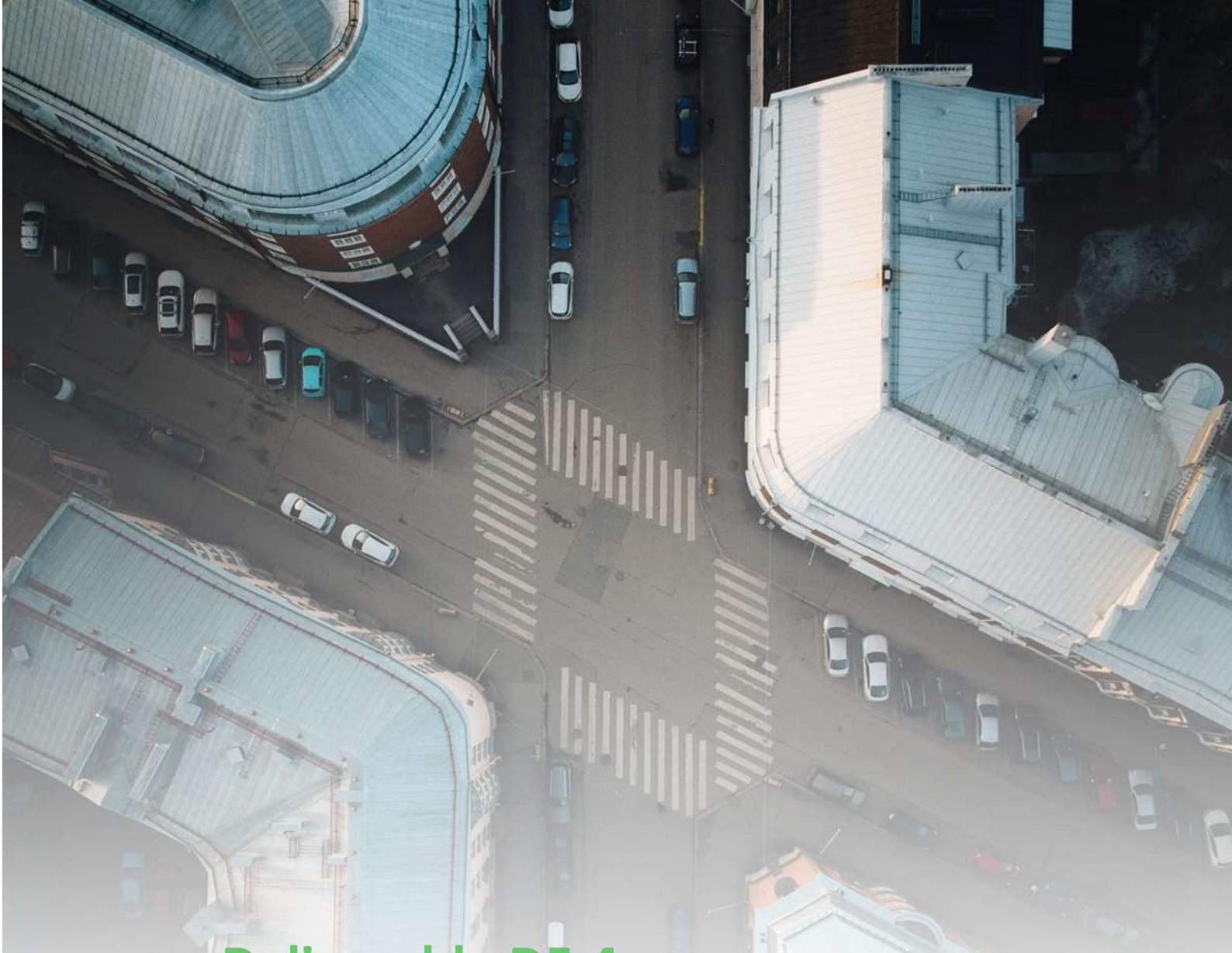

Deliverable D5.4

Policy recommendations

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

Funded by the European Union

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

ALI	Air-liquid interface
APU	Auxiliary power units
AQ	Air quality
AQG	Air Quality Guidelines
BAT	Best available technology
BC	Black carbon
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DF	Dual-fuel
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EAT	Exhaust aftertreatment
ECA	Emission control area
EGR	Exhaust gas recirculation
GPF	Gasoline particulate filter
HOM	Highly oxygenated organic molecules
HPDF	High-pressure DF
IMO	The International Maritime Organization
LNG	Liquefied natural gas
LPDF	Low-pressure DF
NH_3	Ammonia
NM	Non-methane
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen oxides
O_3	Ozone
OFR	Oxidation flow reactor
PAH	Polyaromatic hydrocarbons
PM	Particulate matter
PSD	Particle number size distribution
SCR	Selective catalytic reduction
SecA	Secondary aerosols
SO_2	Sulfur dioxide
SOA	Secondary organic aerosols
TWC	Three-way catalyst
UFP	Ultrafine particles
VOC	Volatile organic compounds
WHO	World Health Organization

Executive Summary

Air quality in Europe has improved along with tightening emission standards; however, air pollution remains the leading environmental health risk, particularly in cities. EU has defined ambitious goals to achieve zero pollution by 2050, while maintaining climate ambitions. Air pollution still causes substantial number of premature deaths annually in Europe. PAREMPI estimated that secondary aerosols contributed to approximately 110,000 premature deaths annually across the EU-27 and the related total external costs were estimated as €544 billion annually. While mitigation strategies such as electrification, low-carbon fuels, and tighter emission standards are advancing, PM formed through atmospheric transformation of exhaust gases into secondary aerosols remains poorly understood and insufficiently addressed. The PAREMPI project generated new scientific evidence, tools, and measurement approaches to assess transport derived aged $PM_{2.5}$, its composition, toxicity, and health impacts, supporting effective and cost-efficient policies to reduce the most harmful transport related $PM_{2.5}$ emissions while acknowledging remaining uncertainties and research needs.

Through PAREMPI results, understanding of the transport sector's contribution to ambient $PM_{2.5}$ levels, its prevention, and associated health impacts were improved through new measurement data, modelling, toxicological insights and health impact assessments. Traffic emissions are significant contributors to ambient $PM_{2.5}$ levels and will be increasingly emphasised when currently underestimated role of organic aerosols, and ammonium nitrate aerosols traffic are integrated in the air quality modelling. The easy-access ePMI software developed in PAREMPI will support $PM_{2.5}$ predictions and health impact assessments in the early phase of technology development.

In PAREMPI, a clear link was identified between precursor gas emissions, the aged PM and its composition. SecA formation was linked with organic precursor gases, and also to inorganic gas species (SO_2, NO_x, and NH_3). Organic compounds dominated aged PM for aviation, nitrates dominated for cars (except an older diesel), while for marine fuels sulfates and organics dominated. Nitrates and ammonium were present in aged PM when having ammonia in exhaust. Strong relationship between precursor gases and SecA formation demonstrated the potential to reduce aged PM by mitigating precursor gas emissions. Development of emission reduction strategies that address both organic and inorganic precursors are needed, as well as cross-sectoral collaboration to ensure that solutions are efficient in holistic perspective. This underscores the need for a multi-pollutant prevention strategy with integrated approaches, since focusing on a single emission species, source or technology, is insufficient. By closing these gaps, better design and implementation of technologies and policies that reduce the formation of harmful SecA and improve air quality are possible.

The ongoing transformation of transport sectors through electrification and cleaner fuels underscores the need for technology-neutral and predictable policies. Additionally, understanding of sector specific contributions to air quality and the applicability of available mitigation measures are emphasized. No single emission reduction technology is applicable for all transport sectors, addressing needs for integrated policy frameworks. When prioritizing technology-neutrality, policy recommendations call for legally binding emission standards, fuel standards, and enforcement strategies (Figure 1). From emission mitigation technologies, promotion of advanced engine and exhaust aftertreatment technologies are identified efficient measures. However, these need to be combined with toxicological studies in early phase of

technological development to ensure “Do No Significant Harm” design and prevent potential new adverse effects. Non-technical strategies are of primary importance, although they are beyond the scope of PAREMPI.

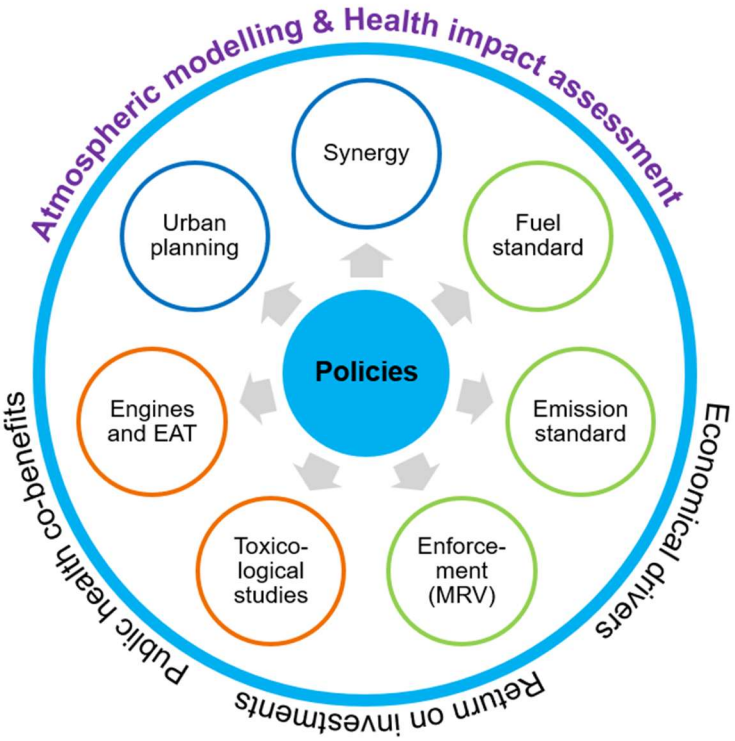


Figure 1. Policy recommendations to mitigate secondary aerosol precursor emissions and ambient PM levels related to transport sources. Green circles represent technology-neutral policy actions, orange circles represent emission prevention technologies and blue circles address other measures. Policy recommendations are supported by integrated atmospheric modelling of secondary aerosol formation at regional and global scales, combined with health impact assessment.

The policy recommendation addressing *stricter emission standards* offers efficient and technology neutral policies to mitigate secondary aerosol precursor emissions, requiring new innovations and technological solutions. In road transport, emission limits are already stringent in Europe, and advanced emission control technologies are used, although these are not sufficient during cold-starts and when PHEVs switch from battery to combustion engine modes. In contrast, emission limits in the aviation and marine sectors are still moderate or non-existing, leaving potential for substantial emission reductions. Aviation represents a special case, since the exhaust aftertreatment technologies are considered infeasible, thus significantly constraining the emission reduction potential. Although the magnitude of emissions reduction potential appears higher in aviation and marine sectors, the road transport sector remains a major contributor to local air quality in urban areas. Furthermore, emission regulations outside Europe are often less stringent, implying that road transport continues to be a significant global source of air pollutant emissions.

In relation to strict legally binding emission standards, the technologies identified having the highest potential to reduce SecA precursor emissions includes *advanced exhaust aftertreatment systems*, and especially, advancements in cold-start performance of EAT are needed to reduce nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in road transport sector. Notably, EAT is not feasible for aircrafts. The other technology, which supports mitigation of traffic related ambient PM levels, concerns *clean fuels,* particularly, by stricter fuel standards on aromatic and sulfur contents of fuels. Switching to clean fuels supports these aims. *Improved engine and turbine technologies* are also needed to meet strict

emission standards. Promotion of these technologies efficiently support meeting the tightening emission standards for transport sectors. However, transport segments are not equal in their capabilities to adopt emission reduction technologies. An important factor is to implement *toxicological studies* in the early stages of development to follow do-no-significant-harm principle.

Policy recommendations address enforcement strategies for emission standards and validate technological developments, emphasizing needs for *measuring, reporting and verification* of data in real-world conditions, which, in addition to enforcement, increases the evidence-base of the contribution of traffic emissions to ambient PM levels. Measuring aged PM from transport sources has been based on complex laboratory measurements while portable, robust measurement systems are approaching. In both cases, *harmonization of measurement methods and protocols* is necessary to gain reliable and comparable data. In PAREMPI, several aspects and parameters critical for reliable measurements to be harmonized were identified. Substantial advancements in evaluation and adopting portable measurement systems for SecA and toxicity were achieved.

Other strategies, although not directly in the PAREMPI scope, are identified, such as transitioning to low-emission mobility; urban planning and agricultural synergies. Residential planning accounting for potentially high-polluted areas near to ports and airports could decrease health impacts for vulnerable groups, women and children, underscoring the need to address social and gender inequalities. Many of the air-quality measures deliver substantial public-health co-benefits, enabling societal and economic returns on investments and contributing to overall well-being.

Introduction

Traffic is a major urban emission source, and secondary aerosols formed from exhaust precursors remain insufficiently addressed. PAREMPI generated new evidence, tools, and measurement approaches showing that both organic and inorganic precursor gases drive aged PM formation and related health impacts. These findings support policy recommendations to effectively reduce contribution of traffic to ambient $PM_{2.5}$ levels.

Evidence of harmful health effects of ambient $PM_{2.5}$ levels is strong, and the major transport sectors contribute to these levels remarkably, especially in urban areas. Transport sectors are cornerstones of modern society, and mitigation strategies for the harmful side-effects are approached, such as efficiency improvements, electrification, low carbon fuels and tightening emission standards. However, the increased PM production by atmospheric transformation (aging) of directly emitted gases to secondary aerosols (SecA) remains insufficiently understood and addressed, despite their significant implications.

Several key questions on the contribution of transport sectors to aged PM in the atmosphere were evaluated in the PAREMPI project. Scientific evidence was generated and tools were developed to support policies to mitigate traffic emissions, specifically those affecting the SecA formation. Extensive studies reached transport sectors' emissions beyond those covered by current emission standards, focusing on the precursor gases forming SecA and affecting quantities and composition of the aged $PM_{2.5}$, particularly in the winter conditions. Harmfulness of transport sectors' total $PM_{2.5}$ emissions was explored by toxicity evaluation, and external costs were estimated based on the health impact assessment. The novel digital ePMI module (software) for quantification of the SecA emissions was developed. Furthermore, robust measurement systems were evaluated for aged PM2.5 measurements in real-word conditions to create representative datasets and for monitoring the efficiency of the mitigation actions. Currently, knowledge on the aged PM emissions from traffic sources is sparse. The results of PAREMPI are synthesized in Deliverable D5.3 (list of public Deliverables in Appendix 2).

In this report, based on scientific evidence and supporting literature, policies are recommended to mitigate traffic emissions contributing to the ambient $PM_{2.5}$ levels, aiming to identify efficient and cost-effective means to improve air quality. Possibilities for retrofitting and other measures with near-term impacts and cost savings are considered, as well as economical justification based on improved estimate of external costs and "polluter pays" options to find ways to fund clean investments. Aspects enabling definitions of limit values, legal enforcement, digital reporting and databases are acknowledged. PAREMPI organised two Transport Policy Recommendations Workshops, where authorities, politicians, ministries, industry and research bodies presented different viewpoints, which were considered for PAREMPI policy recommendations. The PAREMPI recommendations for transport policies to minimise traffic contributions to ambient $PM_{2.5}$ levels, the technological mitigation measures are highlighted, while other mitigation strategies and aspects are recognized, such as dynamics of socio-technical systems and interactions between different strategies. In the course of analyses, the complexity between findings on exhaust emissions from different transport sectors and their relationship with the formation of ambient $PM_{2.5}$ in atmospheric reactions, depending on weather conditions (temperature, humidity, UV, wind) and other constituents present in atmosphere, are acknowledged. The uncertainties identified emphasize the need for further research to approach a holistic view to ensure that no new problems are caused when preventing some. While policy recommendations should develop by the integration of new evidence, the policy actions should not be delayed to avoid causing harm to health, the environment, and the economy.

1. Air quality and standards in Europe

Air quality in Europe has improved along with tightening emission standards; however, air pollution remains the leading environmental health risk, particularly in cities. Fine particulate matter, $PM_{2.5}$, is considered the most harmful pollutant, and urban residents are still exposed to harmful emission levels. The revised EU Ambient Air Quality Directive with binding 2030 limits aligns more closely with the World Health Organization guidelines, and sets a pathway towards zero pollution by 2050.

The European Commission's ambition is to reduce the health impacts of air pollution by more than 55% by 2030, and to reach the zero pollution vision for 2050, while also maintaining the EU climate ambitions of the Fit for 55 package in line with the European Green Deal. Accordingly, the EU Ambient Air Quality Directive (AQD) was revised with legally binding limits for 2030 and a trajectory towards zero air pollution by 2050, aligned more closely with the Air Quality Guidelines (AQG) of the World Health Organization (WHO, 2021). As highlighted by the WHO, clean air is fundamental to human health; and adverse health effects are evidenced at lower pollutant concentrations than previously recognized.

Air quality has improved across Europe over recent decades. However, further emission reductions will be needed to meet the ambitious air quality standards and move closer to WHO air quality guideline levels across the EU. Decreasing levels of nitrogen oxides (NO_x), particulate matter (PM_{10}, below 10 µm), fine particulate matter ($PM_{2.5}$, below 2.5 µm), black carbon (BC), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2) and carbon monoxide (CO) emissions are presented in Figure 2. This development is mainly attributed to stricter emission standards, cleaner transport system, and reduced industrial emissions. An exception is tropospheric ozone (O_3), whose concentrations have not decreased (Figure 3). Despite of generally positive progress with decreasing emission levels, air pollution remains Europe's largest environmental health risk, particularly in urban areas. Of key air pollutants, $PM_{2.5}$ is considered the most harmful from a health perspective. About 95% of Europe's urban population is still exposed to $PM_{2.5}$ levels above WHO guidelines, even though most locations meet current EU limit values.

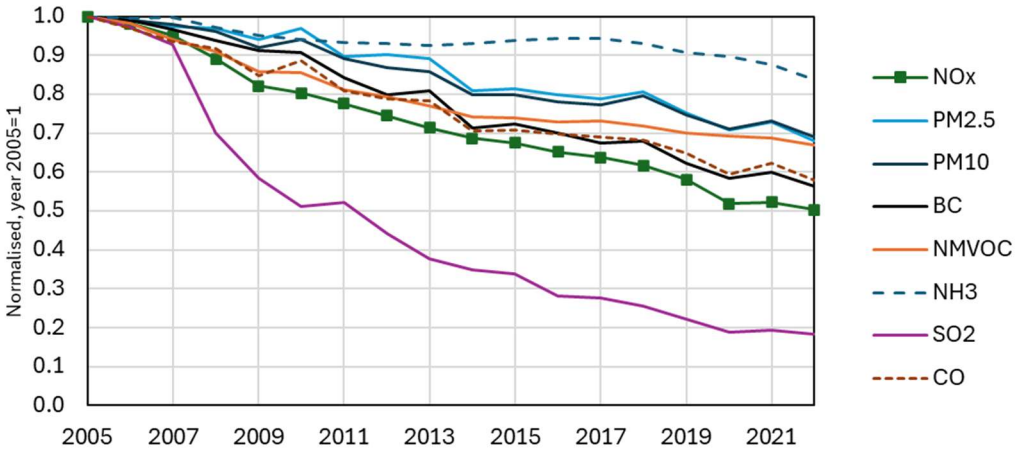


Figure 2. Trends in NH_3, NMVOCs, NO_x, primary PM_{10}, primary $PM_{2.5}$, BC, SO_2 and CO emissions in EU, 2005-2022. Reproduced using data from dataset: https://www.eea.europa.eu/en/analysis/publications/national-emission-reduction-commitments-directive-2024/figure-5-trends-in-eu-emissions-of-nh3-nmvocs-nox-primary-pm10-primary-pm2-5-bc-so2-and-co-2005-2022. Accessed 27.3.2026.

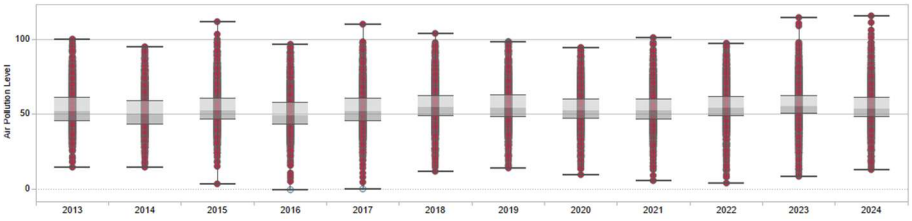


Figure 3. Ozone levels as annual means in EU (European Environment Agency, 2025). *https://www.eea.europa.eu/en/analysis/maps-and-charts/air-quality-statistics-dashboards. Accessed 26.2.2026.*

The revised EU Ambient Air Quality (AAQ) Directive (EU 2024/2881) sets legally binding air quality standards to be met by 2030[1], with a closer alignment with Air Quality Guidelines (AQG) of the WHO (WHO, 2021)[2], and the longer-term zero-pollution objective for 2050. The revised directive limits concentrations for 12 pollutants: $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, CO, benzene, benzo(a)pyrene (BaP), arsenic, cadmium, nickel and lead (Table 1). For BaP, arsenic, cadmium, and nickel, earlier annual target values are revised to limit values. In EU AAQD, air quality monitoring and modelling are expanded, also covering additional pollutants, such as ultrafine particles (UFP, <100 nm), black carbon and ammonia; additionally the supersites and pollution hotspots are introduced. Under 2050 policy trajectory, the "zero pollution for air" objective aims to reduce air pollution to levels that are not considered harmful to human health, ecosystems and biodiversity.

Table 1. Air quality standards (WHO, 2021)(European Environment Agency, 2025).

Pollutant	Averaging time	EU pre-2030 (2008/50/CE)	EU 2030 (2024/2881)	WHO guidelines(WHO, 2021)	Notes
$PM_{2.5}$	Annual; 24-hour	25 µg/m³; -	10 µg/m³; 25 µg/m³	5 µg/m³; 15 µg/m³ a	Regarded as the strongest health impact driver
PM_{10}	Annual; 24-hour	40 µg/m³; 50 µg/m³	20 µg/m³; 45 µg/m³	15 µg/m³; 45 µg/m³ a	Directionally stricter; daily & annual limits tightened Fewer exceedances permitted.
NO_2	Annual; 24-hour; 1-hour	40 µg/m³; -; 200 µg/m³	20 µg/m³; 50 µg/m³; 200 µg/m³	10 µg/m³; 25 µg/m³ a ; -	Aligns more closely with WHO 2021 guidance Complemented by stricter annual limit
SO_2	Annual; 24-hour; 1-hour	-; 125 µg/m³; 125 µg/m³; 350 µg/m³	20 µg/m³; 50 µg/m³;	-; 40 µg/m³	Part of overall tightening package
O_3	Max 8-hour mean /	120 µg/m³ (target value)	120 µg/m³ (100 µg/m³ 2050)	100 µg/m³; 60 µg/m³ b	Progressive tightening foreseen

[1]Additionally, reduced number of allowed exceedances per year, e.g. for PM10 (24-h), from 35 to 18 days, for ozone (8-h) from 25 to 18 days (average of 3 years) and for NO_2 (hourly) from 18 to 3 exceedances per year.
[2] The WHO AQG defines target levels and interim targets for $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO.

	peak season				
CO	24-hour; 8-hour	-; 10	4 mg/m³; 10 mg/m³	4 mg/m³	
Benzene	Annual	5 µg/m³	3.4 µg/m³		Carcinogenic VOC; stricter protection
Benzo(a)pyrene	Annual	1 ng/m³	1.0 ng/m³		PAH indicator compound
Lead (Pb)	Annual	0.5 µg/m³	0.5 µg/m³		Toxic metal exposure reduction
Arsenic, Cadmium, Nickel	Annual	Target values	Lowered target values		Continued tightening towards 2050 goal

According to EEA (EEA, 2025), a large share of reporting stations already indicates pollutant concentrations below the 2030 standards, especially the short-term standards, and the standards for CO, benzene and SO_2.

Challenges remain with the annual limits, especially for $PM_{2.5}$ and NO_2, where some stations had concentrations significantly above the 2030 standards. Approx. 70% of stations had NO_2 concentrations below the 2030 annual limit, while only 59% of stations were below the upcoming limit for $PM_{2.5}$. Notably, 98% of monitoring stations met the current annual NO_2 limit. However, meeting the 2030 EU limits and WHO guidelines will require further reductions, particularly in cities with heavy traffic.

Ozone is a challenging pollutant, especially during summer. Several ozone exceedance episodes were faced in Europe in 2024, particularly in eastern and southeastern regions. Ozone concentrations depend not only on the NO_x and VOC emissions, but also on changing weaker extremes (heatwaves) and climate conditions and related long-range transport, which complicates effective ozone control. Although O_3 target levels were met by over 71% of reporting stations, 27% of stations showed high O_3 levels (120-150 µg/m3).

Regarding the other pollutants, WHO AQG (WHO, 2021) recognizes emerging pollutants, BC, UFP and dust (SDS), although data was insufficient to provide recommendations on levels. Hence, further research on emissions, risks and mitigation approaches is needed for these pollutants. Although AQG levels were not included, recommendations were given on quantification and monitoring of BC and UFP[3], and to include these in emission inventories, exposure assessments and source apportionment studies. In addition, mitigation technologies and, where appropriate, standards for ambient concentrations were recommended.

[3] For UFP, low and high PNC are defined as low PNC < 1 000 particles/cm3 and high PNC > 10 000 particles/cm3 as 24-hour mean or 20 000 particles/cm3 as 1-hour mean.

2. From traffic emissions to secondary aerosols and ambient PM

Combustion of carbonaceous fuels produces CO_2 and water, along with trace levels of other gases and fresh PM, emission levels depending on fuel, engine type, exhaust aftertreatment and operating conditions. After release, exhaust compounds undergo photochemical reactions in the atmosphere, forming secondary organic and inorganic aerosols from precursor gases. These processes can substantially increase ambient PM levels. Besides secondary aerosol formation from precursor gases (NO_x, VOCs, SO_2, and NH_3), semi-volatile compounds may contribute to PM.

Complete combustion hydrocarbon fuels produces carbon dioxide (CO_2) and water. Additionally, trace level of emissions (<0.5 vol%) are formed, including nitrogen oxides (NO_x, from oxidation of N_2 in air), sulfur oxides (SO_x, from fuel and lubricating oil), other gas-phase species such as methane (CH_4), NMVOCs, CO, and particulate matter (PM), which further consists of BC, organic carbon (OC), inorganic ions (sulfates, nitrates, ammonium), and ash (e.g. trace metal oxides). Emission profiles depend on fuel, engine type and operating conditions. For example, combustion of ammonia fuel leads to nitrogen containing emission species. Diesel engines and aircraft turbines operate with excess air, while spark-ignited (SI) engines run near the stoichiometric air-to-fuel ratio leading to anoxic exhaust. Emissions vary across transport sectors as different engines, fuels and exhaust aftertreatment (EAT) systems are used. While EAT systems generally reduce emissions, they can also lead to the formation of by-products, such as ammonia (NH_3), nitrous oxide (N_2O) and benzene from three-way catalysts (TWC) or NH_3 slip from urea-based selective catalytic reduction (SCR) system. Diesel and gasoline particulate filters (DPF, GPF) enable very low emissions of PM, BC and UFP.

Exhaust released into the atmosphere cools, dilutes and mixes with ambient air, forming SecA through reactions of gaseous precursors (SO_x, NO_x, NH_3, certain NMVOCs), depending on meteorology, availability of oxidants, UV radiation, humidity, exhaust composition, and other atmospheric compounds (Figure 4). These reactions can increase ambient $PM_{2.5}$ levels and ultrafine particles (UFP) compared to those directly regulated by emission standards, increasing health and environmental risks. During daytime, NMVOC mainly react with OH radicals and ozone (O_3), while nighttime chemistry involves O_3 and NO_3 radicals. Besides these atmospheric reactions, semi-volatile organic compounds (SVOCs) can contribute to aged PM mass through condensation, but may also re-evaporate depending on environmental conditions. Ambient $PM_{2.5}$ reflects the combined influence of traffic, other anthropogenic (such as residential wood combustion) and natural sources, and long-range transport, complicating source apportionment and impact assessment. Currently, our understanding of the SecA formation process remains limited, particularly across different fuels, engines, aftertreatment systems, and different meteorological conditions.

From a health effects perspective, secondary organic aerosol (SOA) is strongly associated with country-level cardiorespiratory death rates, independent of the total $PM_{2.5}$ mass association (Pye *et al.*, 2021). SOA may also contain harmful polyaromatic compounds, including nitro- and oxy-PAHs, which are both directly emitted and formed in atmospheric reactions.

Among VOCs, monoaromatics (e.g. benzene, toluene, xylenes) and C9-compunds contribute to the SecA formation. Speciated organic gas profiles are used for atmospheric models and

air quality assessments, while semi-volatile compounds (for example PAHs, such as naphthalenes) are typically excluded, leading to underestimated contribution of organic aerosols from transport sources, particularly at low ambient temperatures during prolonged engine and EAT warm-up.

Most sulfur in fuel and lubricating oil is oxidized to SO_2 during combustion, forming sulfuric acid and sulphates in the atmosphere (and a small fraction directly after combustion). Sulphate formation depends on fuel composition, engine operation, and EAT, which can both oxidize and temporarily store sulfur compounds. Sulfuric acid, together with ammonia can drive new particle formation of UFP during exhaust cooling and dilution as well as in the atmosphere, increasing particle number concentrations. Sulfur dioxide emissions are important especially in marine and aviation sectors.

Ammonia originates mainly from agriculture, but traffic is also a significant source, and future marine engines may emit unburned NH_3 when used as fuel. In the atmospheric reactions, NH_3 may form ammonium nitrate (NH_4NO_3) and sulphates ($(NH_4)_2SO_4$, NH_4HSO_4), increasing urban $PM_{2.5}$ levels. Co-emitted NH_3, SO_x, NO_x, and PM can under certain operating conditions promote secondary inorganic aerosol formation.

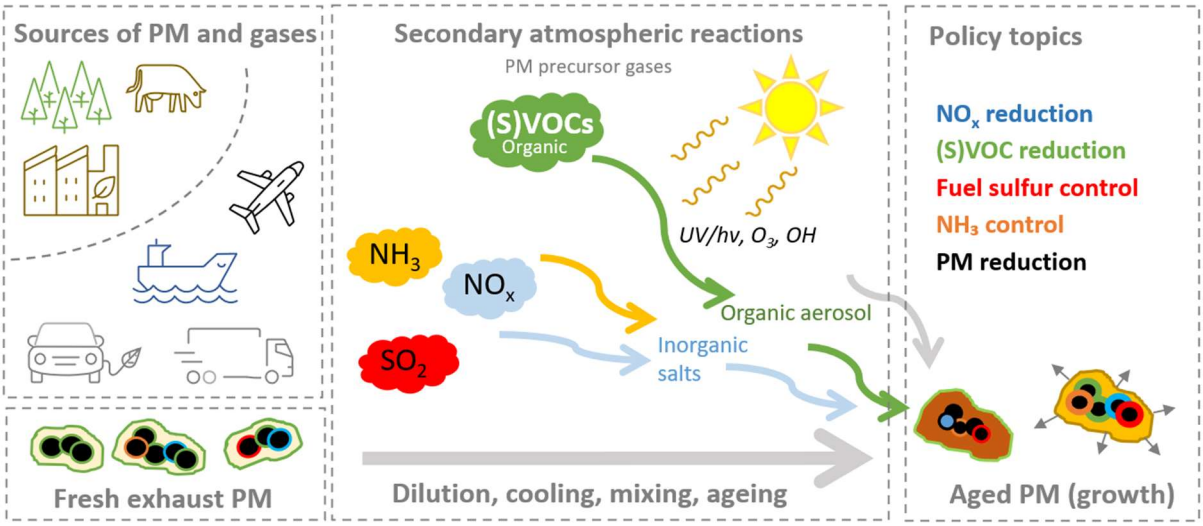


Figure 4. Schematic representation of transport-related fresh PM and gaseous precursors undergoing atmospheric processing to form aged $PM_{2.5}$. Secondary aerosol formation via inorganic (nitrate, sulfate, ammonium) and organic pathways is driven by photochemical oxidation and influenced by dilution, cooling and aging. The figure highlights policy topics for reducing precursor gas emissions to mitigate traffic sectors' contribution to ambient PM. Black balls represent black carbon in fresh and aged PM.

3. Evidence on SecA prevention technologies based on PAREMPI results

This section provides a summary of the key scientific evidence, focusing on PAREMPI conclusions and evaluation of impacts on human health, the environment, climate, and external costs. It also evaluates the mitigation technologies to reduce contribution of traffic on ambient $PM_{2.5}$ levels. Additionally, remaining knowledge gaps are addressed for transparency and policy credibility.

3.1 Transport emissions contribution on air quality

Efficient policy actions to improve air quality in Europe are targeted to the dominating emission sources, on the condition that feasible emission reduction measures are available. This emphasizes the importance of source apportionment of ambient emission levels. In PAREMPI, the impact of transport emissions on the air quality in Europe was modelled. The results showed that road traffic strongly influences NO_x, and indirectly ozone and PM levels in central and urban Europe. From road traffic, NO_x combined with NH_3 is a major source of $PM_{2.5}$ as ammonium nitrate, while BC, organic aerosol, and non-exhaust emission (NEE) sources contribute to lesser extent.

Nitrate dominates $PM_{2.5}$ in many continental regions during winter and early spring. Road traffic contribution to the yearly average total PM2.5 and PM2.5 nitrate levels in Europe are presented in Figure 5. Intense traffic has a low impact on SOA, since NO_x often suppresses SOA formation (both anthropogenic and biogenic). Hence, traffic emissions can both increase or decrease SOA. Large uncertainties remain in SOA mass modelling and applied models still underestimate the organic compounds' concentrations. Formation of SOA from light aromatic compounds and alkanes is a slower process than formation of ammonia nitrates. However, some compounds, for example phenols, potentially form SOA more rapidly than monoaromatics.

In PAREMPI, molecular level SOA modelling, semi-empirical autoxidation mechanisms up to very condensable highly oxygenated organic molecules (HOM), was developed for key monoaromatic hydrocarbons and progress was made on alkane- and polycyclic aromatic hydrocarbon (PAH) functionalization. While the benchmarking experiments agree over wide timescales and experimental conditions, challenges remain in modelling the molecular level formation of SOA mass. The measured condensable HOM product distribution is reflected in the obtained SOA mass.

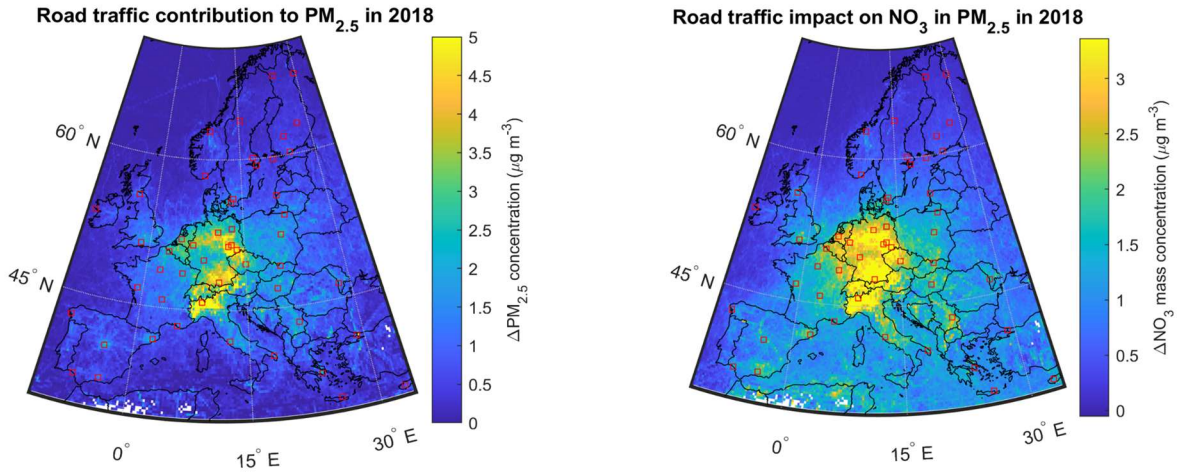


Figure 5. Road traffic contribution to the yearly average total $PM_{2.5}$ and $PM_{2.5}$ nitrate (NO_3^-) levels in Europe. Results from the chemistry transport model ADCHEM.

Ship emissions significantly increase UFP along major shipping lanes, mainly affecting ocean and coastal regions. For larger particles (>100 nm), geographical patterns look different as hotspots occur in the Po Valley and Eastern Europe, especially the Balkans. During certain conditions SecA may grow UFP particles above 100 nm in diameter which will result in decreasing UFP concentrations.

The NO_x and VOC emissions from road traffic contribute to the tropospheric ozone production. Reductions in road traffic NO_x and VOC emissions is an efficient measure to reduce both the $PM_{2.5}$ and surface ozone levels in Europe according to PAREMPI modelling with the European scale chemistry transport model. Especially during heatwaves, reducing road emissions could help mitigate ozone levels.

The contribution of road traffic on yearly average surface levels in Europe for UFP, number of particles larger than 100 nm in diameter and ozone are presented in Figure 6.

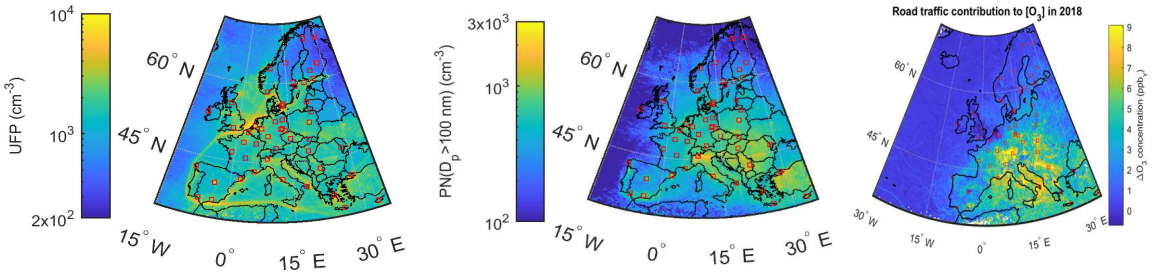


*Figure 6. The yearly average surface levels in Europe. **Left:** UFP, **Middle**: PN >100 nm in diameter, **Right:** Ozone, road traffic contribution. Results from the chemistry transport model ADCHEM. Modeled UFP and PN (>100 nm) concentrations in Europe for 2018.*

In PAREMPI, ePMI software was developed for evaluation of primary and secondary aerosol particle number and mass formation from transport sources in global and regional scales. ePMI software uses simplified parameterizations of SOA and UFP formation based on standard variables ([NO_x], [O_3], [OH], [H_2SO_4], VOC mixtures, [NH_3], temperature *etc.*) and components including BC, OC, non-exhaust emissions and secondary inorganic aerosols (nitrate, sulfate,

ammonium), as well as SOA. ePMI builds on the M7 aerosol dynamics model and improved SOA volatility basis set (VBS) schemes from PAREMPI, as well as particle formation parameterizations. A prototype was implemented in TM5 and compared with ADCHEM. Results show good regional agreement, though ADCHEM predicts higher $PM_{2.5}$ and UFP in urban areas, likely due to resolution and emissions inventory differences. Future work will cross-validate these effects (Figure 7).

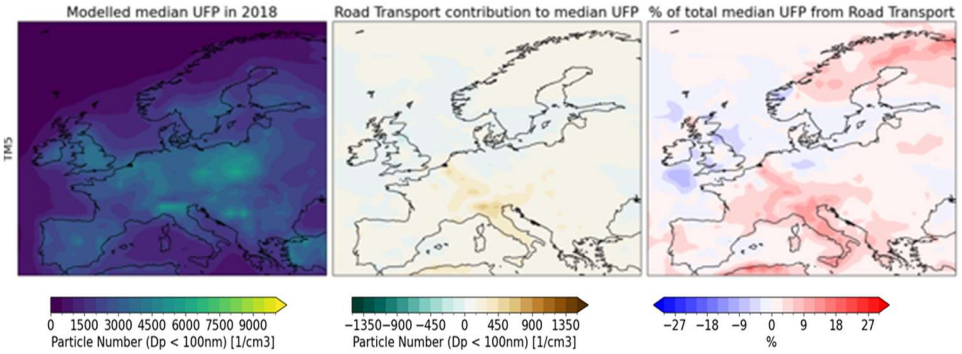


Figure 7. TM5-ePMI and ADCHEM modelling of PM2.5 levels.

3.2 Health impacts and external costs of transport emissions

The air quality limits are based on evidence on relationship of emission exposure with adverse health effects. In the EU, over 180 000 premature deaths annually are attributable to PM2.5 exposure above WHO guideline levels, 63 000 to ozone exposure and 34 000 to NO_2 exposure in 2023, despite of approx. 57% reduction in PM2.5 levels since 2005 (European Environment Agency (EEA), 2025). The majority of the urban population in Europe remains exposed to pollutant concentrations exceeding WHO recommendations.

Figure 8. PAREMPI findings on health impacts and external costs caused by SecA.

In PAREMPI, health impact assessment and external cost evaluations covered the assessment of the impact of road and ship traffic emissions on the air quality and population exposure to $PM_{2.5}$, with related health effects (mortality, morbidity), along with the associated external costs based on toxicological and epidemiological studies in Europe. Health impacts were quantified using established exposure–response functions (ERFs) from recent systematic reviews and epidemiological studies. Excess cases of mortality and morbidity were estimated using modelled $PM_{2.5}$ concentrations, baseline country-specific incidence rates (EU-27), gridded population data (Eurostat GEOSTAT) and relative risks (RRs) for each health outcome. The link between $PM_{2.5}$ and mortality is strong, while the effects of individual $PM_{2.5}$ components (organic and inorganic species) are less certain. Following WHO and EPA guidance, the analysis applied the same toxicity assumption

for all $PM_{2.5}$ mass, supported also by PAREMPI findings of toxicity responses for PM having different compositions.

Mortality-related external costs considered both direct (healthcare, social services) and indirect (productivity losses, informal care) impacts, noting that figures vary by country, healthcare system, and methodology. External costs were monetized using the statistical value of life (VSL) and the value of a life year (VOLY). We used high-resolution exposure data and country-specific mortality and morbidity rates to estimate attributable outcomes across the EU-27. ERFs were sourced from Forastiere et al. (2024), covering cardiovascular and respiratory diseases, dementia, autism, diabetes, and cancer. PAREMPI estimates **approx. 111 000 premature deaths per year in the EU-27 attributed to exposure of SecA, representing almost 62% of the corresponding premature deaths caused by PM2.5. Respective total annual societal cost of these health outcomes due to SecA is estimated at €544 billion (Figure 8). Notably, gaseous emissions as such also pose significant health and environmental risks, directly as harmful gases.**

3.3 Prevention technologies for precursor emissions and toxicity

Findings from PAREMPI measurements and selected supporting literature are presented to highlight technological solutions for preventing SecA precursor gases (VOCs, NO_x, NH_3, and SO_2) and PM emissions, fresh and aged, across different transport sectors. Prevention technologies in focus in this section are exhaust aftertreatment (EAT) systems, fuel innovations, and engine design improvements.

Road transport

In road transport, tight emission standards have reduced emissions efficiently, however, there is still room for improvement, particularly during cold-starts under low ambient temperatures, and when PHEVs switch from battery to combustion engine. Among SecA precursors, NO_x emissions are directly regulated, while SO_x is indirectly controlled through fuel standards. However, organic precursor gases and NH_3 remain unregulated for passenger cars in Europe, highlighting regulatory gap with implications for SecA formation. Further research is essential to fully understand the complex dynamics of SecA formation in real-world driving conditions.

Emission standards. *For cars*, the PAREMPI results highlight how tightening *emission standards* have cleaned the car emissions, new cars emit low overall particle emissions, while cold-start emissions remained elevated leading to SecA formation (Simon *et al.*, 2025). Organic compounds reportedly dominate SecA after cold-start, and ammonium, sulfate, and nitrate with warm engine (Simonen *et al.*, 2019). In PAREMPI, some modern cars, e.g. Euro 6dT CNG car, emitted unexpectedly high aged PM_{aged} emissions, which was attributed to the gasoline backup system. Another example regards Euro 6d PHEVs, which emitted elevated particle levels when switching from electric to combustion mode under dynamic driving. *For trucks*, PAREMPI results showed low SecA precursor emissions, especially for the Euro VI E truck representing the latest emission standards; however, cold-start emissions remained elevated. NH_3 is currently unregulated for cars, and future standards would benefit from stringent and harmonized NH_3 limits.

Fuel composition influences emissions and SecA formation, particularly through their monoaromatic content. Saarikoski et al. (Saarikoski *et al.*, 2024) demonstrated that aromatic-free fuels significantly cut down non-volatile, fresh, and aged particles. Current fuel standards

could still improve considerably, since the gasoline standard (EN 228:2012 + A1:2017) allows up to 35 vol% aromatics in gasoline, a relatively high threshold, and benzene content of max. 1.0 vol%. The European diesel fuel standard (EN590:2022) does not limit the total aromatic content of diesel fuel – only polycyclic aromatic hydrocarbons (PAHs, di+) are restricted to a maximum of 8.0 wt%. Diesel fuels typically contain heavier aromatics than gasoline. Besides SecA formation, aromatic compounds emitted carry harmful health effects as such.

Sulfur levels in diesel fuels in Europe are already minimal (up to 10 mg/kg), which effectively reduces SO_x emissions leading limited possibilities for further reductions. However, the sulfur content in lubricating oils may still contribute to residual SO_x emissions, a factor worth of further investigation

Fuels like methane, paraffins, alcohols, and hydrogen reduce concentrations of some emission species when compared with traditional fuels. For example, engine-out NO_x emissions reduce along with lower combustion temperature, depending on composition of fuel. In contrast, some alternative fuels, such as fatty acid methyl ester (FAME) biodiesel, may slightly increase NO_x compared to diesel fuel, necessitating case-specific evaluation. Clean fuels can reduce directly emitted fresh PM emissions, depending on fuel properties.

EAT. EAT systems can efficiently reduce emissions even to negligible levels. However, EAT performance may not be optimal during cold-starts or when PHEVs switch from battery to combustion modes necessitating further development to secure efficient performance in all operating conditions. Additionally, durability of EAT systems is critical to ensure sustained emission reductions over the vehicle lifetime under real-world operating conditions. Concerning SecA percursors, NMVOC emissions can be reduced with EAT systems having an oxidation function, e.g. TWCs and DPFs. NO_x emissions are reduced by TWC for stoichiometric SI cars, while SCR and LNT concepts are employed in diesel combustion. Possible NH_3 slip from SCR can be mitigated by ammonia slip catalyst (ASC). EAT systems are not applied for SO_x reduction from cars and vehicles. Directly emitted fresh PM emissions are primarily reduced by particle filters (DPF, GPF) in road transport sector.

In PAREMPI, the efficiency of particle filtration was evident, as PM_{fresh} emissions were high for gasoline cars lacking GPFs, especially in cold conditions, while cars with filtration emitted very low particle emissions, though regeneration events may occasionally lead to elevated particle emissions. TWCs performed effectively in reducing NO_x and NMVOC emissions, while NH_3 was observed as by-product with some gasoline and CNG cars (Euro 6b and 6d PHEV, CNG) (Simon *et al.*, 2025). The Euro 6b gasoline car promoted SecA formation, primarily ammonium nitrate (NH_4NO_3), while the Euro 4 diesel car promoted ammonium sulfate ($(NH_4)_2SO_4$) formation. OFR studies may underestimate ammonium nitrate formation when vehicles emit NO_x without co-emitted NH_3, as ammonia from agriculture is typically present in real environments. In NH_3-limited urban environments, gasoline vehicles may act as NH_3 sources, enhancing SecA formation (Simon *et al.*, 2025).

*Two truck*s in PAREMPI, an older Euro VI step A and a newer step E, demonstrated exceptionally low PM_{aged} emissions, which confirm a crucial role of EAT systems in reducing emissions. One issue to note regards long driving distances, which mask the cold-start emissions, which were substantial. Engine-out emissions reflect levels emitted in the operating conditions where EAT system is not performing well. For instance, Karjalainen et al. (Karjalainen *et al.*, 2019) reported engine-out PM_{aged} emissions of the heavy-duty diesel engine as high as 106.2 mg/kWh and PM_{fresh} emission of 44.7 mg/kWh, while these emissions were below 1 mg/kWh after the EAT system. PM_{fresh} was primarily composed of black carbon, while PM_{aged} contained more sulfates and organic compounds. Interestingly, fuel type had only a minor influence on SecA formation, suggesting that lubricants or combustion processes

themselves may be key sources of precursors. Supporting this, Gordon et al. (Gordon *et al.*, 2014) found that Class 8 HD trucks running on fuel with 12% aromatics produced high PM_{fresh} emissions; however, when equipped with diesel oxidation catalysts (DOC) and DPF, emissions dropped to below 2 mg/kWh. Interestingly, Gren et al. (Gren *et al.*, 2021) reported heavy-duty tests showing a clear fuel effect, with biodiesels reducing SecA formation; however, EAT systems were again very effective. These findings underscore the impact of the EATS system, which can reduce both fresh and aged PM emissions by orders of magnitude, significantly mitigating the adverse environmental impacts of heavy-duty vehicles.

Engine internal technologies reducing the amount of unburned fuel may lower also the potential SecA formation through lowering NMVOC emissions. Additionally, reduced engine-out NO_x and BC can be achieved with engine design, e.g. optimization of injection system, injection timing, turbochargers, charge air cooling, variable valve timing and the EGR. These features may have significance, although EAT systems are the major technologies in emission reductions from internal combustion engines.

Outlook. PAREMPI measurements show that SecA precursor emissions could be significantly reduced by improving EAT performance during cold starts and high-load ICE operation in hybrids, and by addressing currently unregulated NH_3 emissions. Light-duty cars are expected to electrify rapidly, while heavy-duty transport is harder to electrify leading to use of ICEs for longer time, especially for long-haul trucks. Euro 7 will impose strict emission limits for heavy-duty applications, reducing SecA precursors (NMVOC and NO_x). PAREMPI measurements showed that a truck meeting the latest standards was very clean, though cold-start emissions remained high. Careful evaluation of emissions and their control is essential when introducing new fuels, such as alcohols. Systematic approaches include limiting exposure by relocating or restricting emissions, for example, ultra-low emission zones could reduce health impacts; even low emissions from modern cars are harmful near populations.

Marine sector

Marine sector is an important emitter representing approx. 15% and 13% of anthropogenic NO_x and SO_x emissions, and 4-22% of $PM_{2.5}$ emissions varying regionally (Crippa *et al.*, 2019). *Additionally, ships mainly operate near coastline and ports close to cities causing air quality problems* (Eyring *et al.*, 2010). *Globally, shipping is estimated to account for approx. 250 000 premature deaths and 6.4 million childhood asthma cases annually* (Sofiev *et al.*, 2018). *In marine sector, emphasis has been on the regulations of sulfur and NO_x emissions, and regulations are anticipated for BC. As the sector moves toward cleaner fuels and utilization of EAT systems is extended, comprehensive strategies that address all major pollutants would improve air quality and enable meeting international environmental targets. This is especially important in marine sector, where emission levels are still substantial.*

Emission standards. The International Maritime Organization (IMO) regulates NO_x emissions depending on engine size and type. IMO Tier III NO_x limits apply in NO_x Emission Control Areas (NECAs) for newbuilds. Global fuel sulfur limit is 0.5% and 0.1% in regional emission control areas for SO_x (SECA). Emission limits for marine engines allow higher emissions than those for road transport leaving possibilities to tighten future regulations. An exception is inland waterways, where strict emission limits are already applied. From SecA precursors, NMVOCs and NH_3 emissions are not limited, and also directly emitted PM is not included although BC emissions have been considered by the IMO. Future regulatory limits for NH_3 emissions deserve consideration, particularly as ammonia as a marine fuel is being demonstrated. Including NH_3 emissions in regulations would address its significant role as a SecA precursor, as well as increasing evidence of its harmful health effects.

Fuels. Clean marine fuels can efficiently reduce emissions. Compliance with IMO NO_x limits is typically achieved with LNG dual-fuel engines (LNG DF) besides SCR aftertreatment. Methane LNG low-pressure dual-fuel (LPDF) and SI engines can meet Tier III NOx limits without SCR, unlike LNG high-pressure dual-fuel (HPDF). Methanol DF emits less NO_x than diesel engines without SCR, but more than LNG DF. Already now, newbuild ships are mainly ordered with dual fuel engines, LNG DF or methanol DF, using diesel-type pilot fuel. Engines using methane or methanol as fuels reduce NO_x, SO_x, NMVOC and PM emissions efficiently when compared with diesel-fuelled engines.

Conventional marine fuels for diesel engines vary by grades defined in standard ISO 8217, where the aromatic contents of fuels are not limited. For a sample of 0.1%S marine fuel, high aromatic contents have been reported, e.g. 42.6 wt%. Aromatics in conventional marine fuels are typically heavier than SecA forming monoaromatics, while they are sources of potentially condensable matter and increase exhaust toxicity. Paraffinic aromatic-free renewable fuels reduce NO_x emissions, while FAME-type biodiesel may increase them; however, these effects are minimal in terms of SecA formation.

Using low-sulfur fuels is an efficient technology to reduce SO_x emissions. Marine fuels have high sulfur contents up to 0.5 wt% globally, and up to 0.1 wt% in SECA. Further reductions in the sulfur contents of conventional marine fuels appear potential. Alternative marine fuels, such as LNG and methanol, are typically sulfur-free. However, there is a complex contradiction related to the sulfur content of marine fuels, since sulphates have a cooling impact on climate.

The PAREMPI marine emissions mimicked by diesel generator and marine fuels revealed a wide range of PM emissions (both fresh and aged), alongside fluctuating levels of precursor gases. *High-sulfur marine fuel* (close to 0.5 wt% sulfur) shifted composition of PM_{aged} to sulfates, pointing to fuel sulfur-driven SecA formation through SO_2 emissions. When using distillate marine fuel, *organic material* was observed in both PM_{fresh} and PM_{aged} emissions, potentially formed by condensation. NMVOC emissions were high when using marine fuels, higher than those from cars and heavy-duty vehicles, aligned with supporting literature. An intentional addition of *NH_3 in the exhaust* (60 ppm) led to remarkable PM_{aged} emission dominated by nitrates and presence of ammonium and organics.

EAT. SCR exhaust aftertreatment efficiently reduces NO_x emissions, and present the main technology to meet IMO NO_x limits in NECA, besides LNG DF engines. SCR reduce NO_x emissions typically more than 90% even with low-quality marine fuels. Based on limited data on the emissions from SCR equipped ships, NH_3 emissions downstream of SCR systems were low (<0.026 g/kWh), indicating efficient ammonia slip control (Aakko-Saksa *et al.*, 2023).

NMVOC emissions could be reduced by marine DOCs, and PM emissions by marine DPFs; however, these available technologies are not commonly installed in ships apart from vessels in inland waterways. SCR has modest oxidative function reducing NMVOC emissions to some extent. Black carbon emissions are not currently regulated in shipping, but mitigation technologies are available, particularly LNG, methanol, marine DPF and wet electrostatic precipitators.

Marine sector is the only transport mode using EAT for SO_x reduction. Scrubbers enable use of high-sulfur fuels, since SO_x reduction is very high, up to 99%, outperforming even utilization of 0.1 wt% sulfur fuels. SO_x scrubbers dissolve NO_2 into the scrubber water; however, removal is limited to max. 12% to avoid nitrate discharge to water (MEPC.259(68)).

PAREMPI measurements with marine fuels were conducted without EAT systems. Only a few studies have explored PM_{aged} emissions from EAT equipped ships. An example is the work by Karjalainen et al. (Karjalainen *et al.*, 2022), who performed onboard measurements on a Roll-

on/Roll-off Passenger ship operating within a Sulfur Emission Control Area (SECA). That vessel was equipped with a DOC and a scrubber. Their findings showed negligible PM_{aged} emissions, suggesting that either the DOC, the scrubber, or their combined operation was effective in eliminating particulates and SecA precursors. The scrubber alone was shown to reduce SO_2 concentrations by over 99%. The same study revealed that engine-out PM emissions were higher when the ship operated on residual fuel compared to distillate fuel. During open-sea cruising, PM emissions were high, with composition primarily of sulfates (66%), followed by organic compounds (30%) and a small fraction of black carbon (4%). These results indicate the potential benefits of transitioning to cleaner marine fuels.

Engine internal technologies enable reductions in emissions, for example, through engine design, such as optimized injection, turbochargers, charge air cooling, variable valve timing and EGR.

Outlook. Overall, emissions from shipping are still high and potential for PM_{aged} reductions is substantial. Especially so, since marine sector is "hard-to-electrify" and dependent on the internal combustion engines. Besides those technologies already introduced, ammonia and hydrogen engines are being developed and may be available in the future. Hybrid solutions with batteries or fuel cells combined with marine engines are applied, besides using only batteries or fuel cells. For all new technologies considered, studies are needed to explore their benefits and adverse effects on emissions. Technologies to reduce SecA emissions from marine sector are available, but not widely implemented.

Aviation sector

The aviation sector faces unique challenges in reducing PM and SecA precursor emissions. While other transport modes can utilize advanced EAT systems, aviation must rely more heavily on fuel innovation, such as SAFs, to mitigate its environmental impact.

Emission standards. Currently, non-volatile particle number (particles above 10 nm) and black carbon emissions (called non-volatile PM in aviation sector) are regulated for aircrafts. On contrary, total PM and NMVOCs emissions are not regulated although they can be extremely high during aircraft idling according to PAREMPI measurements and supporting literature. These emissions are particularly relevant for air quality near airports.

Fuel. Aircraft engines operate without EAT systems, constrained by both operational and design limitations. As a result, the composition of the fuel becomes an important factor for reducing emissions. Given the limited technical options to reduce $PM_{2.5}$ from aircraft, stricter fuel standards, especially for aromatic and sulfur contents, should be considered. Airports' air quality could be improved by the use of sustainable aviation fuels (SAF). In aviation, fuel composition plays a central role in determining exhaust emissions, including those that contribute to SecA formation.

Reducing aromatic content of jet fuels could reduce contribution of aircraft exhaust on SecA emissions. In ASTM D1655, aromatic limit is max. 26.5 vol%, while for synthesized hydrocarbons, ASTM D7566 sets aromatic limit of min. 8 vol%. Many of the SAF fuels are aromatic-free, paraffinic fuels having higher hydrogen to carbon ratio than conventional jet fuels and drive for lower aromatic contents than currently. Paraffinic SAF fuels can also moderately reduce NO_x emissions. Limits for jet fuel aromatics could be reduced, but the process is more challenging than in other transport sectors due to the safety aspects. Jet fuel aromatics may increase ambient PM2.5 levels both by SecA formation and by condensation, and they may increase exhaust toxicity.

In the PAREMPI set-up, exhaust composition resembled the aircraft operation on idle or taxiing, which is typical near to airports. The results showed that both fresh and aged PM

emissions were high and dominated by the organic fraction. Among the precursor gases, NMVOCs exhibited notably high emission levels, exceeding those observed in all other transport sectors. NO_x emissions were in line with values reported in supporting studies. NH_3 emissions were low as expected, since aircraft engines do not employ EAT systems, which are common in road and marine transport. SO_2 levels assumedly correlate with the sulfur content of the aviation fuels used. In PAREMPI, the use of SAF also led to a notable reduction on non-volatile particles emissions (BC). A recent study by Lepistö et al. (Lepistö *et al.*, 2026) found ultrafine particles dominating around a medium-large international airport (Helsinki-Vantaa). Emissions were dominated by particles below 10 nm, including nanocluster aerosols (below 3 nm), indicating a strong contribution from semi-volatile compounds. Additionally, Louie et al. (Louie *et al.*, 2026) have reported of possibilities of SAF adoption to improve UFP-related mortalities around airports.

Turbines. Turbine design technologies that reduce emissions can help to lower the potential for SecA formation. Measures targeted at improving airports' air quality include the development of new combustion technologies. Lean combustion engines like GEnXcs or LEAPs have been shown to greatly reduce non-volatile particles emissions compared to other engines, up to three orders of magnitude. However, these reductions in non-volatile particles occur mainly during cruise and take-off, while during idle or taxiing, two regimes that likely contribute the most to airport air quality, volatile organic emissions dominate. Other measures include limitations on auxiliary power units (APU[4]) use in airports. In many airports, a time limit on use on APU has been introduced. One engine taxiing is a strategy that has recently been included in some airports, only one engine is used to do the taxiing phase, which is the longest one on the landing take-off cycle. In addition, while taxing, the engine is working far from its optimal regime, emissions are usually rich in organic compounds. Recently a new alternative for taxing without powering engines has been developed; the taxi Bot, an electrically powered semiautomatic aircraft tractor that can bring the aircraft from the finger zone to the take-off runway with no need for engines being switched on.

Outlook. Air quality in and around airports is currently a big concern, and regulatory authorities are working to improve it. The main emissions affecting the air quality on airports are those coming from aircraft engines and handling vehicles. From the point of view of handling vehicles, the strategy adopted is clear, to exchange them for electric ones to minimize combustion emissions. In the case of aircraft the solution is not straightforward, since aviation is a hard-to-electrify sector. There is some research linked to electric and fuel cell aircrafts, but this is mainly oriented to small local or at most regional planes, carrying a limited number of passengers. Nevertheless, there are different approaches that are being investigated or even that have started to be introduced in different airports.

Evaluation

Emission reduction technologies preventing PM_{aged} emissions in different transport sectors have variable efficiency, coverage and potential for further improvements, as evaluated in Table 2. Overall, exhaust emission aftertreatment systems efficiently reduce PM_{aged} and its precursor emissions. However, since the renewal of the vehicle fleet is a relatively slow process, changing the fuel standards can be seen as a faster way to affect transport exhaust emissions across sectors, on the condition that new fuels are compatible with existing engines; this aspect is valuable also for dual-fuel engines that use conventional fuels as a back-up.

[4] APU consists of a small-scale turbine situated in the tail of the aircraft that is used to get electrical power and to start engines

Table 2. Evaluation of efficiency, coverage and potential of PM_{aged} prevention technologies. PM_{aged} includes both freshly emitted PM_{fresh} and SecA formed in the atmospheric reactions.

Transport sector	PM_{aged} precursor	Technology	Efficiency (1=Low, 3=High)	Coverage (1=Low, 3=High)	Potential for improvement 1=Low, 3=High)
Light-duty road	NMVOC	EAT: TWC, GPF, DPF, DOC	3	3	2 (cold-start)
	NMVOC	Fuel: Low-aromatic	2*	1	2 (cold-start)
	NO_x	EAT: TWC, SCR, LNT	3	3	2 (cold-start)
	NH_3	EAT: NH_3 slip catalyst	3	1 (SI) 3 (DI)	2 (SI)
	SO_2	Fuel: low-sulfur <10ppm	3	3	1
	PM_{fresh}	EAT: DPF (organics also by TWC, DOC)	3	3	1
Heavy-duty road	NMVOC	EAT: DPF, DOC	3	3	2 (cold-start)
	NMVOC	Fuel: Low-aromatic	2*	1	2 (cold-start)
	NO_x	EAT: SCR	3	3	2 (cold-start)
	NH_3	EAT: NH_3 slip catalyst	3	3	1
	SO_2	Fuel: low-sulfur <10ppm	3	3	1
	PM_{fresh}	EAT: DPF	3	3	1
Marine	NMVOC	EAT: DPF	3	0-1	3
	NO_x	EAT: SCR	3	0-1	3
	NO_x	Fuel: LNG, some other fuels	2	0-1	3
	NH_3	EAT: NH_3 slip catalyst	3	0-1	3
	NMVOC	Fuel: Low-aromatic	2*	0-1	3*
	SO_2	Fuel: Low-sulfur <10ppm	3	0	3
	SO_2	EAT: SO_x scrubber	2	1	2
	PM_{fresh}	DPF, LNG, SCR, clean fuels	3	0-1	3
Aviation	NMVOC	Fuel: Low-aromatic	2*	0-1	2
	NO_x	Fuel: Paraffinic	2*	0-1	2
	NH_3	-	-*	-	-
	SO_2	Fuel: low-sulfur <10ppm	3	0	3
	PM_{fresh}	SAF	2*	0-1	2

*Insufficient data or depends on many parameters.

Toxicological impacts

Toxicological results from the PAREMPI campaigns show that while cytotoxicity was low, clear molecular-level effects, such as oxidative stress, DNA damage, and gene expression changes, were observed indicating that certain biological pathways were responsive to the exhaust exposures. Even short exposures caused relevant toxicological responses, including the cleanest technologies, influenced by ambient temperature.

Exhaust composition (organic compounds, nitrates, ammonium and sulfate species) varied across transport sectors and operating conditions. Despite these differences, overall toxicity remained low and no consistent relationship was identified between toxicity results and specific engine technologies or fuel types.

Although clear differences in toxicological effects in technologies were not evident, some remarks were still made, including *the effect of cold ambient temperature during vehicle operation and higher cytotoxicity and DNA damage for conventional than for renewable paraffinic diesel fuel with trucks.* Notably, toxicity effects induced during cold starts cannot be reversed by subsequent driving, and hence even short period of high exposure levels are

significant. Aviation and marine exhaust simulations showed low acute cytotoxicity but measurable transcriptomic changes, indicating limited short-term risk but potential relevance for sensitive populations or prolonged exposure, which was emphasised when ammonia was present in the exhaust, alongside with elevated PAH emissions.

Transcriptomic endpoints proved valuable for detecting early effects, especially for clean technologies where conventional assays lack sensitivity. Toxicological insight should be included in early design of engines, fuels, and aftertreatment systems under realistic conditions to ensure “Do No Significant Harm” design.

3.4 Tools to support policies: database and robust measurement systems

The PAREMPI database (Excel file, https://parempi.eu/) consist of emission data on secondary aerosol species, their precursors, and associated toxicity from transport sources, focusing on both freshly emitted and aged PM. It includes direct measurements from single sources such as engines, passenger cars, and heavy-duty vehicles, excluding mixed or indirectly derived data. Detailed metadata are provided on transport sector, emission source, fuel type, and measurement conditions when available. Measurement techniques, particularly oxidation flow reactors (OFRs) for ageing PM, are documented, and datasets are traceable to the original literature, prioritising studies from the past decade. The first database version is based on literature and will be updated with PAREMPI data. The most extensive dataset meeting the defined criteria was available for light-duty cars (79 datapoints), compared with 28 for heavy-duty vehicles, three for aviation, and none for marine transport. PAREMPI results will complete some of the gaps identified in the knowledge on SecA and toxicity revealed by the database; however, even then data on marine and aviation sectors are scarce and warrant further studies, as well as road transport sector in real-world conditions.

Robust and reliable measurement methods are essential for building comprehensive evidence on aged particulate matter from transport sources to support policies, which aims at limiting and preventing ambient PM levels. Data are essential also for modelling and health impact assessments. Quantifying the PM_{aged} formed through secondary reactions of precursor gases in the atmosphere remains challenging with current scientific methods, which are often unsuitable for on-road or on-board applications due to their large size, complexity, and sensitivity to harsh conditions leading to limited datasets. PAREMPI identified “a robust measurement system” applicable for use in real-life field conditions and environments to determine exhaust-derived potential PM_{aged} emissions. The system comprises a portable OFR, a dilution system, a particle number size distribution (PSD) device, from which the results are converted to PM mass, instruments for measuring precursor gases (NO_x, NH_3, SO_x, aromatics) that potentially form SecA as well as other necessary gases (NO_x, CO, CO_2) required to define settings for the OFR and to calculate emission factors and toxicity measurement. The recommended emission metric for PM_{aged} is mass per megajoule, defined based on the CO_2 concentrations and fuel properties, eliminating the need for exhaust or fuel flow measurements and therefore simplifying the setup. The robust measurement methods were evaluated alongside a complex measurement system within the PAREMPI project, and the experiences gained were evaluated. The same robust setup could be used regardless of the transport sector studied, although different dilution ratios are needed, and instruments may vary in the setups.

The outlook beyond PAREMPI encompasses the precise definition of conditions and the target settings for the OFR, as well as the detailed requirements for instruments. These detailed definitions are critical to ensure comparability of results across different studies.

Toxicological assessment of transport-derived exhaust with the robust measurement system suitable for real-life conditions was a significant achievement in PAREMPI. Especially, the integration of a portable-size Air-Liquid Interface (ALI) exposure chamber into a moving vehicle, enabling on-road sampling of heavy-duty truck emissions, and in situ toxicity testing. The integration of the air–liquid interface (ALI) exposure system into real-world testing was a key advancement, enabling direct in situ toxicity assessment. However, these setups are complex, resource-intensive, and inflexible, making the testing challenging and sometimes not fully successful. From a prevention perspective, toxicological insight should be included in early design of engines, fuels, and aftertreatment systems. While cheaper early screening helps avoid high-risk choices, full impacts often result from system-level interactions, real-world testing (including SecA formation, and multi-endpoint biological analysis, environment) is needed to capture toxicological effects. To enable this, measurement campaigns must be planned to support toxicological studies through appropriate exposure conditions and sample handling and scheduling.

3.5 Uncertainties

Policy recommendations to prevent secondary aerosol formation from transport sectors and their contribution to ambient PM levels are defined by knowledge gathered in PAREMPI modelling, evaluations, measurements, partners existing knowledge and supporting literature, but many uncertainties and knowledge gaps remain.

Uncertainties related to limited data and knowledge gaps are of concern, especially real-world SecA emissions and exposures. This applies to all transport sectors, but particularly to marine and aviation sectors, where data is almost non-existing. The work done in PAREMPI clearly indicated that PM_{aged} data from all sectors is not sufficient and more measurements are needed. Representative datasets could be approached by implementing the suggested robust measurement systems for aged PM and toxicity, and by developing harmonized protocols. In parallel, findings from toxicological evaluations highlight the need for further systematical in-depth toxicological analysis in real-world conditions. Supporting data is also needed to address the unregulated pollutants like VOCs, sub-10 nm particles, and PAHs. Also, the emission measurements should be planned to support toxicological studies through realistic exposure conditions, sample handling and scheduling to enable the representative toxicological results.

Modelling of the effect of transport emissions on air quality, and health impact assessments could be still improved. For example, contribution of traffic induced SOA in $PM_{2.5}$ levels is underestimated. Furthermore, more evidence is needed on the role of $PM_{2.5}$ composition on the health effects, although the causal link between air pollution, particularly $PM_{2.5}$, and adverse health outcomes is well established.

Estimation of the SecA prevention methods could be supported using tools developed in PAREMPI, such as ePMI, SecA and toxicity databases and molecular-level modelling.

The PAREMPI results were obtained with technologies currently available, reaching the most modern vehicles and even emerging options (e.g. ammonia). However, these results cannot consider possible future innovations to reduce PM_{aged} emissions, and hence further research is needed.

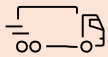
4. Policy recommendations

Reducing exhaust emissions, especially key precursor gases (certain VOCs, NO_x, NH_3, and SO_2) that contribute to secondary aerosol formation, and fresh particulate matter, increasing ambient $PM_{2.5}$ levels, requires combined policies, legislation and technical innovations. Transport policy recommendations presented here consider findings of PAREMPI on the prevention technologies and supporting literature bringing them in broader perspective.

Within the PAREMPI project, together with its sister projects, two Transport Policy Recommendations Workshops were organised to bring different perspectives into dialogue. Representatives from ministries, industry, and the research community highlighted that all transport sectors are undergoing rapid transformation through electrification and the adoption of cleaner fuels and technologies. In this context, participants emphasised the importance of technology neutral and predictable regulations. The importance of understanding sector-specific contributions to air quality was highlighted, together with the effectiveness and technological maturity of available $PM_{2.5}$ mitigation measures. It was further emphasised that integrated policy frameworks are required, as no single solution is capable of addressing all transport sectors. At the same time, fundamental trade-offs were acknowledged; for example, while reducing sulfur emissions improves air quality, it also diminishes the cooling effect of sulfates on the climate. Nevertheless, in line with WHO guidance, reducing ambient air pollution remains essential for achieving a healthy, sustainable, and equitable environment, underscoring the long-term objective of an emission-free future. In parallel, effective mitigation of global warming is necessary to avoid reliance on climate geoengineering approaches, such as compensatory cooling effects from ship emissions.

The policy recommendations of PAREMPI project are compiled in tables below, with information of sector (road, marine, aviation transport), target actors, timeline and impacts.

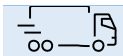
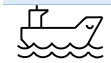
Fuel standards (promoting transition to cleaner fuels)

	**Stricter limits on fuel aromatic contents.** *Note:* Aromatic-free fuels, e.g. renewable diesel, methane, alcohols.
	Stricter limits on fuel sulfur and aromatic contents. *Note:* sulfur- and aromatic-free fuels, e.g. renewable diesel, methane, alcohols and hydrogen.
	Stricter limits on fuel sulfur and aromatic contents. *Note:* SAF fuels have low sulfur- and aromatic levels.
	▪ Standardisation bodies. ▪ Politicians and bodies creating e.g. incentives. ▪ Fuel manufacturers. New fuel concepts involve also engine and EAT manufacturers.
	Fuels compatible with present infrastructure (drop-in) enable fast impact. Introducing new fuels requiring new engines and EAT systems is a relatively slow process.
Trade-offs and needs	▪ Trade-offs between air quality and climate impacts: Integrated climate and air-quality evaluation needed. ▪ Underestimated life-cycle impacts: Full life-cycle assessments needed.

	▪ Infrastructure and technology lock-in: Technology-neutrality principles needed (limits and aims rather than specific fuels). ▪ Health and equity concerns: Impact assessments are needed. ▪ Wide international coordination is needed.

Justification: Fuel standards provide an efficient tool for fast reduction of fuel-related precursor gases: SO_x and monoaromatic emissions. Lowering sulfur content of fuels directly reduces SO_x emissions, as sulfur is primarily combusted to SO_x. This approach can be supported by low-sulfur lubricating oils. Limiting the monoaromatic content of fuels can reduce these SecA precursor gas emissions. This is relevant even for many low-emission technologies during the warm-up phase of the engine and EAT system. Fuels such as methane, paraffinic fuels (e.g. renewable diesel), biodiesel, alcohols, ethers and hydrogen do not contain sulfur or aromatics, and furthermore, they typically burn cleanly. Clean fuels compatible with present infrastructure can offer fast impacts.

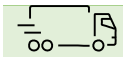
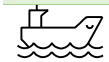
Stricter emissions standards and enforcement

	**Strict limits on NMOG and NH_3 emissions.** *Note:* Light-duty sectors's emissions need attention, since they are less stringent than those of heavy-duty sectors. Cold start and PHEV emissions.
	**Strict limits on NO_x, NMOG, NH_3 and PM (fresh) emissions.** *Note:* Emission regulations have potential for tightening in shipping. Adopting wider emission control areas recommended.
	Strict limits on NO_x, NMOG and PM (fresh) emissions. *Note:* Emission regulations have potential for tightening in aviation.
	Politicians and bodies creating emission standards.
	Fleet renewal is relatively slow process.
Trade-offs and needs	▪ Trade-offs between air quality and climate impacts (SO_x emissions): Integrated climate and air-quality evaluation needed. ▪ Life-cycle, health, equity and economy concerns: Impact assessments are needed. ▪ Regulatory trade-offs, inconsistent standards across regions: Wide international coordination needed. ▪ Real-world compliance, enforcement constrains: Measurements, reporting and validation needed. Mechanisms, e.g. penalties.

Justification: Emissions standards for several SecA precursor gases have been implemented in transport sectors, especially for NO_x emissions, which can be reduced by EAT systems. In contrast, NH_3 emissions, formed primarily in the EAT systems and potentially from future ammonia-fuelled engines, are limited to lesser extent. However, dedicated EAT systems for NH_3-removal technologies are available. VOCs, particularly monoaromatics, are known contributors to SecA formation. While emissions of individual aromatic compounds are scarcely measured or reported, aggregated NMVOC emissions are routinely measured and, when combined with characteristic exhaust profiles, can serve as proxies for aromatic precursor emissions and can be controlled. In shipping and aviation, NMOG or total PM emissions are not limited, although they appear to be elevated. Notably, the potential for further

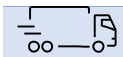
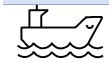
tightening of emission limits is higher in the marine and aviation sectors than in road transport. However, road transport remains a major contributor to urban air quality. Strengthening and enforcing Euro emission standards can effectively curb traffic-related emissions of SecA precursors.

Enforcement: Measuring, reporting and verification (MRV)

	**Requirements for MRV of aged $PM_{2.5}$ and its precursor emissions.** *Note:* Besides enforcement, data is needed in real-world conditions, e.g. during cold starts and PHEV operation. Harmonisation of the methodologies needed.
	**Requirements for MRV of aged $PM_{2.5}$ and its precursor emissions.** *Note:* Besides enforcement, data is needed in real-world conditions. Harmonisation of the methodologies needed.
	Requirements for MRV of aged $PM_{2.5}$ and its precursor emissions. *Note:* Besides enforcement, data is needed in real-world conditions. Harmonisation of the methodologies needed.
	▪ Politicians and bodies creating enforcement of emission standards and validating technological developments. ▪ Researchers and device manufacturer for robust measurement systems capable of monitoring and collecting data in real-world conditions.
	Measurements, reporting and monitoring can start with relatively short lead time.
Trade-offs and needs	▪ High uncertainty in results with unharmonized methods: Harmonized measurement methods needed. ▪ Limited set of emission species measured: Real-world measurement applicability for aged $PM_{2.5}$ and its precursor emissions needed. ▪ Sacrifices in knowledge base: Efficient data collection without compromising measurement principles and quality. ▪ Impact on policies weak: Transparent reporting and verification. Policy integration. ▪ Insufficient resources and funding: policy integration.

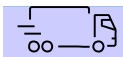
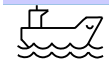
Justification: Robust monitoring, reporting, and verification (MRV) frameworks are essential for supporting the development, implementation, and revision of emission standards. MRV enables the systematic collection of data needed to justify limit values, ensures effective enforcement of standards, and supports transparent reporting of emissions and the performance of mitigation measures. By providing independent verification, MRV strengthens the credibility of reported emission reductions and confirms that they are achieved under real-world operating conditions. As emission sources become more complex, driven by emerging fuels and advanced emission-control technologies, MRV also plays a critical role in identifying pollutants and impacts not fully addressed by existing regulations, while supporting international comparability. In the marine sector, the EU MRV Regulation for greenhouse gas emissions is already in place, and within the EU Air Quality Directive, strengthened monitoring and modelling frameworks provide complementary support structures.

Toxicological studies included in the early stage

	**Toxicological studies included in the evaluations and early stage of development (DNSH principle).** *Note:* Harmonisation of the methodologies needed.
	**Toxicological studies included in the evaluations and early stage of development (DNSH principle).** *Note:* Harmonisation of the methodologies needed.
	Toxicological studies included in the evaluations and early stage of development (DNSH principle). *Note:* Harmonisation of the methodologies needed.
	▪ Scientific community. ▪ Standardisation bodies.
	Relatively short lead time.
Trade-offs and needs	▪ Limited data on real-world exposures: Extended measurements integrated with emission studies. ▪ Mismatch between short- and long-term impacts: Link to health-based studies. Long-term and vulnerable-group perspectives included. ▪ Uncertainty: Harmonized protocols needed. ▪ Support to harmful technologies without toxicity studied.

Justification: Toxicological studies provide essential mechanistic evidence linking air pollutant exposure to adverse health outcomes. Together with epidemiological evidence, toxicology helps to establish causal relationships, identify sensitive biological pathways, and support health-based targets and limit values in air-quality standards and guidelines. As regards engine, fuel and EAT systems developed, toxicological research enables evaluating exposures that are not captured by existing emission standards and cannot be quantified with chemical approaches due to the complex emission mixtures, ageing, and emerging pollutants not yet identified. By characterizing biological responses at realistic exposure levels, toxicological studies help identify potential risks in early phase of development. In measurements, special attention is needed in sampling to assess the realistic exposure levels.

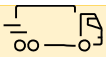
Harmonized measurement methods

	**Harmonisation of measurement methods for aged PM and its precursors** *Note:* Reliable and comparable data between studies is needed.
	**Harmonisation of measurement methods for aged PM and its precursors** *Note:* Reliable and comparable data between studies is needed.
	Harmonisation of measurement methods for aged PM and its precursors *Note:* Reliable and comparable data between studies is needed.
	▪ Scientific community. ▪ Standardisation bodies.
	Relatively short lead time.

Trade-offs and needs	▪ Biased results and comparability of results: Internationally agreed parameters and procedures, as well as definitions of metrics and boundaries on scientific basis. ▪ Barrier to enforcement.

Justification: Harmonized emission measurement methods are essential to ensure that emission data are comparable, credible, and usable. Harmonized measurement approaches reduce uncertainty and improve transparency. This is particularly important when measuring aged PM with OFR, where definitions of the protocol, precise conditions and the target settings, as well as the detailed requirements for instruments would be needed. Methods used in toxicity studies needs also harmonisation of methods.

Advanced engines and exhaust aftertreatment systems

	**Accelerating the development and adoption of advanced engine and EAT technologies.** *Note:* Cold-start emissions and PHEVs. Retrofitting possibilities limited.
	Accelerating the development and adoption of advanced engine and EAT technologies. *Note:* Retrofitting possibilities and extended utilization of EAT.
	Accelerating the development and adoption of low-emission turbine technologies *Note:* EAT not feasible
	▪ Engine and turbine manufacturers. ▪ Exhaust aftertreatment systems manufacturers. ▪ Politicians and bodies creating incentives.
	Fleet renewal is a relatively slow process.
Trade-offs and needs	▪ Emission trade-offs, e.g. heated EAT versus energy consumption: Integrated engine-fuel-EAT development needed. ▪ Real-world performance: measurements are needed in the early stage of development. ▪ Technology readiness, durability, reliability and safety: lead times are needed. ▪ Technology lock-in: Technology neutrality needed. ▪ Insufficient regulation does not support advanced systems: International coordination (e.g. standards).

Justification: Promoting the adoption of low-emission engine technologies and advanced exhaust aftertreatment (EAT) systems is an effective means to reduce SecA precursor emissions (NMVOCs, NO_x, NH_3) and particulate matter across transport sectors. Priority should be given to challenging real-world conditions, such as cold starts and hybrid operations. Mandating best available technologies (BAT), supporting the deployment of advanced solutions (e.g. heated EAT for hybrids), and retrofitting fleets, e.g. marine engines with NO_x abatement technologies, can deliver substantial emission reductions. Current EAT strategies include TWC in stoichiometric gasoline engines, SCR and LNT systems in diesel engines, oxidation catalysts and particulate filters, and ammonia slip catalysts downstream SCR. In

parallel, engine-internal measures such as optimization of injection system, turbochargers, the charge air cooling, variable valve timing and EGR, further reduce engine-out emissions and precursor formation.

Other strategies to minimize societal costs

- **Transition to Low-Emission Mobility**
  Replacing internal combustion engine vehicles with electric vehicles (EVs), bicycles, and enhanced public transport can significantly reduce NO_x, NMVOC and NH_3 emissions, thereby lowering ambient nitrate, organics and ammonia levels, and thereby, formation of SecA emissions.

- **Urban and residential planning and traffic management**
  Interventions such as low-emission zones, congestion pricing, and optimized traffic flow can reduce vehicle density and idling, particularly in urban hotspots where exposure is highest. These measures can lead to immediate and localized air quality improvements.

  Poor air quality e.g. near ports and airports could be taken into account in residential planning. Clean air is necessary for wellbeing of people and also to secure equal possibilities. Reportedly,[5] the adverse health impacts of air pollution are the most severe among vulnerable people, women, and during child development. This affects education and work opportunities, especially among low-income households. Increasing social and gender equalities support effectiveness of policies.

- **Economical drivers, research, innovations and international coordination**
  Many strategies can promote actions towards clean air, such as incentives, penalties ("polluter pays"), funding for research, innovations and international coordination.

- **Agricultural Synergies**
  Ammonium, an important SecA contributor, originates mainly from agriculture, integrated strategies targeting both traffic-related NO_x and agricultural NH_3 emissions may provide synergistic benefits and lower total mitigation costs.

- **Public Health Co-Benefits (enhancing the societal return on investment)**
  Many SecA-reduction measures also contribute to broader public health goals. For example, promoting active transport such as walking and cycling can increase physical activity, reduce traffic injuries, and lower noise exposure, further enhancing the societal return on investment.

- **Responsibilities**
  In EU AQ Directive, supporting structures include legal right for citizens to seek compensation if AQ standards are breached. WHO (2020) emphasises that society is responsible for providing clean air, although individuals can request information on air quality, and reduce their own emissions. As regards personal protection by portable air filters, WHO (WHO, 2020) finds their widespread public health recommendation as premature due to environmental, financial, and equity considerations

[5] https://www.eea.europa.eu/publications/healthy-environment-healthy-lives

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Appendix 1.

List of public Deliverables and scientific articles by PAREMPI (see Deliverable D5.3 for manuscripts under preparation).

Deliverables:

PAREMPI Deliverable D2.2, Rönkkö et al., Measurement results of emissions, secondary aerosol forming potential and methodology, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2025.

PAREMPI Deliverable D2.3, Aakko-Saksa et al., Evaluation of robust measurement methods for estimating secondary aerosol mass, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2025.

PAREMPI Deliverable D3.1, Roldin et al., Aerosol dynamics during exhaust dilution and cooling, Horizon Europe project PAREMPI, available at https://parempi.eu/, 2024.

PAREMPI Deliverable D3.2, Rissanen et al., Secondary aerosol formation from representative (S)VOCs, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2024.

PAREMPI Deliverable D3.3, Roldin et al., European and global scale estimates of the vehicle fleet contribution to organic and inorganic PM2.5 and nano-particle concentrations during all seasons, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2024.

PAREMPI Deliverable D3.4, Roldin et al., Digital equivalent total particles emissions index (ePMI) module software, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2025.

PAREMPI Deliverable D4.1, Oudin et al., Health impact assessment and societal costs (HIA), available at https://parempi.eu/, 2025.

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PAREMPI Deliverable D5.3, Timonen et al., Scientific evidence report, Horizon Europe project PAREMPI, Available https://parempi.eu/, 2025.

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Published scientific articles from PAREMPI:

Aakko-Saksa et al. Transport sectors' real-world emissions: from gaseous precursors to secondary aerosol formation in urban air, Proceedings of the 10th Transport Research Arena

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