconium, silicon, titanium, and calcium.

Chemical composition for brakes tested under WLTP-B according to GTR 24

Table 21 indicates the chemical composition of multiple studies at various facilities, all adhering to different levels of compliance with the GTR 24, and all using the WLTP-B cycle for testing.

Table 21 – Elemental components of the pad friction surface, measured after testing according to GTR 24

Year	Source	Pad	Percent by weight – wt%								
			C	Fe	Ca	Zn	Cu	Cr	Ti	Mo	Mg
2023	[109]	NAO	34	5.8	0.8		1.6		5.3		3.5
2023	[109]	ECE	44.2	8.3	0.6		2.1		0.1	0.8	2.2
2024	[54]	LM		23.9		5.57	0.5	0.37			4.12
2024	[54]	NAO		13.9		0.05	0.01	0.04			9.62
2021	[110]	LM	12	11.2	9.2	9.43	7.4	2.51		13.9	2.66
2021	[110]	LM	43.6	13.6	0.55	4.55	4.14				1.14
2021	[110]	LM	24	13.64	1	414	5.3	0.89		0.77	2.65
2021	[110]	NAO	19.9	7.74	4.55	0.721			7.56	2.18	1.4
2021	[110]	NAO	17.8	5.07	3.51				5.48		0.96
2021	[110]	NAO	14.5	5.11	2.77	1.97	1.2		8.21		0.63
2024	[36]	NAO	24.5	1.1	6.7	0.03	1.9				0.2

Year	Source	Pad	Percent by weight – wt%								
			C	Fe	Ca	Zn	Cu	Cr	Ti	Mo	Mg
2024	[36]	NAO	31.5	2.7	4.6	0.2	0.002				1
2024	[36]	NAO	26.2	4.5	2.4	1.4	0.002				0.9
2024	[36]	NAO	31.6	0.1	3	1.1	0.005				2
2024	[36]	NAO	30.1	4.8	2.8	0.05	0.7				0.5
2024	[36]	NAO	31.5	2.7	4.6	0.2	0.002				1
2024	[36]	LM	40.8	7.4	0.2	1.9	3.1				3.7
2024	[36]	NAO	27.4	1.1	1.7	0.02	1.9				2.3
2024	[36]	LM	42.5	7.3	0.4	0.01	0.02				6.1
2024	[36]	LM	44.6	9.4	0.7	1.2	0.008				7.4
2024	[36]	NAO	34.7	6.6	0.9		1.8				2.7
2024	[36]	LM	40.8	7.4	0.2	1.9	3.1				3.7
2024	[36]	NAO	27.4	1.1	4.6	0.02	1.8				2.3

Table 21 – continued

Year	Source	Pad	Percent by weight – wt%								
			Mn	Si	Ba	Al	Sn	S	Ni	V	Na
2023	[109]	NAO	0.1	3.2	3.2	1.1		0.8			
2023	[109]	ECE	0.1	4.1	1.5	1.8	0.4	2.6	0.1		
2024	[54]	LM	0.1		1.59	0.48	2.86	2.84	0.02	0.01	
2024	[54]	NAO	0.07		0.02	1.56	0.19	2.31	0.01	0.03	
2021	[110]	LM		2.4	1.87	2.28		2.96			
2021	[110]	LM		9.96		0.92	0.41	0.4			
2021	[110]	LM		15.8		3.25	2.55	1.64			
2021	[110]	NAO		4.53	7.17	1.67	1.88	3.16			
2021	[110]	NAO		9.26	9.14	1.96	2.26	2.79			
2021	[110]	NAO		3.59	12.5	1.85		4.21			
2024	[36]	NAO	0.05	3.7	4.2	0.6		1.3			0.2
2024	[36]	NAO	0.09	2.3	3.6	0.6		1.5			1
2024	[36]	NAO	0.04	2.7	5.5	1.3		1.4			0.09
2024	[36]	NAO	0.01	1.3	7.4	0.3		2.3			2
2024	[36]	NAO	0.06	2.8	5.6	0.8		1.5			0.5
2024	[36]	NAO	0.09	2.3	3.6	0.6		1.5			1
2024	[36]	LM	0.05	2.1		4.5		1.6			
2024	[36]	NAO	0.01	3.1	4.5	0.7		1.5			
2024	[36]	LM	0.07	3.7	2.5	0.6		1.7			
2024	[36]	LM	0.06	1.1		2.9		0.9			
2024	[36]	NAO	0.05	2.9	4	2.9		1.2			
2024	[36]	LM	0.05	2.1		2.1		1.6			
2024	[36]	NAO	0.01	3.1	4.5	3.1		1.5			

Industry-sponsored research in Japan [36] conducted an extensive test plan with 31 tests in total, with a significant effort dedicated to understanding the correlation between brake wear, disc wear, emission factors, and chemical composition. Previous studies have tested small pieces based on the intended material formulation or compared a limited sample of commercially available brake types. This study is based on actual vehicle specifications for a commercial brake assembly and a medium sample size (31 cases). One important output from this study is the correlation between individual elements in the friction couple with brake wear (disc + pads), PM_{10}, $PM_{2.5}$, and $PM_{0.12}$ for nanoparticles. Figure 69 shows the trendline for eight elements: C, Mg, Cr, and Fe, which exhibited high positive correlation coefficients, and O, K, Ti, and Ba, exhibiting high negative ones. $PM_{0.12}$ had no apparent correlations, requiring further research to analyze the detailed properties of the materials, such as heat resistance.

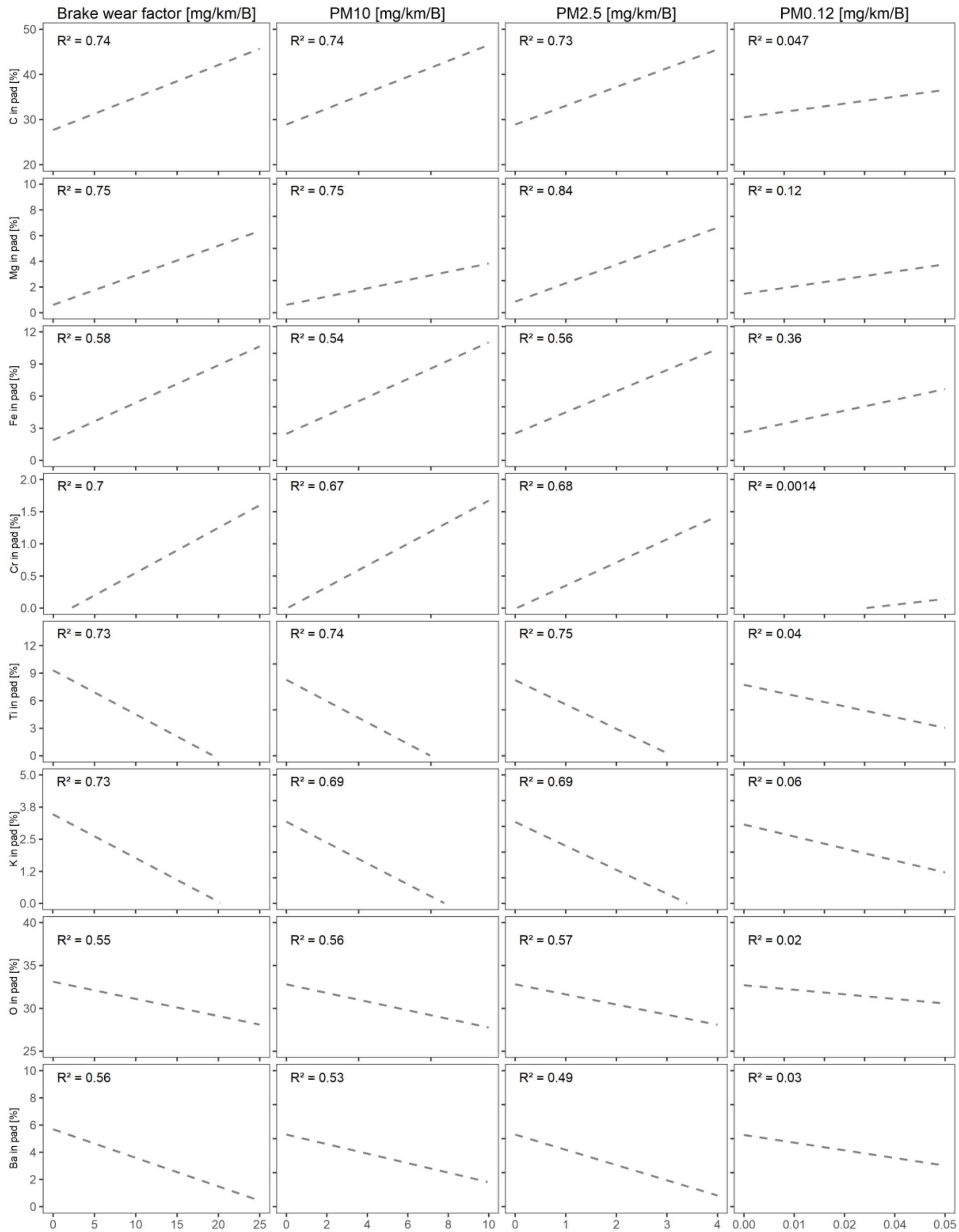


Figure 69 – Simplified representation of the trendline and coefficient of determination R^2 for linear regression of eight elements. C = Carbon, Mg = Magnesium, Fe = Iron, Cr = Chromium, Ti = Titanium, K = Potassium, O = Oxygen, and Ba = Barium. Data processed from open source [36]

Statistically, it is also relevant to consider Pearson's *r* correlation coefficient to measure the linear relationship between two continuous variables. Pearson's *r* varies from -1 (for variables with perfect negative correlation) to + 1 (for variables with perfect positive correlation). Table 22 shows the results from the study [36] ranked in descending order of Pearson's *r* coefficient for PM_{10}, with the ranking performed by the authors.

Table 22 – Ranking of Pearson's r correlation coefficient

Element	Pearson's *r* correlation coefficient			
	Brake wear factor [mg/km/B]	PM_{10} [mg/km/B]	$PM_{2.5}$ [mg/km/B]	$PM_{0.12}$ [mg/km/B]
C - Carbon	++++	++++	++++	+
Mg - Magnesium	++++	++++	++++	+
Cr - Chromium	++++	++++	+++	+
Fe - Iron	+++	+++	+++	+
P - Phosphorus	+++	+++	+++	+
Ni Nickel	++	++	++	+
Al Aluminum	++	++	+	-
Si - Silicon	++	++	++	+
Hf - Hafnium	+	+	+	+
Cl - Chlorine	++	+	+	-
Zn - Zinc	+	+	+	+
Cu - Copper	+	+	+	-
Mo - Molybdenum	+	+	+	-
Mn - Manganese	+	+	+	+
S - Sulfur	+	+	-	-
Sn - tin	-	-	-	+
Sb - Antimony	-	-	-	+
F - Fluorine	-	-	-	-
Sr - Strontium	--	--	-	-
Zr - Zirconium	--	--	--	-
Na - Sodium	---	---	--	-
Ca - Calcium	---	---	---	-
Ba - Barium	---	---	---	-
O - Oxygen	---	---	---	-
K - Potassium	----	----	---	-
Ti - Titanium	----	----	---	-

Pearson's *r* correlation coefficient ranked in descending order for PM_{10}. The (+) and (−) signs indicate the interval for the *r* coefficient: (++++) for the *r* interval of [0.8, 1]; (+++) for the *r* interval of [0.6, 0.8]; (++) for the *r* interval of [0.4, 0.6]; (++) for the *r* interval of [0.2, 0.4]; (+) for the *r* interval of [0, 0.2]; (−) for the *r* interval [−0.2, 0]; (− −) for the *r* interval [−0.4, −0.2]; (− − −) for the *r* interval [−0.4, −0.6]; (− − −) for the *r* interval [−0.6, −0.8]; and (− − − −) for the *r* interval [−0.8, −1]

The same study analyzed the particle size distribution from 31 tests, detecting a large variation among samples after normalizing the data and considering the accumulation ratio. In this study, the peak concentration occurred at around 2.5 µm, which may require further investigation. See Figure 70.

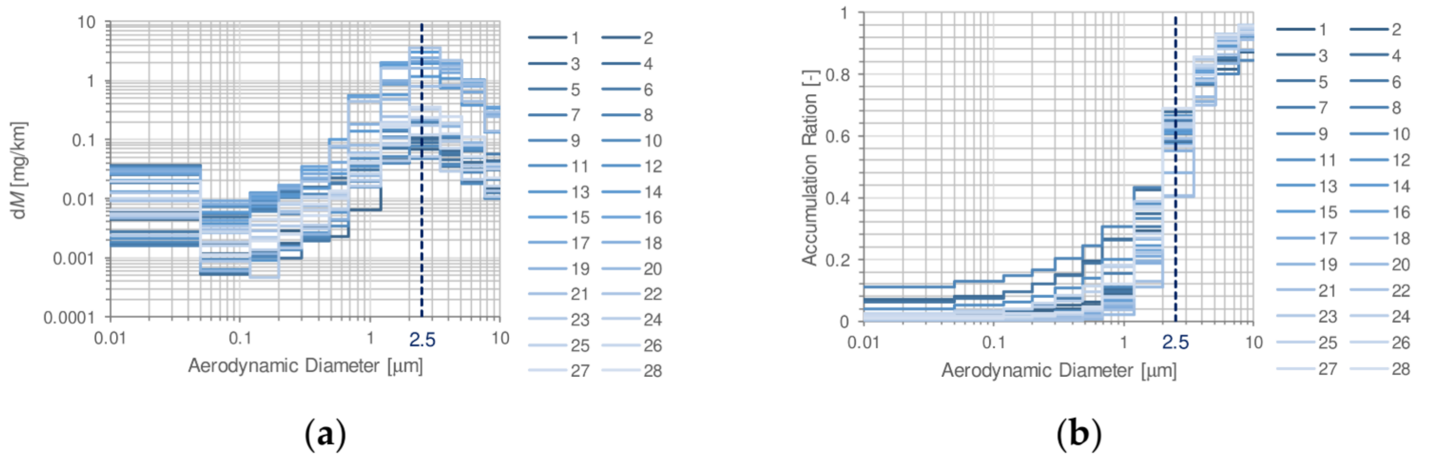


Figure 70 – (a) Emissions mass of brake wear particles and (b) accumulation ratio versus size of aerodynamic particles. Note: Experimental numbers are shown in the legends. Image from open source [36]

Advanced chemical analysis for volatile and semi-volatile organic compounds

Using environmental science technologies in at least one study [84], [111] reports organic compounds from friction brakes with samples obtained during brake dynamometer testing. Figure 71 shows a data visualization from the same study for several compounds found in ceramic and semi-metallic brakes.

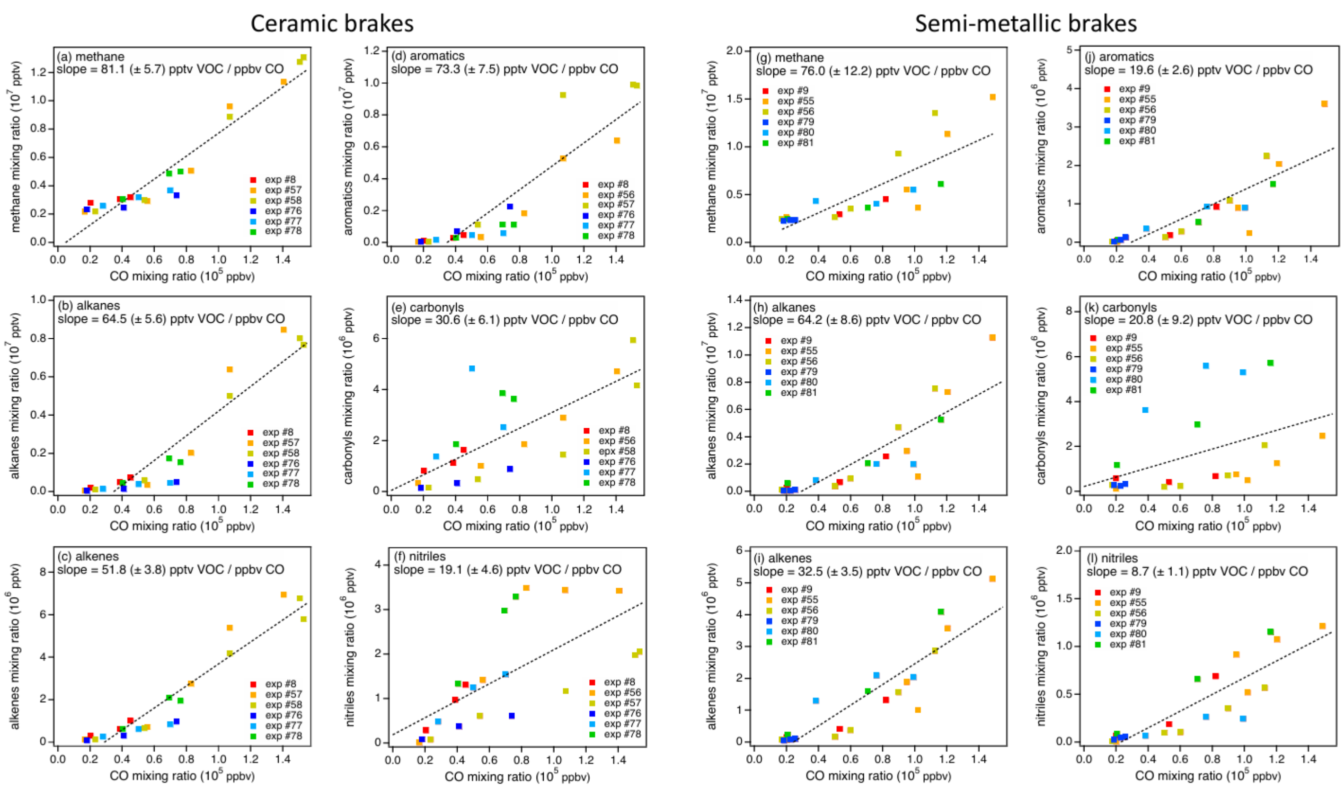


Figure 71– Typical plots of VOC concentration versus CO concentration. The VOCs were classified into 13 chemical categories. Note that the alkane category does not include CH4, but methane is plotted separately (graphs (a) and (g)). Graphs (a-f) correspond to ceramic brakes, while graphs (g-l) are for semi-metallic brakes. A different color represents all six experiments per brake type. The slope of these plots is defined as the chemical family's emission ratio (ER). Image from open source [106], available as Supplementary Information online

Another study [54] conducted a comparative and comprehensive analysis of elemental, organic compounds, and morphology on two brake pads using the GTR 24 test method. The emission factors for PM were consistent with those of other studies and the ILS3 reports. Figure 72, Figure 73, and Figure 74 illustrate heavy metal emission factors, chemical mapping of the brake pad friction surface, and micrographs of two types of particles, respectively.

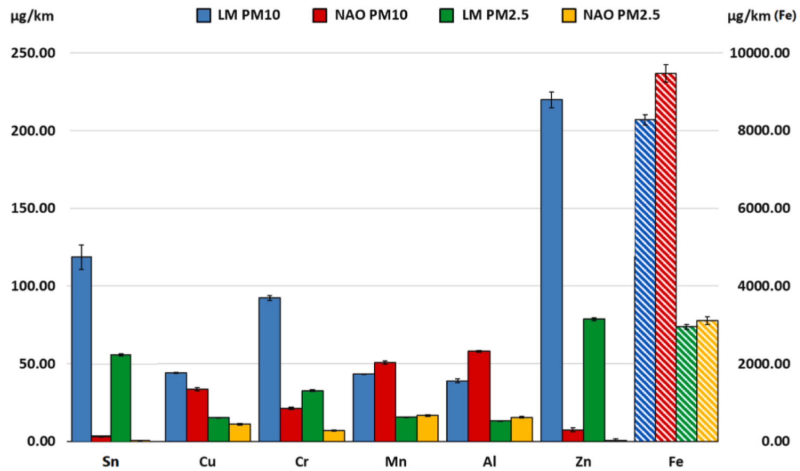


Figure 72 – Heavy metal emission factors at the vehicle level. Hatched bars for iron levels are plotted on the right Y-axis, while solid bars are plotted on the left Y-axis. Image from open source [54]

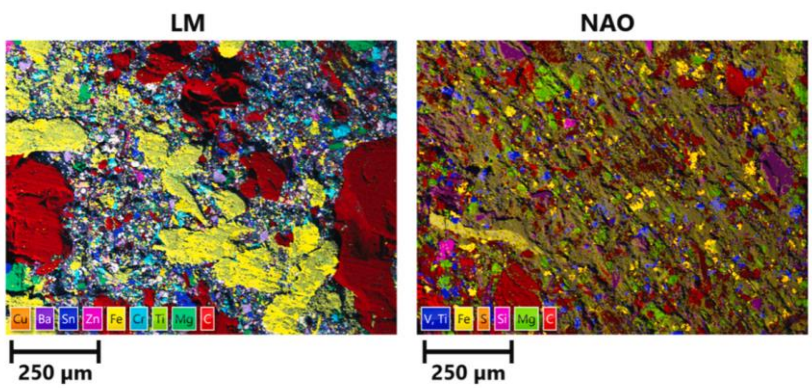


Figure 73 – Chemical mapping of bulk brake pad linings at 100X magnification measured via SEM/EDX. Image from open source [54]

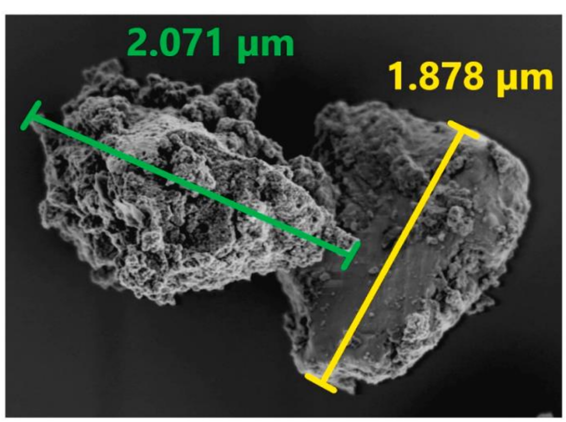


Figure 74 – SEM micrograph of spherical (green) and flake-like (yellow) shaped particles commonly found in brake-wear samples. The particles shown originated from the LM brake pad. Image from open source [54]

Volatile and semi-volatile organic compounds in friction materials

Another field of study that provides more insight into the chemical composition and associations with nanoparticles is measuring (using full brake corner assemblies) organic compounds [84]. Figure 75 shows the relative fraction of selected compounds under two common friction formulations, both in use in the United States.

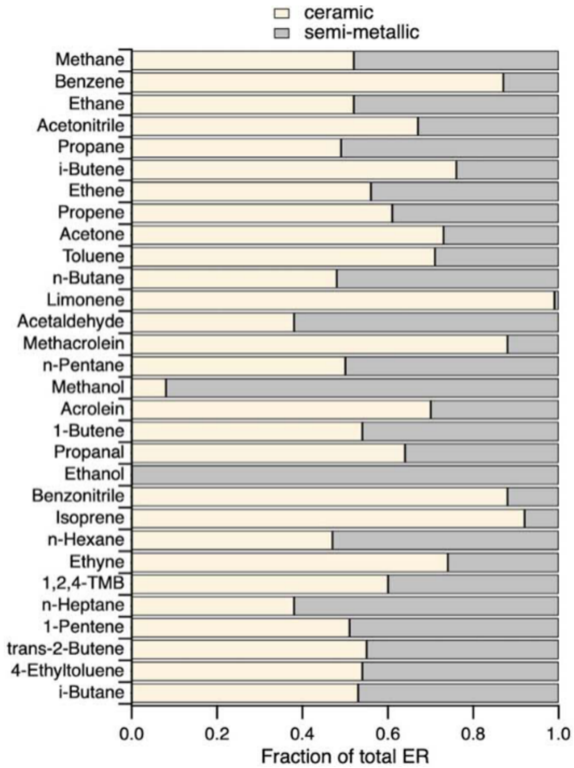


Figure 75 – comparison between brake types. Image from open source [84]

A second study [112] investigated gaseous emissions from brake wear forming secondary particulate matter using a pin-on-disc tribometer in combination with an oxidation flow reactor. The photoxidation of gaseous brake wear emissions can lead to formation of secondary particulate matter, and amplify the environmental effects of brake wear emissions. Figure 76 shows the experimental setup.

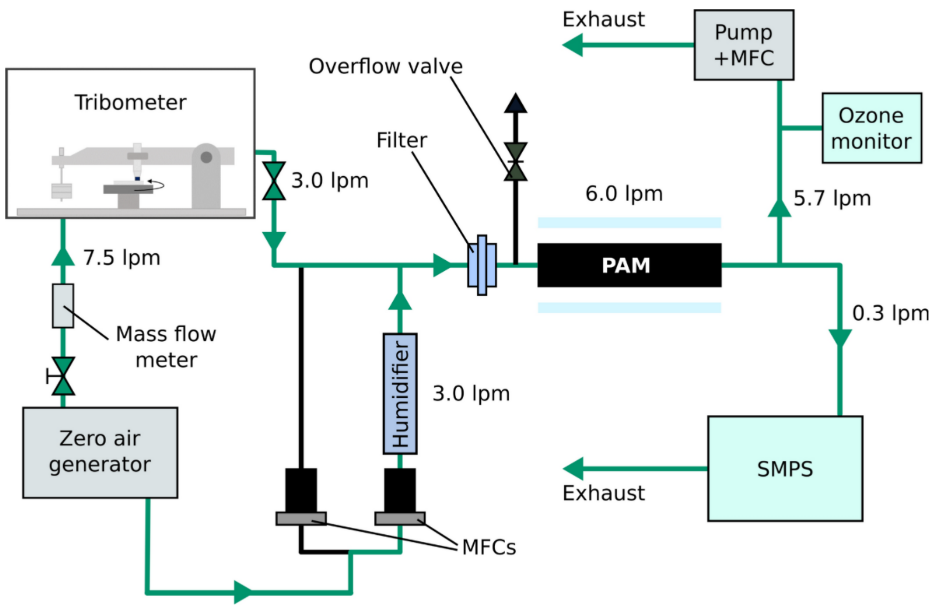


Figure 76 – Experimental setup to generate freshly emitted organic gases and a system (PAM + SMPS) for aging and measuring particle formation. Image from open source [112]

Electrical charge of brake particles

Studies to better understand the physicochemical properties of brake wear particles (BWPs) investigate the electrical properties of BWPs emitted from ceramic and semi-metallic brake pads [113]. Their study shows that up to 80% of BWPs emitted have an electrical charge (positive and negative) and that this fraction strongly depends on the specific brake pad material used. We find that brake wear produces positively and negatively charged particles that can hold over 30 elementary charges and show evidence that more negative charges are produced than positive. Our results will provide insights into the currently limited understanding of BWPs and their charging mechanisms. This behavior (electric charge) may help explain particle transport inside sampling systems, atmospheric lifetimes, and thus their relevance to climate and air quality. Figure 77 shows the nanoparticle size distribution, brake temperature, and torque during a 30-minute test. Figure 78 shows the electrically charged fraction and the corresponding electrical mobility.

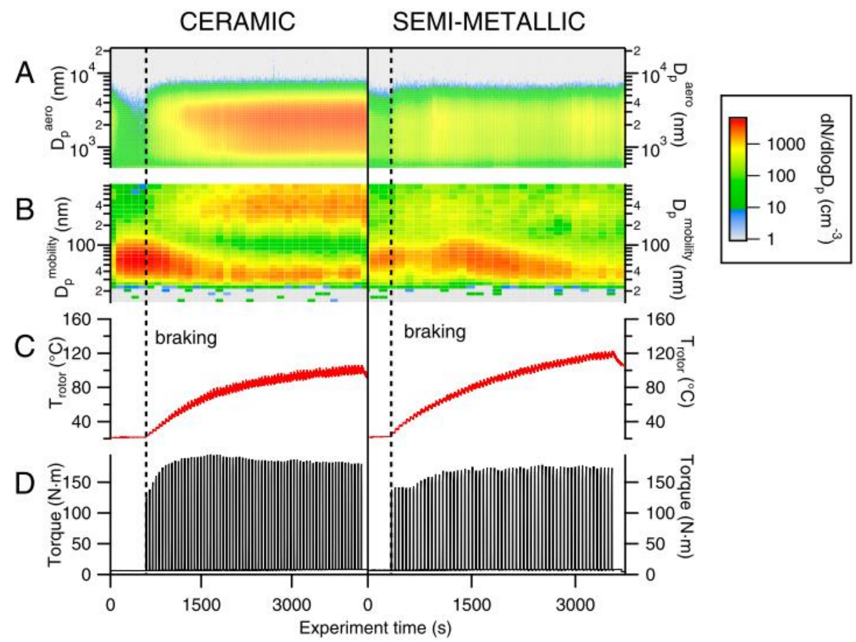


Figure 77 – Dynamometer braking conditions and BWP size distributions during ceramic (Left) and semi-metallic (Right) brake pads experiments. BWP size distributions were collected from (A) an APS, measuring over the aerodynamic diameter range (D_p^{aero}) of (500 to 22 000) nm and (B) from an SMPS, measuring over the electrical mobility diameter range ($D_p^{mobility}$) of (10 to 900) nm. Braking state variables (C) brake rotor temperature and (D) braking torque. Caption and image from open source [113]

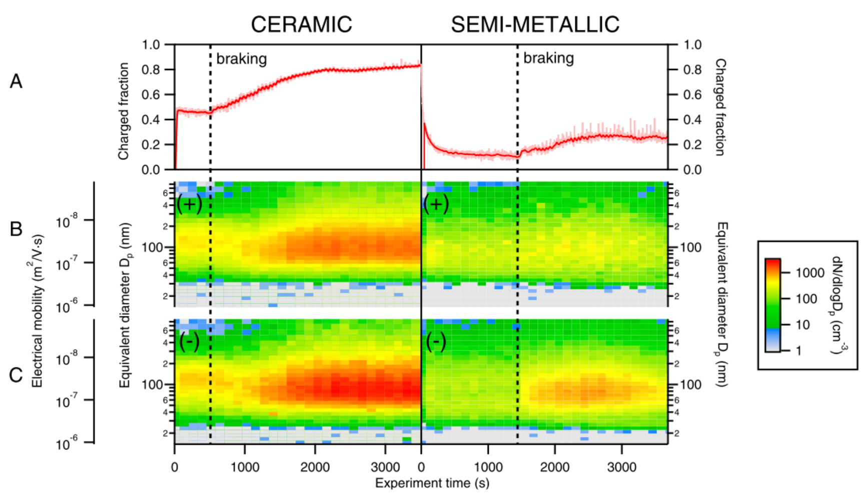


Figure 78 – (A) Charged particle fractions for experiments with ceramic (Left) and semi-metallic (Right) brake pads. Charged particle fractions shown in red are smoothed data, while the variation in the raw data is shown in a lighter shade. The delimited lines mark the initiation of braking. (B and C) SMPS electrical mobility distributions of (B) positive, and (C) negative BWPs for both brake types. Caption and image from open source [113]

Particulate metals using portable devices (TARTA)

To complete the assessment of the main dimensions needed to characterize a friction couple (or tire), it is important to determine the association of environmental measurements with the chemical composition of brake (and tires). One study [114] used a spark-induced breakdown spectroscopy technique to detect (in ng/m³) the concentrations of Al, Be, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Ni, Pb, V, and Zn. The system is portable, compact, and allows unattended or remote-control operation. The device is low-cost, and several devices can be deployed for ambient air measurement campaigns.

17.3.2 Tires

On the contribution of road vehicle tire wear to microplastics and ambient air pollution

A recent review [18] reports a peak particle mass size distribution at around (20 to 100) nm, with a second peak in the (2 to 10) µm range. Some studies have reported a nucleation mode. It is known that tire size, composition, pattern, vehicle application, axle position, road characteristics, environmental conditions, and driving style influence abrasion levels. The same study provides a tabulation of estimated chemical composition as reported in the literature. Data on tire composition is neither recent nor readily available. Table 23 presents, from the same study, an excerpt for C1 and C3 tires for Japan from 2012 data.

Table 23 – Composition of selected tires

Compound	Ingredients	C1 tire (195/65R15, 8.5 kg)	C3 tire (275/80R22.5, 55.5 kg)
Rubber / Elastomer	Natural rubber	20–23 %	37–39 %
	Synthetic rubber	26–31 %	10–11 %
Fillers	Carbon black	20–25 %	23–25 %
	Silica	1–8 %	0–1 %
	Others	n/a	n/a
Process oils	Mineral oils	4–5 %	1 %
Vulcanization agents	ZnO	2 %	2 %
	Sulfur	1–2 %	1 %
	Others	n/a	n/a
Additives	Preservatives, antioxidants, etc.	n/a	n/a
Reinforcement agents	Textile fibers	4–5 %	0 %
	Steel wire	11–12 %	21–22 %

Some highlights reported in [18] related to chemistry, morphology, and density include the following:

- The size distribution of tire wear particles spans a wide range of sizes [58], [115] with a bimodal distribution typical
- Typically, based on road samples, the mass distribution peaks at (10 to 200) µm, mostly (50 to 100) µm
- In the airborne sub-20 µm range, a (2 to 10) µm peak was also found in laboratory studies
- In a few cases, a nucleation mode in the (10 to 50) nm range is measured due to localized high-temperature hot spots on the tire tread, which is not rare
- PN emissions from one tire, measured on the chassis dynamometer, were 3.3 × 109 #/km/tire and ~0.6 × 10^9 #/km/tire with hot sampling, exemplifying a strong contribution of volatile particles. The ultrafine size distribution had a peak at (10 to 20) nm, even when heated at 180 ◦C, a peak at 30 nm remained
- In general, due to the large particles generated, the total suspended matter and the PM_{10} and $PM_{2.5}$ fractions are considered low
- Regarding morphology, the shape of the large particles is elongated, cylindrical, and “sausage-like”. Spherical or round particles are commonly seen, especially in the lower size ranges. Some researchers report that the elongated/round particles appear with variable amounts of mineral encrustation from road material
- Irregularly sized particles have also been reported as two separate types of tire wear particles, denoted as firm elastic and sub-elastic
  - the sub-elastic type was characterized by the commonly seen cigar shape and embedded mineral grains, being far more common in the laboratory than the firm-elastic type
  - the firm-elastic type was more irregular, knobby, and had superficial mineral encrustations
  - the average aspect ratio of particles collected from roadside or tunnel samples is around 1.65
- The densities of the materials typically found in tires are 5.1 g/cm³ for metallic particles, 2.7 g/cm³ for minerals, and 1.2 g/cm³ for rubber. Road constituents such as bitumen have a density of 1.0 g/cm³, and road coarse particles have a density of around 2.5 g/cm³
- Depending on the tread and road dust particle ratio, different densities can be calculated for tire wear particles
  - on highways with little road-encrusted material (<10 %), a tire wear particle density of 1.26 g/cm³ was estimated

  - from road dust near a bus stop, tire wear particles with sizes (63 to 500) µm collected had densities in the (1.3 to 1.7) g/cm³ range
  - highway or parking lot particles (i.e., tire wear and others) had densities between 1.55 g/cm³ and 1.94 g/cm³. Recent studies found densities of (1.8 to 1.9) g/cm³ for tire wear particles; nevertheless, higher values have been reported as well
- Several studies have shown that various compounds are added to improve the properties of tire rubber.
  - Sulphur (and other chemicals such as thiazoles, sulphonamides, selenium, tellurium, organic peroxides, nitro compounds, and azo compounds) are added to vulcanize the rubber and obtain a highly elastic material
  - Zinc oxide (also calcium, lead, or magnesium oxides) is added as a catalyst (to activate the vulcanization process)
  - Carbon black is added as a filler and to make the tire resistant. Over time, these additives have also been modified, e.g., carbon black has been partially replaced by silica to improve the rolling resistance of tires
  - oils are added to make the tire more flexible and control hardness

One important aspect to ensure a proper understanding of the wear mechanisms and the influence of the test surface is the use of high-resolution imaging. Figure 79 from [18] tire wear particles collected on the road, from the roadside with a sampler, a drum dyno, or roadside dust. Blue squares indicate typical mass size distribution peaks, and their relative contributions to the total mass, sources from smaller to larger particles are available from open-access articles. The blue arrow indicates a tire wear particle to distinguish it from the stone particles in the same figure.

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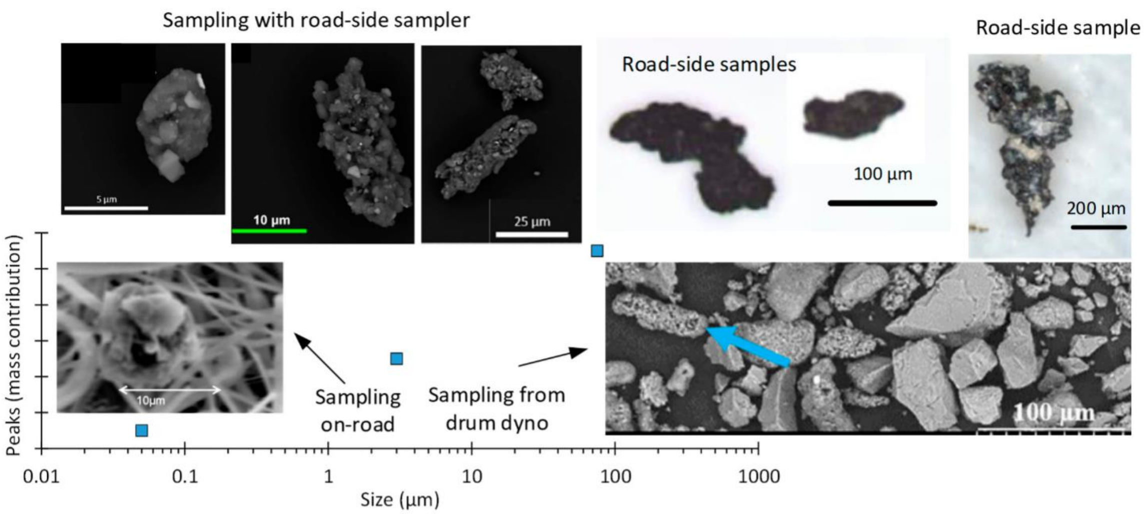


Figure 79 – Morphology of different tire wear debris. Image from open source [18]

Chemical composition of tires and markers

Two of the main areas of study involve detailed chemical analysis of organic compounds, carbon black, and microplastics [116], with an average of 410 compounds per tire. The dominant compounds include benzenoids, lipids, and lipid-like molecules, as well as hydrocarbons. Ten chemical species were detected as recurring in the four groups of tires tested (new and old, small and large). The study in [117] considered the microscopy and chemical composition of samples of snow-covered areas at high altitude (2865 to 3690) m in the Upper Colorado River Basin (UCRB). Some high-level findings related to morphology include the following:

- Microplastics, similar to many previously described in road dust, were observed in each snow sample as cloudy white/translucent, blue, red/pink, green, gray, and black fibers and flakes. A few fibers from road surfaces and tire shreds were also colored in blue and red/pink hues, and some of these colored fibers were partly and thinly coated by a black substance
- The fibers were typically (5 to 10) µm in diameter, and many were shaped as ribbons twisted or curled along their lengths of tens to hundreds of micrometers, suggesting mechanical deformation.
- These particles' chemical compositions and origins were indeterminate by shape, size, or color.

- A black substance coated a few of the cloudy white/translucent fibers or was embedded within clusters of such fibers. Identical and similar, black-coated fibers were found in road-surface and shredded tire samples.
- The fibrous particles with associated black matter in snow were rare and not observed in every sample. Their sparse presence, nevertheless, generated the hypothesis that these particles consisted of tire-derived fibers partly coated by black tire matter.
- Because of possible contamination, statistical counting of microplastics was not done; only those fibrous particles having intimately associated black matter, possibly TWPs, and those consisting mostly of black matter, possibly RTWPs, were targets of further chemical investigation by EDS.
- all samples contained nearly equant black particles (typically <10 µm) that far outnumbered microplastic fibers and flakes and lacked diagnostic features of their possible origins.

The same study measured reflectance and pyrolysis gas chromatography for chemical speciation.

17.4 Test methods to characterize non-tailpipe PM emissions

17.4.1 Brakes

Table 24 reflects the main instruments or methods used to characterize brake emissions. The ranges indicated are typical and do not reflect the entire catalog of models and specifications.

Table 24 – Commonly used sampling devices during brake emissions testing

Measurement or analysis	Equipment	Application
Total particle count	CPC, with or without dilution	10 nm to 2.5 µm
Solid particle count	CPC with Volatile Particle Remover	10 nm to 2.5 µm
PM_{10}	Gravimetric sampling with a cyclone	PM with median aerodynamic diameter < 10 µm
$PM_{2.5}$	Gravimetric sampling with a cyclone	PM with median aerodynamic diameter < 2.5 µm
PM_1	Gravimetric sampling with cyclone	PM with median aerodynamic diameter < 1 µm
$PM_{0.12}$	Gravimetric sampling with cyclone	PM with median aerodynamic diameter < 0.12 µm
Time-resolved particle size distribution	Electrical particle sizers for measuring the size distribution (EEPS, ELPI+) Optical particle counters based on light scattering	EEPS: (6 to 560) nm ELPI+: 6 nm to 10 µm OPC: (0.3 to 20) µm OPS: (0.3 to 10) µm APS: (0.5 to 20) µm DustTrak: (1, 2.5, and 10) µm
morphology and chemical composition	Transmission/scanning electron microscope (TEM/ SEM) with an energy-dispersive X-ray analysis of filters Pyrolysis–gas chromatography/mass spectrometry (Pyr-GC/MS)	Several
Mass loss of parts	Weighing balance	Several
Volatile and semi-volatile organic compounds	Several per [84], [111]	Several
Airborne metals	Toxic-metal Aerosol Real Time Analyzer (TARTA)	Several (Al, Be, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Ni, Pb, V, and Zn)

17.4.2 Tires and road

In addition to the instruments, measurements, and techniques indicated for brakes, Table 25 lists other measurement or sampling devices used by [102], [103].

Table 25 – Commonly used sampling devices during tire and road emissions testing

Measurement or analysis	Equipment	Application
Environmental sampling	Passive air sampler	Sigma-2 Deposition buckets
Meteorological data	Monitoring station	Precipitation Wind direction Wind speed Air temperature
Road dust sampling	Wet dust sampler	340 mL on WDS-II with high-pressure deionized water
Sediment and water from the roadside gully pot and the stormwater well	Telescopic surface water sampler (similar to the NASCO swing sampler but built in-house)	1 L glass bottles
	sediment tube sampler	Hydro-Bios, Sediment Corer
Air and transect samples	Passive air sampler at a given distance and height from the road	Sigma-2 for dry deposition PM_{80-1} µm fraction
Road dust, sediment, and water deposition samples	Gravimetry with the sieving process	Filtered through a pre-weighted Munktell 00H filter (particle retention 1–2 µm). The total particle mass (1–2000 µm)
	Particle size distribution (0.125 to 2000) µm by laser diffraction	Mastersizer 3000
	Sieving ~300 g for road dust samples collected adjacent to the curb and ~ 500 g for stormwater, transect buckets, and road dust samples collected in between wheel tracks	using VWR test sieves into two size fractions: (20 to 125) µm and < 20 µm
SEM/EDX preparation	Transfer onto membrane filters and dispersion	Whatman Cyclopore Membrane (pore size 0.4 µm) Dispersion on boron substrates using a Morphology G3ID by Malvern disperser
Air samples	Boron substrates are placed on standard aluminum discs	Custom made
Analytical methods [102]	Single particle SEM/EDX analysis	Zeiss Gemini 300 Field Emission Gun (FEG)-SEM with an Oxford X-MAX EDS detector with an 80 mm² window, high efficiency 4 quadrant backscatter electron (BSE) detector, and particle analysis software AZtecFeature (©Oxford Instruments) Particle classification and quantification were performed with a machine learning (ML) algorithm
Separation by size	Sieve shaker	Octagon 200 with standard sieves of (1000, 500, 212, 106, 63, 38, and 20) µm or equivalent
Morphology analysis	Digital microscope	Leica DM4 M, Leica Microsystems, Germany). The wear particles larger than 500 µm were classified into tire-road wear particles (TRWP) and road-pavement wear particles
Density separation of the wear particles	Saturated sodium iodine	sodium iodide (NaI, purity: 99.0 wt%) solution

Extensive field and laboratory studies provide evidence of particle mass, particle number, and size distribution of Nordic tires with emphasis on road dust sampling, and are reported by [118].

Figure 80 adapted from [119]This provides a structured summary of current analytical methods for identifying and quantifying TRWP in environmental samples, based on peer-reviewed studies. The same study highlights several important aspects to consider:

- Limited studies in environments far from the road
- Potential to incorporate upcoming methods such as time-of-flight secondary ion mass spectrometry (ToF-SIMS), thermogravimetric analysis (TGA) [46], Laser-Induced Breakdown Spectroscopy (LIBS), FTIR, and elemental analysis such as micro-X-ray fluorescence (µXRF) if they are coupled to synchrotron technology
- TRWPs demonstrate that these particles are not uniform, but rather heteroaggregates of tire and road-related particles with a wide range of sizes, densities, morphologies, and chemical components. This further complicates the tasks of identifying and quantifying TRWPs in environmental samples.

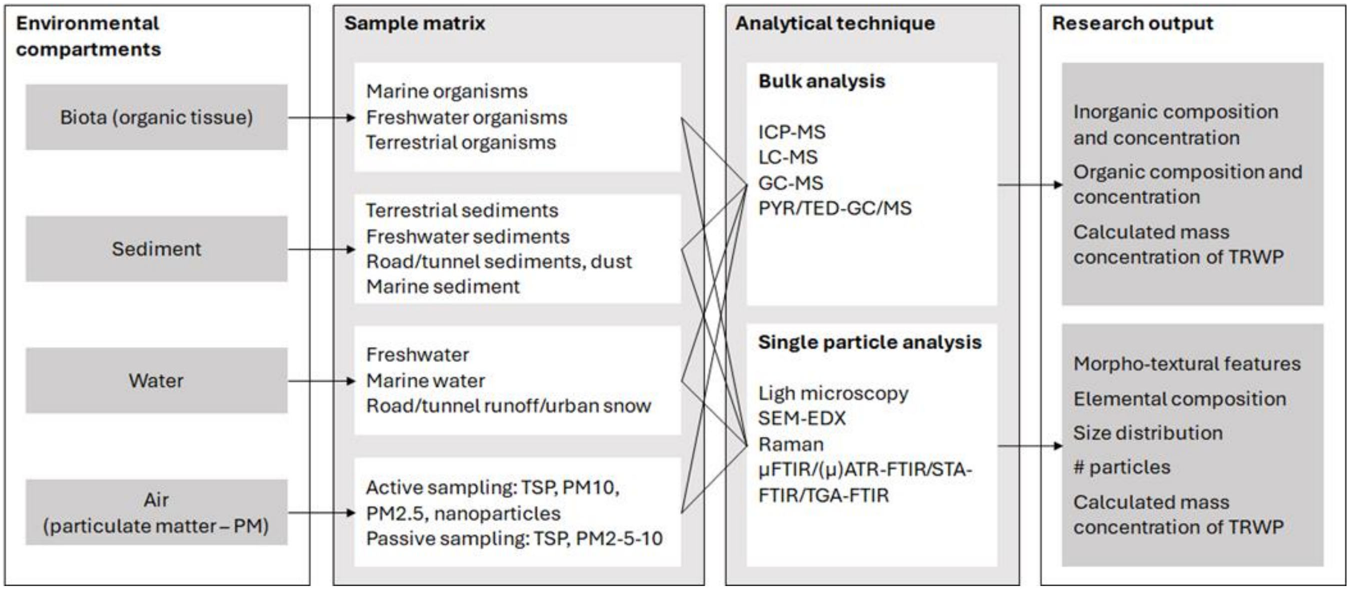


Figure 80 – Summary of current analytical methods for identification of TRWPs in environmental samples. Adapted from open source [119]

17.5 Strengths or weaknesses of test or measurement methods

17.5.1 Brakes

Findings from the ILS3 interlaboratory study of the European Commission

[31] reports findings related to a large systematic study involving up to 14 laboratories in a multi-year effort led by the JRC of the European Commission. After several rounds of improvements based on peer-reviewed analysis, the following are some enhancements and limitations of the current GTR 24-based laboratory measurements:

- The evolution of GTR 24 since its original draft has helped improve quality and reduce variability in test controls and outputs
- The practical implementation at multiple testing facilities of the GTR 24 provided specific items that allowed refining the document into its Amendment 2
- Compliant setups exhibit stable and low background levels for PN measurements, 1-to-2 orders of magnitude below the EF measured during the tests
- Standard deviations for PM have reduced (compared to ILS2) and are comparable for Ford Puma and JLR at approximately 0.5 mg/km/B. This level of variation induces a three-fold difference when expressed as % covariance
- Influence of airflow on brake temperature is negligible
- Most labs exhibited some non-compliance (e.g., lack of experience, incomplete data, incorrect reporting, inconsistent units)

- Lack of sufficient evidence of the principal factors determining EF variation within the same brake. Further analysis may reveal the effect of airflow, kinetic energy dissipation, sample and tribological effects, and test-to-test variation
- Such studies require a significant effort from multiple parties, with large amounts of the work directed towards organizing and validating the data before embarking on a serious statistical assessment of repeatability and Reproducibility (partially completed at the time of this report)

[7] indicates that, based on more than 80 dynamometer tests, the effects of axle position (front v rear), friction couple formulation, vehicle size, type, and speed induce significant variation in PM. Also, the California Air Resources Board has concerns regarding the discrepancies between state and federal emissions inventories and the lack of speed-dependent EF. Another aspect worth considering is the need to qualify the actual test procedure used for testing before conducting any meaningful comparison. One important trend in brake research is the integration of the latest studies, which utilize the GTR 24 test as the primary laboratory test. Vehicle testing still requires further harmonization to achieve greater comparability. Although the WLTP-B can be driven on the proving ground, the cost of conducting testing on a closed track may deter the industry from using it more frequently. On the topic of test repeatability, this study used results from five tests distributed along the timeline of the study using the OE NAO friction material on the front brake of the F150 and considered repeatability (95% limit) for control parameters on the brake inertia dynamometer (e.g., speed, deceleration, torque) and outputs (e.g., brake temperatures, total wear, and emission factors. Speed and deceleration were within 5% of the setpoint, brake temperature for the time-controlled CBDC was 4% of the average, and emission factors (including total wear) were about 25% of their average values. The five repeats on the F150 front brake also exhibited the same bimodal PSD between 5.6 nm and 500 nm (EEPS) and between 0.5 µm and 18 µm (APS). Based on results from the same study, no single factor (e.g., vehicle type, axle, friction couple, test mass) can predict the EF alone. Additionally, the estimation of the EF requires actual results from both axles, as the brake work split cannot predict the front-to-rear ratio without accepting a significant uncertainty. Lastly, brake inertia dynamometer testing (using industry cycles such as WLTP-B or CBDC) can distinguish the brake emissions response to vehicle type, test mass, axle position, and friction couple formulations.

An independent study from Japan [36] was able to provide evidence of the validity of the cooling air adjustment method from the GTR 24, as shown in Figure 81. Test 18 had one of the highest test inertias and was conducted at the maximum wheel load-to-disc mass ratio (121:1) for the experiment.

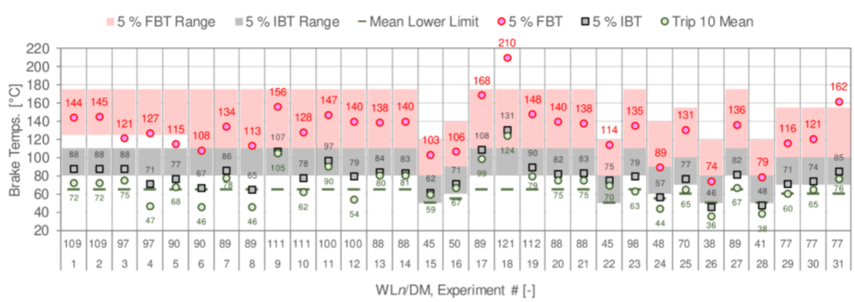


Figure 81– The brake temperature tolerances, the mean disc temperature, the initial brake temperature (IBT), and the final brake temperature (FBT) for trip#10. Image from open source [36]

With the advent of regenerative braking as a mature approach for hybrid and electric vehicles, it is important to understand the feasibility of applying simplified regenerative control during the actual test, as shown in Figure 82. Figure 83, using the friction work results, it confirms that the dynamometer controls can recreate the vehicle's regenerative braking.

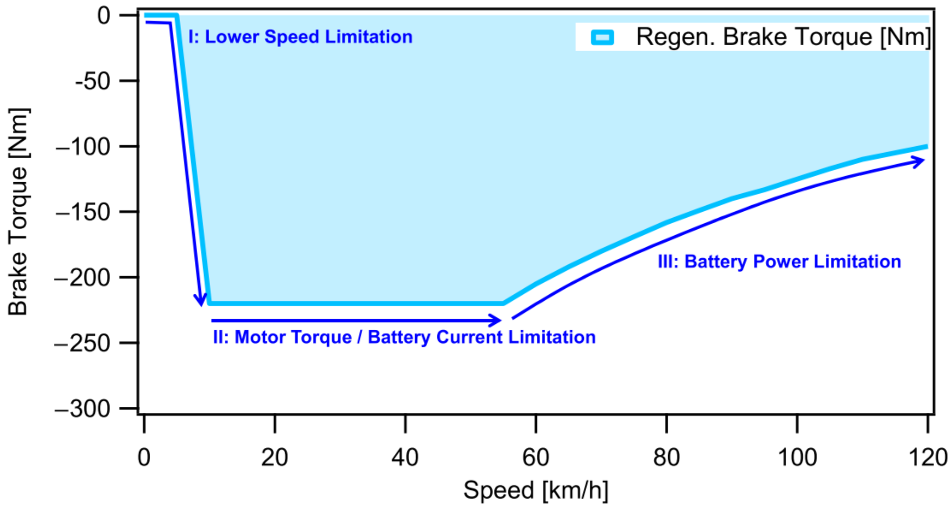


Figure 82 – Example of torque/speed characteristics of regenerative braking in regenerative-friction brake coordination control. Image from open source [36]

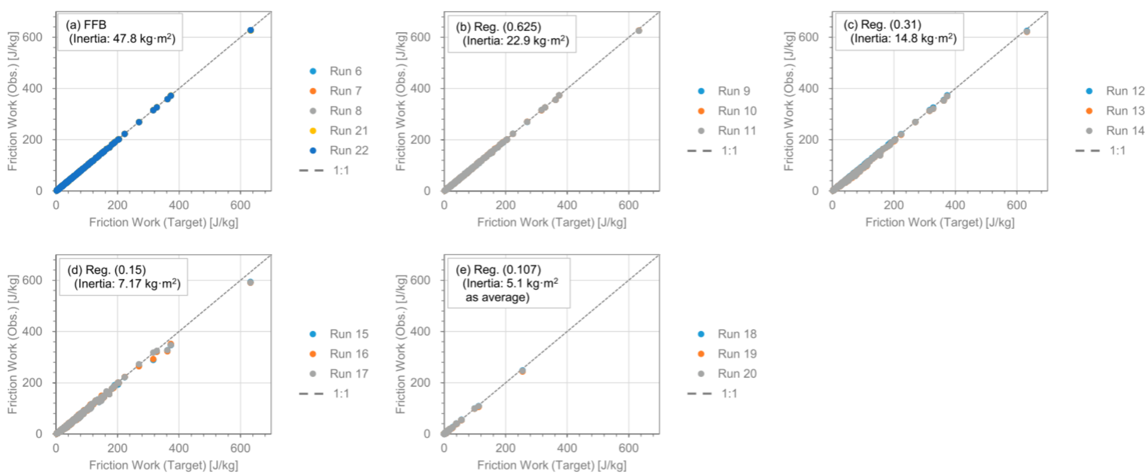


Figure 83 – Comparison of friction work targets and observations for brake events #1–303. Image from open source [36]

17.5.2 Tires and road

Root causes for tire abrasion variability remain elusive; at least one review. [18] found a range of (82 to 151) mg/km for 15 summer tires, 205/55 R16, tested in 2021, and a range of (56 to 202) mg/km for 50 similar tires tested in 2023. This points to the market's spread between low- and high-emitting tires. One benefit of such studies is the selection of representative tires in the market and the distance they travel. Technical surveys indicate these are the most popular sizes, making them good candidates for future studies.

- C1: 205/55 R16, 225/45 R17, 195/65 R15, 175/65 R14, 225/40 R
- 8, and 225/60 R16
- C2: 215/65 R16, 235/65 R16, 205/65 R16, 205/75 R16, and 225/65 R16
- C3: 315/80 R22.5, 315/70 R22.5, 385/65 R22.5, 295/80 R22.5, and 385/55 R22.5

[18] highlights the range for the ratio of $PM_{2.5}/PM_{10}$ for tire particles used in the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook using a value of 0.70 (70 %). At least one study reported a ratio of 80 %, while others reported values around (35 to 55) % or even less than 15 %. An atmospheric study reported values ranging between 1 % and 100 %, with most of the calculated ratios

smaller than 20 %. The same study found that in a ring road in Tokyo, the PM_{10} concentration included only particles in the $PM_{2.5}$ size fraction. However, the $PM_{2.5}/PM_{10}$ ratio from ambient air studies can be affected by road wear, resuspended soil dust, long-distance dust transport, coal mining and processing industries in the vicinity, and other mechanical activities. Recent efforts from the European Commission, the European Tire and Rim Technical Organisation (ETRTO) [120], and The Japan Automobile Tire Manufacturers Association, Inc. (JATMA) [121] as part of developing the Euro 7 limits for tire abrasion rates, data from market assessments for more than 100 tires are updated using convoy and laboratory drum testing methods. Regarding PM_{10} EF, the same recent review study [18] found reports ranging from about 0.2 mg/km to about 10 mg/km using roadside measurements. The same study indicates two main types of rubber found in light-duty vehicle tires: natural rubber (NR—polyisoprene [C5H8]n) and synthetic rubbers, which include styrene butadiene rubber (SBR) and butadiene rubber (BR). NR is preferred for high-performance tires used in aircraft, trucks, and buses. However, this was disputed recently, with a study showing that SBR and BR are also present in heavy-duty vehicle tires, sometimes even at higher concentrations than in some light-duty vehicle tires. A recent study highlighted the high natural and synthetic rubber variability between brands and models. Over time, the evolving composition and the true complexity of the compounds make it more challenging to trace PM and chemical (inorganic and organic) compounds to tires. A common-sized all-season passenger tire may contain 30 kinds of synthetic rubber, 8 kinds of natural rubber, 8 kinds of carbon black, 40 different chemical additives, several inorganic compounds, and up to 214 different organic chemicals which 145 were classified as leachable, thus indicating a large potential for transport in the environment. A second challenge concerns metals at high concentrations (e.g., Si, S, Zn, Ca, Al, and Fe) used as markers for tire wear emissions in ambient PM apportionments. Some metals may originate from encrusted material from other sources, such as Zn, which is common in corrosion from crash barriers and brake wear, and can skew concentration measurements attributable to tires.

As pointed out by [18]Laboratory-based measurements provide well-controlled, less complex-to-manage, and easily repeatable conditions. The disadvantages include less realistic wheel movement, limited representativeness of real-world driving patterns, and the use of a non-realistic counter surface (sandpaper) against which the tires can wear. On-road sampling can be significantly affected by resuspension or other sources (e.g., brakes, road markings, sand) that must be considered. In most cases, only a portion of the tire-derived particles is captured; therefore, researchers must make assumptions regarding proportionality or dilution (weather, wind speed, and traffic effects). For roadside ambient measurements, source apportionment methods must be applied, or specific tire wear tracers must be assigned to distinguish tire particles from other sources (e.g., dust). A similar approach applies to samples taken from water or soil. While the first two methods may be used to measure tire-specific emission factors, they do not consider possible transportation and transformation, which may introduce significant errors in the final estimation of the emission factors. On the other hand, the last two methods provide average fleet emissions in the specific collection area; thus, no particular information about the tires is available.

Another aspect to consider per [18] There is a lack of standardized methods for sampling, sample preparation, and analysis, with multiple assumptions requiring reassessment. International Organization for Standardization (ISO) standards ISO/TS 21396:2017(E) [122] and ISO/TS 20593:2017(E) [123] quantify tire wear particles in soil/sediment and assume that the total mass of synthetic and natural rubber in all tire treads is constant (e.g., assumes the total rubber content is 50 % of the mass of the tread, passenger car tires contain 44 % SBR+BR, truck tires contain 45% NR). In the market, there is a large variation in compositions. Similarly, there is a high degree of uncertainty in the applied percentages for the different markers used to quantify tire tread mass. Additionally, [18] continues to highlight some challenges, such as:

- Few emission factor studies based on experimental data after the year 2000
- Influence of other factors during on-road testing (e.g., background, brakes, pavement)
- PM EF based on laboratory measurements or estimates as a fraction of total tire wear
- Significant discrepancies in EF (for both PM and PN) between studies as a result of using different instruments, cycles, loads, surfaces, vehicles, or weather conditions
- Lack of detail given to allow for the comparability among studies and results

[14] indicates that more than half the studies on emission factors use data from measurements carried out in the 1970s, with a limited scope on vehicle types. Additionally, geographical variability (e.g., the use of winter tires) and vehicle fleet composition (especially heavy commercial vehicles) may vary in terms of vehicle type, loading, and applicable regulations. Another limitation is that the same tire can be applied to multiple vehicles with varying loads. One possible solution (already included in the proposed Euro 7) is the normalization of the EF per tonne of vehicle mass during the test. This study also highlights the limitations of accurate and recent data on vehicle fleet composition, vehicle miles, influencing factors on emissions, and tire life metrics (e.g., mass loss in kg).

17.6 Information about the distribution of non-tailpipe PM from the point source

As shown in Table 26, several studies [124] have simulated the contribution of microplastics (primarily tires and brakes) in tonnes of PM_{10} and $PM_{2.5}$. The same study found high particle transport efficiency in remote regions (as far as Antarctica). About 34% of the coarse TWPs and 30% of the coarse BWPs (100 kt yr^{-1} and 40 kt yr^{-1}, respectively) were deposited in the World Ocean. These levels are like the total estimated direct and riverine transport of TWPs and fibers to the ocean (64 kt yr^{-1}). Values are averaged for the two different methodologies used (CO_2 ratio and GAINS [125] model emissions). The corresponding ranges represent variations of continental geometric standard deviations from geometric means (presented within parentheses) following a log-normal distribution. The airborne PM_{10} fraction was assumed to be 2.5%, 5%, 10%, 20%, and 40% of the total TWP emissions, while $PM_{2.5}$ was supposed to be 0.25%, 0.5%, 1%, 2%, and 4% of the total TWP emissions. For BWPs, it was assumed that 30%, 40%, 50%, 60%, and 70% of total BWPs are $PM_{2.5}$, while 60%, 70%, 80%, 90%, and 100% of the total BWPs are PM_{10}.[13] Note that Russia has been excluded from Europe and Asia and is listed separately, while America has been divided into three parts (north, central, and south).

Table 26 – Annual continental emissions (in kt) of road microplastics. Data from open source [124]

Tire/Brake		Tire Wear Particles kt·year^{-1}		Brake Wear Particles kt·year^{-1}	
PM		$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}
Europe	min-max	2.3–15	42–82	13–32	28–37
	Geometric mean	5.8	58	21	32
Asia	min-max	4.8–30	85.0–167	26–62	50–67
	Geometric mean	12	113	40	58
Russia	min-max	0.26–1.6	4.6–9.0	2.5–6.0	6.9–9.1
	Geometric mean	0.64	6.4	3.9	7.9
North America	min-max	2.6–16	46–90	11–26	22–29
	Geometric mean	6.4	64	17	25
Central America	min-max	0.32–2.0	5.7–11	1.7–4.0	3.2–4.2
	Geometric mean	0.8	8	2.6	3.7
South America	min-max	0.8–5.0	14–28	4.4–10	8.4–11
	Geometric mean	2	20	6.8	9.7
Africa	min-max	0.56–3.5	10–20	3.4–8.1	6.5–8.6
	Geometric mean	1.4	14	5.2	7.5
Oceania	min-max	0.19–1.2	3.4–6.8	0.97–2.3	1.9–2.5
	Geometric mean	0.48	4.8	1.5	2.2
Total	min-max	12–75	113–826	63.4–152	85.8–248
	Geometric mean	29	288	98.2	146

[13] From the same study [119], mass fractions of $PM_{2.5}$ and PM_{10} size modes of TWPs and BWPs with respect to total TWPs and BWPs are assumed in the emissions ingested in the FLEXPART model. Five scenarios were created assuming that 2.5%, 5%, 10%, 20% and 40% of the total TWP were emitted as PM_{10} and 0.25%, 0.5%, 1%, 2% and 4% as $PM_{2.5}$. Accordingly, 60%, 70%, 80%, 90% and 100% of the total BWPs were assumed PM_{10}, and 30%, 40%, 50%, 60% and 70% were assumed $PM_{2.5}$, based on the range of values reported in the literature. These values were used in the ensemble of 120 members (Methods) together with assumptions on particle size distribution (eight for each of the $PM_{2.5}$ and PM_{10} fractions, Supplementary Figure 4) and CCN/IN efficiency (three different sets of scavenging coefficients per fraction, Supplementary Table 2).

Even though the definitive answer on how much brakes and tires contribute to ambient pollution remains elusive, several studies using different tools in different regions have attempted to gain deeper knowledge in this field over the past three years. In addition to others already mentioned elsewhere in this report, the ones we discovered during the literature search are the following:

- Evaluating the Impact of Road Layout Patterns on Pedestrian-Level Ventilation Using Computational Fluid Dynamics (CFD) [126]
- Detection of Atmospheric Particulate Metals in Near Real-Time: Tunnel, Urban and Rural Environments using the Toxic-metal Aerosol Real Time Analyzer (TARTA) in the California region [127]
- Influence of Local Circulation on Short-term Variations in Ground-level $PM_{2.5}$ Concentrations using measurements in South Korea [128]
- Quantifying Impacts of Local Traffic Policies on PM Concentrations Using Low-Cost Sensors in two main locations in Berlin [129]
- Highly Time-Resolved Elemental Source Apportionment at a Prague Urban Traffic Site [130]
- Improving Fugitive Dust Emission Inventory from Construction Sector Using UAV Image Recognition in China [131]
- Correction Method for Resuspended Road Dust Emission Factors according to Vehicle Speed Using a Mobile Monitoring Vehicle with measurements in South Korea [132]
- Characterizing Traffic-Related Ultrafine Particles in Roadside Microenvironments: Spatiotemporal Insights from Industrial Parks in Taiwan [133]
- Trends in Air Pollution in Europe, 2000–2019 [134]
- The study Environmentally Optimal Tires and Brakes Phase 1 Report for National Highways for the UK [2] estimates from the literature, the following allocations are per Table 27.

Table 27 – Estimates of pathways for tire and brake emissions

Pathways	**Source**	
	Tire abrasion	**Brake abrasion**
Airborne emissions	< 10 %	~ 50 %
Dust on the wheels and chassis	n.a.	Unknown
Deposited on the road	Unknown	Unknown
Emissions to soil	(25 to 75) %	Unknown
Emissions to water	(10 to 50) %	Unknown

17.6.1 Brakes and other non-exhaust sources

[36] indicates that brake and other non-exhaust emissions can account for more than half of all vehicle-derived particulate matter in cities. One study used a portable and low-cost device to trace metals at three locations, including traffic emissions: Caldecott tunnel, CA (in August 2021), agricultural emissions from a rural site in Davis, CA (in July 2021), and urban emissions measured at a warehouse near downtown Sacramento, CA (from March to May in 2022). Figure 84 illustrates the diurnal concentrations of PM2.5 and several elements at the urban and tunnel sites. The graphs show the TARTA device's ability to differentiate between tunnel and urban site concentrations.

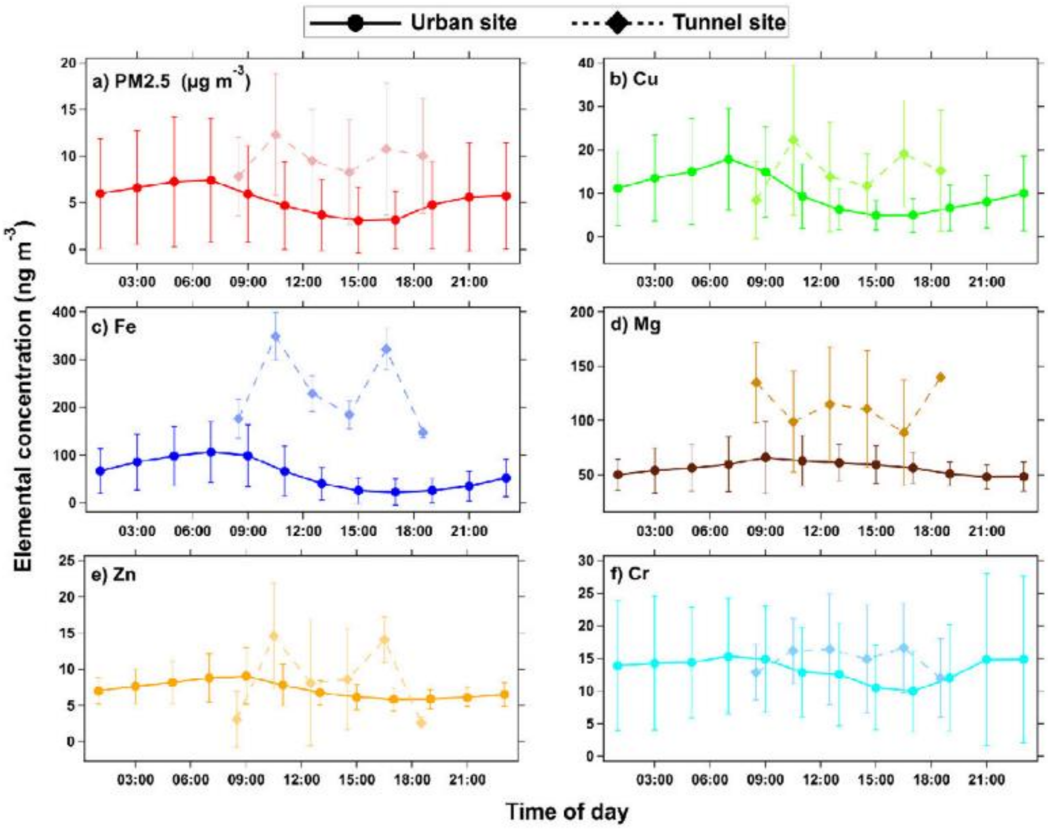


Figure 84 – Diurnal variations of $PM_{2.5}$ and elemental concentrations at the urban and tunnel sites (panel a). The results are shown as mean ± standard deviation for each hour. The tunnel site's results are shifted by 30 minutes to visualize their trend better. Caption and image from open source [36]

Near-road contribution to PM in California

Another study [135] that followed up on the CARB project measured the contributions of non-exhaust vehicle emissions to near-road PM and PM_{10} at two sites in California. Figure 85 depicts the percentage distribution of non-exhaust sources. The chemical analysis indicated stronger correlations among individual elements at the I-5 Anaheim site than at the I-710 Long Beach site. Non-tailpipe markers selected include Fe, Cu, Zr, Ti, Ba, and Zn. The road dust chosen markers were Al, Si, K, and Ca. The study also illustrates the size distribution (0.1 to 100 µm) for both sites, along with the background PSD and particle mass distribution. Except for Sb (Antimony), all elements exhibited a distribution significantly different from and above the background.

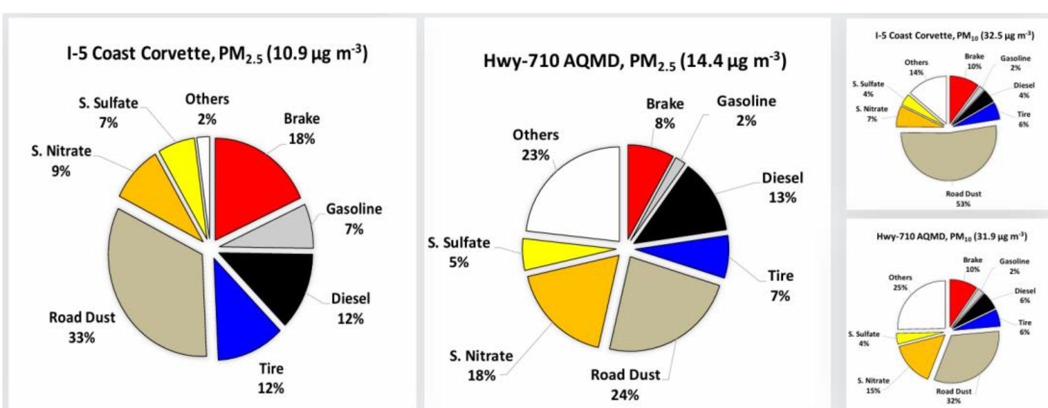


Figure 85 – Source apportionment for the two sites. Image from open source [135]

The same study compared the $PM_{10}/PM_{2.5}$ ratios between lab measurements (CARB 17RD016) and field measurements, indicating similar behavior, with the field measurement indicating a slightly lower offset (0.15 vs. 0.2) compared to the lab measurement, and a larger fraction, which may be attributed to other sources, the measurement environments (laboratory vs. near-road), and the difference by-design between a small sample of brakes under a fixed test cycle (lab testing) compared to *average* vehicles with *average* driving under *average* conditions (field measurements). See Figure 86 for the correlation plot.

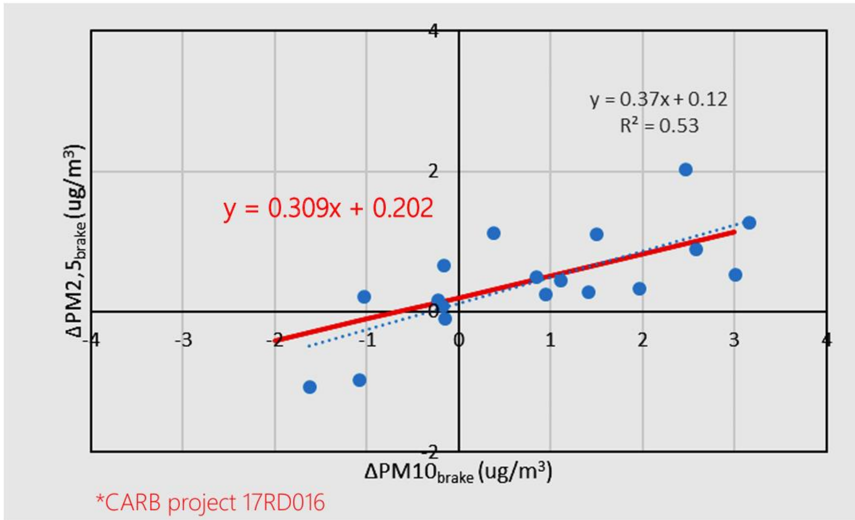


Figure 86 – $PM_{2.5}/PM_{10}$ fraction during site measurements and dynamometer testing. Image from open source [135]

17.6.2 Tires

Since measuring and assessing the distribution and fate of particulate matter involves both temporal and spatial aspects, some studies have developed models for material flow in open environments. One study [136] We considered the lifecycle of tires in Switzerland and developed a simplified version from the study, as depicted in the flowchart in Figure 87.

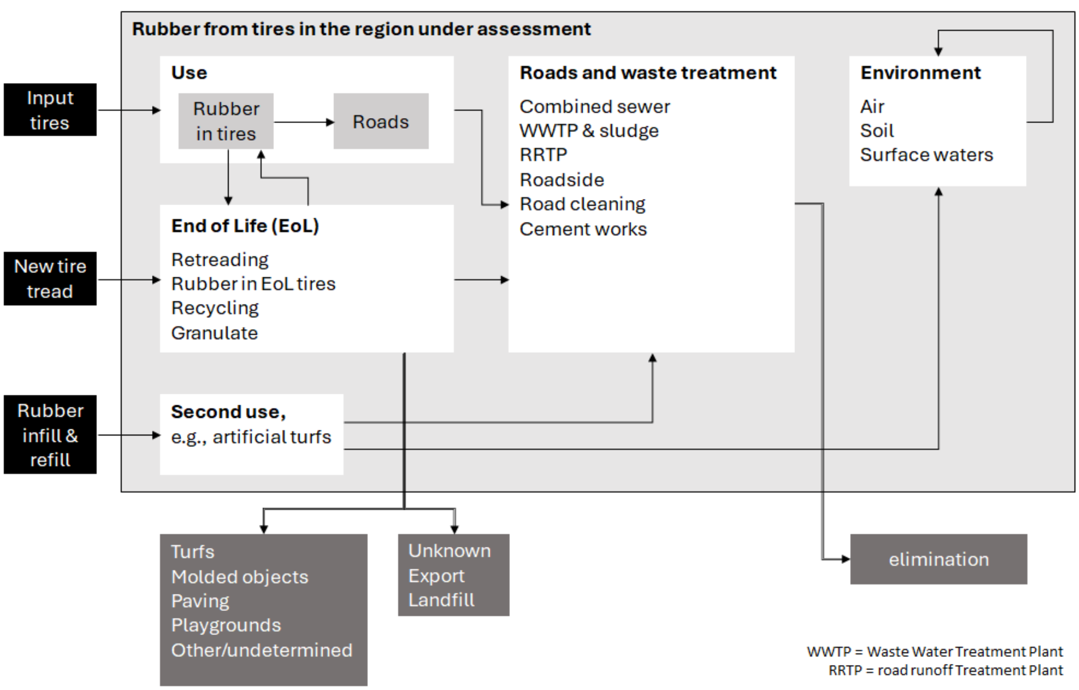


Figure 87 – Simplified lifecycle for tires. Developed from [136]

This same study estimates that for Switzerland, from 1988 to 2018, the total rubber environmental sink is (219 ± 22) kt, with 77% deposited on the roadside, 19% on surface waters, and 4% on soil. For 2018, the initial release from tires was (10,600 ± 3,800) t/y or (1.25 ± 0.45) kg per capita per year. Other studies, as in [137] have developed similar models for Germany and other countries, with a detailed tabulation of parameters and assumptions, as shown in Table 28. The significant difference between the two global estimates from 2019 and 2023 is noteworthy.

Table 28 – Tires' contribution to microplastics (MP) pollution in various countries

Year	Country	MP emissions $kt \cdot year^{-1}$	Tires' contribution to MP emissions	Tire fraction released to the aquatic environment
2014	Norway	8.4	54%	50%
2015	Denmark	5.5–13.9	56%	12–26%
2016	The Netherlands (1)	5.4–32.9	11–96%	10–18%
2017	Sweden	10.5–13.5	60–77%	42% (2)
2018	Germany	330	43%	22%
2018	Switzerland	87.8	93% (3)	22%
2018	EU	787	64%	19%
2019	China	737	54%	10%
2019	Global	3000	47%	n/a
2022	Sweden	9.6	85%	n/a
2022	The Netherlands	7.6	35%	9%
2023	EU	450	36%	n/a
2023	Global	800	62%	14%

Comments: (1) ranges provide values from the two studies; the high contribution from tires in one study is because land-based litter fragmentation was not included; (2) value of 42% reported; (3) also includes end-of-life tire losses but not paints.

[138] reports the magnitude and fate of tire wear in the EU. See Figure 88.

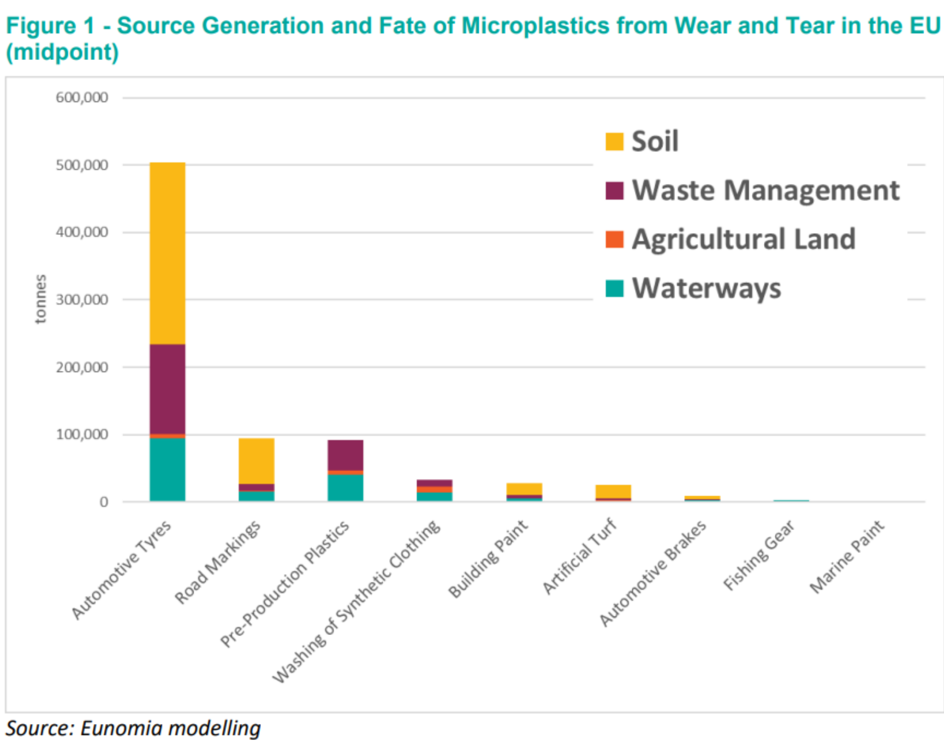


Figure 88 – source and fate of microplastics from automotive and other sources. Image from open source [136]

[139] presents a Conceptual Exposure Model (CEM) for tire emissions during vehicle use, considering three main groups:

- *Leachables* for dissolved compounds that can be released from tires (direct emission) and TRWPs
- *Volatiles* for gaseous compounds which are vaporized during the use of tires (direct emission) and from TRWPs
- *Tire and road wear particles (TRWP)* as indirect emissions from for heteroaggregates consisting of particulate tire wear and mineral particles located at the surface of the road pavement (direct emission)

The same study presents a proposed scheme to characterize TRWP with four tiers of analysis, with increasing time, cost, and needs for quality assurance, including:

- *Tier 0 – Exploratory* or qualitative informational methods
- *Tier 1 – Screening* microscopy or chemical surrogates for tread polymers
- *Tier 2 – Mass* quantification of TWRP in suspended particles, sediments, soil, road dust, air filters, and other media
- *Tier 3 – Single Particle* characterization of TWRP by particle
- *Tier 4 – Chemicals* using refined measurement of leachable or extractable organic compounds by complex methods

In the same study, the authors reviewed 23 recent py-GC/MS studies, focusing on quality controls, sample preparation, and media. The percentage of studies by element is shown in Figure 89.

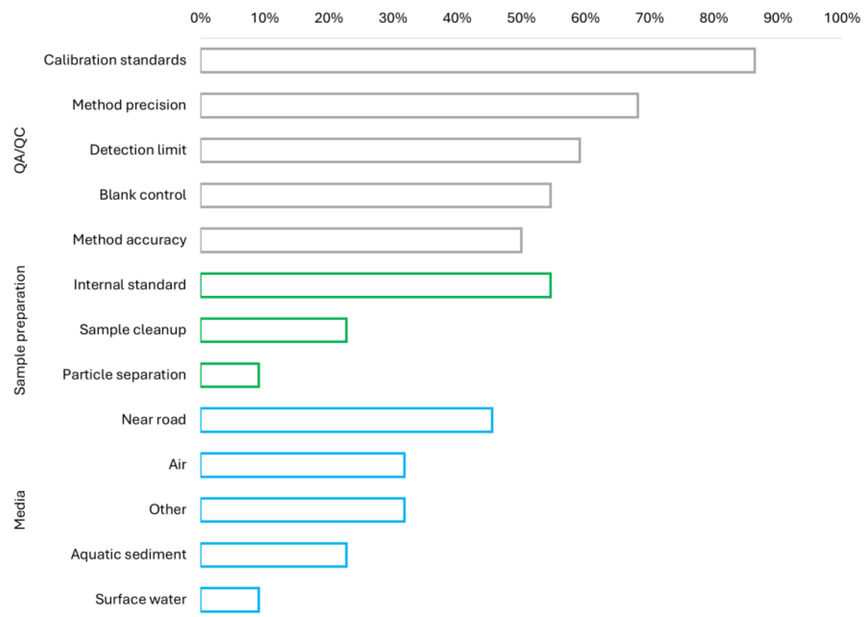


Figure 89 – Percent of studies for tire suspended particles fulfilling specific elements for quality assurance, sample preparation, and media sampling. Adapted from [139]

The recent review [18] indicates the following findings on the contributions of tires to ambient particulate matter, as shown in Table 29.

Table 29 – Estimates of contributions of tires to air, soil, and water pollution

Scope	Values	Comments
Overall	Tire wear: road wear ~1:1	(a) Many experimental studies have found that tire constituents are the major contributors. (b) A study found only a 25% contribution from encrusted particles (c) Another study found that only 6% of the particles had a ratio of road-to-tire fractions ≥ 1:1 (d) The road contribution by volume can be as low as 6 % (e) A laboratory study found a (70 to 80) % contribution of asphalt to the particles, depending on the road, tire materials, and particle size
Soil concentration	(10 to 158) mg_{tire}/g_{soil}	(a) Most published studies base their results on modeling and report that the major part of tire wear particles end up in the soil (b) Soil concentration depends on traffic intensity, the type of road surface or asphalt, vehicle speed, and the runoff and drainage system. (c) The concentration at the roadside and runoff also depend on the number of days without rain
Surface water concentration	Average: 50 mg_{tire}/g_{runoff} Range: (10 to 150) g_{tire}/g_{runoff}	(a) After precipitation (b) Tire wear can reach surface waters indirectly when road runoff is first discharged to a wastewater treatment plant
Airborne	(2 to 5) %	(a) Some studies assume a much higher percentage (10%)
Ocean waters	34 % of the airborne fraction	(a) Plausible that the direct deposition of airborne road microplastics is at least an equal source for the ocean compared to direct wash-out from the land
Remote areas	n/a	(a) Others found microplastics, including tires, from the Alps to the Arctic
End of Life Tires (ELT) End of Life (EoL)	3500 kt @ 2019 in the EU	(a) Includes discarded non-reusable tires (b) 55 % of these tires were treated through material recovery (c) 40 % went through energy recovery (d) < 5 % (160 kt) were stocked or unknown (e.g., illegally landfilled)
Tire particles as a source of microplastic emissions	Overall (11 to 93) % (35 to 85) % excluding the min-max values	(a) Some variations in the fraction of TWP come from differences in the microplastic sources considered in each study. (b) In many studies, the second contributing source accounted for (10 to 29) % of the total MP emissions. E.g., household dust and laundry, 12 %; rubber granules, 10 %; artificial turf, 18 %; synthetic fibers, 29 %; road markings, 12 %; and pre-production plastics, 12 % (c) Nevertheless, sources such as paints, pellets, packaging, and agriculture are also important (d) The European Commission identified paints as a similar contributor to microplastic emissions in the EU as tires, with approximately 36 %
Tire contribution to PM_{10}	Overall (0.3 to 4.5) % (5 to 31) % to road transport Source appointment (5 to 6) %	(a) Road transport overall (10 to 15) % (b) Can be higher in cities, near roads, or closed environments (tunnels) (c) A review found the contribution of tires to the total PM_{10} to be below 10% in most studies (d) In addition to the size distribution of tire particles, the cut-off size of the cyclone or impactor is important
Tire contribution to $PM_{2.5}$	Overall (1 to 10) % Source appointment (0.1 to 0.4) %	(a) Values are mostly based on data from 20-year-old studies and indirect calculations from only a few observational studies (b) The contribution of emitted volatile organic compounds to secondary aerosol formation has not been quantified
Regional contribution to ambient PM	Various	(a) The German Environment Agency (UBA) reported that in Germany, road traffic contributed an overall 13.8 % to ambient PM_{10} in 2017, of which tires had a share of 3.1 %. For $PM_{2.5}$, the respective numbers were 18.8 % and 4.6 % (b) Similar estimates (to UBA) from the Air Quality Expert Group for the UK (c) The European Environmental Agency estimated a 4 % contribution to PM_{10} and a 2 % contribution to $PM_{2.5}$ from tires (d) Measurements of airborne concentrations of tire particles in urban and rural areas of France, Japan, and the United States found (0.6 to 22) % contributions to PM_{10} (e) Results from the same project (i.e., the Tire Industry Project, TIP) indicated tire particle contributions of (0.1 to 0.7) % to ambient $PM_{2.5}$ concentrations in the same areas (f) On-road and laboratory measurements in South Korea found that tire particles accounted for between 3% and 7% % of $PM_{2.5}$ and PM_{10} (g) PM_{10} (4 to 6) % was measured in Stockholm (Sweden) (h) Road dust samples from a highway in Sweden contained more than 10 % tire particles (i) The annual average mass fraction of tires in PM_{10} was 1.8 % at an urban background site in Switzerland and 10.5 % at an urban curbside site (j) A study with a single-particle aerosol mass spectrometer at the roadside of a port highway in China found a 6.6 % contribution of tires to the total PM

17.7 Factors known to control or affect the magnitude or type of non-tailpipe PM emissions

Combining brake and tire peak PM measurements to assess the effect of vehicle mass and braking intensity

One important application (and benefit) of in-vehicle testing is the ability to use the same technical and logistical infrastructure to assess emissions from both brakes and tires within a single study. [98] reports results from testing three vehicles (Nissan Sentra, Honda Accord, and Chevrolet Silverado). This study focused on quantifying peak PM_{10} and $PM_{2.5}$ peak concentrations for brake and tire at multiple deceleration rates, as shown in Figure 90.

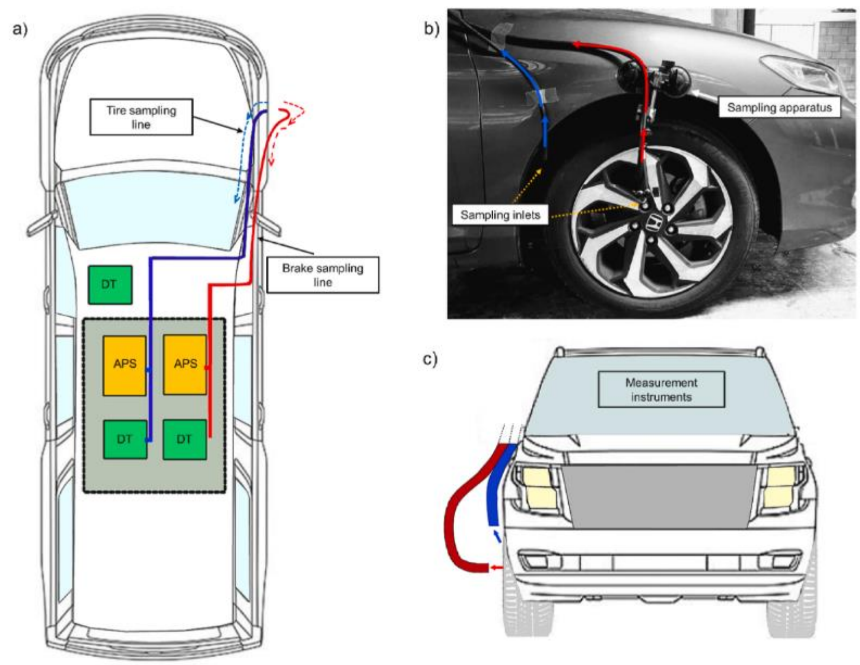


Figure 90 – Schematic diagrams for the test vehicle with the sampling configuration. (a) Top view. Illustration of the sampling instruments installed inside the vehicle, including APS (TSI APS 3321) and DT (TSI DustTrak 8532). (b) The test vehicle and sampling apparatus. The arrows indicate the direction of the sampling flow from the brake and tire. (c) Front view. The tire particles are measured from the rear side of the right front wheel. The brake particles are measured at the center of the right front wheel. Image from open source [98]

Figure 91 shows the scatter plots for peak PM vs. deceleration, and Figure 92 depicts the boxplots for each vehicle's peak deceleration by deceleration ranges. Two limitations of this study that hinder the ability to compare with other studies are: a) reporting only peak values that do not correspond to metrics in mg/km/B or mg/km/V, and b) the test schedule applied most of the deceleration levels above 2 m/s^2, which is the upper limit in the GTR 24 [6]

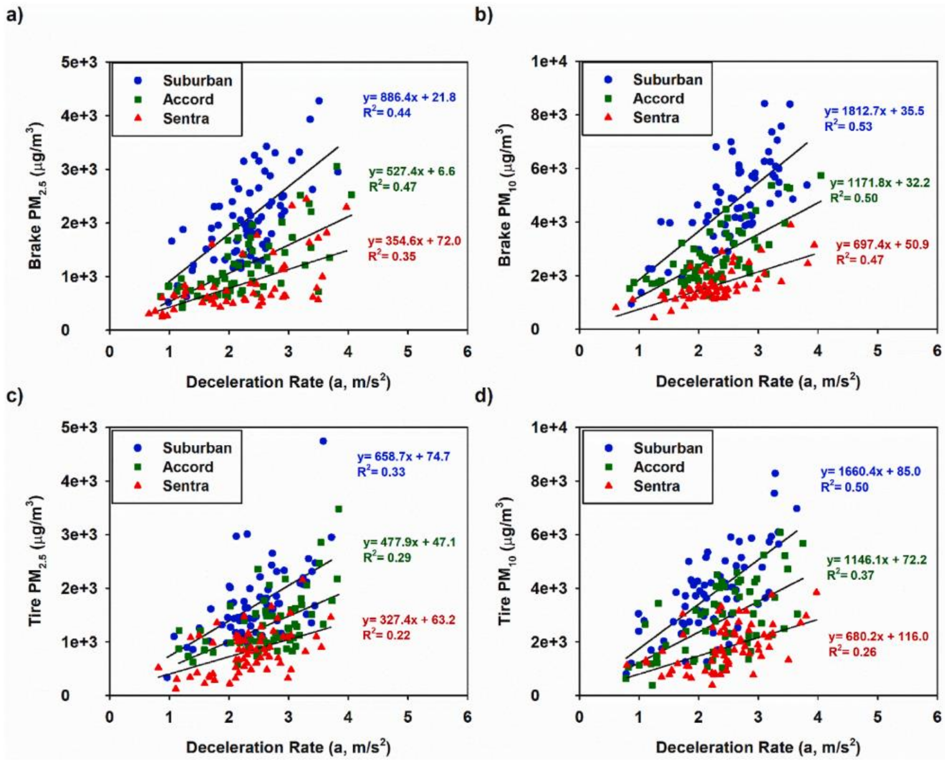


Figure 91 – Relationships between the peak values in PM concentrations and the average deceleration rate (a) brake $PM_{2.5}$, (b) brake PM_{10}, (c) tire $PM_{2.5}$, (d) tire PM_{10}. Image from open source [98]

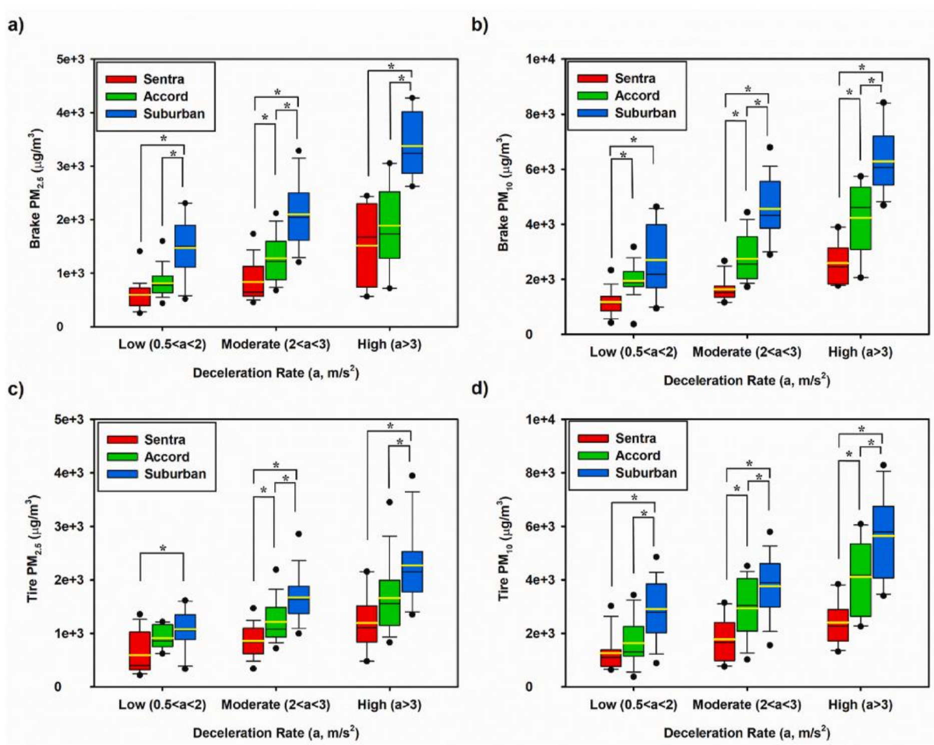


Figure 92 – Peak values in PM concentrations for the test vehicles at three deceleration rates (i.e., braking intensity) levels: (a) brake $PM_{2.5}$, (b) brake PM_{10}, (c) tire $PM_{2.5}$, (d) tire PM_{10}. Image from open source [98]

17.7.1 Brakes

Study [18] compiled estimates of the relationship between airborne particles and PM_{10} relative to the mass loss of gray cast iron discs. Table 30 illustrates the main findings from the literature.

Table 30 – Airborne and particulate matter PM10 fractions of total mass loss for gray cast iron disc brakes. Some information about the studies can be found in Table 11

Year	Airborne/Mass Loss	PM_{10}/Mass Loss	Comment
2008	63%	60–62%	95–98% from airborne
2016	2–29%	-	-
2017	35–58%	-	-
2019	-	57%	Based on the recovered deposited mass
2020	37%	-	-
2020	<10%	-	-
2019	49%	-	-
2021	-	24–51%	30–40% with CC and HMC
2022	-	28%	Both LM and NAO
2023	-	35–48%	21% for Drum
2023	-	40%	-
2023	-	48–57%	-
2023	-	66%	Six SM and ceramic pads
2023	-	35–40%	Both ECE and NAO
2023	-	25%	NAO

CC = carbon ceramic; HMC = hard metal coated discs; LM = low metallic; NAO = non-asbestos organic; SM = semi-metallic.

Effect of assorted factors during CBDC testing on six light vehicles for CARB

One important aspect of testing to estimate PM10 emissions in mg/km/V against the Euro 7 limit of 7 mg/km/V for ICE vehicles is the ability to assess the vehicle's emissions factor using the front brake emission factor. [7] analyzed this behavior and found the vehicle-to-front-brake ratio average of 2.7:1, ranging from 4.1:1 for a heavily loaded Toyota Sienna to 1:1 for a Toyota Prius at Equivalent Test Weight. The 3:1 rule of thumb used by industry seems like a useful approximation if it is qualified as an estimate. This variation in the EF ratio implies that the engineer has a large margin of uncertainty until comparable results are obtained from both axles (as in light vehicles).

The combination of vehicle size, loading conditions, and friction material is the primary factor that induces variation in the EF. The same study [7] found the PM_{10} EF (mg/km/B) to have a turndown ratio of almost 10:1 for a heavy-loaded F150 using low-met friction compared to a Toyota Prius using NAO brake pads when assessing the results from the front and rear axles independently. Regarding PN EF (#/km/B), the same study reports a turndown ratio of 9:1 for a Toyota Prius with aftermarket NAO brake pads compared to a Toyota Camry with OE NAO brake pads on the front axle. The ratio on the rear axle was 4:1 for a Toyota Camry, using the LM OE brake shoe, compared to the Toyota Prius, which used the OE NAO.

Effects of assorted factors during Caltrans testing on heavy-duty commercial vehicles

The study on heavy-duty vehicles [16] was able to assess the effect of several factors from the vehicle application (axle position, friction material, vocation, and loading) and the test setup (cooling airflow). All the factors, except for friction material type (OEM vs. aftermarket), exhibited significant effects on the EF, as shown in Figure 93. The difference in the PM EF between disc and drum brakes can be attributed to the semi-enclosed condition provided by the drum assembly, which limits the ability of particles to enter the airstream that could carry them outside the brake enclosure and into the sampling train. It is also important to highlight the significant effect cooling airflow may have (see Figure 94) on the EF measured, especially within the PMP TF5, considering the airflow settings for the upcoming UN Regulation for commercial vehicles. One aspect that requires attention is the dual purpose of the cooling air: to provide sufficient air to maintain the brake's thermal regime during testing and to transport particles from the interface to the sampling plane.

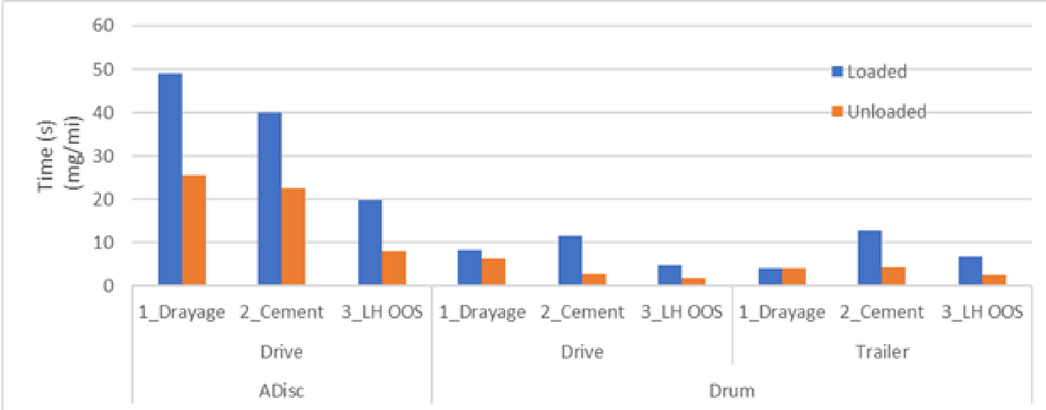


Figure 93 – Effect on emission factor for different axle positions, brake types, and loading

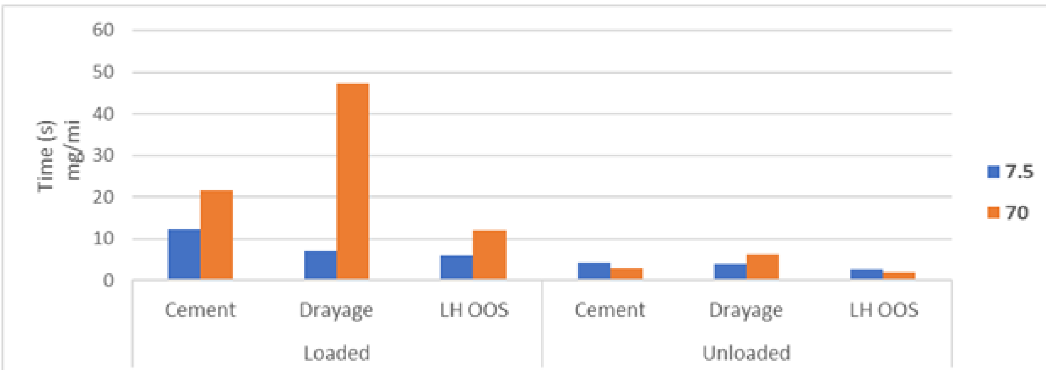


Figure 94 – Effect of airflow level on emission factors

Figure 95 shows the effects and the difference in the $PM_{2.5}/PM_{10}$ ratio, with drum brakes at about 50 %, compared to air disc brakes.

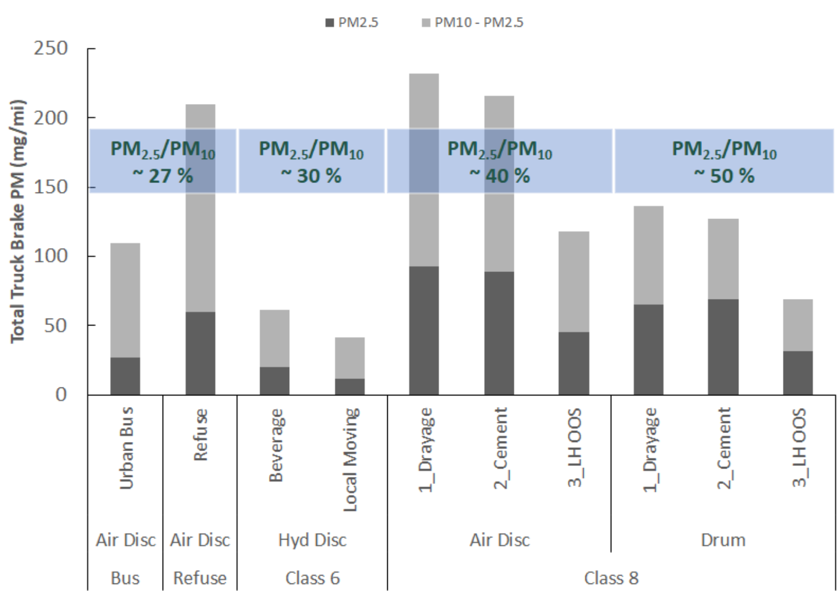


Figure 95 – Effect of airflow level on emission factors

Miscellaneous assessments and comparisons for different strategies to mitigate non-exhaust emissions, as studied by [18]

Table 31 – Compared to ECE pads, the potential reduction of brake emissions with NAO (non-asbestos organic)

Year	PM_{10}	$PM_{2.5}$	PN	Comment
2003	78%	-	-	-
2018	65%	-	-	-
2019	52–84%	42–83%	40–88%	2 × NAO
2020	84–89%	73–76%	75–79%	Pickup truck
2020	22–48%	14–43%	50–58%	2 × NAO
2020	-	-	75%	-
2021	-	-	75%	-
2022	80%	64%	-	-
2022	72–77%	64–78%	-	3 cycles
2023	62%	65%	55%	-
2023	26%	22%	58%	-
2023	55%	-	-	-
2023	-	-	64%	-
2023	62%	55%	-	-

Table 32 – Potential reduction of emissions by replacing gray cast iron (GCI) disks with carbon-ceramic (CC) or hard metal-coated (HMC) disks

Year	Wear	PM_{10}	$PM_{2.5}$	PN	Comment
2017	43–72 %	38–57 %	-	44–67 %	HMC 1
2019	32 %	-	-	-	HMC 2
2020	56 %	-	-	-	HMC 3
2020	21 %	-	-	57 %	HMC 4
2021	78–84 %	94 %	-	83–91 %	CC*
2021	-	74 %	76 %	57 %	CC (+opt. pad)
2021	-	55 %	50 %	(30 % incr.)	HMC 5
2021	-	70 %	63 %	10 %	CC
2021	-	73 %	70 %	89 %	HMC 5
2021	-	90 %	87 %	-	CC
2023	-	79 %	71 %	64 %	CC
2023	-	63 %	-	-	HMC

1 WC/CoCr; 2 Cr_2O_3-40%TiO2; 3 20NiCrBSi-WC12Co; 4 Ni-SF, SFTC; 5 WC; * PM_{10} determined with an electrical low-pressure impactor (ELPI). CC = carbon ceramic; HMC = hard metal coated.

Table 33 – The brake particle collection efficiency of various filters

Year	PM	PN	Filter	Comments
2016	92 %	-	Passive	At the ventilated disc
2020	68–95 %	50–90 %	Active	Grooved pad. 84% at WLTP-B
2020	75 %	40–50 %	Active	Grooved pad. Negligible improvement with passive
2021	20–39 %	-	Passive	Can increase with a smaller gap to the disc
2022	53 %	-	Passive	Ceramic filter porosity 52%
2022	-	50–80 %	Passive	Inertial separator. Above 2.2 µm. WLTP-B
2022	60–75 %	>50 %	Passive	Inertial separator and ESP. Above 0.5 µm. WLTP-B
2023	61 %	-	Active	WLTP-B. Collection efficiency is 80% with continuous sampling.
2023	77 %	-	Active	WLTP-B. Collection efficiency 84% with continuous sampling

ESP = electrostatic precipitator; PM = particulate matter; PN = particle number; WLTP-B = worldwide harmonized light vehicles test procedure brake cycle

Table 34 – Electrified vehicles stock and activity share in 2020's fleet based on the European Commission's (EC) impact assessment study and the expected use of friction brakes depending on the electrification level based on GTR 24. Activity is defined as the multiplication of vehicles and annual km traveled

Category	PCs Share	PCs Activity	LCVs Share	LCVs Activity	Regenerative Braking
Petrol	53.0 %	37.5 %	7.7 %	3.2 %	0 %
Diesel	41.1 %	57.2 %	90.5 %	95.3 %	0 %
HEV	1.5 %	2.0 %	0.3 %	0.4 %	10–48 %
PHEV	0.4 %	0.6 %	0.1 %	0.1 %	66 %
BEV	0.4 %	0.6 %	0.3 %	0.3 %	83 %
other	3.60%	2.00%	1.20%	0.70%	0%

BEV = battery electric vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid vehicle.

Table 35 – Emission factors of electric vehicles for mass (mg/km/V) or particle number (#/km/V). Percentages in parentheses give the emissions reductions compared to their internal combustion engine (ICE) counterpart with full friction braking (i.e., with regenerative braking deactivated)

Year	Type	Pad	Test mass kg	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN × 10^9 #/km/V	Comments
2020	Disc	NAO	1600	2.0–2.3	1.0–1.4	1.3–8.9	PHEV
2021	Disc	n/a	1800	0.9	-	-	BEV
2023	Disc	ECE	1660	5.7 (–62%)	3.4 (–57%)	7.3 (–40%)	PHEV
2023	Disc	ECE	1660	3.1 (–79%)	2.3 (–71%)	2.1 (–82%)	BEV
2023	Disc	ECE	1350	10.5	4.5	141	HEV, Chassis, WLTP-E
2023	Disc	ECE	1228	-	-	0.5* (–4%)	Chassis, WLTP-B
2023	Disc	ECE	1228	-	-	0.5* (–65%)	Chassis, WLTP-E
2023	Disc	ECE	1228	-	-	4* (–90%)	Chassis, RDE
2023	Disc	NAO	1533	0.3 (–86%)	0.14 (–78%)	0.05 (–84%)	PHEV, WLTP-B **

* back-calculated to emissions without regenerative braking and multiplied by 2.83/0.83 to convert to total vehicle emissions from rear brake;
** multiplied by 2.83 to convert to vehicle emissions. n/a = not available.

Table 36 – Summary of estimated emission factors per brake corner (one wheel's braking system, including the brake disc (or drum), caliper, pads (or shoes), and associated wheel-end foundation brake components) for mass (mg/km/B) and particle number (#/km/B

Category	Test mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN × 10^9 #/km/B	Comment
ECE (all)	1902	6.0	2.5	3.9	Average Table 2 on [18]
ECE (PCs)	1752	5.8	2.5	3.5	Average Table 2 on [18]
ECE (LCVs)	2838	7.1	2.7	5.6	Average Table 2 on [18]
ECE	1525	4.7	1.9	3.2	Average Table 2 on [18]
ECE (N1-III)	1760	5.5	2.2	3.7	Average Table 2 on [18]
ECE (N1-III)	2250	7.0	2.9	4.7	Average Table 2 on [18]
NAO	1807	1.7	0.8	0.7	Average Table 2 on [18]
CC and HMC	2152	1.8	1.1	1.0	Average Table 2 on [18]
Drum	1844	0.7	0.5	1.5	Average Table 2 on [18]

B = brake; CC = carbon-ceramic; ECE = Economic Commission for Europe; HMC = hard metal coated; LCV = light commercial vehicle; NAO = non-asbestos organic; PC = passenger car.

Table 37 – Brake emission factors EF at the vehicle level for mass (mg/km/vehicle) and particle number (#/km/V) for different disc and pad combinations. Emission factors per brake EFB are given in Table 11. PC = passenger cars; LCV = light commercial vehicles

Scenario	Test mass kg	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	PN #/km/V	Comments
ECE	1525	13.4	5.5	9.1	EF_B, ECE × 2.83
ECE	1760	15.4	6.3	10.5	EF_B, ECE × 2.83
ECE	2250	19.7	8.1	13.4	EF_B, ECE × 2.83
ECE + Drum	1760	12.2	5.5	10.5	2 × EF_B, ECE + 2 × EF_B, Drum
ECE + Drum	2250	15.3	6.7	12.5	2 × EF_B, ECE + 2 × EF_B, Drum
NAO	all	4.7	2.2	2.1	EF_B, NAO × 2.83
NAO	1525–2250	5.4–7.9	2.5–3.6	4.1–6.0	−60% from ECE
CC/HMC + NAO	all	6.9	3.8	3.5	2 × EF_B, CC + 2 × EF_B, NAO
PC	1525	13.1	5.4	8.9	Fleet activity Table 7 on [18]
LCV	2250	19.6	8	13.4	Fleet activity Table 7 on [18]

Table 38 – Light-duty vehicles' brake emissions based on field studies and receptor modeling (mg/km/V). PC = passenger cars; HDV = heavy-duty vehicles

Year	PM_{10} mg/km/V	$PM_{2.5}$ mg/km/V	Comments
2003	0–80	0–5	Freeway exits, North Carolina, USA
2004	6.9	-	Tunnel London, UK (13% HDV, incl. tire wear)
2010	8	-	Urban, Zurich, CH (9% vans)
2010	1.6	-	Interurban freeway, Zurich, CH (15% vans)
2016	1.6–6	-	Urban and ring road, Paris, France
2016	3.8–4.4	-	Tunnel, London, UK (8% HDVs)
2019	9.2	-	Grenoble, France (PC and HDV)
2020	0.3–1.0	0.1–0.5	Tunnels in four cities in China
2021	12.9	-	Urban, London, UK (3.2% HDV)
2023	4.4–7.4	-	Birmingham, UK (3% HDV)
2023	-	0.28	Urban tunnel, Tianjin, China (gasoline)

The following data focus on laboratory WLTP-B tests conducted with full-enclosed sampling systems at different hybridization levels, expressed as total specific friction work per test. The higher the friction work, the less hybridization there is, while the lowest friction values correspond to BEVs. Results indicate that high electrification (reducing specific friction) can reduce PM10 emissions by 80% through regenerative braking. High PN & PM numbers are associated with brake pad bedding. A comparison between NAO and ECE under conventional operation (maximum specific friction) suggests that PM10 findings from NAO pads can reduce emissions by 64-9898%. See Table 39 derived from [140] .

Table 39 – Specific friction work (SFW) per cycle and emission factors in comparison between ICV, PHEV, and BEV models

Year	Powertrain	SFW J/kg	Axle	Type	Pad	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN #/km/B	Comments
2023	Conventional	15184	F	D	ECE	1660	5.40	2.80	4.30E+09	WLTP-B Segment C
2023	HEV	3618	F	D	ECE	1660	2.00	1.20	2.60E+09	WLTP-B Segment C
2023	BEV	1591	F	D	ECE	1660	1.10	0.80	7.60E+08	WLTP-B Segment C
2024	Conventional	16000	F	D	NAO	1533	1.90	0.61	5.84E+09	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	1.31	0.43	4.13E+09	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.99	0.31	3.00E+09	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	1.00	0.31	2.38E+09	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	1.07	0.34	5.52E+08	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.80	0.24	1.60E+08	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.79	0.23	1.13E+08	WLTP-B

Year	Powertrain	SFW J/kg	Axle	Type	Pad	Mass kg	PM_{10} mg/km/B	$PM_{2.5}$ mg/km/B	PN #/km/B	Comments
2024	Conventional	16000	F	D	NAO	1533	0.74	0.22	8.80E+07	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.37	0.15	5.16E+07	WLTP-B
2024	Conventional	15000	F	D	NAO	1533	0.29	0.12	4.64E+07	WLTP-B
2024	Conventional	15000	F	D	NAO	1533	0.33	0.14	5.15E+07	WLTP-B
2024	Conventional	15000	F	D	NAO	1533	0.22	0.10	4.02E+07	WLTP-B
2024	Conventional	14500	F	D	NAO	1533	0.16	0.09	3.16E+07	WLTP-B
2024	Conventional	14500	F	D	NAO	1533	0.25	0.11	3.83E+07	WLTP-B
2024	Conventional	14500	F	D	NAO	1533	0.09	0.04	1.52E+07	WLTP-B
2024	BEV	1800	F	D	NAO	1533	0.08	0.04	1.40E+07	WLTP-B
2024	BEV	1800	F	D	NAO	1533	0.07	0.03	1.31E+07	WLTP-B
2024	BEV	1800	F	D	NAO	1533	0.10	0.05	1.70E+07	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.12	0.06	2.02E+07	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.10	0.04	1.98E+07	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.73	0.23	3.22E+08	WLTP-B
2024	Conventional	16000	F	D	NAO	1533	0.63	0.19	7.53E+07	WLTP-B

The trailing 0 on some values is to provide alignment for data visualization of the relative magnitudes

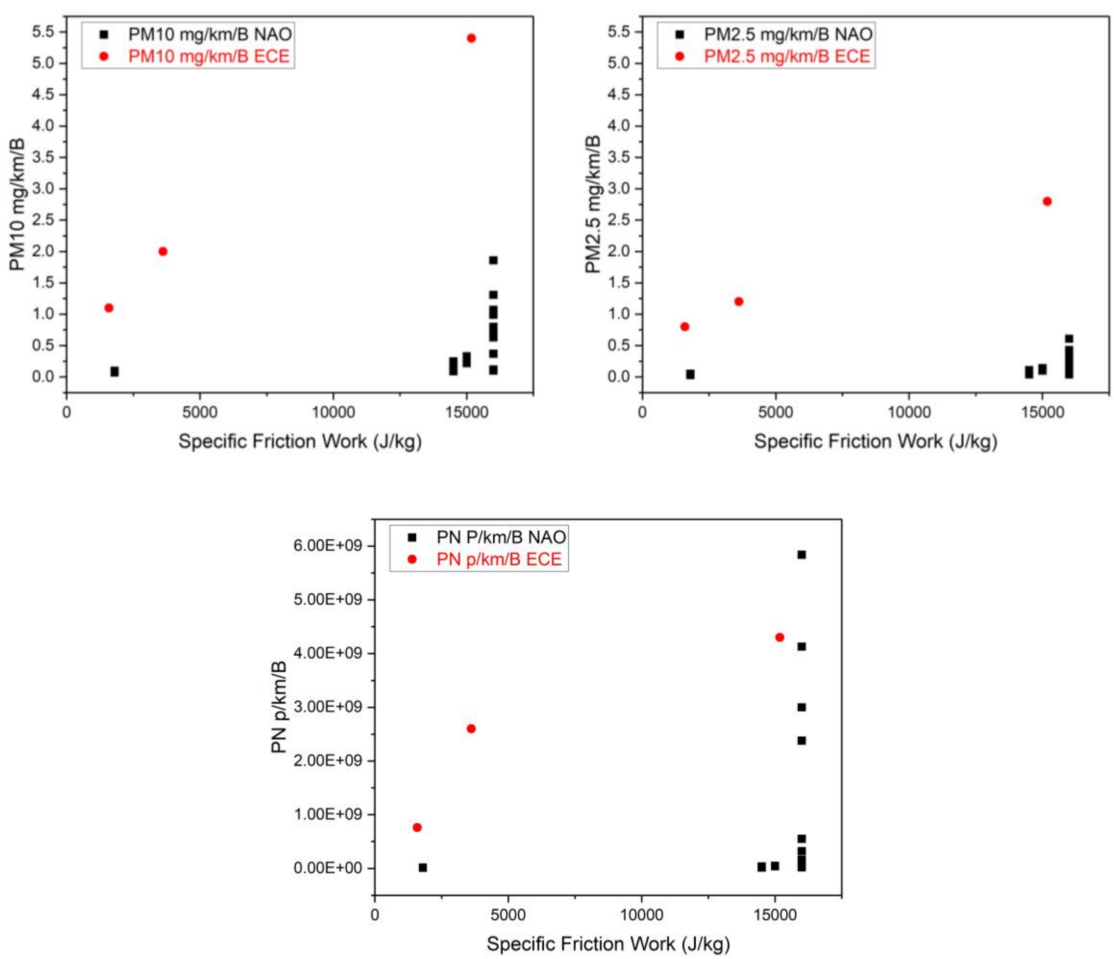


Figure 96 – PM_{10}/$PM_{2.5}$ and PN emission factors as a function of friction work between ICV (high friction), PHEV (medium friction), and BEV (low friction) modes under WLTP-B testing conditions

Systematic assessment of methods to mitigate brake emissions for light-duty vehicles

Other studies, such as [138] report a series of systematic measurements to determine the effect of primary measures to mitigate brake emissions on light-duty vehicles. One of the factors investigated was the effect of recuperation (regenerative braking) for plug-in hybrid and battery-electric vehicles. Figure 97 shows all the deceleration events from the WLTP-B cycle overlayed with the recuperation map (green and orange deceleration vs. velocity curves). Brake events inside the respective curve are performed purely electrically. Those crossing or outside the curve include brake blending or complete takeover by the friction brake, respectively. Table 40 lists factors and test parameters for other investigations during the same study.

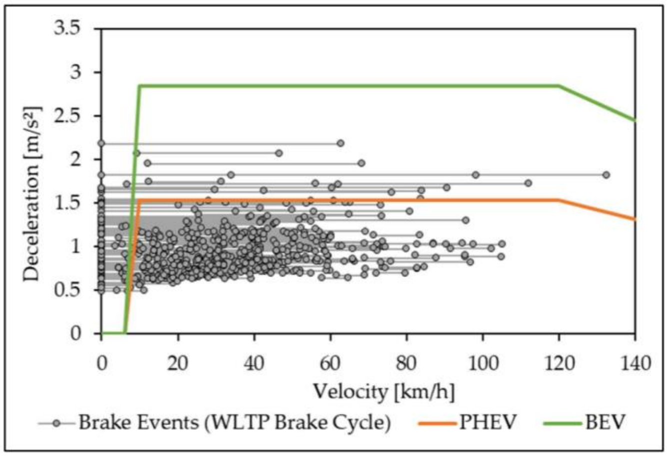


Figure 97 – Recuperation map for the simulation of PHEV and BEV. Image from open source [138]

Table 40 – Description of each investigation's main elements

Investigation	Vehicle parameters	Elements or factors
Total vehicle emissions (front vs. rear emissions)	Vehicle class C; 1660 kg test mass Inertia split FA/RA = 66/33 Disc brake FA and RA	FA disc: Grey Cast Iron ventilated FA pad: standard ECE, NAO, aftermarket RA disc: Grey Cast Iron solid RA pad: standard ECE
Drum brake shoe comparison	Vehicle class C; 2040 kg test mass Inertia split FA/RA = 66/33	RA drum: simplex drum brake RA shoe: pairs 1 & 2 *resembling* low-steel, pair 3 *resembling* NAO
Conventional vs. alternative brake disc	Vehicle class J; 2113 kg test mass Inertia split FA/RA = 60/40	FA disc: Grey Cast Iron, ventilated and Hard Metal Coated ventilated FA pad: ECE and Hybrid
Level of electrification	Vehicle class C; 1660 kg test mass Inertia split FA/RA = 66/33	FA disc: Grey Cast Iron ventilated FA pad: standard ECE Electrification levels: — Internal Combustion Engine Vehicle — Plug-in Hybrid Electric Vehicle; 85 kW — Battery Electric Vehicle; 115 kW

Figure 98 summarizes the findings from five evaluations within the same study, indicating that all considered factors significantly influence the PM and PN emission factors.

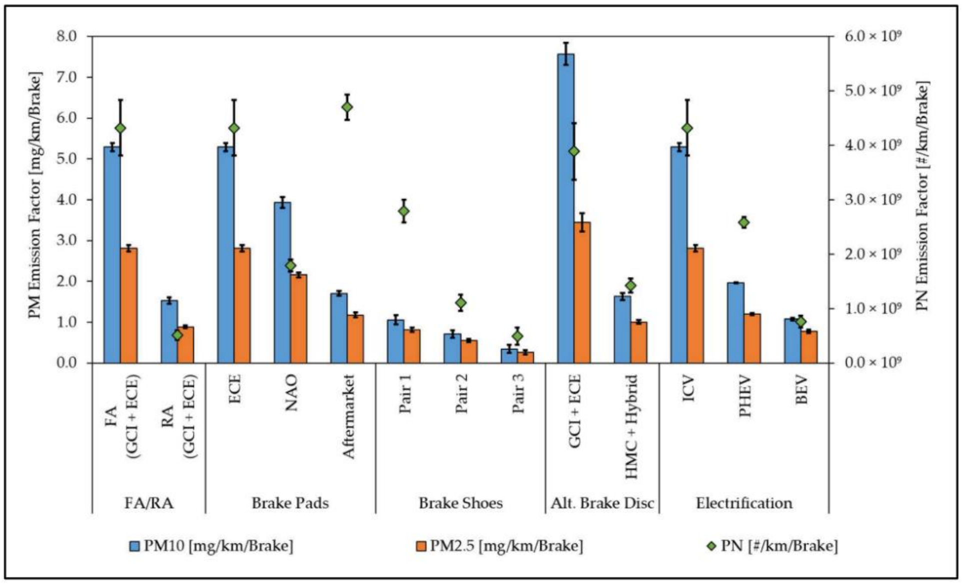
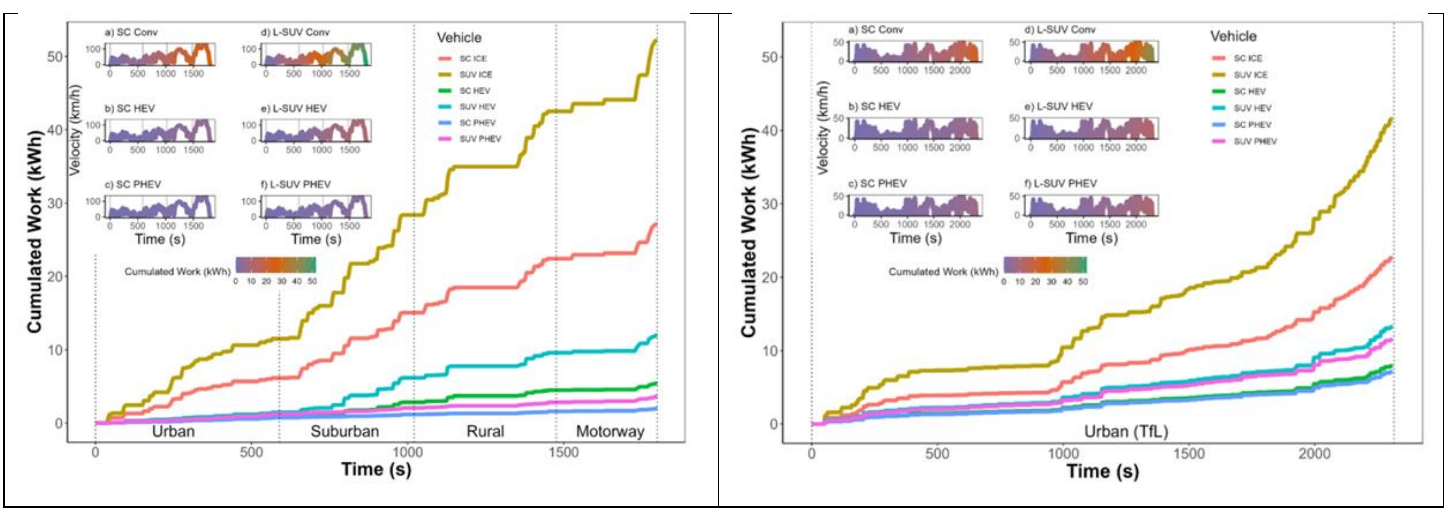


Figure 98 – Overview of reported emission factors and their measurement variability. Image from open source [138]

Using simulation and emissions inventories together

To understand the potential benefits of regenerative braking, academia and others are relying on simulation tools with detailed models of the powertrain, vehicle chassis, and emission factors from the European Environment Agency for Air Pollutant Emission Inventory Guidebook [3]. One simulation study [141] shows that Regenerative Braking Systems would reduce brake wear by 64-95%. The study highlights the effect of aggressive braking on the amount of friction brake power required, with electric powertrains more likely to require friction braking for short, yet aggressive, braking maneuvers. Brake wear reductions varied across different driving conditions, as the level of mitigation depends on the complex interactions among several variables, including vehicle speed, deceleration rate, regenerative braking technology, state of charge, and vehicle mass. Urban brake wear emission factors for electric powertrains ranged from (3.9 to 5.5) mg/km for PM_{10} and 1.5–2.1 mg/km for $PM_{2.5}$, resulting in an average reduction in PM emission factors of 68%. Rural and motorway driving conditions had lower brake wear emission factors, with plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) emitting negligible PM_{10} and $PM_{2.5}$ brake wear. Figure 99 illustrates the time-resolved cumulative work for the two cycles tested (WLTP and TfL UIP).



Left panel: Cumulated friction brake work (kWh) for the assessed vehicle types under the WLTP drive cycle. The WLTP drive cycle has been split into urban, suburban, rural, and motorway segments, separated by vertical dotted lines. The drive cycle inserts plot the velocity (km/h) by time (s) and cumulative brake work (kWh) required for each vehicle class: SC (a–c) and L-SUV vehicles (d–f); ICE powertrains (a,d), HEV

powertrains (b,e), and PHEV powertrains (c,f). Brake power during the WLTP drive cycle ranged from 0.05 MW/km (motorway) for an SC PHEV to 3.5 MW/km (suburban) for an LSUV ICE.
Right panel: Cumulated friction brake work (kWh) for the assessed vehicle types under the urban TfL UIP drive cycle. The drive cycle inserts plot the velocity (km/ h) by time (s) and cumulative brake power (kWh) required for each vehicle class: SC (a–c) and L-SUV vehicles (d–f); ICE powertrains (a,d), HEV powertrains (b,e), and PHEV powertrains (c,f). The SC PHEV requires the least brake power, whereas the L-SUV ICE requires the most. Average friction brake power ranged from 0.8 MW/km for an SC PHEV to 4.7 MW/km for an L-SUV ICE.

Figure 99 – Cumulative friction works by simulating two cycles on multiple vehicle classes. Image from open source [141]

Using chassis dynamometers to compare the effects of different powertrains and disc coatings

A practical use of chassis dynamometers is to study the effects of the native regenerative braking system and vehicle-level effects of coated discs, as studied by [51] using CPC, EEPS, and OPS for a total dynamic range from 4 nm to 10 µm. Table 41 shows the reduction in PN for both experiments. The WLTP Brake – Trip 10 experiment may have failed the pad reset mechanism, resulting in brake drag and increased emissions during the brake-off portions of the cycle.

Table 41 – Percent reduction in PN for different cycles and strategies to reduce emissions

Driving cycle	**Reduction in PN EF due to recuperation %**		**Reduction in PN due to disc coating %**	
	4 nm to 3 µm	**300 nm to 10 µm**	**4 nm to 3 µm**	**300 nm to 10 µm**
WLTC Class 3b	65.4	67.9	18.5	33.9
WLTP Brake – Trip 10	4.3	−15.2	71.7	78.0
Real Driving Cycle	89.9	34.6	78.9	83.0

Figure 100 and Figure 101 show the time-resolved results for the three cycles relative to speed, brake pressure, and PN with OPS and CPC. The temperature trace during the WLTP Brake (labeled as WLTC) shows an unusual brake-temperature behavior, which makes the brake-retraction issue plausible.

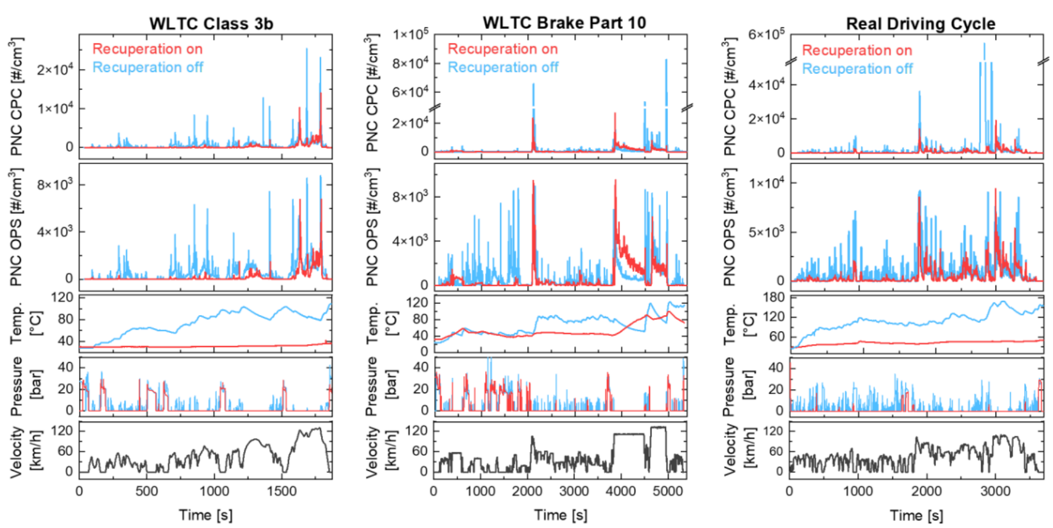


Figure 100 – Comparison of airborne particle emissions for three driving cycles with and without recuperation. Image from open source [51]

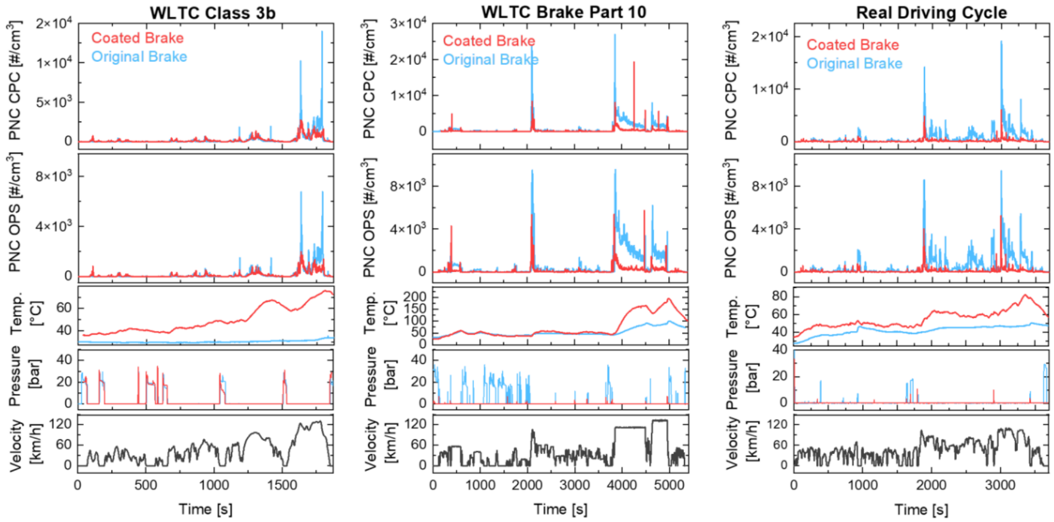


Figure 101 – Comparison of airborne particle emissions for three driving cycles with the original and a coated brake disc. Image from open source [51]

Using brake dynamometers to investigate different factors under reproducibility for the test setup, and facility conditions

Another study involving 31 tests [36] investigated the effect of the cooling airflow at 60 m³/h (JASO C470 method) [142] and 600 m³/h (GTR 24 method) on emission factors. According to the UNECE-PMP-IWG data and findings, the airflow level does not significantly affect PM_{10} or $PM_{2.5}$, has a moderate effect on the brake wear factor, and has a significant effect (12.1:1) on PM0.12, which is close to the 10:1 ratio also observed for cooling airflow. The latter, in the nanoparticle range, accounted for a small fraction of the PM_{10} EF and did not skew the results. See Figure 102.

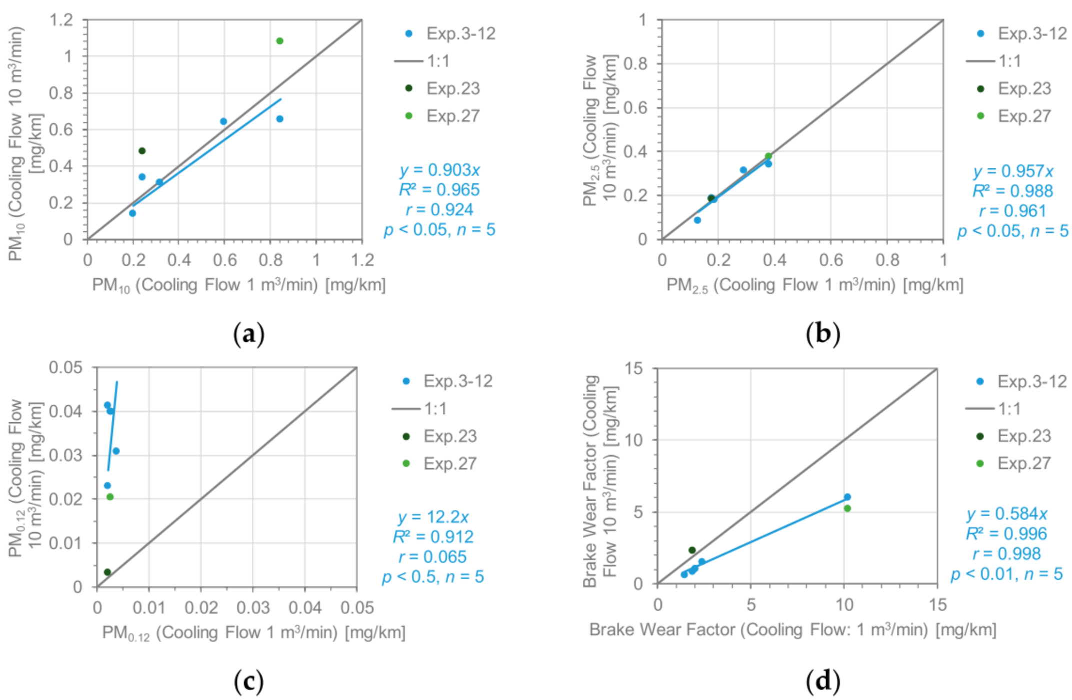


Figure 102 – Comparison of emission factors for (a) PM_{10}, (b) $PM_{2.5}$, (c) $PM_{0.12}$, and (d) brake wear factors with the increase in cooling air flow rate in experiments 3–12. Experiments 23 and 27 are shown for comparison, as described in the study. Image from open source [36]

17.7.2 Tires

From contributions of tires to microplastics and air pollution

[18] found no studies on the impact of a vehicle's electrification level on tire emissions, an important topic based on the rapid increase in electric vehicles. Most studies assume that the increase is due to the higher mass of electric vehicles compared to equivalent vehicles with conventional fuel engines. A positive relationship exists between vehicle mass and non-exhaust emissions, especially for PM derived from dust resuspension (e.g., an electric vehicle with a 20 % higher mass than two internal combustion engine vehicles had (25 to 30) % higher tire abrasion). Also, a monitoring study of 76 taxis (all vehicles in the study were fitted with 205/55R16 94V tires and had similar curb masses) found, on average, 72 mg/km per vehicle for hybrids and 53 mg/km per vehicle for taxis with only an internal combustion engine. Subgroup A of the data, consisting of taxis with only internal combustion engines, measured 53 mg/km per vehicle for summer tires, 112 mg/km per vehicle for all-season tires, and 160 mg/km for winter tires. Factors of 3:1 and 5:1 in favor of winter tires over summer tires were also reported in other studies. When considering multiple tires, they tend to reduce (e.g., <5% for 205/55 R16 tires and 23% for 185/65 R14 tires).

Another factor from the same study highlights differences in abrasion levels across vehicle categories. A study in South Korea for light commercial vehicles (assuming tire replacement around 94,000 km) found tires losing 14 % of their mass (25 kg) with:

- 224 mg/km/V for light commercial vehicles (six tires per vehicle)
- 800 mg/km/V for buses (six tires per vehicle); about 2.5 times compared to passenger cars
- 950 mg/km/V for trucks (eight tires per vehicle); about 8 to 11 times compared to passenger cars

The difference is expected to decrease after normalizing the abrasion levels to mg/km/t.

The location of the measurement site and [18] references studies comparing road-deposited sediments at curves or traffic light spots, which show much higher concentrations of tire wear particles than, e.g., in parks. More tire wear particles were found within roadside drains where driving required increased braking and accelerating than within the drains of roads with high traffic densities [143]. Another study demonstrated that high traffic volume and maneuvering density resulted in higher emissions of brake, tire, and road particles than at other sampling sites. Table 42, using data from [18] provides a qualitative analysis of the parameters influencing tire abrasion and PM emission levels. [18] also includes a comprehensive citation of studies that assessed each factor. The (+) markers are our work to ease readability.

Table 42 – Potential impact on tire abrasion from several factors

Influencing Factor	Impact from	Impact on Abrasion
Tire	Construction and structure	+ + + +
	Tire size (surface area)	+ +
	Summer, winter, studded	+ + +
	Treadwear resistance[1]	+ + +
	Driving distance and aging	+ +
	Tire pressure	+ / + +
	Tire storage before installation	+
Vehicle	Weight (tire load)	+ + +
	Suspension (toe angle)	+ + +
	Suspension (camber angle)	+
	Vehicle control (hybrids)	+ / + +
Road [2]	Surface (micro and macro)	+ + + +
	Material/binder	+ + +
	Road dust loading	+
Driving style	Speed	+ +
	Acceleration, longitudinal	+ + +
	Acceleration lateral, cornering[3]	+ + + +

Influencing Factor	Impact from	Impact on Abrasion
	Braking	+ + +
Environment	Ambient temperature	+ + +
	Humidity/wetness	+ / + +

(+) low; (+ +) medium; (+ + +) high; (+ + + +) very high
[1] includes chemical composition; [2] includes road curvature included in lateral acceleration; [3] includes slip angle variations

[138]Describes some of the main parameters influencing PM_{10} and particulate tire wear emissions (≤ 10 µm). Since the experimental designs, particle types, and sizes differ across studies, the tabulation considers only qualitative results that were consistent across many studies. Table 43 shows an extract and simplified findings.

Table 43 – Parameters that affect PM_{10} and particulate tire wear emissions

Category	Parameter	Factor	Effect
Vehicle/driving style	Driving speed	↗ Driving speed	↗ Particulate tire wear and PM_{10} emissions
		↗ Driving speed	↘ Average particle size of PM_{10} emissions
	Longitudinal force (acceleration/braking event)	↗ Longitudinal force	↗ PM_{10} emissions
		Lower longitudinal force at a higher speed v high longitudinal force at low speed	→ PM_{10} emissions
	Lateral force (cornering)	↗ Lateral force	↗ Particulate tire wear and PM_{10} emissions
		↗ Superimposing cornering and acceleration/braking	↗ Emissions
	Vehicle load	↗ vehicle load at constant tire pressure	↗ Particulate tire wear and PM_{10} emissions
Road	Road profile	no direct influence	Particulate tire wear and PM_{10} emissions vary
		Definition of the number and intensity of corners, brake/acceleration events, and driving speed	Particulate tire wear and PM_{10} emissions vary
		Traffic situation	Particulate tire wear and PM_{10} emissions vary
		Superimposition and variability of parameters	Ranking of EF for rural, urban, and highway sections is not possible
	Road surface texture	↗ Surface roughness	↗ Particulate tire wear and PM_{10} emissions
		↗ Surface roughness	↗ Average particle size of particulate tire wear
	Road surface type	Asphalt v pavement	Particulate tire wear emissions are ambiguous
Tire	Inflation pressure (examined in conjunction with vehicle load)	↗ Inflation pressure	↘ Particulate tire wear emissions
		↗ Inflation pressure	↗ PM10 emissions
	Composition	Studded > winter > all-season > summer tire	↘ Particulate tire wear emissions
Environmental conditions	Humidity	Humidity amount	Particulate tire wear and PM_{10} emissions unknown
		↗ Humidity amount	↘ Average particle size (< 10 to > 400) µm
	Temperature	↗ Temperature	↗ Particulate tire wear and PM_{10} emissions (summer and winter tires)
		↗ Temperature	↗ Particular tire wear emissions (<18 µm) on custom-made tire material

The study from [14] used the tire wear emission factor (EF) to represent the tire wear per kilometer traveled for one tire (g/tire/km). Some factors that directly influence the EF include driving style, road conditions, weather, and tire positioning (e.g., driven or steering axle), which can affect wear. The EF averages across various drivers, vehicles, and road conditions to be applicable for estimating tire wear. Any subdivision into groups should be done carefully to ensure the validity of the specific wear emission factor. This study categorized different vehicle types, including passenger cars and tire types. Since tire wear is influenced by acceleration, braking, and steering frequency and severity, which differ on different road classes, another important factor is the road class: urban, rural, and motorway, each with a different mix of speeds, longitudinal, and lateral accelerations

17.8 Future work and research

Environmentally optimal tires and brakes

[2] is a major study focused on the UK market, covering multiple dimensions of tires and brakes from an environmental perspective. After a literature review, it offers chapters on the following topics related to manufacture, use, and disposal:

- Characteristics of environmentally optimal tires and brakes
- Assessment of current and proposed regulations and standards
- Performance optimization, trade-off, and conflicts
- Performance of tires and brakes currently on sale and in use
- consumer awareness of environmental impacts
- Influence of driver behavior
- Influence of road surface and design
- Key findings for tires, brakes, and surface
- Regulations and standards index

Microplastics from tire and road wear

[144] is a major study on microplastics in Sweden, considering multiple aspects including: sources, dispersal and presence; effects and risks, characteristics and chemical composition of tires and road markings; tire and road wear factors and ways to calculate; sampling methods for tire, road markings, road dust, soil, deposition, and a, runoff from roads, drainage, and sediment; and, methods for preparation and analysis of samples. The main drivers for the future studies relate to: i) the high cost of current non-standardized sampling and analysis techniques, ii) the complexity of the microplastics topics, and iii) the small number of well-rounded and current studies. Amongst the research, development, evaluation needs, and knowledge requirements are the following, *verbatim* for topics aligned with the scope of this systematic review:

(a) There is a need for both laboratory studies (e.g., measuring sorption, density, and size changes over time and under different conditions, and degradation tests) and field studies (measuring concentration, size distribution, distribution of various types of microplastic particles, etc., in different environments). There is also a need for the development of models (for estimation of expected dispersal pathways, concentrations, and exposure in other representative environments)

(b) Validated, faster, more automated, and more standardized methods for sampling, preparation, and analysis of microplastic particles from road traffic need to be developed for the determination of shape, size, number, chemical composition, mass, etc. of the particles. This is required, for example, to enable comparisons of findings across studies, increase our understanding of the presence and spread, and facilitate a more accurate evaluation of risks.

(c) Analyses are often limited to particles within a limited size or density interval, which also makes comparison difficult. For this reason, the size and density of the analyzed particles should also be standardized to enable comparisons across studies and to increase our understanding of the presence and spread of particles in various media (water, sediments, soil, and air). To measure particles across broader size and density intervals, it is essential to enable both assessing overall presence and modeling spread and distribution across different media.

(d) Different measures for reducing the generation and spread of microplastic particles from road traffic should be identified and evaluated. For example, studies on the relationships between measures and effects regarding emissions and driving behavior, tire types, road surface materials, tire pressure, wheel alignment, and road surface structure are needed.
(e) There are significant uncertainties in the calculation methods and models used to assess the contribution of tire and road wear particles to emissions, and how this varies, for instance, for different types of tires, road surfaces, driving behavior, seasons, and tire air pressure. These methods should, therefore, be improved and validated.
(f) To assess the tire wear in the road environment, and how it influences the generation of microparticles from tire wear, measurements need to be carried out in controlled driving simulation studies and the field, on various types of roads, road surfaces, in different weather conditions, and for other types of tires.
(g) Knowledge is needed on what policy instruments, and types of policy instruments, are the most appropriate to achieve desired outcomes under different circumstances. In some situations, financial or legislative instruments may be more suitable; in others, increased information and data from research may be more appropriate. There may also be situations where a combination of different instruments is the best option.

Other topics not mentioned in the study, yet already being considered in others, include:

- Better understanding of overall tire emissions from commercial vehicles
- Assessment of lifetime effects of vehicle electrification
- Wear effects (on tire and road) from the increased use of super-single tires for commercial vehicles

Some potential routes described by [2] to reduce the environmental impacts of the different phases, including the ones listed in Table 44. Some strategies (primarily for tires) address environmental effects, including Greenhouse Gas emissions.

Table 44 – Potential routes or strategies to reduce particulate matter and Greenhouse Gases (GHG) tire and brake emissions during their lifecycle

Phase	Tires	Brakes
Manufacture	− Product development must move towards sustainably sourced, low-GHG-impact materials and low-carbon energy sources − Reduce reliance on crude oil processing during manufacturing or synthetic rubber; manufacturing is the second most polluting life cycle phase − Consider bio-based (Guayule) alternatives to synthetic rubber. Bio-based rubber is expected to produce lower harmful PM/PN emissions than synthetic rubber. Without counting land use or biomass management, Guayule rubber could reduce CO_2 by 50 % over its life cycle − Green silica: Substitute traditional carbon black with green silica to reduce abrasion and particle release. Research alternatives to carbon black, such as HD-HS silica, to provide a 25 % saving in GHG and 10 % in rubber consumption − Improved tread design: Optimize tread patterns to minimize mechanical wear and reduce particle shedding. − Alternative rubber matrices: Explore bio-based or synthetic alternatives with lower wear rates	− Product development needs to move towards sustainable production through minimizing the use of scarce (or emitting) resources and energy, − Developing products that use sustainably sourced, low-GHG-impact materials − Since the manufacturing of discs/drums and pads/shoes is the most polluting life cycle phase, innovative formulations and designs are needed to reduce the overall environmental footprint − Based on limited studies, consider reducing environmental burdens by reducing global warming potential (GWP), acidification and cumulative energy demand (accounting for high energy demand in the production of brake discs) and mineral scarcity (accounting for production of iron, brass, tungsten and cobalt required for brake pad production).
Use	− Reducing rolling resistance and impact on GHG by optimizing tire materials' composition and tread design while considering any trade-off with wet grip (safety) and noise	− alternative pad materials, disc coatings, and regenerative braking, while meeting safety requirements − Driver demands for braking performance and minimizing the use of toxic substances of concern

Phase	Tires	Brakes
	− Emerging and new technologies may enable further optimization of tire design to reduce cumulative energy demand (CED) − Better understand the nanoparticle size distribution, chemical speciation of metals, and organic compounds of the different materials that go into the manufacture of tires	− Emerging technologies may enable lower emissions and more sustainable friction materials − Expand LCA for formulations beyond semi-metallic brake pads to include other legacy and new formulations and drum brakes − Better understand the nanoparticle size distribution, chemical speciation of metals, and organic compounds of the different materials that go into the manufacture of consumable brake components (discs, drums, pads, and brake shoes) − An increase in local temperatures of just +15 °C over a critical temperature (typically between 150-250°C) has been found to exacerbate brake wear particle number emissions by about 5000 times. These temperatures can be reached in high-speed or repeated braking conditions, even during normal driving or slope (hilly routes) descent. Therefore, formulations and design considerations that facilitate local temperature dissipation/ diffusion when brakes are engaged are crucial for reducing brake wear and improving dust control.
End-of-Life	− Circular economy strategies for tires should minimize unwanted environmental impacts and exploit emerging technologies, including maximizing the use of tires (e.g., through safe part-worn and re-treaded tires, recycling of tire carcasses and materials, and maximizing the energy extracted with minimal environmental impact) − Reduce incineration without energy recovery (ER) by increasing uses in civil engineering (modified asphalt) or synthetic flooring − While carbon black is recyclable, consider pyrolysis of ELT that generates pyrolysis oil to produce an alternative fluid for industrial use	− Further recycling within circular economy strategies for brakes could utilize emerging technologies, including disc remanufacturing, pad material extraction and recycling, and maximizing the energy extracted with minimal environmental impact − None of the studies provides a comprehensive coverage of EoL routes for brake discs and pads. Despite including this life cycle stage in the analysis, there is no compelling evidence of a significant environmental impact from this stage, despite the current global practice of disposing of used and worn-out brake pads in landfills. This topic deserves further evaluation, with emphasis on larger brakes for commercial vehicles
Other factors and considerations	− Nanomaterials: silica and nanoclay as fillers − Green silica − Improved tread design − Elimination of vent spews − Porous tread tires − Non-pneumatic (airless) tires − Alternative rubber matrix materials − Other natural reinforcing fillers − Materials to improve aging resistance to biological degradation, UV light, moisture, and oxidation − Self-healing materials − Retreaded tires − Recyclability and use of recycled content	− Brake system design − Disc materials − Alternative binders − Temperature constraints (formulation, cooling, mechatronics for thermal balance) − Coated discs − Alternative disc and pad materials − Natural binders − Zero-drag brakes − Natural fibers − Active and passive filters − Regenerative braking − Enclosed, wet, or driveline brakes

Potential future work for consideration within the CRC

From the broad knowledge gained during this systematic review and the interactions with the industry,

Table 45 summarizes some proposals (from the authors) for future research or studies sponsored or supported by the CRC for brakes. Before proceeding to the next phase, these proposals would require feasibility evaluations and alignment with the CRC's technical or research roadmap.

Table 45 – Possible projects for brakes

Project # 1	**Design, validation, and use of in-vehicle sampling systems**
Why (justification)	1. Many aspects still need vehicle-level measurements 2. All extraction and sampling devices thus far are one-off designs 3. There are no established methods to assess extraction and sampling efficiency for nano- and micron-size ranges 4. Lack of standard setup for brake dynamometer testing extending beyond GTR 24 (gravimetric PN, TPN10, and SPN10)
How (approach)	5. Invite all parties interested to present their operational or intended designs. 6. Define high-level requirements for the intended vehicle, route, or test setup, and test cycle 7. Define qualifying criteria for the intended measurements (e.g., gravimetric, particle count, PSD, organics, metals, electrical change) 8. Set up experimental validation of particle extraction and transport efficiency 9. Collaborate with CARB, EPA, and industry consortia 10. Baseline on a standard GTR 24 setup
What (deliverables)	11. Agnostic standard protocol with minimum requirements, guidelines, and best practices (there may be more than one design for different purposes) 12. Technical report with experimental validation of the protocol 13. Make it mandatory for all future in-vehicle testing
Project # 2	**Minimum requirements for reporting results from non-Euro 7 tests**
Why (justification)	1. Significant difficulties comparing results from different studies 2. Lack of proper mechanisms to validate the results from the study 3. Lack of transparency in documenting and reporting test setup, test cycle, and test conditions
How (approach)	4. Develop a taxonomy for the type of test, test vehicle, and test measurements 5. Invite *leading* stakeholders to contribute (with experimental results) to the definition of minimum reporting requirements per the taxonomy developed in item 4 6. Invite *other* stakeholders to apply the reporting protocol to experimental results
What (deliverables)	7. Taxonomy of types of test reports 8. Protocol with requirements, calculations, output metrics, and quality controls 9. Technical reports with numerical examples
Project # 3	**Cross-section of emission factors for main emission mitigation strategies**
Why (justification)	1. Lack of systematic evaluation of the potential reduction of brake emissions for current technology developments 2. Lack of a common method to rank and compare the feasibility of technical solutions (or combinations of) 3. Need to understand technical systems or redesign in light of potential rulemaking with limits
How (approach)	4. Create an inventory of all technical solutions that are test-ready by TBD 5. Invite all parties interested to present their technical solution (e.g., regen and mechatronics, formulations and coatings, filtration devices, new braking concepts) 6. Create a project to test utilizing outputs from projects #1 and #2
What (deliverables)	7. Inventory of technical solutions to reduce brake emissions 8. Benchmarking with current product designs and formulations 9. Baseline for potential limits during rulemaking
Project # 4	**Baseline of organic compounds, chemical speciation with metal content, morphology with particle density, and electrical charge for representative vehicles (and propulsion systems) and friction couples on the U.S. market**

Table 46 Indicates the potential projects for tires.

Table 46 – Possible projects for tires

Project # 1	**Design, validation, and use of in-vehicle and laboratory testing sampling systems**
Why (justification)	1. Many aspects still need vehicle-level measurements with subsequent laboratory testing 2. All extraction and sampling devices thus far are one-off designs 3. There are no established methods to assess extraction and sampling efficiency for nano- and micron-size ranges

How (approach)	4. Invite all parties interested to present their operational or intended designs. 5. Define high-level requirements for the intended vehicle, route, or test setup, and test cycle 6. Define qualifying criteria for the intended measurements (e.g., gravimetric, particle count, PSD, organics, metals, electrical change) 7. Set up experimental validation of particle extraction and transport efficiency 8. Collaborate with CARB, EPA, and industry consortia
What (deliverables)	9. Agnostic standard protocol with minimum requirements, guidelines, and best practices (there may be more than one design for different purposes) 10. Technical report with experimental validation of the protocol 11. Make it mandatory for all future in-vehicle testing
Project # 2	**Minimum requirements for reporting results from non-Euro 7 tests**
Why (justification)	1. Significant difficulties comparing results from different studies 2. Lack of proper mechanisms to validate the results from the study 3. Lack of transparency in documenting and reporting test setup, test cycle, and test conditions
How (approach)	4. Develop a taxonomy for the type of test, test vehicle, and test measurements 5. Invite *leading* stakeholders to contribute (with experimental results) to the definition of minimum reporting requirements per the taxonomy developed in item 4 6. Invite *other* stakeholders to apply the reporting protocol to experimental results
What (deliverables)	7. Taxonomy of types of test reports 8. Protocol with requirements, calculations, output metrics, and quality controls 9. Technical reports with numerical examples
Project # 3	**Cross-section of emission factors for main abrasion reduction and emission mitigation strategies**
Why (justification)	1. Lack of systematic evaluation of the potential reduction of tire abrasion and emissions for current technology developments 2. Lack of a common method to rank and compare the feasibility of technical solutions (or combinations of) 3. Need to understand technical systems or redesign in light of potential rulemaking
How (approach)	4. Create an inventory of all technical solutions that are test-ready by TBD 5. Invite all parties interested to present their technical solution (e.g., designs, compounds, filtration devices, new tire concepts) 6. Create a project to test utilizing outputs from projects #1 and #2
What (deliverables)	7. Inventory of technical solutions to reduce tire abrasion and emissions 8. Benchmarking with current product designs and formulations 9. Baseline for potential limits during rulemaking
Project # 4	**Baseline of organic compounds, chemical speciation with metal content, morphology with particle density, and electrical charge for representative tires (and propulsion systems) and vehicle applications on the U.S. market**
Project # 5	**Build an *inventory/library* of physical samples of the predominant popular tire designs, sizes, and compositions, road surfaces, soil, and other microplastic sources from the road (e.g., lane markings)**
Project # 6	**Benchmark U.S. driving circuits with Euro 7 metrics for tire abrasion and potential compression for laboratory or tire emissions tests**
Project # 7	**Benchmarking of new propulsion systems (including solutions for vehicle electrification) and their impact on tire abrasion, tire emissions, and road emissions on different vehicle categories and tire designs**

17.9 Who's Who

Below is a list of the **main government agencies, research institutions, and industry consortia** involved in brake and tire emissions research across the U.S., Europe, China, Japan, and South Korea. For other industry consortia active on non-exhaust emissions, reference paragraph 3:

17.9.1 United States

Entity	Names / Contacts	Site	Main Objectives
U.S. Environmental Protection Agency (EPA)	Office of Transportation and Air Quality (OTAQ)	epa.gov/otaq	Develops the MOVES model; regulates and studies non-tailpipe emissions; supports brake and tire wear research.
California Air Resources Board (CARB)	Research Division	ww2.arb.ca.gov	Developed the California Brake Dynamometer Cycle (CBDC); funds and oversees brake/tire emissions studies.
Caltrans (California Department of Transportation)	Environmental Division	dot.ca.gov	Conducted brake temperature and emissions studies for heavy-duty vehicles.
UCR CE-CERT (University of California, Riverside)	Zisimos Toumasatos, Georgios Karavalakis, Kent Johnson	cert.ucr.edu	Lead academic partner in CRC E-143; conducts brake and tire emissions testing and modeling.
USTMA (U.S. Tire Manufacturers Association)	Tracey Norberg tnorberg@ustires.org	Ustires.org	National trade association for tire manufacturers that produce tires in the United States

17.9.2 Europe

Entity	Names / Contacts	Site	Main Objectives
European Commission – JRC (Joint Research Centre)	B. Giechaskiel, G. Trentadau R. Vedula	joint-research-centre.ec.europa.eu	Leads GTR 24 development; coordinates interlaboratory studies on brake emissions.
UNECE GRPE / GRBP	Informal Working Groups (PMP, TF3, TF5, TF TA)	wiki.unece.org	Develops global technical regulations (e.g., GTR 24 for brakes, UNR 117 for tires).
EEA (European Environment Agency)	Air Quality Division	eea.europa.eu	Maintains emission inventories (e.g., COPERT); supports non-exhaust PM modeling.
ETRTO (European Tyre and Rim Technical Organisation)	Technical Committee	etrto.org	Provides tire specifications and supports the Euro 7 tire abrasion regulation.
TIP (Tire Industry Project)	Larisa Kryachkova kryachkova@wbcsd.org	tireindustryproject.org	anticipate, understand, and address global environmental, social, and governance (ESG) issues relevant to the tire industry and its value chain

17.9.3 Japan

Entity	Names / Contacts	Site	Main Objectives
JATMA (Japan Automobile Tyre Manufacturers Association)	Technical Committee	jatma.or.jp	Participates in tire abrasion studies and Euro 7 regulatory development.
JASIC (Japan Automobile Standards Internationalization Center)	Standards Division	jasic.org	Supports harmonization of vehicle standards, including non-exhaust emissions.
JARI (Japan Automobile Research Institute)	H. Hagino	Jari.or.jp/en/	testing and evaluation of technology related to automobiles

17.9.4 South Korea

| **Entity** | **Korean Ministry of Environment / KATECH** | me.go.kr / katech.re.kr | Conducts tire and brake emissions research; supports international regulatory alignment. |

17.9.5 China

| **Entity** | **CATARC (China Automotive Technology and Research Center)** | catarc.ac.cn | Leads national research on vehicle emissions, including non-exhaust sources. |

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SUPPLEMENTAL INFORMATION

Tabular summary of studies investigating particulate matter emissions

This addendum is an integral part of the main report, outlining key items from several studies relevant to brake, tire, and road particulate matter emissions. The studies are listed in chronological order of publication, from most recent to oldest. To ensure fidelity, the content of this tabular summary includes some verbatim text from the original study. The selection of studies included in this supplement focuses on new methodologies or measurement methods, as well as correlations or comparisons with vehicle or field measurements, and environmental effects and possible strategies to mitigate non-exhaust emissions.

Year	Ref.	Conclusions and Recommendations (excerpt)
2025	[145]	**Knowledge gaps** A considerable lack of data on particle chemical composition, the emission rates, environmental factors, driving behaviors, and the influence of different components and materials on the dispersion of the emissions The variability in the NEE data that exists in terms of collection, processing, and reporting The inconsistent or improper monitoring of NEEs across European cities remains a barrier to effective policymaking **Recommendations at a local level** NEEs from road transport are one of the major sources of air pollution in their cities, and incorporating NEEs into urban planning Policymakers must take proactive measures at the local level to tackle NEEs, as relying on Euro 7 will not be enough Controlling traffic volume and flow, reducing vehicle speeds, and promoting smoother driving styles in the short term In parallel, it is recommended to launch public awareness campaigns to educate the public on the environmental issues (including air, soil, and water) Put measures in place that limit or penalize heavier combustion vehicles Fleet electrification will overall benefit NEEs, at least in urban areas where the use of regenerative braking is more extensive and significantly reduces brake wear Prioritize the proper maintenance of the cities' roads, as this is the most effective measure against road wear in the short term **Recommendations at a national level** Advocating for the establishment of effective and timely enforcement mechanisms, such as consistent emissions monitoring and compliance testing. At the same time, increasing public awareness and supporting original equipment manufacturers (OEMs) in adapting to the new standards is also essential for the smooth, gradual integration of not only the impending and future limits but also the latest technological solutions necessary to accomplish them The promotion of wear-resistant components and materials for brakes and tires Support national research programs focused on improving the durability and performance of wear-resistant components, ensuring that new materials do not introduce unintended negative effects (e.g., increased toxicity) encourage the establishment of national databases for tracking NEE emissions and mitigation efforts, ensuring data consistency and comparability across regions The exploration of public procurement policies that prioritize low-wear vehicles and road maintenance strategies in publicly funded transport and infrastructure projects **Recommendations at an international level** Engage in discussions and cooperate on the development of standard monitoring and harmonized measurement protocols for brake, tyre, and road wear emissions Regulations such as the EU's REACH regulation, which already addresses the risks posed by hazardous chemicals, including those used in tyre production, could serve as a foundation for developing future complementary rules to address the tradeoffs between wear and toxicity over component/vehicle lifetime to evaluate long-term environmental impacts

Year	Ref.	Conclusions and Recommendations (excerpt)
		Promoting the need for new, definitive conclusions on measures like wear-resistant components and materials (e.g., brake pads, low-density vehicle materials, tire formulations), road run-off treating, and particle collection or filtration devices Securing sufficient funding for research and development, as well as supporting on-road measurements, is also crucial for closing the knowledge gaps on NEEs and the effectiveness of potential measures. Policymakers can push for global funding mechanisms to support innovation and advocate for global industry cooperation in designing and testing next-generation tires and brake components with reduced wear and toxicity. Policymakers may support international partnerships for large-scale studies on NEE health and environmental effects, as well as fostering industry-academia collaboration to accelerate innovation and policy adaptation In conclusion, addressing NEEs is crucial for achieving sustainable improvements in urban air quality and protecting public health. Policymakers need to recognize that Euro 7 alone is not a standalone solution, but rather a starting point that necessitates additional actions to achieve meaningful environmental solutions promptly. Targeted interventions, supported by robust policies, innovation, and international collaboration, can pave the way for a cleaner and healthier future. Intervention strategies should be regularly evaluated and refined as new data and technologies emerge to ensure alignment with air quality targets and public health goals

Each entry in the table below includes the following:

Year	Year of publication
Reference	[XXX] independent of the reference numbering from the main report
Source	System or component under testing and measurement
Parameters Examined	Main effects or outcomes of the testing and measurement
Testing or Evaluation Conditions	Main elements of the test setup or evaluation methods
Main Conclusions	Key findings from the study relevant to this report

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
2025	[146]	Modelling of TWP	This study projects TWP emissions in the United States until 2044, using the Motor Vehicle Emission Simulator (MOVES) model	MOVES relies on historical data, trends in vehicle usage, advancements in technology, improvements in fuel economy, and regulatory changes. MOVES accounts for population and economic growth, cleaner vehicle technologies, and shifts toward lower-emission fuels The two critical factors used in MOVES projections, the population of vehicles and annual mileage traveled, are based on the U.S. Department of Energy's Annual Energy Outlook (EIA, 2023) The study updated MOVES to consider additional tire wear due to increased EV vehicle weight The study parameterized the emissions rates (g/h) of ($PM_{2.5}$ TWP) and (PM_{10} TWP) as a function of vehicle mass (kg). Additionally,	EVs are projected to contribute up to 40% of tire wear particle emissions by 2044 TWP emissions from ICEVs will decrease by 18 % Total TWP emissions from EVs could rise 17-fold in the next 20 years $PM_{2.5}$ emissions from EVs may increase from 0.1 kt in 2024 to nearly 2.0 kt in 2044, while PM_{10} emissions may increase from 0.2 kt in 2024 to almost 3.1 kt in 2044 Innovations in tire design and lighter vehicles are crucial to reducing TWP emissions Since the study does not account for the extra torque at low speed in EVs, the true difference between ICEV and EV emissions is likely greater The study compared MOVES' airborne TWP estimates with those from other studies, using both a bottom-up approach with the GAINS model and a top-down method based on the TWP/CO_2 ratio. The simulation for

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
				it is estimated that EVs in the U.S. are, on average, 43 % heavier than similarly sized (using vehicle volume as the comparison metric) ICEVs	the year 2014 estimated $PM_{2.5}$ TWP emissions in the U.S. at 3.5 kilotons (kt), which is reasonably consistent with the geometric average $PM_{2.5}$ TWP of 6.4 kt (range: 2.6–16 kt), underscoring the validity of our approach and highlighting its potential for future refinement.
2024	[147]	Tire and Road field samples	TRWP analysis using Py-GC/MS and particulate Zinc method TOC, DOC, TSS NR to SBR/BR ratios	TRWP along the coast of Osaka Bay from surface water and sediment samples at Osaka Bay (Japan) Three sediment traps for nine weeks near the mouth of the Yodo River Sediment sampling: 9 sites × , 2 replicates, and 2 field duplicates using Van Veen grab samplers Water sampling: 10,000 L collected 1 m below the surface with 100, 10, and 0.5 µm filters Sediment traps: nine weeks at three locations (transects at 3.3, 5.5, and 20.5 km from the confluence)	TRWP with spatial variation Median TRWP in surface water was 231 µg/g (dry weight) and 1.53 µg/L (volume of water) TRWP in sediments of 312 µg/g in grab, and 460 µg/g in trap samples NR-to-SBR/BR ratio of 0.32 (potentially lower than expected based on EU and U.S. data) Sediment TRWP deposition flux from 2.05 to 5.87 mg/cm²/yr (highest at location closest to the river confluence) Reliability of using PCH to quantify TRWP Particulate Zn is a useful screening method (accessibility, cost, ease of use). Not specific to the tire-derived Zn
2024	[148]	Tire abrasion testing at two locations	Tire abrasion rates Vehicle dynamics and temperature Mass loss per mm of tread wear	Same tire model driving in Santa Oliva (Spain) and Zhaoyuan (China) Measurement of wear rates separately for urban, rural, and motorway routes Accelerations with accelerometers in the middle of the vehicle or high precision GNSS, tire and asphalt temperature, and ambient temperature on the top-right side of the vehicle Run-in period in Spain ~ 3000 km, and 500-1000 km in China Testing: vehicle alignment and loading → tread depth and Shore A hardness measurement → tire assembly weighing → run-in driving → repeat for urban, rural, and motorway driving The overall load was lower than the recommended in UNR 117 for such testing (51% vs. 67%). Therefore, tests cannot be characterized as UNR117 compliant	The abrasion rates varied from 22 mg/km to 123 mg/km per vehicle, depending on the route (urban, rural, motorway) and ambient temperature The overall average trip abrasion rates were 75 mg/km and 45 mg/km per vehicle at the two locations, respectively. When corrected for the different ambient temperatures, the rates were 63 mg/km and 60 mg/km per vehicle, respectively The average tread depth reduction was estimated to be 0.8–1.4 mm every 10,000 km Vehicle loading, in most cases, shows an almost linear relationship with the abrasion rate for a specific tire In general, the tests in Spain were conducted at an ambient temperature of 10 ◦C higher than in China (24 ◦C vs. 14 ◦C). On average, the asphalt temperature was also 17 °C higher in Spain compared to China The standard deviation values of our study should be interpreted with care Mass loss was around 300 g/mm in Spain and 108 g/mm in China. There is no clear explanation for the difference

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
					On average, 0.8-1.4 mm was expected to be lost every 10,000 km, in good agreement with recent studies, while having high uncertainty
2024	[149]	Tire wear from laboratory testing	Particle mass Particle count and size distribution Chemical composition	Laboratory testing rig with an inner diameter of 3.8 m, speed > 140 km/h, and 7 kN loading. AC 11 D S Asphalt surface, ground before each experiment Milled stone dust and sand as third body particles 14-stage ELPI (6 nm to 10 µm) 100 L/min high-flow impactor ICP-MS for chemical composition SEM with EDX for imaging sub- and micron-sized particles A catalytic stripper to measure aerosol solid particles for some experiments Lack of an air-tight setup, no measurements of EF	Milled stone dust significantly disrupted the nanoparticle size range Sand showed comparatively lower background noise within the nanoparticle region Steady-state cycles with high lateral loads (>2 kN) yielded the highest nanoparticle concentrations, two orders of magnitude surpassing background levels Approximately 70% of nanoparticles emitted are semi-volatiles Despite the need for third-party particles (operational reasons), the measurement of particle emissions is inhibited due to the high background concentrations 95% of TRWP PN are < 250 nm Chemical fingerprint of the TRWP shows similar components to the total tire, but with different elemental ratios Milled stope dust significantly interferes with nanoparticle size bins
2024	[129]	A new generation of small, low-cost air pollution sensors	$PM_{2.5}$ by location	Three sites in Berlin (Germany) Plantower PMS 5003 (OPC) sensors to measure $PM_{2.5}$ alongside three local traffic policies. The sensor draws parcels of ambient air into a chamber with a fan, where a beam of light is emitted. The particles present in the parcel of air scatter the light from the beam, which is then translated into particle densities in six size bins and further into particle mass concentrations EarthSense Zephyrs©, containing small sensors for measuring air pollutants and environmental parameters Measurement stations that are a part of the Berlin air pollution monitoring network (BLUME) Sites: a new bike lane, a temporary community space, and a pedestrian zone LCS is lower cost and allows greater uptake and higher spatial resolution	Sensor specifications are useful for measuring $PM_{2.5}$ The study found no significant effect of any of the local transport policies on local concentrations of $PM_{2.5}$, despite previous studies of these policies showing reductions in local NO_2 concentrations Differences in median concentrations were seen on the primary mobile measurements route along the KD of -0.61 ± 1.76 µg m^{-3} for $PM_{2.5}$. A similar increase of PM concentrations was observed at the secondary mobile route (-0.51 ± 1.75 µg m^{-3} for $PM_{2.5}$). On the side street, the difference in median concentrations between days with and without the community space was -0.12 ± 2.18 µg m^{-3} for $PM_{2.5}$ In no case did these differences exceed the propagated uncertainty associated with the measurements, though almost all were statistically significant At FR, a median difference of 0.64 ± 2.61 µg m–3 was measured. At two other locations, changes of a similar magnitude and direction were measured, indicating the changes were not localized to FR. None of the differences exceeded the range of uncertainty calculated

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
				LCS sensors show high inter-sensor agreement, require correction for relative humidity and seasonality, and have a complex dependence on the size distribution and composition of particles Plantower provides proprietary-calibrated concentrations for PM_1/$PM_{2.5}$/PM_{10}, and often requires recalibration or adjustment depending on the application Several studies have shown this to be possible using recalibration, linear adjustment, or using raw size distribution data from the six size bins Calibration includes a seven-step open-source method, the use of reference data from the BLUME stations, and ML using GBM and SVM	for these sensors, despite all being statistically significant at $p < 0.005$ Larger-scale policies tackling urban and regional emissions of PM will be needed to improve PM concentrations and meet WHO standards LCS have shown promise in measuring $PM_{2.5}$, but are ineffective at measuring PM_{10}
2024	[130]	Air quality monitoring stations	$PM_{2.5}$ (indirectly) metals, EC/OC Source apportionment (local heating, soil/road dust, SIA, traffic, and road salt) Seasonal effects (spring/winter)	City of Prague (population ~1.2 million), at the bottom of an open and ventilated valley. Local traffic emissions from the adjacent street consist of ~12,300 cars, 400 heavy vehicles, and 700 trams per day, with a tram stop located 100 m southeast. Further, there is a railroad station 200 m southwest (through which most trains entering Prague pass) and a highway 800 m away, which has a traffic volume of ~77,500 vehicles per day Spring campaign: 142 valid samples Winter campaign: 258 valid samples EC/OC using a semi-continuous analyzer on quartz filters at two-hour intervals Elemental composition (20 elements in spring, and 17 in winter) using Xact625i Ambient Metals Monitor PMF to estimate $PM_{2.5}$ per EPA protocol Air mass trajectories per NOAA model Planetary Boundary Layer Height and Ventilation Index to calculate wind speed and direction using Copernicus Climate Change Service	Five factors were obtained for (total mass contribution) spring: Local heating (39%), Soil/road dust (21%), Secondary inorganic aerosol (20%), Traffic (12%), and Road salt (9%) Four factors were resolved for winter: Local heating (20%), Soil/road dust (31%), Secondary inorganic aerosol (SIA; 36%), and Traffic (13%). Aside from SIA, the sources were of local origin Traffic was associated with both tailpipe and non-tailpipe traffic emissions. Zn was emitted from the combustion of lubricating oil, and some tyre wear particles (being a component of tyres as a vulcanizing agent. Cu and Fe emissions found in the Traffic factor originate from brake wear particles (BWP) Total $PM_{2.5}$ concentrations varied between the two seasons (total 5.9 and 15.8 µg m^{-3} for spring and winter, respectively). They were consistent throughout all variables, aside from Br (due to the presence of salts). PM values were lower than those in other locations and seasons in Czechia. However, nitrate data were missing from the total $PM_{2.5}$ concentrations Although direct traffic emissions were relatively low in terms of mass concentration, traffic had further involvement through the suspension of road dust, made up of both crustal and anthropogenic-sourced elements, and road salt

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
2024	[101]	Tire, brake, and road wear particles from the test track and public roads	PM_{10}, PN, Particle size distribution A proportionality between the TRWP emission factor EF_{TRWP} and the frictional power $P_{friction}$	Front wheel drive light duty vehicle Constant volume sampling behind the front right tire (brake and tire) PM_{10} with DustTrak II OPS and eFilter for particle size distribution VBOX/IMU for speed, position, and accelerations (longitudinal and lateral); pyrometer for tire temperature and lateral tension potentiometer for suspension travel Testing using an 87-km RDE route with even distances (urban, rural, highway), and on a test track cycle The power transmission is assumed to be proportional to the wheel load on each tire The dynamic tire load change is calculated by the deflection of the potentiometer, and the spring constant for the right front tire Detailed elaboration of the effects of road surface type and condition on EF	Road surface pollution and changing road surfaces remain influential factors Most high acceleration maneuvers (>0.3 g) occur at a vehicle speed below 60 km/h and are correlated with high particle concentration levels The emissions potential increases with higher vehicle speeds, also for significantly lower acceleration values Frictional processes cause temperature and particle emissions peaks TRWP during public road driving shows that an increase in frictional power does not necessarily lead to higher emission values On average, the TRWP emission response to the frictional power is significantly lower. This indicates a dependence on the road surface and dust resuspension More importantly, the highest particle concentrations are measured while the frictional power is low (ax/ay » 0 g). This effect has to be attributed to local road dust contamination and tire-induced resuspension The urban segment (lower vehicle speed and high maneuver density) contributes significantly to PM10. Considerably lower emissions from rural segments. Highway segment (with long straight stretches) shows only a few emissions peaks (except during the acceleration/deceleration events at the start and end of the segment Sampling efficiency about 40% (speed ≤ 30 km/h), and < 10% (speed > 60 km/h)
2024	[150]	Experimental and numerical study of tire tread rubber and road minerals mixing	Composition and migration of rubber compounds and minerals Shear rate influence on mixing	A rubber specimen on an experimental setup, along with SEM observations Use of longitudinal sections to show the mineral migration into the surface ESEM, GAD for surface observations 3D non-contact optical surface profiler Tribometer (rubber ring with 25 mm inner radius, 35 mm outer radius, and 8 mm thickness) with constant normal load and resin-bonded aggregates (sandstone) for a road-like surface Four specimens with 1.5, 3.0. 4.0, and 6.0 m sliding distance	The results show that mixing mainly depends on the shear rate in the layer containing the minerals As a result, the shear rate in the mixed layer decreases, and therefore the mineral migration This coupled mechanism explains why the mixing process stops before reaching a homogenized state in the entire domain A clear boundary between the mixed layer and the bulk is visible in the longitudinal section, confirming the numerical results. This layer could be responsible for the change in wear properties The relationship between mixing and wear rate should be investigated in future studies

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
				Five simulations with different thicknesses to study the effect of local shear rate 200 mg of kaolinite powder reproduces the impact of road minerals Numerical model (multibody meshfree code MELODY): modeling the rubber mix as a packing of separable bodies; elastic modulus of the rubber mix, relatively low compared to the stress level; ability to model interactions between rigid and highly deformable bodies; robust numerical method for computing deformation and detecting contacts; and tribological stresses with an appropriate space and time scales The model handles 28 minerals, a constitutive model (to allow highly deformable grains), road-like surface stiffness, a contact model, and simplified surface roughness	Considering mechanical mixing as a diffusive process provides some tools for understanding the mixing mechanism, such as the notion of a stochastic process
2024	[133]	Ultrafine particles and black carbon at different roadside microenvironments	UFP and BC	Measurements at different types of roadside environments in an industrial park area in Zhongli district, Taoyuan City, Taiwan Two portable condensation particle counters Portable Aethalometer for BC Traffic activities data were categorized into heavy vehicles, gasoline cars, and motorcycles. Heavy vehicles at IN consisted of heavy-duty containers, city buses, industrial vehicles (such as excavators, forklifts, and tractors), and trucks. On the other hand, heavy vehicles at RS consisted of only small trucks and minibuses, which occasionally drove across the road Hourly meteorological conditions data, including relative humidity, wind direction, wind speed, and temperature from TCWB Six weeks of measurements at three sites per season with daily measurements for UFPs, PNC, BC mass concentration, meteorological conditions, and vehicle activities. The daily measurement durations were 10 hours, and pollutant concentrations were collected at a 1-minute interval	The observed average roadside UFPs particle number concentration (UFPs PNC) and BC concentrations were in the order of IN (38,000 ± 9,000 # cm^{-3} and 2,500 ± 600 ng m^{-3}) > RS (25,000 ± 8,000 # cm^{-3} and 1,900 ± 300 ng m^{-3}) > UB (23,000 ± 9,000 # cm^{-3} and 1,400 ± 300 ng m^{-3}) 11.26%–16.06% and 20.35%–24.32% increases of the average UFPs PNC and BC mass concentrations were identified during the cold period at all sites Peak average concentrations of UFPs, PNC, and BC at IN and RS during morning rush-hour and weekdays periods, following the diurnal profiles of traffic flux compositions and total vehicle number per day Intra-urban spatial variability of UFPs was identified between roadsides and urban background, highlighting the heterogeneity characteristic of the pollutant Traffic activities significantly influenced pollutants at IN and RS, while at UB, they were associated with meteorological conditions and secondary emissions The effect of meteorological conditions on the UFPs' PNC was more visible at UB The semi-diurnal profile of RH was inversely proportional to the UFPs concentration at UB

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
				Average daily traffic volume on the industrial roadside can reach up to 12,000 vehicles, and 3,500 cars on the residential roadside Simultaneous measurement campaigns at industrial roadside (IN), residential roadside (RS), and urban background (UB) throughout different seasons Spatiotemporal variability as well as correlations between pollutants and confounding factors (traffic profiles and meteorological conditions) Industrial activities and heavy-duty vehicles mainly contributed to the pollutant concentrations in the industrial roadside area The primary emission source on the residential roadside comes from different vehicle compositions such as small trucks, pick-ups, and motorcycles	Typically, the variation of RH is also inversely correlated with solar radiation. RH and solar radiation normally played a significant role during the NPF process of secondary UFPs There was no significant correlation between UFPs, PNC, and BC ($r = -0.04$) Influences from traffic-related activities on UFPs, PNC, and BC were identified at IN and RS Significant correlations were found between UFPs PNC and BC at both IN ($r = 0.80$, $\rho < 0.005$) and RS ($r = 0.87$, $\rho < 0.05$) (Fig. S5). BC is the main tracer pollutant of vehicle exhaust emissions from traffic activities One of the main strengths of this study is related to the different traffic composition observed at IN and RS Modest correlations were also identified between wind speed, relative humidity, and pollutants at IN and RS. This result could highlight the possibility of dispersion/dilution due to the wind turbulence generated either from traffic activities or the wind Due to instrument constraints, this study only focuses on quantifying UFPs PNC for particles > 10 nm and does not include any discussion about nanoparticles < 5 nm Further studies with more sampling points, longer time resolutions (i.e., 24-hour and multi-year sampling), and chemical characterizations are essential in the future
2024	[151]	Tire and Road field samples	TRWP with Py-GC/MS and particulate Zinc method TOC, DOC, TSS NR to SBR/BR ratios	TRWP along 400 km of the Seine River (France) Surface water and sediment at eight sampling locations (transects) between Paris and Le Havre Two samples (left- and right-bank) per transect: water depth, salinity, temperature, turbidity, and river current velocity	Increasing salinity with depth Strong positive correlation between salinity and turbidity DO is suitable for aquatic life TRWP from 330 to 5920 mg/kg in solid samples, and from 90 to 2300 mg/kg in sediments TRWP has a higher concentration in retained solid samples, and a decreasing concentration from roadside to retained solids and sediments, consistent with environmental fate and transport processes NR-to-SBR/BR ratio of 0.15
2023	[152]	Brake, tire, and road particles	PM10 TT, BW, RW	Estimation of road dust sources using a mass balance model Literature and data search plus statistical analysis	RD exhibits comparable source characteristics from Asia, Europe, and North America The elemental composition of RD is almost the same in Asia, Europe, and North America, with sources and constituents not yet fully available or understood

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
					TT accounts for 3%, BW for 1% and RW for 96% of road dust Tire wear is most prominent below 10 µm, at 10% Tire and road wear particles from laboratory test stands may not reflect the elemental composition of those in the environment Limited comparability of global RD (Zn > Cu > Pb > Cr > Co > Ni > V > Cd, in declining concentration order) TT contributes not only Zn but a range of metals to RD Abrasion wear from TT is highly dependent on driving conditions, the type of tire, pavement, and vehicle. EF can range from 30 to 117 mg/km/vehicle for passenger cars, and for heavy trucks, EF can be ten times higher Airborne fraction can range between 0.1 and 10% Metal composition of brake wear shows patterns despite high fluctuations There is less available data on the composition of road wear The chemical composition of TRWP as an RD component depends on the formation conditions TRWP from test stands needs a careful chemical characterization before using it for other assessments Proposal to extend the data with organic compounds (using multiple markers) to track TT and BW
2023	[153]	Tire and road wear particles (TRWP and CMTT)	The chemical composition of TRWP and CMTT was characterized by determining 27 compounds, including antioxidants, vulcanization agents, and their transformation products (TPs) Particle size distribution between 10 and 3600 µm Particle morphology for particle size, aspect ratio, and circularity (dynamic image analysis mode) Electron microscopy with double-sided SEM Density fractionation by sequential centrifugation in triplicate Analysis of organic compounds with extraction of organic additives,	A lab study simulates temperature (3 years), sunlight (0.5 years), and mechanical stress Seventy days at 70 °C represent the aging progress of a tire in service in Phoenix (AZ, USA) for 6 years concerning tire functionality. Forty-two days of artificial sunlight represent 167 days of environmental sun exposure in Germany, corresponding to an acceleration factor of 4. TRWP and CMTT from a blend of three models of tires TRWP from the production process contained ~44% of loose stone dust Elevated temperature: samples in petri dishes at 60 °C for 42 days	The aging of tire and road wear particles changes their properties in an unknown manner. Aging effects on particle size distribution and density of TRWP were not significant Sunlight exposure affected the amount of extractables more strongly than elevated temperature, for TRWP (−45 % vs −20 %) and CMTT (−80 % vs −25 %), with a clear shift from parent compounds to their TPs Chemical composition shifted from parent compounds to transformation products TRWP aging significantly alters environmental exposure to tire-related chemicals No significant effects from the applied mechanical stress on the mean properties of pristine particles After sunlight exposure, up to 40 % of the mass was lost from the TRWP, likely due to the loss of mineral incrustations from their surface

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
			sample preparation for leaching, and UPLC-HRMS analysis	Artificial sunlight: samples in petri dishes at 30-35 °C and 5000 W/m² Mechanical stress: stirring 3 g of TRWP suspended in 1 L water at 200 rpm, for 1 to 4 h. 3 g of TRWP were mixed with 17 g of pre-sieved sand vibrating in an automated sieving tower for 1 to 4 h with an amplitude of ~3 mm and frequency of ~28 s^{-1} Combined aging: thermal aging at 80 °C, plus mechanical stress	For many TPs, concentrations in leachates were higher than in extracts The results highlight that abiotic aging of TRWP leads to strong changes in their chemical composition, which affect their particle properties and are of relevance for environmental exposure to tire-related chemicals Information on the residence time in the road environment with elevated temperature and sunlight exposure would be needed to assess the extent to which the effects observed in this laboratory study apply to TRWP
2021	[154]	Individual tire and road wear particles in road dust, tunnel dust, and sediment	Extension of density separation and chemical mapping protocol for TRWPs toward the identification and characterization of individual TRWPs in more complex road dust, road dust-spiked artificial sediment, tunnel dust, and environmental settling pond sediment samples Combination of physical and elemental surface characteristics	Road dust sample from a vacuum-assisted street sweeping (Leipzig, Germany); environmental sediment from an open settling pond treating highway runoff near Leipzig; tunnel dust from Königshainer Berge tunnel with pressure washer and vacuum cleaner. A sampling procedure was selected to ensure the collection of fine particles <50 µm Organic surface markers, overlapping FTIR spectra with tread reference material, and resistance to heat-induced deformation were used to confirm particle identification SPA procedure with classification for non-TRWP and TRWP origin: density separation (<2.2g/cm³) → wash step; vacuum filtration → optical microscopy and backscattered SEM (primary method) → EDX mapping (primary method) → ToF-SISM → FTIR	The TRWP size displayed an increasing average trend of 54, 158, and 267 µm by number (94, 224, and 506 µm by volume) in tunnel dust, road dust, and environmental sediment, respectively TRWP size distributions within road dust, 10X diluted with artificial sediment, agreed with those of pure road dust samples The SPA methodologies determined the size distribution of TRWPs in environmental sample types with increasing sample complexity Potential impact of particle collection efficiencies on the operational definition of particle size for road dust (collected by a street sweeper) and tunnel dust (collected by a pressure washer with a vacuum) The manual nature of TRWP identification and primary particle size analysis is time-intensive, and individual particle identification requires the integration of several lines of evidence. In the undiluted road dust sample It is possible that dilute samples or water samples may not contain enough TRWPs; therefore, they may represent a more qualitative assessment
2013	[155]	TRWP sampling stations	TRWP in PM_{10}	Roadside sampling stations on three continents x 27 sites at each continent: − France (Troyes, Reims, Paris-Rouen) − U.S. (Harrisburg, PA; Washington, DC; Maryland; Virginia) − Japan (Osaka, Hyogo, Shiga, Kyoto, Mie) 20 × residential + 46 × industrial / commercial + 12 × school / church / hospital + 11 × recreational Population 60,000 to 12 million residents	Tire and road wear particles (TRWP) are part of non-exhaust emissions from vehicles Chemical markers specific to tire tread were used to quantify TRWP in PM_{10} Average air concentrations ranged from 0.05 to 0.70 mg/m³ TRWP contributed on average 0.84% to total PM_{10} and a range of 0.14%-2.80% for the sub-areas, with the highest contribution observed in Troyes

Year	Ref.	Source	Parameters Examined	Testing/Evaluation Conditions	Main Conclusions
				Vehicle density 17,000 to 265,000 veh/day The sampling locations represent a variety of settings, including both rural and urban cores, and within each residential, commercial, and recreational receptors PM10 sampling per country-specific methods, with all samples 1.5-2.5 m above ground, at 1 m^3/h, onto 47-mm quartz filters 24-48 h sampling after 48-h stabilization (controlled temperature and humidity) Analysis of TRWP concentrations consists of the thermal decomposition of rubber polymers in environmental samples at 670 °C by Curie-point pyrolysis, followed by gas chromatographic separation of the thermal decomposition products and quantification of the pyrolysis fragments with a mass-selective detector An aliquot of 1/3 of the filter was analyzed to provide an archive for future analyses, with a resultant detection limit of 780 mg/g Statistical analysis for TRWP concentration used ANOVA	A simple mass balance analysis of the Paris metropolitan area showed good agreement between this study and literature estimates of tread PM_{10} emission rates from road vehicles Although the sampling program represents a cross-section in time, the diversity of locations and demographics provides a robust dataset to understand global exposure to TRWP in ambient air