Deliverable D5.2

Summary report of precursor emissions, secondary aerosol forming potential and toxicity (database)

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PAREMPI
Particle emission prevention and impact: from real-world emissions of traffic to secondary PM of urban air

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List of abbreviations

AMS	Aerosol Mass Spectrometer
BC	Black carbon
CPC	Condensation Particle Counter
CO_2	Carbon dioxide
CFV-CVS	Critical Flow Venturi
CVS	Constant Volume Sampling
DI	Direct injection
DMA	Differential Mobility Analyzer
DOC	Diesel Oxidation Catalyst
DOFC	Dekati Oxidation flow reactor
DPF	Diesel Particulate Filter
EATS	Exhaust After-treatment System
EF	Emission factor
ELPI	Electrical Low Pressure Impactor
FID	Flame ionization detector
FTIR	Fourier transform infrared spectroscopy
GDI	Gasoline Direct Injection
HC	Hydrocarbon
HD	Heavy-duty
HVO	Hydrotreated Vegetable Oil
LD	Light-duty
MOC	Methane Oxidation Catalyst
NH_3	Ammonia
NMHC	Non-methane hydrocarbons
NMOG	Non-methane Organic Gases
NRMM	Non-road mobile machinery
NO_x	Nitrogen oxides
nv	Non-volatile
OC	Organic Carbon
OFR	Oxidation flow reactor
PAM	Potential Aerosol Mass chamber
PEMS	Portable Emission Measurement System
PFI	Port-fuel injection
PM	Particulate matter (mass)
PM_{aged}	Aged particulate matter (mass) after the chamber, aged particles including SecA
PM_{fresh}	Freshly emitted particulate matter (mass) before ageing
PN	Particle number
PN23	Number of particles larger or equal to 23 nm in diameter
PN10	Number of particles larger or equal to 10 nm in diameter
PDP-CVS	Positive Displacement Pump
RDE	Real Driving Emissions
SecA	Secondary aerosols

SI	Spark Ignition
SMPS	Scanning Mobility Particle Sizer
SO_2	Sulfur dioxide
SP-AMS	Soot Particle Aerosol Mass Spectrometer
VPR	Volatile particle removal
TSAR	Tampere Secondary Aerosol Reactor
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WHTC	World Harmonized Transient Cycle
WHSC	World Harmonized Stationary Cycle

1. Executive Summary

The PAREMPI database was developed as a comprehensive resource to consolidate emission data on secondary aerosol species, their precursors, and associated toxicity from various transportation sources. The database focuses on freshly emitted particle matter (PM_{fresh}) mass emissions and PM after ageing (PM_{aged}) through formation of secondary aerosols, incorporating direct measurement results from single emission sources such as engines, passenger cars, and heavy-duty vehicles, while excluding mixed emissions like those from roadside or tunnel measurements and data derived from indirect calculations. The database covers precursor gases (nitrogen oxides (NO_x), ammonia (NH_3), sulfur dioxide (SO_2), aromatics) potentially forming secondary emissions, as well as mass and composition of fresh and aged PM. Other emission species included are for example carbon dioxide (CO_2), non-methane organic gases (NMOG), and particle number (PN) emissions. From each study included in the database, detailed information is presented on the classifications of transport sectors (light-duty, heavy-duty, marine and aviation), emission classes, engine combustion technologies, fuel types, engine sizes and measurement conditions, including driving cycles, temperatures, and geographical locations, ensuring a thorough understanding of emissions under various scenarios. Measurement techniques in the included studies employ advanced instruments. Studies included from literature are traceable via references. Presented in an Excel format, the database is accessible and can be updated with newest results from PAREMPI project and literature.

The first database version is based on literature only. Literature data on secondary aerosols from transport sources appeared to be sparse for cars and heavy-duty vehicles, and especially so for ships and aircrafts. Additionally, technical details on transport applications and fuels studied used and relevant emissions were often reported limitedly. In literature, no secondary aerosol studies were available in real-world, real-driving, on-board, or field conditions. Data from PAREMPI consortium will partly fill this gap in knowledge by providing data obtained in real-word conditions.

This report presents an outlook of the database following the integration of unpublish data from earlier projects of the PAREMPI consortium, along with our complementary measurements. This enables identifying remaining data gaps beyond the PAREMPI project.

Already in its current form of database, comprising literature data only, the database indicates that emissions from older diesel cars without diesel particulate filters (DPFs) emit substantially higher particle emissions, both fresh and aged, than modern cars equipped with DPFs, often approaching near-zero levels. Notably, gasoline direct injection (GDI) engines also exhibit particle emissions, particularly under high-load conditions, as observed in the database. Also, the fuel was seen to have a clear impact on secondary aerosol formation. The database, in its final form, will be versatile, supporting research, policy-making, and engineering applications by enabling a holistic assessment of transport emissions and their environmental and health impacts. Its comprehensive, user-friendly structure makes it a valuable tool for evaluating and mitigating the role of transportation in air quality degradation.

2. Introduction

Secondary aerosol emissions from transport form in the atmospheric aging process from gaseous precursors after the exhaust emissions are released to the atmosphere. The secondary aerosol formation takes time from fractions of seconds to days and weeks. Due to dilution, cooling and mixing in the atmosphere, it is not possible to directly measure atmospheric secondary aerosol formation. The ambient aerosol is always a mixture of freshly emitted particles and aged particle mass formed via secondary aerosol formation process. The source apportionment studies have indicated that typically 20-40% of PM1 mass is secondary in atmosphere (e.g. Chen et al., 2022). The development of oxidation flow reactors (OFRs) have enabled studies of secondary aerosol formation potential in the laboratory conditions (Zhang et al., 2024).

In the PAREMPI project (https://parempi.eu/) a new secondary aerosol (SecA) and toxicity database focusing on transportation emissions was developed. The database is described in Deliverable D5.1 as follows:

"In the PAREMPI project (https://parempi.eu/), a new database of emissions, secondary aerosols and toxicity rating was developed. Database provides a comprehensive collection and analysis of data on the emission rates of fresh and aged secondary aerosol species, their precursors and toxicity of fresh and aged aerosols emitted from various transportation sources. The database is complemented with the other data available from the measurements including various types of gaseous and particle emissions. The database is an Excel file constantly updated with newest results from PAREMPI project and literature.

The database has two separate parts; emission studies and toxicity studies. In the emission database we considered only direct measurement results from single sources, such as those from engines, passenger cars, and heavy-duty vehicles, while excluding mixed emissions like those from ambient roadside or tunnel measurements or results obtained through indirect calculation. The focus is in most recent studies from past 10 years where the aged emissions were studied using oxidation flow reactors (OFRs), the older studies were included when considered relevant. In the toxicity emission database, we considered the studies with toxicity measured from the different transport sources.

A large amount of information related to all studies were collected. Parameters related to study, engine, aftertreatment and fuel as well as large number of parameters related to precursors of secondary emissions, fresh particulate emissions and aged emissions. For toxicity part, the database includes study and engine information, as well as information about toxicologican endpoints and toxicity rating. The database is in the format of an Excel file to ensure easy access and possibility to modify the resulting dataset as needed. Furthermore, the database is constantly updated to include the most recent results from the consortium and literature. »

Database for secondary aerosols and toxicity are separate, however, combined in one Excel file in two tabs. These two databases include different studies, where background data and measurement conditions are not uniform with each other. In this report, analysis of the secondary aerosols and toxicity parts of database are also presented separately in two sections.

The dataset is well-structured including the following main categories:

- Transport sector: Light-duty, Heavy-duty, Marine, Aviation.

- Application: Details the application type (e.g., passenger car, ship), emission class, engine combustion technology and fuel.
- Testing conditions: Driving cycle, temperature, and geographical location.
- Secondary aerosols database tab: Precursor gases (NO_x, NH_3, SO_2, aromatics), PN, fresh and aged PM and PM composition (black carbon (BC), organics, inorganics). Many other emission species are also covered, if available in the studies included in the database.
- Toxicity database tab: Results of the toxicity studies with toxicity rating

At the time of compiling this report, the studies included in the database are only from literature and conducted only in laboratory. Hence, the general description of laboratory measurements is presented in section 3.1. Other measurement methods are not included in this report in detail, while those are presented for precursor gases and aged PM in Deliverable 2.3 and for the PAREMPI complementary measurements in Deliverable 2.2.

Updates of the database will include PAREMPI consortium's unpublished data on the secondary aerosols (laboratory measurements of cars and engines, and real-world measurements on-board ship) as well as PAREMPI complementary measurements in laboratory (marine, aviation), real-world simulation (cars) and real-world, on-road testing of two trucks. Interpretating the secondary aerosol and toxicity databases requires expertise, given to the limited number of available results for the complex interdependences between emission sources, measurement technologies and observed outcomes.

3. Secondary aerosols database

3.1 Measurement sites

At the time of compiling this report, the database covers the transport sector's secondary aerosols results from laboratory measurements only, since all published studies so far have been carried out in laboratory. Laboratory measurements typically follow the basic setup for standardized emission testing protocols as regards driving cycles, instrumentation for gaseous and particle emissions. In PAREMPI, measuring fresh and aged (secondary) aerosols employes a specific dilution and conditioning setup, as well as instrumentation. The dynamometer-based measurements provide repeatable and standardized testing conditions under various driving cycles by using systems such as Constant Volume Sampling (CVS) or mini dilution tunnels. The data from PAREMPI partners include also results from real-world, real-driving measurements, which is an increasingly important and essential aspect to study. In this section, we describe general features of sampling procedures in laboratory measurements and in real-world conditions.

Laboratory measurements: CVS and dilution tunnels

Laboratory emissions testing is conducted in controlled environments using chassis dynamometers for complete vehicles and engine dynamometers for standalone engines. These tests follow standardized procedures such as the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) for light-duty (LD) vehicles and the World Harmonized Transient Cycle (WHTC) or World Harmonized Stationary Cycle (WHSC) for heavy-duty (HD) engines but can also be extended into various other test procedures. The vehicle or engine operates under predefined driving cycles that simulate urban, highway, and mixed driving conditions, allowing for repeatable and comparable emissions measurements. During testing, a CVS used to collect and dilute exhaust gases ensures stable and accurate measurements of regulated pollutants such as carbon monoxide (CO), CO_2, NO_x, hydrocarbons (HC), particulate matter (PM) and non-volatile particle number above 23 nm (nvPN23), which is employed to capture even ultrafine solid particle emissions.

Controlled laboratory testing minimizes influences of variation of temperature, humidity, and driving behavior, amongst others, making this procedure suitable for regulatory certification and compliance testing. For HD engines, engine dynamometer testing allows precise evaluation of engine performance and exhaust after-treatment system (EATS) efficiency. Fuel consumption and energy efficiency are also measured during these tests to assess overall vehicle performance. However, while laboratory tests offer consistency and repeatability, they do not necessarily reflect real-world real-driving conditions, leading to the increasing importance of on-road, on-board and field testing for a more comprehensive emissions assessment.

Constant Volume Sampling is a widely used method in the measurements of exhaust emissions from internal combustion engines, particularly for regulatory compliance testing. It operates by continuously diluting the entire exhaust flow with filtered air, ensuring that the sampled gases are representative and preventing condensation of certain pollutants. A key component of the system is the dilution tunnel, a controlled environment where the exhaust mixes with dilution air to maintain stable sampling conditions. The flow rate is kept constant

using either a critical flow venturi (CFV-CVS) or a positive displacement pump (PDP-CVS), allowing for accurate measurement regardless of variations in engine load or speed. The dilution tunnel ensures that pollutants are well-mixed, avoiding stratification and improving measurement accuracy. Figure 1 represents the Dilution tunnel and emission laboratory at BOSMAL, LD vehicle testing for PAREMPI campaign. The diluted exhaust is then collected in sample bags over a test cycle for subsequent analysis. The collected “BAG” samples are analyzed for key emissions, including CO, CO_2, HC and NO_x, which need to be converted to wet concentrations if measured as dry concentrations to correspond with the CVS measurement of entire diluted exhaust flow (see next section for PM and non-volatile particles).

Figure 1. Dilution tunnel and emission laboratory at BOSMAL, LD vehicle testing for PAREMPI campaign.

On-road, on-board, field measurements

From PAREMPI consortium, results obtained in real-world conditions will be included in the database.

Real-world emission measurements usually refer to on-road emissions testing of LD and HD vehicles, and in marine and aviation sectors, on-board and field measurements. Unlike in laboratory tests, Real Driving Emissions (RDE) measurements do not follow fixed driving cycles, ensuring that emissions performance is evaluated under a wide range of operating conditions. This approach assists in identifying discrepancies between laboratory results and real-world performance. Unlike traditional laboratory-based emissions testing, which is conducted in controlled environments using chassis or engine dynamometers, on-road testing provides a more accurate representation of actual emissions. For vehicles, test typology provides a realistic assessment of vehicle emissions under actual driving conditions where vehicles are measured during their operation in normal traffic, experiencing variations in speed, load, road gradient, and ambient temperature.

A Portable Emissions Measurement System (PEMS) is advanced mobile testing device designed to measure vehicle emissions in real-world driving conditions. The PEMS system is typically mounted on the vehicle and connected to the exhaust system, continuously collecting and analyzing exhaust gases while the vehicle is in operation. These PEMS systems consist of multiple integrated components, including gas analyzers, particle measurement devices, exhaust flow meters, and data acquisition systems. The PEMS can measure pollutants such as CO, CO_2, NO_x, HC, and PM, while also tracking vehicle parameters such as speed, acceleration, altitude, temperature fluctuations, and different driving patterns using GPS and weather sensors. The PEMS systems are essential for testing compliance of vehicles with stringent emissions regulations like Euro 6d cars with the RDE test procedure. To ensure accuracy, PEMS employs advanced correction algorithms that compensate for environmental influences and sensor drift. The use of portable measurement systems has become increasingly important as regulatory bodies shift towards real-world emissions testing to better assess the effectiveness of emissions control technologies in realistic conditions. With

increasing regulatory focus on real-world emissions compliance, on-road testing has become a mandatory part of emissions certification for both LD and HD vehicles.

In PAREMPI measurements, a unique setup was built for on-road measurements of aged PM and other emission species comprehensively from two trucks (Figure 2). These procedures are described in Deliverables D2.2 and D2.3.

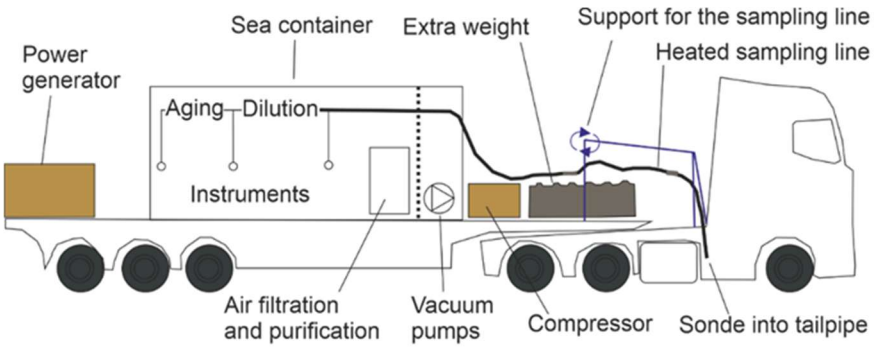

Figure 2. Emission measurement setup for RDE measurements of two trucks during PAREMPI HD campaign.

3.2 Measurement methods

This section describes measurement methods of emissions included in the database. More detailed description of measuring aged PM and discussion on the ageing conditions are presented in Deliverable 2.3. Furthermore, Deliverable 2.2 presents setup and methods used in the PAREMPI measurements. For measuring relevant exhaust particles and gases many principles are available, though many instruments are only feasible for use in laboratory.

The database contains results from a wide range of instruments used for laboratory emissions testing, focusing on both gaseous precursor emissions and particles. The instruments used include gas analyzers defined in emission standards, as well as FTIRs, for quantifying gaseous emissions. For particles, PM filter collections are employed as well as online characterization of particles with variety of instruments such as ELPI, Aethalometer and mass spectrometers (Soot particle Aerosol Mass Spectrometer; SP-AMS, high-resolution time-of-flight AMS; HR-ToF-AMS, and Quadrupole Aerosol Chemical Speciation monitor; Q-ACSM) to assess both particle mass, number and chemical composition, allowing for detailed evaluation of total and ultrafine particle emissions.

The combination of gas, particle number, mass and composition measurements, and oxidation chamber results makes this database valuable for analyzing emissions across a broad spectrum of regulated and unregulated pollutants, reinforcing the controlled laboratory setting as a key tool in emissions research.

3.2.1 Gases, PM (filter-based) and non-volatile particle number

Studies encompassing potential SecA precursor gases, NO_x, NH_3, SO_2 and aromatics, are essential to generate sufficient knowledge for constructing models to estimate SecA formation based on precursor gases in exhaust. Hence, these emissions are included in the database, when available in the cited studies. Aromatic precursor gases are not typically reported along

with aged PM, and hence also groups of organic gases are included in the database. CO_2 is essential for calculating emission factors, when the results are published only as concentrations (see section 3.4).

Notably, some gases, such as SO_2 and VOCs, originate from fuel and lubricating oil, whereas nitrogen oxides are formed from nitrogen in the air at high combustion temperatures. NH_3 and N_2O are formed in the exhaust aftertreatment systems (Suarez-Bertoa and Astorga 2016, Selleri et al. 2021).

Nitrogen Oxides (NO_x): NO_x emissions include nitrogen monoxide (NO) and nitrogen dioxide (NO_2), both of which contribute to air pollution and secondary aerosol formation. NO_x emissions are particularly high in diesel vehicles due to high combustion temperatures and lean-burn conditions. Selective catalytic reduction (SCR) and lean NOx traps (LNT) are used to mitigate NO_x emissions, and the dataset collected to database reflects these variations across different engine types and emission control technologies.

Ammonia (NH_3): NH_3 emissions may form as a byproduct of SCR systems used in diesel vehicles for NO_x reduction. While SCR reduces NO_x, it may lead to NH_3 slip if not properly managed. Spark-ignited engines equipped with three-way catalysts (TWC) may emit high concentrations of NH_3. The dataset captures NH_3 emissions, highlighting differences between vehicles.

Organic gases: Hydrocarbons (HCs) and Non-Methane Organic Gases (NMOG) or non-methane hydrocarbons (NMHC) are documented in the database, and when available, also alkanes, alkenes, alkynes, oxygenated organic compounds, and aromatics. These compounds contribute to tropospheric ozone formation, with aromatics being particularly important contributors to secondary organic aerosols (SOA) formation in the atmosphere.

Carbon Monoxide (CO): CO is primarily produced from incomplete combustion of fuel and is more prevalent in gasoline engines. The dataset provides CO emissions when available. Emission control strategies, such as three-way catalysts (TWC) in gasoline vehicles, reduce CO levels effectively. CO is not considered as precursor for secondary aerosol formation.

Carbon Dioxide (CO_2): As a major greenhouse gas, CO_2 emissions are directly related to fuel consumption and it provides insights into fuel efficiency trends across different vehicle technologies, combustion modes, and driving conditions. Hybrid and alternative fuel vehicles typically show lower CO_2 emissions compared to conventional gasoline and diesel vehicles. The dataset includes CO_2 emissions when available, enabling calculation of emission factors (in unit per MJ) even when only concentrations of emission species are reported.

Portable FTIR equipment for gases: In the real-world (on-road, on-board, field) measurements, capability to measure as many emission species as possible simultaneously is a substantial advantage. The Fourier transform infrared (FTIR) is such instrument capable of measuring many gaseous compounds with high data acquisition frequency. Although FTIR technology for measuring exhaust gases has been used since the 1980s, new evaluations are needed for major changes in exhaust matrix due to the possible interferences caused by the new compounds in the exhaust. The IR spectrum is a sum of the spectra of all individual compounds of the exhaust sample, hence, for quantitative analysis a wavelength region with minimum overlapping of the other compounds is needed, as well as definition of the interfering signals. Each compound present in the exhaust gas is typically calibrated by instrument manufactures in several concentrations and included in so called methods or recipes. Verification of FTIR results have been carried out in many studies against the procedures used in the measurements of regulated emissions as reviewed by Giechaskiel and Clairotte (2021). Comparability of the results obtained byFTIR and traditional measurement methods have been

satisfactory for CO_2, CO, NO_x, NH_3 while higher deviation have been found for hydrocarbons. Most of the PEMS-FTIR instruments include also measurement of aromatic compounds, which is a specific strength in secondary aerosol studies.

Particle matter mass (filter-based) and non-volatile particle number measurements

The dataset includes measurements of particle emissions in different forms, including filter-based PM measurements and particle number concentrations. Gasoline direct injection (GDI) engines are known to emit higher PM levels than traditional port-fuel injection (PFI) engines, and the database allows for comparisons between these technologies. Diesel particulate filters (DPFs) in modern diesel vehicles effectively reduce PM emissions, a trend observable in the dataset.

Particulate matter mass measurement involves collecting and weighing particles present in the diluted exhaust from an engine or vehicle. The process typically uses dilution to mix the exhaust with filtered air, preventing condensation and ensuring a stable sampling environment. A known volume of the diluted exhaust is then passed through a special filter, where particulate matter is trapped. After sampling, the filter is carefully weighed before and after exposure to determine the total mass of collected particles. This gravimetric method provides an accurate assessment of PM concentration, however, with distinct detection limits. To ensure reliability, PM measurement must account for factors like humidity, temperature, and volatile particle evaporation; hence, sample conditioning is applied.

The dataset provides also detailed information on black carbon emissions, a component of PM having significant implications for air quality, human health, and climate change. BC is a product of incomplete combustion, particularly from diesel engines. Measurement methods for BC are described in section 3.1.3.

Non-volatile particle number measurement focuses on counting the total number of solid particles in the exhaust. This method is particularly important for detecting ultrafine solid particles. The measurement process begins with sampling the exhaust through a dilution system and then treatment with a volatile particle removal (VPR) system. After this conditioning, the sample enters a particle counter, which detects and counts individual solid particles within a defined size range, usually down to 23 nm or 10 nm in diameter. PN measurement is essential for evaluating the performance of modern emission control systems, such as gasoline and diesel particulate filters, which are designed to reduce the number of harmful particles released into the air. Figure 3 represents a schematic representation of the exhaust sampling and PN measurement system.

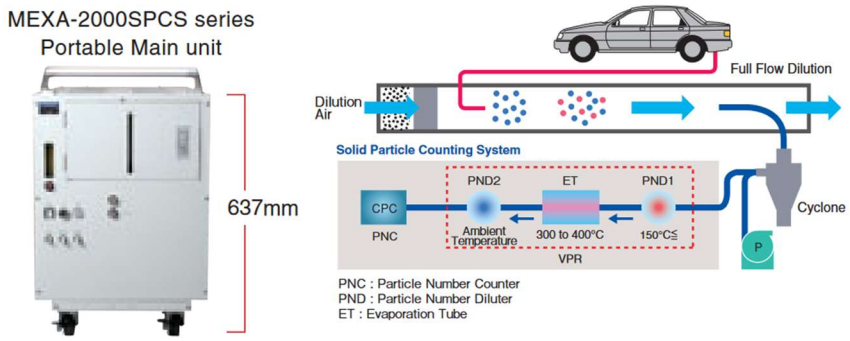

Figure 3. Schematic of exhaust sampling and PN system.

3.2.2 Oxidation flow reactors for simulating PM ageing

In the studies focusing on secondary aerosols, different oxidation chambers are used for simulating atmospheric aging and secondary aerosol mass formation. Such setups allow researchers to study secondary aerosol formation and the transformation of pollutants over time, improving the understanding of real-world atmospheric chemistry.

In the database, we have included only OFR-studies to enable comparison of the results between studies. A few smog-chamber studies were included to the database in cases where the data was not available from OFR and was considered important. However, we note that all smog chambers are unique in terms of size, oxidation conditions and losses and thus comparison of results between smog chambers is challenging. Following chapters include description of the used OFRs in the studies included in the database. For the smog-chamber descriptions, the reader is advised to read the articles referred to in the database.

A variety of different instruments were utilized to measure either mass, size distribution or composition of Aged PM after the oxidation flow reactor in the studies included in the database. In the optimal case, same instrument would be always used to measure fresh and aged PM concentrations, enabling realtime detection of PM enhancement during aging. However, due to availability of the instruments, either switching between fresh and aged or repeating same experiments twice to capture both fresh and aged emissions are often used. In addition to Aged PM measurements, quite many studies include the measurement of precursor emission either before or after the chamber, to characterize the role of precursors in the Aged PM formation process.

Due to high variability in exhaust emissions during driving, several oxidation flow reactors (OFRs) with short residence times have been developed (see Deliverable 2.3). One such reactor, TSAR (Tampere University Secondary Aerosol Reactor), features a ~40 s residence time and near-laminar flow, enabling the study of transient vehicle emissions and their secondary aerosol formation. TSAR is an OFR254-type reactor, generating OH radicals via ozone photolysis at 254 nm, with minimal particle losses. DOFR™ (Dekati Oyj) integrates sample conditioning and oxidation in one unit. It uses UV-C (254 nm) and injected oxidants (OH, O_3) to simulate atmospheric aging in under a minute, equivalent to 1–35 days of real-world exposure. All parameters are software-controlled, and the laminar flow minimizes particle loss. The PAM reactor (Aerodyne Research) is a widely used aluminum OFR (13 L) that simulates days of atmospheric oxidation in minutes using 185 and 254 nm UV lamps. A humidification system is used to maintains 30–50% RH to generate OH and HO_2 radicals. OH exposure is often calibrate via CO reduction. While PAM is effective for lab studies, its larger volume and residence time make it less ideal for transient exhaust emissions.

3.2.3 Instruments for measuring aged PM

Aged PM including secondary exhaust aerosols

In the studies collected to the database, several different instruments were utilized to measure the emissions (e.g. emission factor, mass or number concentrations) and properties (e.g. composition, size distribution) of Aged PM after the OFR. The aerosol mass spectrometer (AMS) is the most commonly used instrument for measuring the chemical composition, organic and inorganic compounds (NO_3^-, SO_4^{2-}, NH_4^+, and Cl^-) of secondary aerosols. Notably, BC is not included in the AMS analysis; hence PM(AMS) in database is not equivalent to PM_{aged}. This advanced analytical instrument enables real-time measurement of the size and chemical

composition of airborne particles, providing crucial insights into secondary aerosol formation process. In AMS data analysis, the oxidation state of organic aerosols is often inferred using the oxygen-to-carbon (O:C) ratio or the hydrogen-to-carbon (H:C) ratio, derived from high-resolution mass spectra. A higher O:C ratio can be used to indicate higher oxidation state, suggesting that the aerosol has undergone extensive atmospheric aging through processes such as photooxidation, heterogeneous reactions, or secondary organic aerosol (SOA) formation.

The combination of BC analysis with AMS data enables determination of PM_{aged} emissions. Many methods can be used to measure black carbon emissions. The SP-AMS with a Nd:YAG laser at 1064 nm, can detect and analyze refractory aerosol components such as refractory black carbon (rBC), metals, and other high-temperature-resistant particles that standard AMS instruments cannot efficiently detect. Although BC is often assumed to resist oxidation in oxidation flow reactors, oxidized components can mix with BC and alter its absorption properties. However, also the SP-AMS has limitations primarily due to size detection constraints and vaporization inefficiencies in detecting BC compared to dedicated instruments such as the Multi-Angle Absorption Photometer (MAAP), instruments using photoacoustic principle (such as AVL MSS), laser induced incandescence (LII) or the Aethalometer (AE33). The AMS lens system is optimized for measuring particles with vacuum aerodynamic diameters ranging approximately from 50 nm to 700nm, while large fraction of BC particles from engine emissions are typically smaller. An organic carbon/elemental carbon (OC/EC) analyzer has been employed for similar analyses. The AMS also provides chemically resolved size distributions, albeit with the aforementioned size limitations.

Other instruments

Aged PM can be also determined by conversion of the size-distributed number measurement to PM mass emissions, as described in Deliverable 2.3. Instruments such as the Electrical Low-Pressure Impactor (ELPI) and the Scanning Mobility Particle Sizer (SMPS) are commonly used. The SMPS is an advanced instrument designed to measure the size distribution of submicron particles, typically ranging from 2 nanometers up to 1 micrometer. It classifies particles based on their electrical mobility with a Differential Mobility Analyzer (DMA) and counts them using a Condensation Particle Counter (CPC). This high-resolution instrument is widely used in air quality research, including in engine emission studies. The ELPI, on the other hand, is a real-time instrument capable of measuring particle size distributions over a broader range, typically from 7 nanometers to 10 micrometers. It operates based on inertial impaction combined with electrical charge measurement. In the ELPI, particles are first charged before entering a cascade impactor, where they are separated by size due to inertia. The collected particles generate electrical signals proportional to their number concentration. The ELPI provides both number- and mass-based size distributions with a high temporal resolution, making it widely used in engine exhaust studies after the OFR. While the SMPS excels in measuring nanoparticles with high resolution but requires longer scanning times, the ELPI is preferred for real-time monitoring of a broader particle size range, making it particularly useful for applications that require rapid data acquisition.

3.3 Aged PM results in database

3.3.1 Overview

Datasets included in the 1st version of database based on literature are presented in Table 1. From literature, the most extensive secondary aerosol dataset was found for light-duty vehicles, comprising 79 data points. For heavy-duty applications, only 28 datapoints met the defined criteria. For aviation, only 5 datapoints were identified from literature, and none for marine sector. Already before the detailed analysis, and even when considering the oncoming updates from the PAREMPI Consortium, secondary aerosols from marine and aviation sectors warrants further studies.

Table 1. Dataset included in the 1st version of database based on literature.

N.	Transport Sector	Quantity
1	Light-Duty	79
3	Heavy-Duty	28
4	Aviation	14
5	Medium-Duty	5
6	Marine	0

3.3.2 Light-duty vehicles

Available data in literature

The dataset comprises 79 datapoints for LD vehicles (Table 2). For each datapoint, database includes 72 columns covering a broad range of parameters, including engine characteristics, fuel properties, emission control systems, and various pollutant emissions.

Table 2. Summary for LD applications in the database.

Factor	Number of unique values
Application	4
Emission class	18
Model year	18
Engine combustion technology	7
Fuel	16
DOI	23

The data includes information on vehicle applications, such as passenger cars, and emission classes like Euro 5 and Euro 6. The majority of the entries belong to passenger cars under the light-duty vehicle category, with emission classifications primarily falling within Euro 5 and Euro 6 standards. Euro 5 regulations, introduced in 2009, set stricter limits on particulate matter and nitrogen oxide emissions, while Euro 6, implemented in 2014, further reduced NO_x emissions, especially for diesel vehicles. The dataset captures vehicles from different model years, spanning from older Euro 5 cars to newer Euro 6 models, allowing for comparative analysis of

emission performance across regulatory changes. Additionally, the dataset differentiates between various engine technologies within these emission classes. Gasoline direct injection (GDI) engines are prevalent in Euro 5 vehicles, while Euro 6 vehicles show a mix of GDI and port-fuel injection technologies. This distinction is crucial, as GDI engines tend to emit higher levels of particulate matter compared to PFI engines, despite gasoline engines generally producing fewer NO_x emissions than their diesel counterparts. Emissions for various EATS comprised 12 studies using mostly TWC for 60 records, DOC for 4 records and MOC + SCR for 2 records. Model years covered cars from 1987 to 2017 in the database, thus representing models from very old to modern vehicles.

Laboratory-based testing provides insights into the emissions from these vehicles under different conditions such as temperature, driving conditions and with different fuels. Some data points reflect emissions recorded during standardized driving cycles like WLTC (Worldwide Harmonized Light Vehicles Test Cycle) and NEDC (New European Driving Cycle), while others represent real-world driving conditions where emissions can be significantly higher due to variations in driving behavior, load, and environmental factors.

Fuel types range from conventional diesel and gasoline to alternative fuels like E85 and HVO (Table 4). Fuel had an important effect on non-volatile particle number emissions. We selected nvPN23 to be presented as an example in Table 3.

Table 3. Non-volatile particle number emissions for various fuels and temperature conditions. "Warm" is for temperature range from 22 to 24 °C, while "Cold" is for - 8 to 2 °C. Results adapted from Saarikoski et al., 2024.

Fuel	Emission standard	Test Condition	nvPN23 [#/km]
CNG (with back-up EN228)	Euro 6d	Cold	5.00E+10
CNG (with back-up EN228)	Euro 6d	Warm	9.00E+10
EN228 Gasoline (ArH)	Euro 6d	Cold	2.20E+12
EN228 Gasoline (ArH)	Euro 6d	Warm	5.50E+11
EN590 (Ar20)	Euro 6d TEMP	Cold	2.30E+08
EN590 (Ar20)	Euro 6d TEMP	Warm	1.80E+08
HVO (Ar0)	Euro 6d	Cold	1.60E+08
HVO (Ar0)	Euro 6d	Warm	1.40E+08
alkylate (Ar0)	Euro 6d	Cold	6.50E+11
alkylate (Ar0)	Euro 6d	Warm	5.60E+11

Temperature had impact on emissions. CNG (Compressed Natural Gas) showed slightly higher particle numbers in warm conditions than cold and EN228 Gasoline (ArH) had much higher particle emissions in cold conditions — about double compared to warm. This is a typical trend due to a longer warming up period of EATS at lower than at normal temperatures. Also, EN590 (diesel) also showed slightly increased PN emissions in the cold, though data is limited.

One example of fresh and aged PM obtained with a Euro 6 SI GDI car by Simonen et al., (2019) is presented in Table 4. The data shows that for all driving cycles, PM_{aged} emissions are significantly higher than fresh emissions. NEDC (CSUDC) has the highest PM_{fresh} value at 0.3162 g/km, while WLTC has the lowest PM_{fresh} value at 0.1355 g/km. However, PM_{aged} emissions follow a different trend, with WLTC showing the highest PM_{aged} level at 3.8373 g/km, indicating that under more dynamic and realistic driving conditions, secondary aerosol formation or aging processes may be more intense. NEDC (HUDC) presents the lowest values for both fresh and PM_{aged}, but even here, PM_{aged} is roughly 14 times higher than fresh. Another

study by Timonen et al., 2017 showed that when increasing the fuel ethanol content from 10 to 85 and 100% significantly decreased the PM_{aged} emissions. For E10 the aged/fresh ratio was 14.3 whereas for E85 it was 1.5 and E100 the ratio was slightly lower than one, indicating that SecA formation was negligible.

These comparisons highlight the importance of considering aged emissions in evaluating the true environmental impact of vehicles to ambient air quality. PM_{fresh} measurements alone may significantly underestimate the particulate burden, especially under cycles that better simulate real-world driving like WLTC. Also, results indicate that the used engine and after-treatment technologies and fuel has significant impact on both fresh and aged emissions.

Table 4. PM fresh vs. PM aged data by driving cycle for passenger car Euro 6 SI GDI adapted from Simonen et al., 2019.

Driving Cycle	PM_{fresh} [g/km]	PM_{aged} [g/km]	PM_{aged}/PM_{fresh}
NEDC (CSUDC)	0.32	3.04	9.5
NEDC (HUDC)	0.15	2.11	14.1
WLTC	0.14	3.84	27.4

PAREMPI consortium's light-duty data to be updated in database

PAREMPI consortium has conducted secondary aerosol studies on the light-duty technologies presented in the following Table. Results published after database version 1.0 have been updated in the database version 2.0.

Table 5. Light-duty studies on secondary aerosols conducted by PAREMPI consortium published after database version 1.0, and updated in database version 2.0 .

Cars	Cycles	Tempera-ture [°C]	Fuels	Emission species	Reference
Gasoline, gasoline GPF, Diesel, CNG, all Euro 6d	WLTC	+23, -7	High and low aromatic diesel and gasoline, renewable diesel, CNG.	Gases, fresh and aged PM/PN, SVCs, toxicity	Saarikoski et al. 2024. Hakkarainen et al. 2024. (EU TUBE No 814978)
PHEVs, gasoline, diesel, CNG, Euro 6d, older cars	RDEsim in lab	+35, +23, -9	Gasoline, diesel, CNG	Gases, fresh and aged PM/PN, SVCs, toxicity	Simon et al. 2025 (PAREMPI project).

3.3.3 Heavy-duty applications

Available data in literature

PAREMPI database contains 28 data entries on emissions from heavy-duty transport sector published by two 2 different studies (Table 6). Specifically, the database covers two primary vehicle applications, predominantly tractors classified under emission classes like "Class 8," with model years primarily from 2006 to 2010.

Table 6. Summary for HD applications in the database from literature.

Factor	Number of Unique Values
Application	2
Emission class	2
Model year	3*
Engine combustion technology	1
Fuel	5
DOI	2

* Only one reference reports the model year.

The database provides extensive engine specifications such as combustion type (direct injection diesel engines), engine size (ranging from 4.4 to 14.9 liters), cylinder configurations (commonly six-cylinder inline, turbocharged diesel engines), and exhaust after-treatment technologies. It also specifies testing conditions, including laboratory and real-world scenarios, type of driving cycles, engine loads, and fuel types used.

Emissions data include PM, CO, BC or EC, and various organic aerosols, both fresh and aged, as well as detailed analysis of the aerosol composition via advanced measurement instruments. However, several emissions-related parameters like precursor gases (NO_x, SO_2, NH_3, aromatics) remain largely unreported. The studies primarily utilize gravimetry and OC/EC analysis instruments for particle emission measurement.

An example of the HD results is presented in Table 7. Impact of exhaust aftertreatment on emissions was analysed by comparing emissions from Class 8 HD tractors using the same fuel (ULSD with 12% aromatics) under three exhaust aftertreatment setups: DOC+DPF+SCR, DOC+DPF, and no aftertreatment. Vehicles without aftertreatment showed drastically high emissions. CO averaged over 4100 mg/kWh, compared to under 80 mg/kWh for vehicles equipped with EATS. PM emissions exceeded 620 mg/kWh without exhaust aftertreatment but stayed below 2 mg/kWh with DOC+DPF systems. Organic aerosols and elemental carbon were also significantly higher without emission control, with EC reaching ~758 mg/kWh versus under 2 mg/kWh when equipped with EATS.

Only vehicles without exhaust aftertreatment systems produced aged organic aerosols, indicating a higher risk of secondary aerosol formation, and thus higher aged PM.

Exhaust aftertreatment systems like DOC+DPF and DOC+DPF+SCR cut harmful emissions by orders of magnitude. They not only reduce primary fresh tailpipe pollutants but also limit the formation of secondary aerosols in atmosphere, proving cleaner heavy-duty transport.

Table 7. Mean values of emission for ULSD (12% aromatics) fuel (Gordon et al., 2014).

Exhaust aftertreatment	CO [mg/kgfuel]	PM fresh [mg/kgfuel]	Organics fresh (AMS) [mg/kgfuel]	EC [mg/kgfuel]	Organics aged (AMS) [mg/kgfuel]
DOC+DPF	79.5	1.85	3.05	1.9	0
DOC+DPF+SCR	77.5	0.9	5.75	2.1	0
no aftertreatment	4147	623.2	199.9	757.6	53.3

Another example of analysis of heavy-duty data from literature in the PARMEPI database compares two fuels—Diesel and Renewable diesel (paraffinic) —across three aftertreatment configurations: DOC+DPF+SCR, DOC+SCR, and No EAT, all under the same cycle (NRSC 2100 rpm; Karjalainen et al., 2019).

The PM-related emissions were significantly lower for both fuels when using DOC+DPF+SCR. For example, diesel engines with no aftertreatment emitted ~5.2 mg/kWh of PM, while that dropped to <1 mg/kWh with DOC+DPF+SCR. Similarly, aged PM emissions for diesel application without EATS reached ~26.6 mg/kWh, compared to just ~0.9 mg/kWh when using the DOC+DPF+SCR system.

For renewable paraffinic fuel, emissions were consistently lower than for diesel fuel, regardless of exhaust aftertreatment used. Notably, even without DPF, aged PM levels with paraffinic fuel and DOC+SCR stayed relatively low (~3.8 mg/kWh), indicating inherent cleanliness of the fuel.

The combination of renewable paraffinic fuel and DOC+DPF+SCR aftertreatment provides the cleanest emission profile. Lack of exhaust aftertreatment sharply increases PM emissions, especially aged particles, which are more likely to contribute to atmospheric pollution. Even without full filtration, renewable fuels reduce emissions, making them a strong complement to advanced exhaust systems.

Table 8. Emission for diesel and renewable paraffinic fuel. PM_{aged} measured with AMS does not include BC.

Fuel	Exhaust aftertreatment	Engine size [l]	Engine load of MCR/Thrust	PM (PN-to-PM) [mg/kWh]	PM_{aged} (AMS) [mg/kWh]
Diesel	DOC+DPF+SCR	4.4	100	1.0	0.9
Diesel	DOC+SCR	4.4	100	4.5	5.1
Diesel	No EAT	4.4	100	5.2	26.6
Renewable paraffinic	DOC+DPF+SCR	4.4	100	0.6	0.7
Renewable paraffinic	DOC+SCR	4.4	100	2.6	3.8
Renewable paraffinic	No EAT	4.4	100	5.2	24.9

PAREMPI consortium's heavy-duty data to be updated in database

PAREMPI consortium has conducted secondary aerosol studies on the heavy-duty technologies presented in Table 9. These results will be updated in the database after publications.

Table 9. Previous unpublished heavy-duty studies conducted by PAREMPI consortium.

Cars	Cycles	Location, temperature	Fuels	Emission species	Reference
Heavy-duty diesel engine without EATS	RMC-C1	Lab, room temperature	High and low aromatic diesel (Ar20, Ar0)	Gases, fresh and aged PM/PN, SVCs, toxicity	Hakkarainen et al. 2023. SecA unpublished (EU TUBE No 814978)
Heavy-duty diesel engine without EATS	RMC-C1	Lab, room temperature	EN590, renew. diesel, oxyg. diesel	Gases, fresh and aged PM/PN.	Aakko-Saksa et al. 2023. Unpublished SecA. (eFuel project)
Two trucks	On-road	Finland. Down to zero temp. Cold&hot starts.	EN590, HVO	Gases, fresh and aged PM/PN, SVCs, toxicity	Unpublished data (PAREMPI project)

3.3.4 Aviation

Available data in literature

The available data in the PAREMPI database originates entirely from a single scientific study focused on emissions from a CFM56 variant turbofan engine (Table 10). The study, conducted by Kılıç et al. (2018), on the Zurich Airport in Switzerland, aimed to identify precursors of secondary aerosols emitted by aircraft engines. The database compiles detailed measurements from this experiment, covering various emission parameters. The dataset includes information on engine combustion technology, instrumentation used during the measurements, and specific emission outputs such as particle numbers at various sizes (e.g., 2.3 nm, 10 nm, 23 nm), both fresh and aged. The study employed advanced tools like the PTR-ToF-AMS and AMS to analyze VOCs and particulate matter, respectively. They observed very high SOA (secondary organic aerosol) formation potentials, SOA emissions being 10 and 100 times higher than primary emissions at the cruising and idle conditions.

Table 10. Summary for Aviation applications in the Database.

Factor	Number of Unique Values
Application	1
Emission class	-
Model year	-
Engine combustion technology	1
Fuel	1
DOI	1

The dataset includes 13 data points where both fresh and aged organic aerosol emissions were measured using an AMS. The fresh organic emissions range from about 0.23 to 7.3 [mg/kgfuel], with an average value around 4.15 [mg/kgfuel]. In contrast, the aged organic emissions span a much wider range—from 100 up to 1500 [mg/kgfuel], with an average of approximately 484.6 [mg/kgfuel]. For Jet A1 with sulfur content of approx. 460 mg/kg, SIA emission factors reached even 1610 mg/kgfuel.

This indicates a dramatic increase in organic aerosol concentration following atmospheric aging. In fact, for most of the paired values, the aged organic mass emission is several hundred to over a thousand times higher than the fresh organic mass emission. For example, one entry shows an increase from 0.23 (fresh) to 1400.0 (aged) [mg/kgfuel], a nearly 1400-fold increase.

The difference between aged and fresh PM consistently reflects this trend, with all aged PM results being significantly greater than fresh PM results. The median aged PM is 100 [mg/kgfuel], but the upper quartile reaches 1000 [mg/kgfuel], showing that while some increases during aging are modest, others involve substantial secondary organic aerosol formation.

In relation of emission versus engine load, the scatter plot (Figure 4) clearly illustrates a positive relationship between engine load and fresh organic aerosol emissions. At low engine loads (around 3–5%), organic emissions are quite low. As engine load increases, emissions rise significantly. Black carbon emissions (fresh) shows similarly a positive correlation with engine load, demonstrating higher soot emissions at greater engine loads. The data clearly

supports the common understanding that increased engine loads result in higher emissions for most pollutants, particularly fresh organics and black carbon.

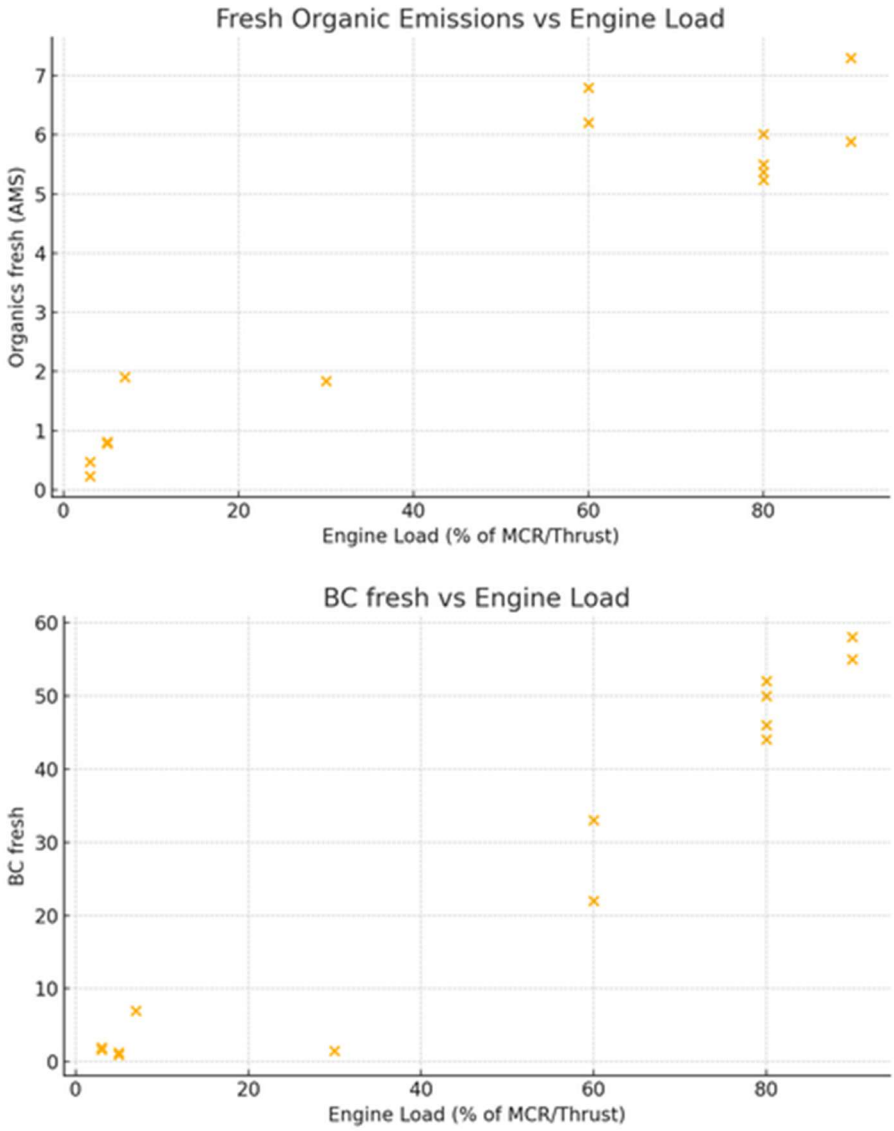

Figure 4. a) Fresh organic emissions [mg/kgfuel] to engine load [% of MCR/Thrust], b) BC fresh [mg/kgfuel] to engine load [% of MCR/Thrust] based on results published by Kılıç et al. (2018).

PAREMPI consortium's aviation data to be updated in database

In addition to published studies, the PAREMPI Consortium has conducted PM_{aged} studies on the aviation technologies presented in Table 11. The results are updated in the database as they become publicly available.

Table 11. Previous unpublished Aviation studies conducted by PAREMPI consortium.

Engine	Cycles	Location, temperature	Fuels	Emission species	Reference
Simulation with CAST	Steady-state, two modes.	Lab, simulation.	Six jet fuels including Jet A-1 and SAF.	Gases, fresh and aged PM, SVCs, toxicity	PAREMPI data, not published

3.3.5 Marine sector

Literature data from marine sector secondary aerosols is scarce at the time of the D5.2 report preparation. The database will be updated with several studies later (Table 12). Karjalainen et al. (2022) has published emission factors for PM_{fresh} (327 mg/kWh, calculated from the SMPS result and 281 mg/kWh calculated from AMS+AE33 results after PAM chamber) for on-sea cruising at 65% load with HFO. The measurements were conducted on-board a RoPax ship, exhaust was sampled from one of the ship's four main engines (Wartsila 9L46D). The engine was equipped with and open loop scrubber (ECO-DeSOx, Ecospray Technologies), and a DOC (Ecospray Technologies). The results indicate that secondary aerosol formation was negligible, likely due to the oxidation catalyst (DOC) oxidating the precursors. However, we note that without DOC the SecA formation could have been significantly higher. In addition to this study, the PAREMPI consortium has conducted secondary aerosol studies on many marine sector technologies (Table 12); these will be updated in the database when published.

Table 12. Unpublished marine studies conducted by the PAREMPI Consortium.

Engine, Fuels	Location, cycles	Fuels	Emission species	Reference
DG, several	Lab, simulation	Marine fuels 0.1%S and 0.5%S, NH3 and ash in exhaust. FAME blend.	Gases, fresh and aged PM/PN, SVCs, toxicity	PAREMPI data, not published
Wärtsilä Vasa 4R32 LN, 1.6 MW	Laboratory, 75% and 25% engine loads	HFO 2.5%S, 0.5%S, MDO 0.1%S, Biofuel	Gases, fresh and aged PM/PN	Aakko-Saksa et al. 2016 (SEA-EFFECTS BC project)
Cruise ship, 9.6 and 14.4 MW engines, SCR, scrubber.	On-board, 75% and 40% engine loads.	HFO 0.7%S, MGO0.1%S.	Gases, fresh and aged PM/PN	Kuittinen et al. 2021 Unpublished SecA (SEA-EFFECTS)
Wärtsilä Vasa 4R32 LN modified for CNG	Lab engine	CNG + MGO pilot fuel	Gases, fresh and aged PM/PN	HERE, Alanen et al., 2020
Passenger/Ro-Ro Cargo/ Wärtsilä four-stroke 8ZAL40S	on-board, RDE	MGO, Methanol	gases, fresh and aged PM/PN	SCIPPER/ https://www.scipper-project.eu/wp-content/uploads/2023/02/scipper-d3.3_s.pdf

3.4 Aged PM emission factors

In the updated PAREMPI database, emission factors will be presented in original units of studies (per kg fuel, per km, per kWh, per m^3 exhaust STP) and in harmonised unit per MJ fuel. For unit conversions, the fuel properties presented in Table 13 were used. For conversions from per kg fuel, energy content of fuel is necessary, while for conversions from per km, fuel consumption or CO_2 results are needed. Additionally in the latter case, carbon fraction of fuel is necessary. For conversions from mg/m^3 STP, CO_2 concentration in the

exhaust is an essential source information, as well as carbon fraction of fuel. Conversions from per kWh were conducted using a known factor (1 MJ is equal to 0.2778 kWh).

Table 13. Parameters selected for marine sector EF calculations.

Sector	Fuel	Carbon in fuel [wt%]	LHV [MJ/kg]
Road transport	Gasoline [f]	~86.5 [b]	43.774 [a]
Road transport	Diesel	~86.5 [b]	42.695 [a]
Road transport	CNG	75 [b]	48 [a]
Road transport	Renewable diesel (HVO)	~85 [b]	44.1 (AMF)
Road transport	Fatty acid methyl esters (FAME)	77 [b]	37.3 [a]
Road transport	Ethanol	52.1 [b]	28.8 [a]
Marine	Residual	2.5%S: 86.2 [c] 0.5%S 86.8 [c]	2.5%S: 40; [c] 0.5%S 42 [c]
Marine	Distillate	0.1%S: 87.0 [c]	42.5 [c]
Marine	Bio-FA(30%)	83.0 [c]	41 [c]
Marine	LNG	75 [b]	49 [d]
Aviation	Jet A-1	85.8 [e]	43.2 [e]

[a] EMEP/EEA Guidebook (2023) [b] Advanced Motor Fuels. Fuel Information system. [c] Aakko-Saksa et al. 2016.
[d] Verbeek et al. (2011). [e] Kılıç et al. 2018. Carbon content calculated from hydrogen content of 14.2 wt%.
[f] Includes E10 gasoline.

A general overview of the PM_{aged} emission factors of database converted in harmonised unit (per MJ) are shown in Figure 5. Some studies include only secondary organic and/or inorganic aerosols without addressing PM_{aged} data, which would include also black carbon portion of PM. However, SOA and SIA results are presented in Figure 5, since these enlighten potential secondary aerosol formation.

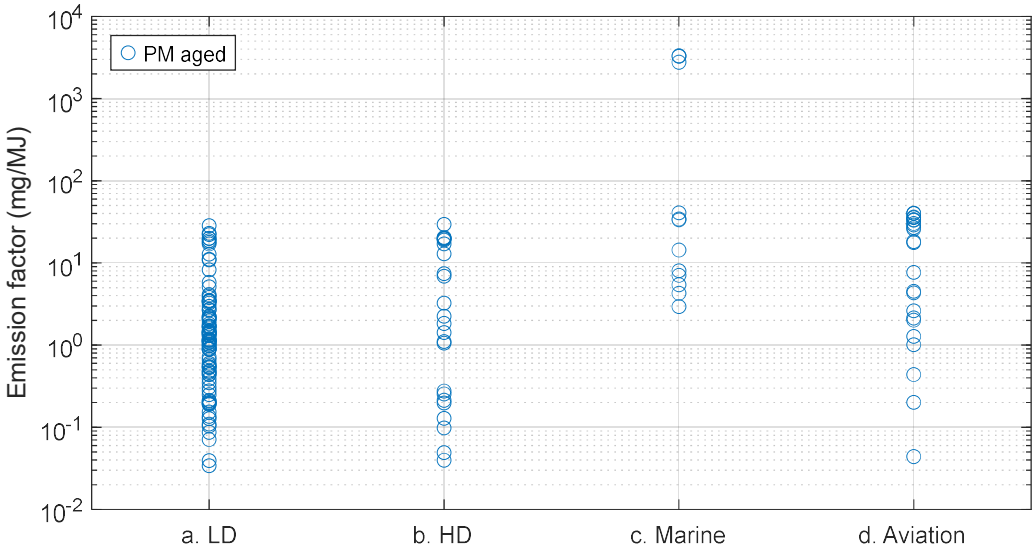

Figure 5. Overview of the results for aged PM in database version 2.0 (references in database).

3.5 Outlook of aged PM database

Light-duty vehicles

Literature data on secondary aerosols was more extensive for light-duty vehicles than for other transport sectors, and database already includes the PAREMPI complementary measurements with a comprehensive characterization of aged particulate matter emissions from seven cars (gasoline, diesel, CNG, PHEVs) studied at three temperatures under controlled laboratory conditions (Simon et al. 2025). The measurement protocols and emission profiles in the PAREMPI measurement exhibit a high degree of comparability with on-road RDE testing based on the real route driven on-road and its transfer to laboratory to simulate this route. Table 5 lists the LD studies conducted by PAREMPI consortium, published after database version 1.0 and updated in database version 2.0.

The new PAREMPI dataset simulating RDE driving conditions brings valuable information of the secondary aerosol data in the database. However, on-road measurements under actual driving conditions remain a recognized gap in the knowledge for this transport sector. Especially, FFVs complying with the latest emission standards are interesting.

Deliverable 2.3 of the PAREMPI project introduces a robust measurement system specifically designed for PM_{aged} quantification. However, although this system comprises portable equipment and enables deployment in relative small space, passenger cars present still notable challenges - applicability could be more feasible in larger light-duty vehicles.

Heavy-duty vehicles

Table 9 lists the unpublished HD studies conducted by PAREMPI consortium. The new PAREMPI data with a comprehensive characterization of secondary aerosols from two heavy-duty trucks (Euro VI-E and Euro VI-A), will bring a valuable dataset to the database besides the laboratory studies collected from literature. The PAREMPI on-road measurements conducted in dark and cold winter conditions reached even northern Finland.

PAREMPI consortium will also update database with presently unpublished studies on measurements with a heavy-duty engine using aromatic diesel, renewable diesel and oxygenated component. However, even after these updates, knowledge on secondary aerosol derived by heavy-duty applications is limited, especially as concerns non-road applications and alternative fuels. Deliverable 2.3 of the PAREMPI project introduces a robust measurement system secondary aerosol studies. This system would be suitable for measurements of heavy-duty vehicles and applications.

Aviation sector

Table 11 lists the unpublished aviation studies conducted by PAREMPI consortium. PAREMPI dataset simulating aircraft using various jet fuels, including SAF blends, increases substantially current knowledge on the secondary aerosols from aircrafts when compared to only one published study so far. In the database version 2.0, results published by Miracolo et al. (2011) were updated in the database. However, even after these updates, knowledge on the secondary aerosols derived by aircrafts remains limited suggesting needs for further research

Marine sector

Table 12 lists the marine studies conducted by PAREMPI consortium, for which aged PM results are not published, yet. PAREMPI datasets simulating marine engines using different fuels, including variation of sulfur and ash contents, and reaching even ammonia containing

exhaust, will substantially increase current knowledge on the secondary aerosols from shipping. Furthermore, several unpublished earlier studies by PAREMPI consortium include real marine engines and even measurements on-board ships. These updates of the database will enlighten role marine engines in potential formation of secondary aerosol emissions, which is currently unknown field. Notably, during preparation of the database version 1.0, no studies on aged PM from marine sector were available in literature. In database version 2.0, studies by Karjalainen et al. 2022 and Kuittinen et al. 2026 were updated.

Other projects

In addition to the PAREMPI datasets, significant advancements are anticipated from ongoing projects on transport-derived secondary aerosols.

4. Toxicity database

In the PAREMPI project, the toxicology section of the database was developed in addition to secondary aerosol database. It includes 85 entries covering various aspects of transport emissions and their toxicity assessments; however, these studies cover almost only the fresh PM, while only one study investigated toxicity of aged PM including SecA. Toxicity database tab contains data on Exposure Classes such as on-line exposures at the ALI (the Air-Liquid Interface), PM pre-collected (standard and water-based), for both liquid-liquid (traditional) and the ALI testing. Emission Sources include PM fresh exhaust, PM aged (secondary aerosol), and PM mixed with volcanic ash. The database spans Transport Sectors, including Light-Duty (LD), Heavy-Duty (HD), and Non-Road Mobile Machinery (NRMM), with Applications covering Cars, Engines, Generators, Buses, and Tractor engines. Engine Combustion Types are categorized into Spark Ignition (SI) and Direct Injection (DI).

It is important to note that the toxicological section includes only already published data and does not incorporate results from PAREMPI WP4. The findings from WP4 will be presented separately in Deliverables D4.2 and D4.3, and will be also updated to database. This dataset provides a comprehensive toxicological assessment of both fresh and aged emissions across different transport sectors. It supports evaluations of health risks by categorizing toxicity based on specific assays and exposure conditions, while ensuring easy access and the possibility to modify the dataset as needed in its Excel table format.

4.1 Criteria of the database

The database aims to be as thorough as possible. However, several key criteria were applied. First of all, quality of the study; if there were obvious discrepancies in a study, the study was excluded. Studies with well characterized materials of exposure were used, however it is worth to mention, that toxicology papers usually characterize materials less than general chemical papers.

Complexity of the study evaluating several toxicological endpoints, or different time-points was also crucial. In order to be able to evaluate each study separately, although its complexity can differ, the toxicity rating was introduced (see below).

Studies not older than 15 years were preferred, however high quality, complex study older than 15 years was also included.

The database considered only direct measurement results from single sources, such as those from engines, passenger cars, and heavy-duty vehicles, while excluding mixed emissions like those from ambient roadside or tunnel measurements or results obtained through indirect calculation.

4.2 Toxicity rating

The toxicological rating in the database provides a structured evaluation of the health risks associated with transport emissions. It categorizes toxicity based on multiple biological impact markers, enabling comparative assessments across different emission sources and exposure conditions.

The rating system is structured around five primary parameters:

- Cytotoxicity (C): Measures the extent to which emissions compromise cell viability.
- Genotoxicity (G): Evaluates DNA damage potential, indicating possible long-term carcinogenic effects.
- Oxidative Stress (O): Assesses the formation of reactive oxygen species (ROS) and antioxidant depletion, key indicators of inflammatory responses.
- Other Endpoints (D): Includes additional biological responses that may indicate broader health risks.

The Toxicity Rating is represented as a combined code of C, G, I, O, and D (e.g., C.0-G.0-I.0-O.0-D.0 to C.3-G.nd-I.3-O.3-D.2), providing a clear and standardized assessment of emission toxicity. The rating follows the scale in Table 15.

Table 14. Toxicity rating codes.

Rating Code	Description
nd	No data available
0	No harmful effects found
x	Unclear results
1	Potentially harmful ($p<0.05$)
2	Slightly harmful ($p<0.01$)
3	Clearly harmful ($p<0.001$)
4	Harmful in high confidence level ($p<0.0001$)
5	Very harmful in high confidence level

This structured approach allows for a systematic and easily interpretable comparison of toxicity levels across various emissions and conditions. By implementing this rating system, the database enables a systematic comparison of emission toxicity from different transport sectors, fuel types, and aging processes. It provides valuable insights into the relative health impacts of fresh vs. aged emissions and supports evidence-based policymaking for air quality management.

4.3 Methodology description

The Air-Liquid Interface (ALI) exposure methodology is a widely used technique in toxicological studies for assessing the effects of airborne pollutants on human lung cells under physiologically relevant conditions. It enables direct exposure of cultured respiratory epithelial cells to aerosolized pollutants while maintaining cellular integrity and functionality. ALI exposure systems allow for the deposition of fresh and secondary aerosols onto lung cell models, simulating real-world inhalation exposure. These systems utilize specific setups where cells grown on porous membranes are exposed to air on one side and nutrient medium on the other, mimicking in vivo conditions. In addition to ALI exposures, submerged exposure techniques are used where particles collected on filters are resuspended in liquid media and applied to cells cultured under submerged conditions. This approach enables comparative toxicity analysis for particle fractions that may not be effectively delivered in aerosol form or for offline measurement.

Cells are placed on inserts within an exposure chamber designed to regulate temperature, humidity, and airflow. The system allows controlled exposure to fresh engine emissions and secondary aerosols generated via oxidation flow reactors (OFRs). In laboratory settings, exposure occurs under standardized conditions using chassis dynamometers, ensuring reproducibility, while on-road and on-board exposure systems allow real-world emissions testing, capturing variations in traffic and driving conditions.

Particulate matter and gaseous pollutants settle onto the cultured cells through diffusion, sedimentation, and electrostatic forces. Unlike submerged exposure methods, ALI systems prevent artifacts related to liquid-phase interactions, enhancing physiological relevance. The advantages of ALI exposure include its ability to mimic real-world exposure by providing a direct inhalation-like scenario, bridging the gap between in vitro and in vivo models ensuring findings are scientifically robust and policy-relevant.

4.4 Results

Extracts of the 1st version of the literature-based database are presented in Tables 15-16. In addition to these, the database includes other datasets, such as those from a gasoline engine study. As previously mentioned, toxicity data from cars and heavy-duty engines/vehicles remains limited, and such data is virtually non-existent for the marine and aviation sectors.

Despite of the inclusion of a visual toxicity rating system, interpretating the toxicity database requires toxicological expertise. This is due to the limited number of results available for a complex set of emission sources and toxicity models evaluated. A general overview of the findings suggests that, for passanger cars, some exhaust emission studies indicated potentially harmful effects. Furthermore, for the heavy-duty sector, including non-road mobile machinery (NRMM), exhaust toxicity was in some cases rated even Class 4, indicating harmfulness in high confidence level.

In certain cases, gasoline cars equipped with TWC exhibited potential toxicity in both cytotoxicity (C) and different (D) Classes. This was observed also for the aged PM. Interestingly, gasoline direct-injection (GDI) cars did not show toxicity in the reviewed literature studies, nor did the Euro 6 gasoline, CNG and E85 fueled cars under normal test temperature.

Heavy-duty engine and vehicles, including one study on the non-road sector, also indicated potential toxicity in the oxidative stress (O) Class.

Table 15. Database extract of toxicity results on light-duty vehicles.

Sector	Application		Temp. (°C)	Fuel		Note	Toxicity rating C	G	O	D	References
LD	Car	E 6a	-7	Gasoline	TWC *	PM pre-collected	1	0	0	1	g
LD	Car	E 3	~23	Gasoline	TWC *	PM pre-collected (H2O)	nd	nd	nd	1	a
LD	FFV GDI	E 5b	~23	Gasoline	TWC *	ALI, different	0	nd	0	0	b
LD	FFV GDI	E 5b	~23	Gasoline	TWC *	toxicity models	nd	nd	0	1	b
LD	FFV GDI	E 5a	~23	Gasoline	TWC *	ALI, Gasoline E0	0	0	0	0	c
LD	FFV GDI	E 5a	~23	Gasoline	TWC *	ALI, Gasoline E10	0	0	0	0	c
LD	Car	E 5	~23	Gasoline	TWC *	**ALI, Aged PM**	1	nd	0	1	d
LD	Car	E 5	~23	Gasoline	TWC *	Different	1	nd	nd	1	d
LD	Car	E 5	~23	Gasoline	TWC *	toxicity	0	nd	nd	1	d
LD	Car	E 5	~23	Gasoline	TWC *	models	1	nd	nd	0	d
LD	GDI	E6b	~23	Gasoline	TWC *	ALI	0	nd	0	0	b
LD	GDI	E6?	~23	Gasoline	TWC *	ALI	0	nd	0	0	e
LD	GDI	E6?	~23	Gasoline	TWC *	ALI	0	nd	0	0	e
LD	GDI	E6b	~23	Gasol., high ash oil	TWC *	ALI	0	nd	0	0	b
LD	GDI	E6b	~23	Gasol., high ash oil	TWC *	ALI	0	nd	0	0	b
LD	Car	E5b+	~23	Gasoline	no GPF	ALI	0	0	0	0	f
LD	GDI	E6b	~23	Gasoline	GPF	ALI	0	nd	0	0	b
LD	FFV, GDI	E5b	~23	Gasoline	GPF uncoated	ALI	0	nd	0	0	b
LD	FFV, GDI	E5b	~23	Gasoline	GPF coated	ALI	0	nd	0	0	b
LD	Car	E5b+	~23	Gasoline	GPF	ALI	0	0	0	0	f
LD	Car, CNG	E6a	-7	CNG	TWC *	PM pre-collected	0	0	0	0	g
LD	Car, FFV	E6a	-7	FFV/E85	TWC *	PM pre-collected	1	0	0	1	g
LD	Car, FFV, GDI	E5a	~23	FFV/E85	TWC *	ALI	0	0	0	0	c
LD	Car	E2	-7	Diesel	na	PM pre-collected	0	0	0	1	g
LD	Car	E6a	-7	Diesel	na	PM pre-collected	0	0	0	1	g
LD	Car	E2	~23	Diesel	DOC	ALI	0	0	1	1	c
LD	Car	E4+	~23	Diesel	DPF retrofitted	PM pre-collected (H2O)	nd	nd	nd	1	a
LD	Car	E2	~23	Diesel+add.	no	ALI	0	nd	1	0	h
LD	Car	E2	~23	Diesel+add.	no	ALI	1	nd	1	0	h
LD	Car	E2+	~23	Diesel+add.	DPF	ALI	0	nd	1	1	h
LD	Car	E1	~23	FAME	No	PM pre-collected (H2O)	nd	nd	nd	1	a

[a] Tzamkiozis et al. 2010. DOI 10.3109/08958378.2010.519408 [b] Bisig et al. 2018. DOI 10.1016/j.envpol.2017.12.061
[c] Bisig et al. 2016. DOI 10.1016/j.envres.2016.09.010 [d] Künzi et al. 2015. 10.1038/srep11801
[e] Tomašek et al. 2018. 10.1016/j.envpol.2018.01.115 [f] Bisig et al. 2015. DOI 10.1007/s40825-015-0019-6
[g] Hakkarainen et al. 2020. DOI 10.1186/s12989-020-00348-0 [h] Steiner et al. 2015. DOI: 10.1007/s00216-014-7878-5

Table 16. Database extract of toxicity results on heavy-duty vehicles and engines.

Sector	Application		Temp. (°C)	Fuel		Note	Toxicity rating C	G	O	D	References
HD xxxx	Bus	Euro V	Cold/ warm start	Diesel	SCR	ALI	0	0	2	0	l
HD	Bus	Euro V	Cold/ warm start	Diesel	SCR	Different tox. models	0	0	0	0	i
HD	Bus	Euro V	warm start	Diesel	SCR	ALI	0	0	2	0	i
HD	Bus	Euro V	warm start	Diesel	SCR	Different tox. models	0	0	0	0	i
HD	Generator		~23	Diesel	EGR	ALI, Warm start	0	nd	0	nd	j
HD	Generator		~23	Diesel	EGR	ALI	0	nd	1	nd	j
HD	Generator		~23	Diesel	EGR	ALI	0	nd	4	nd	j
HD	Generator		~23	Diesel	EGR, DOC, DPF	ALI	0	nd	0	nd	j
HD	Generator		~23	Diesel	EGR, DOC, DPF	ALI	0	nd	0	nd	j
HD	Generator		~23	Diesel	EGR, DOC, DPF	ALI	0	nd	4	nd	j
HD	Generator		~23	FAME	EGR	ALI	0	nd	0	nd	j
HD	Generator		~23	FAME	EGR	ALI	0	nd	1	nd	j
HD	Generator		~23	FAME	EGR	ALI	0	nd	4	nd	j

HD	Generator		~23	FAME	EGR, DOC, DPF	ALI	0	nd	0	nd	j
HD	Generator		~23	FAME	EGR, DOC, DPF	ALI	0	nd	0	nd	j
HD	Generator		~23	FAME	EGR, DOC, DPF	ALI	0	nd	4	nd	j
NRMM	N/A	Stage IIIb	~23	Diesel	N/A	ALI	0	0	1	0	k
NRMM	N/A	Stage IIIb	~23	Diesel	N/A	ALI	0	0	1	2	k
NRMM	N/A	Stage IIIb	~23	Diesel	N/A	ALI	0	0	1	1	k
NRMM	N/A	Stage IIIb	~23	Diesel	N/A	ALI	0	0	2	2	k
NRMM	Tractor engine		~23	Diesel	N/A	PM pre-coll. to ALI	0	nd	1	1	l
NRMM	Tractor engine		~23	Diesel	N/A	PM pre-coll. to ALI	0	nd	0	1	l
NRMM	Generator		~23	Diesel	N/A	ALI	0	nd	nd	0	m
NRMM	Generator		~23	Diesel	N/A	ALI	2	nd	nd	3	m
NRMM	Generator		~23	Diesel	N/A	ALI	2	nd	nd	3	m
NRMM	Generator		~23	Diesel	N/A	ALI	0	nd	2	2	m
NRMM	Generator		~23	Diesel	N/A	ALI	1	nd	3	2	m
NRMM	Generator		~23	Diesel	N/A	ALI	3	nd	3	2	m
NRMM	Generator		~23	Diesel	N/A	ALI	nd	nd	3	2	m
NRMM	Generator		~23	Diesel	N/A	ALI	nd	nd	3	2	m
NRMM	Generator		~23	Diesel	N/A	ALI	nd	nd	3	1	m

[i] Zarcone et al. 2018. 10.1016/j.tiv.2018.01.024 [j] Hawley et al. 10.1093/toxsci/kfu147 [k] Zarcone et al. 2017. 10.1186/s12931-017-0510-4 [l] Ji et al. 2018. 10.1186/s12989-018-0256-2 [m] Zarcone et al. 10.1152/ajplung.00064.2016

4.5 Outlook of toxicity database

The toxicity database tab will be updated to include recent studies, such as those from Hakkarainen et al. (2023, 2024) and Yang et al. (2024, DOI: 10.1039/d4ea00062e). Additionally, the PAREMPI consortium has conducted secondary aerosol studies on cars, heavy-duty, marine and aviation sectors. Although these results are not yet published, they will be incorporated into the database once available (manuscripts submitted).

During the literature review process for the toxicity database, it became evident that many publications lack the fundamental data for classification and integration of the results. This highlights the need for standardised reporting practices in studies examining transport sector emissions and exhaust toxicity. A recommended set of minimum parameters reporting parameters could include, amongst others: transport sector category, application type and details, exhaust aftertreatment, emission standards, test type (laboratory/RDE), test cycle, temperature, fuel category and details (sulphur and aromatic contents), CO_2, NO_x, NH_3, NMHC (preferably also aromatics), SO_2 and PM.

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