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From Traffic Emissions to Urban Secondary PM: Evaluating Particle Emission Prevention and Its Environmental Impact

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Abstract

This paper introduces the PAREMPI project — Particle Emission (PM) Prevention and Impact: From Real-World Emissions of Traffic to Secondary PM in Urban Air – funded under the Horizon Europe program. The study outlines the research motivation, project objectives, methodological approach, and organizational structure. It highlights the specific tasks, deliverables, focus areas, and key considerations that guide the project. Particular attention is given to the experimental methods employed to generate high-quality data aimed at filling critical knowledge gaps and supporting the development of a comprehensive emissions database. This database, a primary deliverable of the project, serves as the foundation for evidence-based policy recommendations. Preliminary results are also presented, including examples of the ratio of secondary aerosol (SecA) formation to primary PM mass emissions. Early findings indicate that SecA formation from exhaust emissions is strongly influenced by several technology-related factors, such as fuel type and the configuration of exhaust aftertreatment systems.

Keywords: real traffic emissions, light-duty and heavy-duty vehicles, secondary PM of urban air, aviation & marine measurement, particle emissions prevention, health effect

1. Introduction

The global economy is critically dependent on mobility and freight transport, encompassing road transport, aviation, and shipping. These sectors remain largely reliant on internal combustion engines and fossil fuels, while simultaneously facing increasing pressure to reduce both air pollutants and greenhouse gas (GHG) emissions. For more than a century, the private automobile has shaped modern society by providing unprecedented personal mobility. Today, over 250 million passenger cars are in operation within the European Union (EU), serving as the dominant mode of transport and enabling the average European to travel more than 12,000 kilometres annually (ACEA, 2025).

Persistent concerns regarding emissions from the road transport sector continue to drive regulatory developments, which now demand substantially lower emission levels from newly manufactured vehicles compared to past standards. Although "exhaust gas" is often understood as gaseous compounds, the mixture of combustion by-products emitted from internal combustion engines also contains non-gaseous pollutants (Wahlström et al., 2009; Woodburn et al., 2022). Transport-related exhaust emissions comprise a heterogeneous combination of gaseous and particulate components (Rönkkö and Timonen, 2019). Their characteristics are strongly influenced by engine and aftertreatment technologies, fuel properties, driving dynamics (e.g., speed, acceleration, deceleration), and ambient conditions (e.g., temperature). Of particular concern are ultrafine particles (diameter <100 nm), which present significant health risks due to their high pulmonary deposition efficiency, ability to translocate to other organs including the brain, and chemically toxic composition (Kittelson et al., 2023). In densely populated urban areas, where traffic volumes are high, residents experience chronic exposure to these pollutants, which, despite their toxicity, remain largely unregulated (Rubino et al., 2023).

Although long-term strategies promote electrification, combustion-powered vehicles, non-road mobile machinery, aircraft, and ships are expected to remain in widespread use for decades. Legislative frameworks for light-duty vehicles––such as the Worldwide Harmonized Light Vehicles Test Procedure (WLTP), Real Driving Emissions (RDE), and the Euro 7 standards–together with non-road emission regulations, reflect a growing global consensus on the necessity of accurate, real-world emissions assessment (Bielaczyc et al., 2021).

Emission requirements for heavy-duty vehicles (HDV) are task-specific; however, based on standard test results, various derived parameters can be calculated, including distance-specific, tonnage–distance-specific, CO_2-specific, and gravimetric fuel-specific values. Currently, CO_2 and fuel consumption are not explicitly regulated during on-road testing for either light- or heavy-duty vehicles. Nevertheless, these parameters must be measured, and the resulting data provide valuable insights for research and policy development (Bielaczyc and Woodburn, 2022).

This paradigm shift has facilitated the transition from traditional laboratory--based certification toward more comprehensive, data-driven, and portable testing methods using Portable Emission Measurement Systems (PEMS). Current particulate matter (PM) emission limits are defined under real-world driving conditions with PEMS, accounting for measurement uncertainty and remaining technology- and fuel-neutral. Additionally, the minimum detectable particle size threshold has been reduced from 23 nm to 10 nm (Giechaskiel et al., 2021).

For the first time, the Euro 7 regulation also addresses particulate emissions originating from non-exhaust sources. Within this framework, methodologies for quantifying tyre abrasion and brake emissions have been developed by the Particle Measurement Programme (PMP) group of the United Nations Economic Commission for Europe (UNECE) (Giechaskiel et al., 2024; 2025). Brake emission testing is based on Global Technical Regulation (GTR) No. 24 for light-duty vehicles (Grigoratos et al., 2023). This protocol

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includes: (i) a dedicated braking cycle derived from the WLTP-Brake driving database, (ii) technical specifications for the brake dynamometer facility and instrumentation, and (iii) standardized procedures applicable to both internal combustion and hybrid vehicles with regenerative braking (Grigoratos et al., 2023).

Once released into the atmosphere, exhaust emissions undergo cooling and dilution while mixing with ambient pollutants. Semi-volatile compounds may condense onto existing particles or nucleate, thereby altering the physical and chemical properties of the emissions. Further atmospheric processing, driven by oxidants (e.g., OH radicals, O_3) and UV radiation, can result in the formation of new aerosol mass, commonly referred to as secondary aerosol (SecA). The formation of SecA from precursors such as SO_2, NO_x, NH_3, and NMVOCs/NMOGs, in conjunction with other atmospheric constituents, is a complex and dynamic process (Fig. 1).

The impacts of transport-related emissions on air quality, health, and climate depend on both their chemical composition and ambient concentrations. Several studies (e.g., Timonen et al., 2017; Kuittinen et al., 2021) have demonstrated that the mass of secondary aerosol formed from gaseous precursors can exceed the directly emitted PM currently regulated. However, the mechanisms underlying secondary aerosol formation and the characterization of secondary emissions from transport sources remain poorly constrained. This knowledge gap arises from continuous advances in engine and aftertreatment technologies, the diversity of fuels, and the inherent challenges of simulating and measuring atmospheric processes under realistic conditions.

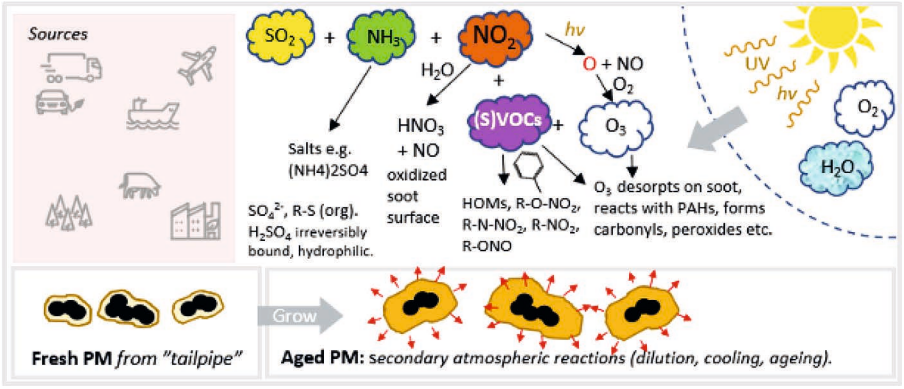

Fig. 1. Schematic representation of the transformation and growth of fresh "tailpipe" PM to aged ambient PM through atmospheric reactions during dilution, cooling and ageing (source: Aakko-Saksa et al., TRA2024)

Over the past decade, several oxidation flow reactors (OFRs) have been developed to study SecA formation under controlled laboratory conditions. Among the most widely used are the Potential Aerosol Mass (PAM) chamber, originally developed at Pennsylvania State University and later commercialized by Aerodyne Research Ltd. (Kang et al., 2007), and the Tampere Secondary Aerosol Reactor (TSAR), developed at Tampere University and commercialized by Dekati Oy (Simonen et al., 2017). To date, more than 150 scientific studies have employed OFRs to advance understanding of SecA formation. By contrast, traditional smog chambers–although widely used–operate as batch systems, limiting their applicability for real-time measurements, particularly under transient driving conditions.

2. PAREMPI – Project Introduction and Scope

The PAREMPI project (Particle Emission (PM) Prevention and Impact: From Real-World Emissions of Traffic to Secondary PM in Urban Air), funded by Horizon Europe, is an international collaboration involving seven partners: the Finnish Meteorological Institute, VTT Technical Research Centre of Finland, and Tampere

University (Finland); Lund University (Sweden); BOSMAL Automotive Research and Development Institute (Poland); the Institute of Experimental Medicine (Czech Republic); ONERA (France); and Magellan (Portugal). The project focuses on understanding and mitigating secondary aerosol (SecA) formation from transport-related and other relevant emission sources. With a strong emphasis on real-world conditions, PAREMPI examines how gaseous and semi-volatile precursor emissions–such as VOCs, NO_x, and NH_3–contribute to SecA formation, ambient $PM_{2.5}$ concentrations, ultrafine particles, and non-exhaust emissions. Furthermore, the project investigates the toxicity of these emissions and their broader public health implications (Bielaczyc et al., 2024; 2025).

PAREMPI integrates advanced scientific research, large-scale experimental measurement campaigns, toxicological assessments, and health impact studies with the development of next-generation modelling tools. Its overarching objective is to improve the quantification of transport-related externalities. The project is structured around three main pillars:

(i) establishing the scientific basis of SecA formation and its environmental and health impacts,
(ii) quantifying emissions and advancing state-of-the-art modelling methodologies, and
(iii) identifying and assessing technologies and strategies for emission prevention (Honkisz et al., 2025).

A key innovation of PAREMPI is the development of the Equivalent Particle Mass Index (ePMI) and a toxicity rating system designed to evaluate emissions from diverse transport sources. By consolidating existing knowledge, addressing critical research gaps, and generating new high-resolution experimental data, PAREMPI aims to provide actionable insights to support evidence-based policymaking, inform future regulatory frameworks, and stimulate technological innovation toward cleaner and more sustainable transport systems in Europe.

3. Measurement Campaigns and test results.

3.1. Testing methodology

Five intensive measurement campaigns were carried out, encompassing emissions from light-duty and heavy-duty road vehicles, marine engines, aviation exhaust, and brake wear. These campaigns investigated both particulate and gaseous pollutants under controlled laboratory conditions and real-world operation, thereby generating comprehensive datasets on primary and secondary emissions.

The experimental setup was built around a portable Oxidation Flow Reactor (OFR), which enables the controlled simulation of atmospheric aging processes by exposing diluted exhaust to elevated concentrations of oxidants (OH, O_3). This design allows for accelerated secondary aerosol (SecA) formation, providing results that are representative of several hours to days of atmospheric processing. The OFR was coupled to a dilution system, which ensured stable and reproducible concentrations while maintaining realistic temperature and humidity conditions.

Particulate emissions were characterized using a Particle Size Distribution (PSD) instrument, capable of measuring number concentrations across the submicron size range. PSD data were subsequently converted into particulate mass concentrations using established density and morphology assumptions. This approach facilitated the estimation of both fresh and aged PM fractions.

In addition to particle-phase characterization, the system included analyzers for key precursor gases (NO_x, NH_3, SO_x, volatile aromatics), which play a central role in secondary aerosol formation. Supporting measurements of NO, CO, CO_2 and selected toxicity markers provided additional insight into combustion

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efficiency, fuel-specific emission indices, and potential health impacts (Fig. 2) (e.g., Junninen et al., 2010; Krechmer et al., 2018).

For emission quantification, the recommended metric for aged PM was defined on an energy-specific basis (per megajoule of fuel energy). This metric was calculated from measured CO_2 concentrations in combination with fuel properties, thereby avoiding the need for direct exhaust flow or fuel consumption measurements. This approach substantially simplified the setup while maintaining consistency across diverse transport modes. In parallel, regulated PM was also determined, enabling the calculation of aged-to-fresh PM ratios and facilitating direct comparisons with existing regulatory standards (Honkisz et al., 2025).

The measurement framework developed in PAREMPI represents one of the first robust and portable systems capable of estimating $PM_{2.5}$ formation through secondary aerosol processes across multiple transport sectors under realistic conditions. By combining real-world measurement campaigns with advanced atmospheric simulation techniques, this methodology significantly enhances the capacity to investigate knowledge gaps in the characterization and regulation of transport-related particulate emissions.

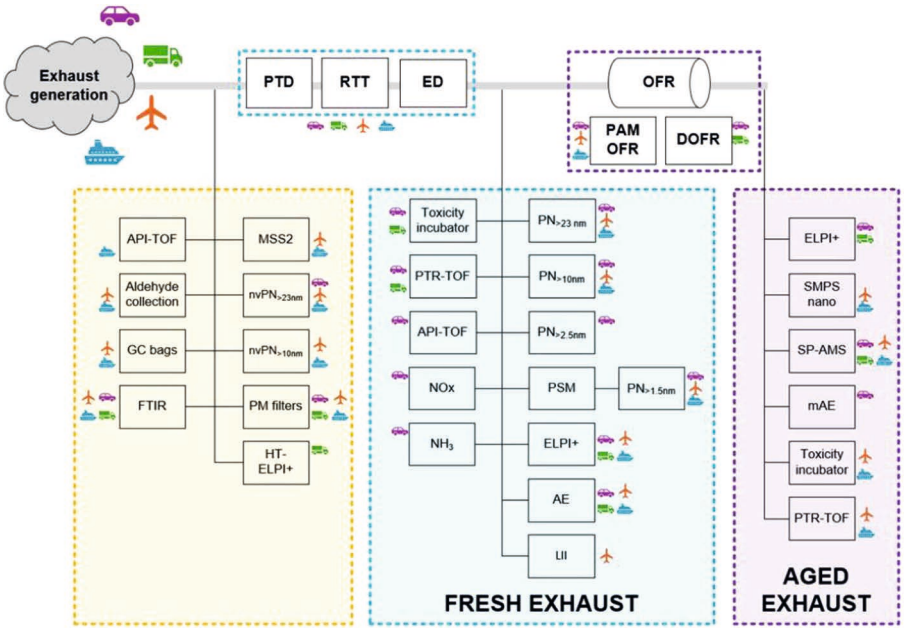

Fig. 2. Generalized schematic of PAREMPI set-ups. With each instrument/metric/part of the schematic, symbols (car, truck, airplane, ship) indicate the experiment where it was used (source: D5.3)

Abbreviations: *AE = Aethalometer, API-TOF = Atmospheric Pressure Interface Time of Flight, DOFR = Dekati Oxidation Flow Reactor, ED = Ejector Diluter, ELPI = Electrical Low Pressure Impactor, FTIR = Fourier Transfer Infrared, GC = Gas Chromatograph, HT = High Temperature, LII = Laser Induced Incandescence, mAE = Micro Aethalometer, MSS = Micro Soot Sensor, NH_3 = Ammonia, NO_x = Nitrogen Oxides, nvPN = Non-Volatile Particle Number, OFR = Oxidation Flow Reactor, PAM = Potential Aerosol Mass, PM = Particle Mass, PN = Particle Number, PSM = Particle Size Magnifier, PTD = Porous Tube Diluter, PTR-TOF = Proton Transfer Reaction Time of Flight, RTT = Residence Time Tube, SMPS = Scanning Mobility Particle Sizer, SP-AMS = Soot Particle Aerosol Mass Spectrometer. Note that PM filters were used after dilution and cooling of exhaust.*

3.2. Light-Duty Vehicles – RDE Exposure Conditions (BOSMAL, Poland)

Five passenger cars, representing different emission levels and equipped with various emission control technologies, were tested at the BOSMAL Emissions Testing Laboratory under real-driving emissions (RDE) conditions. Tests were

conducted at two ambient temperatures (+23 °C and –9°C), alongside clean-air and blank control exposures to ensure comparability.

While no major differences in toxicological outcomes were observed among the Euro 6 vehicles tested, the results suggest that longer or repeated exposure periods may be required to capture potential vehicle-specific effects. In contrast, ambient temperature demonstrated a clear influence: even vehicles with comparatively low emissions produced measurable cellular damage under cold conditions (–9°C). These findings indicate that winter driving scenarios can substantially increase the toxicity of exhaust, regardless of vehicle emission control level (Honkisz et al., 2025).

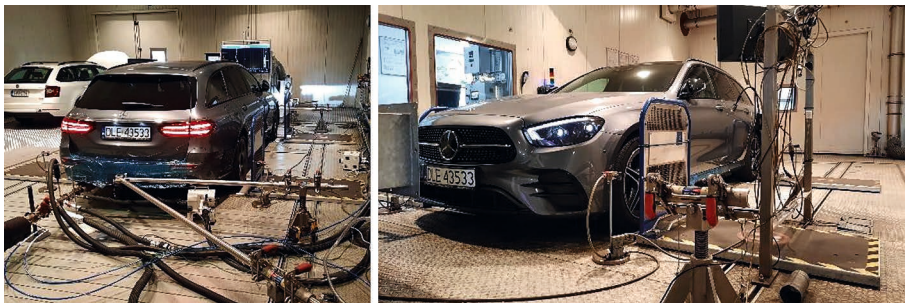

Fig. 3. LD vehicle mounted on the chassis dyno at the BOSMAL Emissions Testing Laboratory (photo by W. Honkisz)

To further investigate secondary aerosol (SecA) formation from emitted exhaust, the total particulate mass was calculated from particle number size distributions across the full size range, both for fresh exhaust samples and for exhaust subjected to OFR treatment. The average total particulate mass concentration for all tested vehicles over the complete RDEsim cycle is shown in Fig. 4a. The composition of the aged particles was determined using synchronous particle–time-of-flight aerosol mass spectrometry (SP-AMS) and is presented in Fig. 4b.

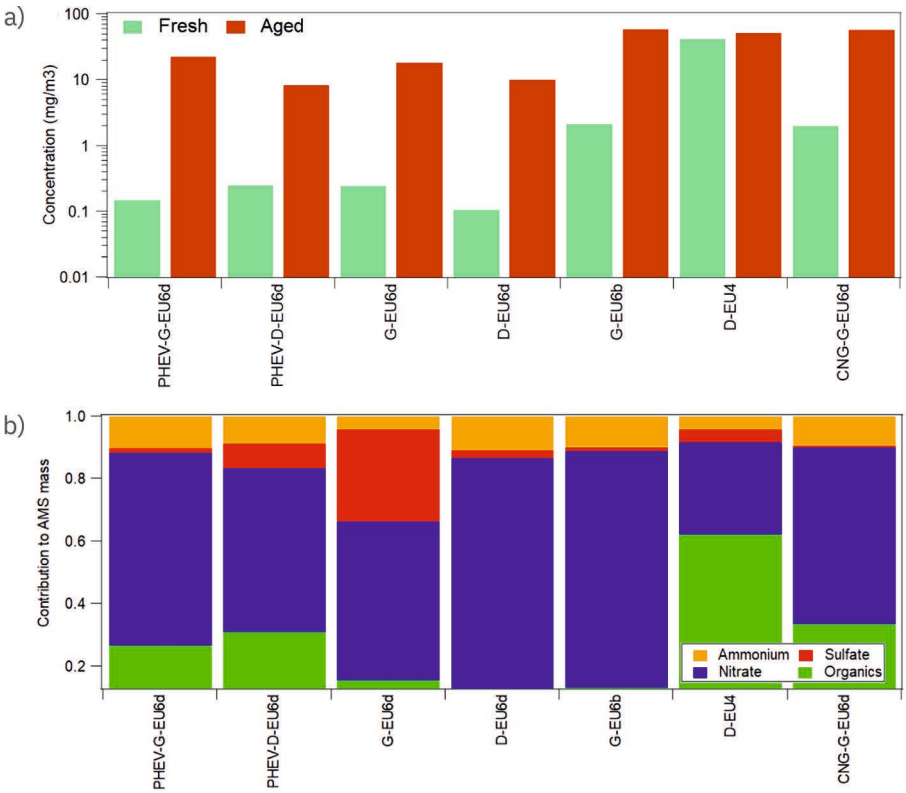

Fig. 4. Particulate mass concentrations of fresh and aged aerosol samples for different vehicles and contribution (a) and average contributions (%) of non-refractive components of aged exhaust particulate matter, measured with AMS (b) (source: D2.2)

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The results indicate that engine technology, aftertreatment systems, and fuel type strongly influence SecA formation from emitted exhaust. While the relative increase in particulate mass was higher for newer vehicles compared, for example, to older diesel cars, the total results demonstrate that older technology vehicles still exhibit the highest overall potential to contribute particulate mass to ambient air. In addition to affecting mass concentration, vehicle technologies also influenced the chemical composition of aged exhaust particulate matter measured after OFR exposure (Simon et al., 2025).

3.3. Heavy-Duty Truck Testing in Winter Conditions (TAU, Finland)

Two heavy-duty (HD) trucks were tested on-road under winter conditions. Both vehicles exhibited minimal to no cytotoxic effects on exposed cells, suggesting that well-maintained trucks can have relatively low toxicity. Moreover, trucks fueled with hydrotreated vegetable oil (HVO) caused less cellular damage compared to those using conventional EN590 diesel. Control cells remained stable even at low ambient temperatures, confirming the feasibility of conducting on-road winter testing for long-term exposure studies (Fig. 5) (Honkisz et al., 2025).

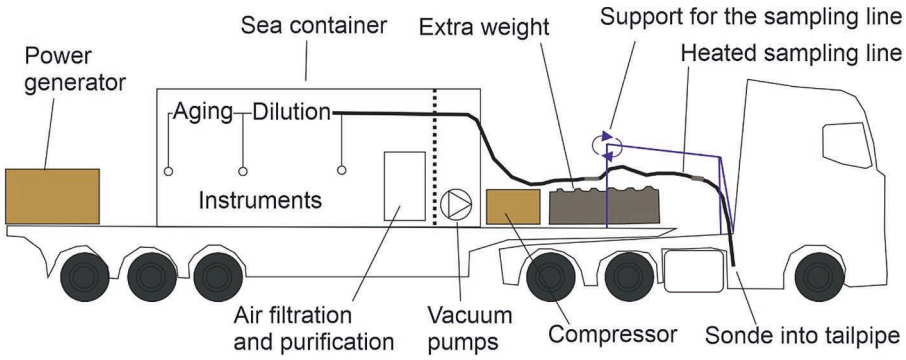

Fig. 5. Measurement setup employed for the heavy-duty truck campaign (source: by W. Honkisz))

In the HD truck experiments, secondary aerosol formation and the chemical composition of aged exhaust varied significantly with driving route (Fig. 6). During the first nine tests, aged aerosol concentrations remained below 100 µg/m^3, except for a 500 km drive where NH_4^+ and SO_4^{2-} concentrations were elevated. To increase sensitivity at low aerosol levels, the dilution factor was reduced by

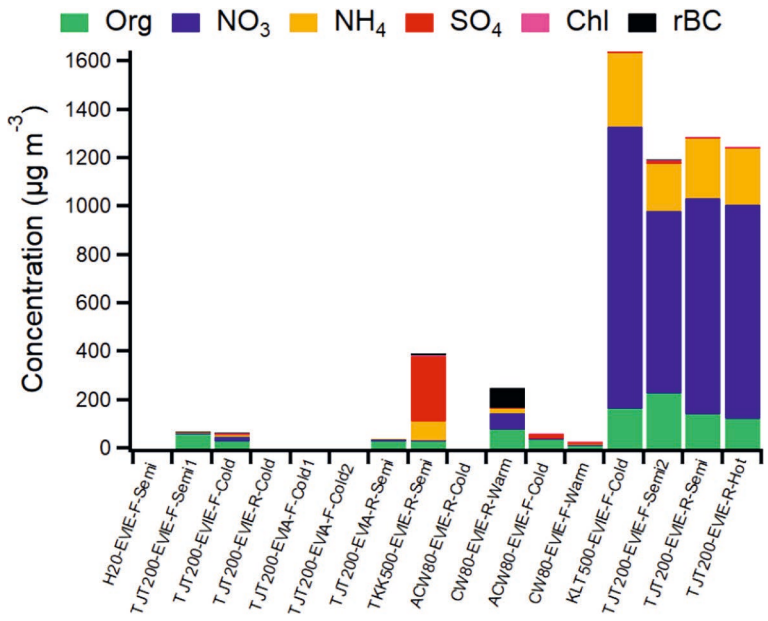

Fig. 6. Aged aerosol particle concentrations measured with a SP-AMS downstream an oxidation flow reactor. Results are averaged over the driving routes and corrected for dilution factors. After noticing low emission levels, we changed the dilution factor from 140 (as it was used during all other campaigns) to 26 by removing one ejector diluter from upstream the DOFR. The measurements with a lower dilution factor are marked with a pink background (source: D2.2)

removing one ejector diluter (DF 5) before the DOFR and SP-AMS instruments. Consequently, the AMS dilution factor decreased from 140 to 26, which likely affected aerosol mass formation in the last seven measurements relative to the first nine. The SP-AMS consistently sampled aged aerosol downstream of the DOFR.

The ELPI+ instrument required post-OFR dilution to maintain adequate sample flow, with DF values initially at 2400 and later reduced to 450. At these dilution levels, particle number concentrations were low (14–75 particles/cm^3), limiting measurement confidence unless secondary aerosol formation was substantially higher.

Overall, modern HD diesel exhaust exhibited low secondary aerosol potential, with nitrate and ammonium as the dominant components and a limited contribution of secondary organic matter.

3.4. Marine and Aviation Engine Testing (VTT, Finland)

Laboratory tests were conducted using three different marine fuels and three aviation fuels. Clear differences in emissions and cytotoxic impacts were observed between fuel types in both sectors. Comprehensive evaluation of the full dataset is ongoing.

The chemical composition of marine engine exhaust aerosols was determined using SP-AMS downstream of a Potential Aerosol Mass (PAM) chamber, alternating between UV-light “off” and “on” modes to simulate atmospheric aging (Fig. 7).

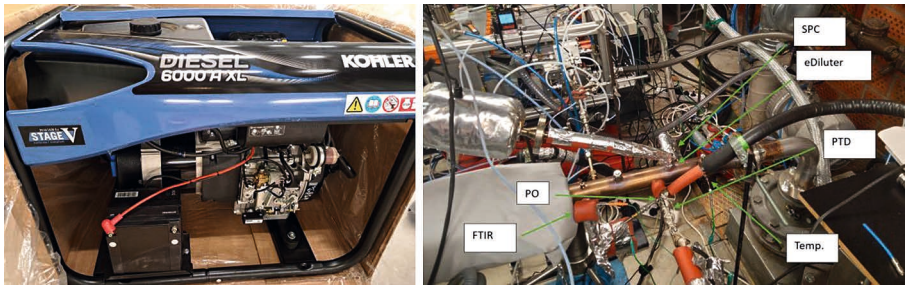

Fig. 7. Diesel generator and measurement setup for the marine campaign (photo by W. Honkisz)

Marine powertrain emissions

As shown in Fig. 8, the use of DMB fuel resulted in high organic content in particulate matter, with significant secondary organic aerosol (SOA) formation observed after approximately three days of UV-induced aging. Ammonia (NH_3)

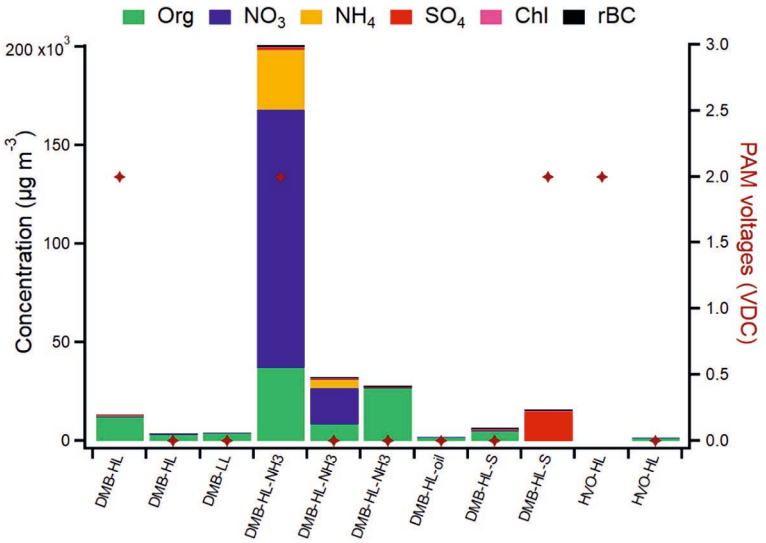

Fig. 8. Chemical composition of fresh and aged exhaust particles measured with a SP-AMS during the marine engine exhaust simulation. Note that the y-axis has a multiplier of 103. Values are corrected for the dilution factor, and “UV-lights off” and UV-lights on” modes of PAM are indicated by the PAM voltages shown on the right (source: D2.2)

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played a key role in SOA formation: addition of NH^3 to the exhaust prior to the PAM chamber led to elevated NO_3^- and NH_4^+ concentrations, particularly in the aged aerosol. Nitrate concentrations were roughly three times higher than organics, while ammonium levels were comparable to organics. Ammonia also influenced the composition of fresh exhaust.

Fuel sulfur content and fuel type modifications affected aerosol composition in a manner consistent with observations for fresh exhaust. Higher sulfur content increased sulfate in aged particles, while switching from DMB to HVO fuel substantially reduced particle concentrations.

Particle size distribution data (Fig. 9) confirmed that particle concentrations were highest for the DMB-HL-NH_3 configuration. The presence of ammonia promoted the formation of secondary organics in larger particles, suggesting that ammonia enhances particle growth and contributes to internal mixing of exhaust components.

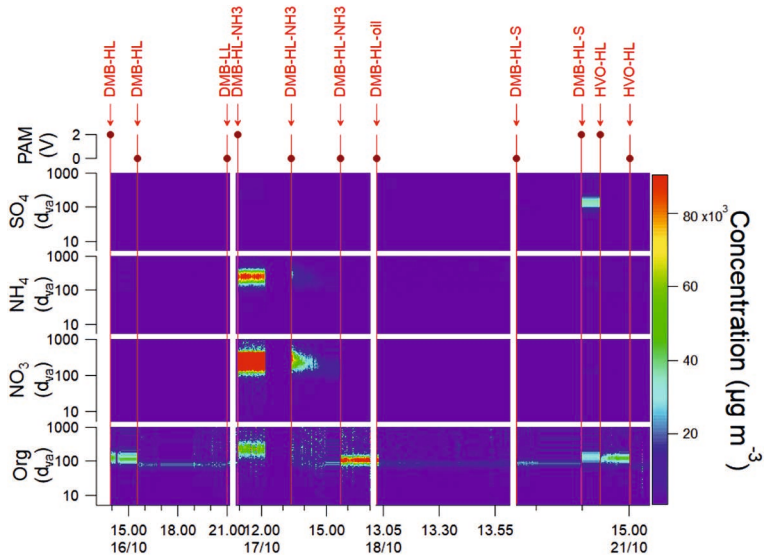

Fig. 9. Concentrations of different fresh and aged exhaust particle compounds as a function of particle size, measured with a SP-AMS. Note that the y-axis' are logarithmic. Values have been corrected for the dilution factor (source: D2.2)

Aviation Particulate Matter (PM) Emissions

The chemical composition of aviation engine exhaust aerosols was determined using the Combustion Aerosol Standard Generator (CAST), supplemented with lubrication oil vapors (Fig. 10).

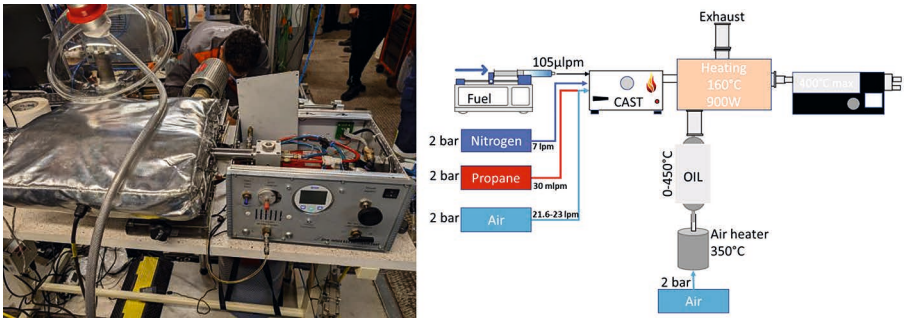

Fig. 10. Combustion Aerosol Standard Generator (CAST) with added lubrication oil vapors (source: by W. Honkisz; D2.2)

Particle composition from simulated aircraft engine exhaust was analyzed following the same approach as in the marine experiments, for both fresh and aged exhaust samples (Fig. 11). PAM chamber UV-light exposure was used to control the aging process.

Fresh exhaust from the J1-F1-HER-Oil configuration exhibited the highest particulate emissions, followed by aged exhaust from J1-F1-LER-Oil and J2-F2--LER. Secondary organic aerosol (SOA) levels were generally elevated, whereas

fresh exhaust, particularly under certain HER conditions, contained higher black carbon concentrations (PAREMPI D.2.2, 2025).

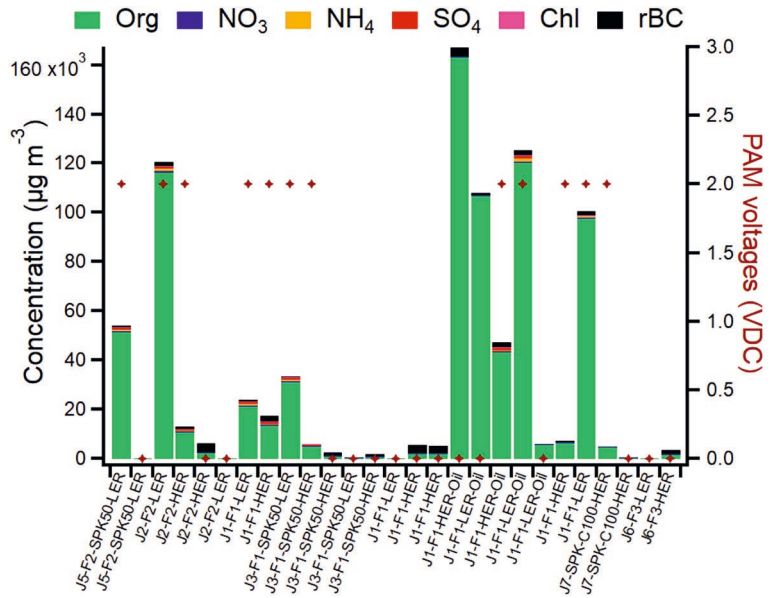

Fig. 11. Fresh and aged exhaust aerosol particulate mass concentration and chemical composition of particles measured by a SP--AMS with various aviation fuels, utilizing the laboratory setup to simulate aircraft emissions. Note that the y-axis has a multiplier of 103. Concentrations were corrected for the dilution factors. "UV-lights off" and UV-lights on" modes of PAM are indicated by the PAM voltages shown on the right (source: D2.2)

3.5. Brake Wear Emissions

A pin-on-disc tribometer was employed in the PAREMPI project to simulate brake pad–disc interactions. A pin, representing the brake pad, is pressed against a rotating disc under a controlled dead weight to maintain consistent contact pressure. The instrument (Fig. 12) can apply a normal force of up to 100 N and disc speeds up to 5000 rpm.

As real pad–disc interactions are dominated by sliding, this method provides a representative, downscaled simulation. Previous studies have demonstrated that the setup accurately reproduces the number and size distribution of wear particles observed in both laboratory test stands and field measurements (Wahlström et al., 2009).

Fig. 12. Left: the pin in contact with the disc (where the contact force is applied by the dead weight at the top); right: blue polycarbonate enclosure on top of the pin-on-disc tribometer (source: D5.3)

The tribometer also records the coefficient of friction and disc temperature during operation. To ensure a clean measurement environment, the system was enclosed in a polycarbonate chamber supplied with particle-free air and lined with conducting aluminum foil to minimize deposition of highly charged brake particles (Thomas et al., 2024).

Under mild braking conditions, the LM brake pad produced higher mean concentrations of $PM_{2.5}$, PM_{10}, and particle number (PN) compared to the NAO brake pad, as illustrated in Fig. 13. In contrast, under harsh braking conditions, the NAO pad generated the highest emissions in terms of particulate mass. Overall, harsh braking resulted in higher mean particle concentrations for all three measured parameters ($PM_{2.5}$, PM_{10}, and PN) compared to mild braking conditions.

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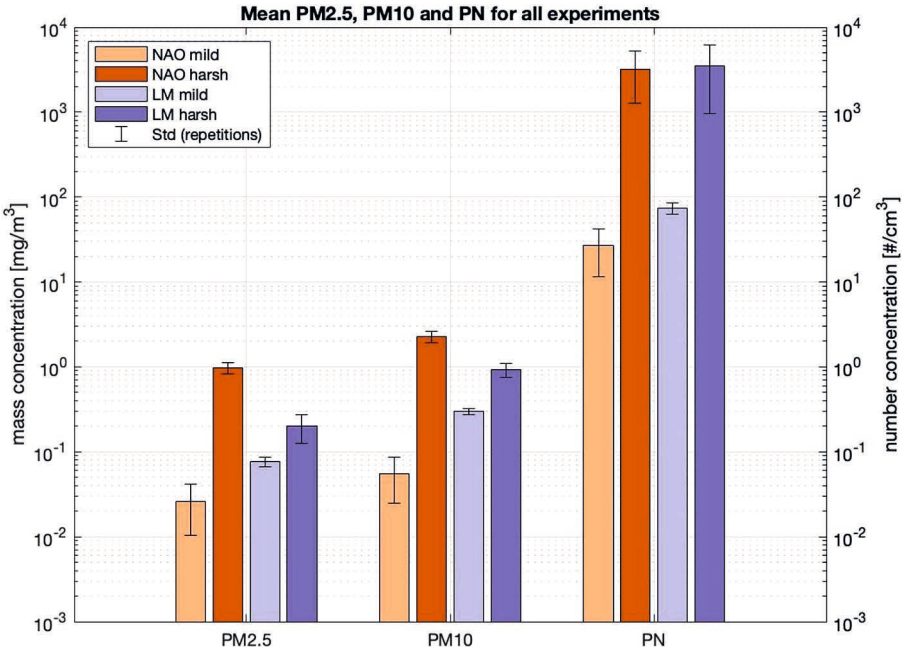

Fig. 13. Mean concentration of PM2.5, PM10 and particle number from 4 nm (PN) for two braking pad materials (Low Metallic, LM and Non-Asbestos Organic, NAO) under two braking conditions (mild and harsh) (source: D2.2)

3.6. Discussion

The results of the PAREMPI exhaust experiments highlight the critical importance of PM_aged formation potential for assessing the overall atmospheric impact of emissions from different transport modes, with direct implications for air quality and public health. The formation of aged particulate matter was found to depend strongly on technology-related parameters, including fuel type and exhaust aftertreatment systems.

In both light-duty and heavy-duty vehicle experiments, cold-start conditions were identified as a key factor influencing exhaust emissions and their contribution to secondary aerosol (SecA) formation potential. SecA was primarily associated with gaseous organic compounds, typically originating from fuel and lubricating oil, but also with inorganic gaseous pollutants such as SO_2, NO_x, and NH_3. Consequently, mitigating the total SecA impact on air quality cannot be achieved by focusing on a single technology alone.

It is also important to note that modern vehicles emit relatively low amounts of regulated pollutants, which may enhance the relative contribution of currently unregulated emissions—particularly those with the potential to form SecA in the atmosphere. Results from light-duty vehicle experiments indicate that the smallest particles (<10 nm), currently unregulated, play a proportionally greater role in modern vehicles compared to older ones. Polycyclic aromatic hydrocarbons (PAHs) were detected in exhaust from both modern cars and trucks, emphasizing the persistent presence of potentially harmful compounds despite advanced emission control technologies.

At the same time, the high efficiency of exhaust emission reduction techniques was demonstrated, particularly through low black carbon emissions from vehicles equipped with filtration devices. Overall, these findings underscore the need for continued development of fuels, lubricating oils, engines, and aftertreatment technologies to mitigate emissions of SecA, nano-sized particles, and PAHs, which collectively pose health risks.

Brake wear experiments showed that emissions are strongly influenced by brake pad type and braking conditions. Approximately 30–50% of PM_{10} emissions were within the $PM_{2.5}$ size range. Moderate ultrafine particle (UFP) emissions were observed during harsh braking events. Brake wear particles (BWP) were dominated by iron oxides, which absorb in the infrared region and thus contribute to the measured black carbon from road transport.

4. Emission modelling

4.1. 4.1. Equivalent Particle Mass Index (ePMI)

The Equivalent Particle Mass Index (ePMI) is a novel tool developed within PAREMPI to estimate both primary and secondary aerosol particle numbers and masses from anthropogenic transport emissions. It is designed for integration into large-scale atmospheric models such as TM5, EC-Earth, and ADCHEM.

ePMI incorporates semi-empirical autoxidation frameworks to simulate SecA formation from rapid functionalization reactions and harmonizes anthropogenic SOA with biogenic SOA schemes. By linking emission data with modeling, ePMI provides a consistent metric for evaluating long-term impacts of transport emissions and supports both regulatory and research applications (Fig. 14) (Aakko-Saksa et al., 2025).

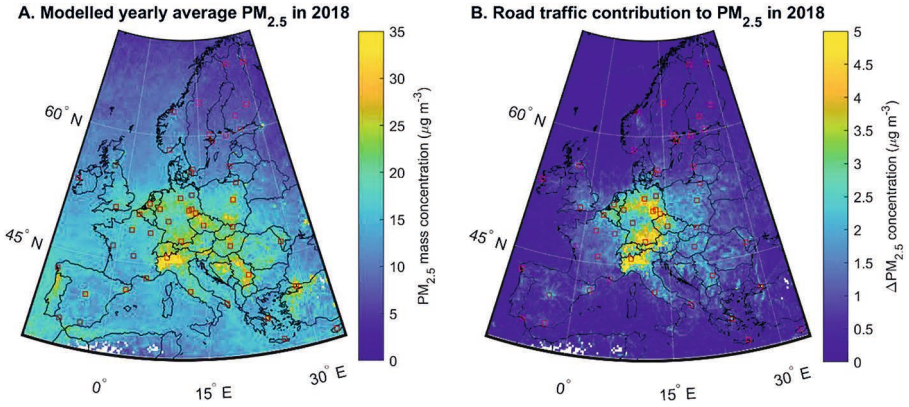

Fig. 14. Modelled average PM2.5 levels over Europe in the year 2018. Left panel shows the absolute concentrations from the basecase model simulations including emissions from all known sources. Right panel show the concentration difference between the basecase and simulations with road traffic emissions turned off in the model (WoRoad) (source: D5.3)

4.2. Modelling of atmospheric SecA formation

The road traffic emissions in Europe cause complex non-linear effects on atmospheric chemistry and secondary aerosol formation. Road traffic NO_x emissions in combination with agriculture NH_3 emissions are an important source of SecA PM2.5 in the form of ammonium nitrate. According to our European scale model simulations, NH_4NO_3 is the dominating component of PM2.5 in most regions of Europe during the winter and early spring. The total OA PM2.5 content shows less variation over the year, but POA is the dominating OA source in the wintertime while SOA dominates during the summer season. NO_x emissions have a major impact on the VOC oxidation chemistry and tend to suppress the SOA formation. Thus, although the road traffic contributes to important SOA precursors (aromatics and large alkanes) the net impact on the atmospheric SOA levels can be both positive and negative depending on the amount of BVOC emissions. The substantial NO_x emissions are also an important source of tropospheric ozone and increase the atmospheric hydroxy radical (OH) concentrations (the atmospheric oxidative capacity), especially during extreme ozone episodes during European heatwaves with high BVOC emissions and NOx--limited ozone production (Fig. 15). Thus, preventing road traffic NO_x emissions, especially during forecasted heatwaves, can be an efficient measure to mitigate dangerous tropospheric ozone levels in Europe.

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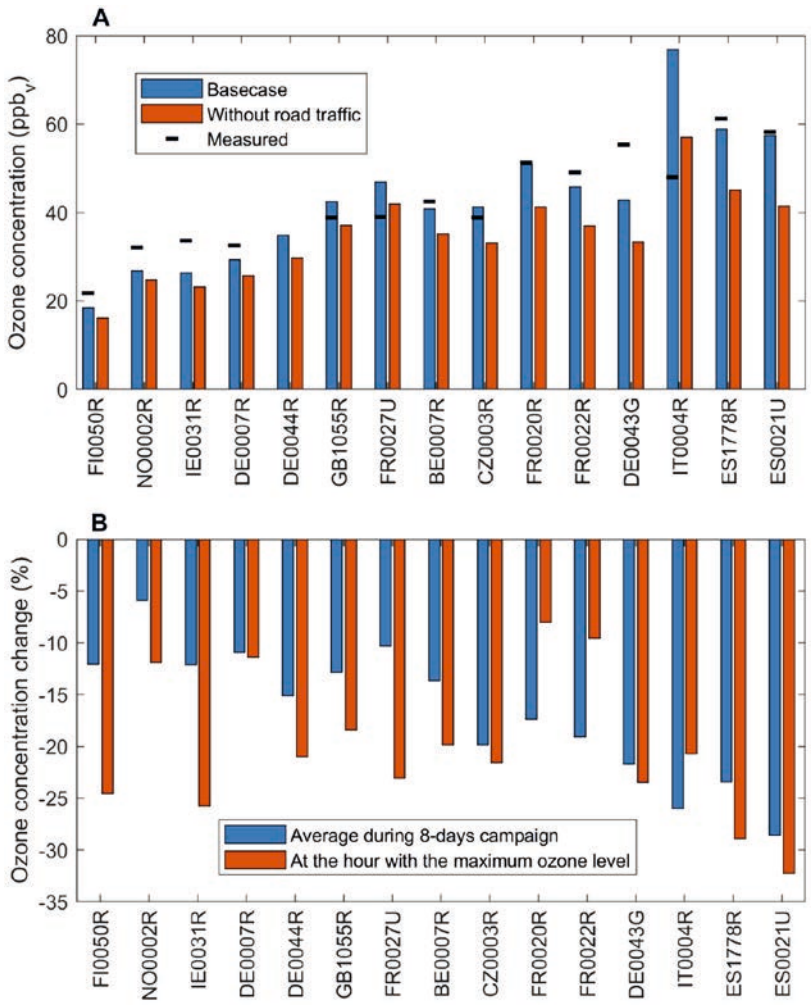

Fig. 15. Measured and modelled (ADCHEM) average surface ozone concentrations (panel A) and relative ozone concentration changes as a result of the hypothetical removal of road traffic emissions in Europe (panel B). The results are from a European summer heatwave episode from July 12–19, 2022, when over 30 stations participated in an intensive EMEP VOCs, ozone and carbonaceous aerosols measurement campaign (EMEP, 2023). Results from 15 of these EMEP stations are show in the Fig. Panel B shows both the modelled average and maximum peak ozone concentration decrease which would be achieved if all road traffic exhaust emissions were removed in Europe (source: D5.3)

5. Toxicity Rating

Toxicity testing was performed using physiologically relevant human lung models cultivated at the air-liquid interface (ALI) to replicate real-world inhalation exposures. While traditional 2D epithelial and macrophage cultures are widely employed for their simplicity and reproducibility, they lack the structural complexity of human lung tissue.

Advanced 3D ALI cultures, such as MucilAir® and EpiAirway™, provide more accurate representations of airway physiology, enabling long-term studies of barrier integrity and inflammatory responses. Additionally, lung-on-a-chip systems offer dynamic flow and mechanical stretch, further mimicking in vivo conditions.

Controlled exposures were conducted using chassis dynamometers to generate reproducible emissions, complemented by real-world on-road sampling to capture authentic driving conditions. Aerosols were delivered directly to cell cultures through commercial or custom ALI exposure systems, designed to account for particle size, deposition efficiency, exposure duration, and environmental parameters (Fig. 16).

Subsequent toxicological assays evaluated multiple endpoints, including cytotoxicity, oxidative stress, inflammatory signaling, DNA damage, and metabolic disruptions. By integrating these advanced cell models, exposure methods, and assay systems, the toxicity assessment framework ensures scientifically rigorous and human-relevant evaluation of health risks associated with real-world transport emissions (Vojtíšek-Lom et al., 2020; 2025).

Fig. 16. Cell incubator for cell exposition during the tests (Cervena at all, 2025)

Toxicological testing revealed that, although overall acute toxicity of exhaust emissions was low, molecular-level effects–including oxidative stress, DNA damage, and immune responses–were significant, particularly under cold-start conditions and in the presence of SecA-rich aerosols. Fuel composition, engine condition, and ambient temperature all played critical roles in modulating these responses.

The application of advanced in vitro lung models combined with transcriptomic analyses enabled a detailed understanding of the biological relevance of modern exhaust emissions. These findings underscore the importance of incorporating sensitive toxicological endpoints into emission assessments and regulatory frameworks.

Cold-modified vehicle emissions were observed to activate immune stress responses in airway cells that closely resemble antiviral defense mechanisms. Notably, even vehicles with low emissions under standard test conditions elicited this response. A conserved 72-gene signature was identified across both “clean” (Euro 6 gasoline hybrid) and “dirty” (Euro 4 diesel) vehicles at −9°C, highlighting the dominant influence of cold exposure (Fig. 17) (Červená et al., 2025).

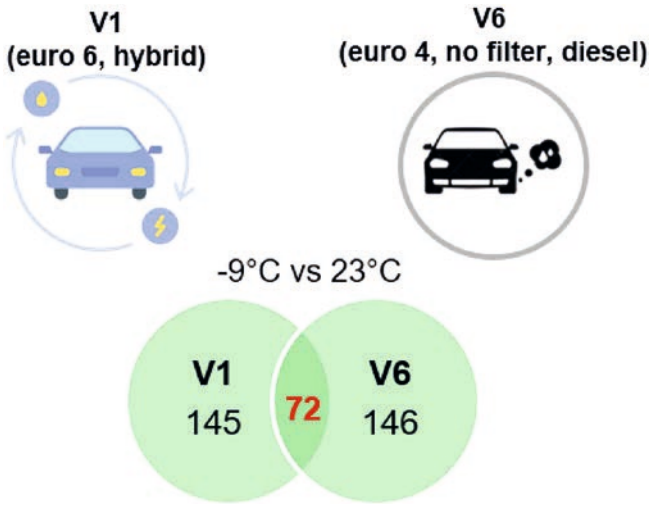

Fig. 17. 72 common genes with differential expression in the vehicles in the most different categories (V1 and V6) (source: PTNSS, 2025)

6. Summary and Conclusions

The PAREMPI project provides a comprehensive assessment of secondary aerosol (SecA) formation and the factors influencing emissions from the transport sector, integrating new experimental data, existing literature, and

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novel analytical tools. The project identified significant data gaps, as previous studies and measurement campaigns have largely focused on single transport technologies. To address these gaps, PAREMPI developed the Equivalent Particle Mass Index (ePMI), a software tool that estimates total particle mass formation potential based on exhaust gas precursors. Combined with toxicological testing, health impact assessments, and external cost evaluations, this approach enables improved quantification of the externalities associated with transport emissions, providing actionable insights for policymakers and legislative development.

Results from exhaust experiments emphasize the critical role of PM_aged formation potential in determining the atmospheric impact of emissions from different transport modes, with direct implications for air quality and human health. SecA formation was found to depend on multiple technology-related parameters, including fuel type and exhaust aftertreatment. In light- and heavy--duty vehicle experiments, cold starts were identified as particularly influential in enhancing both overall emissions and SecA formation potential. SecA was associated with gaseous organic compounds from fuel and lubricants, as well as inorganic pollutants such as SO_2, NO_x, and NH_3, indicating that mitigation cannot rely on a single technology.

Modern vehicles, while emitting low levels of regulated pollutants, may produce higher relative contributions of unregulated emissions, particularly sub--10 nm particles capable of SecA formation. Polycyclic aromatic hydrocarbons (PAHs) were still detectable in exhaust from the newest vehicles. Conversely, advanced emission control technologies demonstrated high efficiency, particularly through low black carbon emissions in vehicles equipped with filtration systems.

Brake wear particle (BWP) studies revealed that emissions are strongly dependent on pad type and braking conditions. Between 30–50% of PM_{10} emissions fell within the $PM_{2.5}$ size range, with ultrafine particle emissions occurring during harsh braking. BWPs were dominated by iron oxides, which absorb in the infrared region and contribute to measured black carbon from road transport.

Overall, these findings demonstrate that, in addition to SecA formation potential, nano-sized particles and PAH compounds present in modern exhaust reinforce the need for continued development of fuels, lubricants, engines, and aftertreatment technologies. Integrating experimental results, toxicity assessments, and ePMI-based modeling provides a robust scientific basis for policy recommendations. Such measures should promote “do-no-significant--harm” (DNSH) technologies and uphold the “polluter pays” principle, ensuring effective mitigation of harmful transport-related emissions and their societal impacts.

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