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Health impact assessment and societal costs (HIA)

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PAREMPI
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List of abbreviations

BC	Black carbon
COMEAP	Committee on the Medical Effects of Air Pollutants
EPA	Environmental Protection Agency
ERFs	Response functions
GIS	Geographical Information System
HIA	Health impact assessment
IQR	Interquartile range
PM	Particulate matter
RR	Relative risks
SecA	Secondary aerosols
SIA	Secondary inorganic aerosols
VOLY	Value of a Life Year
VSL	Value of a Statistical Life
WHO	The World Health Organization

1. Executive Summary

This report presents a comprehensive health impact assessment (HIA) of exposure to secondary aerosols (SecA)—a major component of fine particulate matter ($PM_{2.5}$)—across the EU-27. The assessment estimates the burden of disease and associated societal costs using standardized epidemiological methods, exposure modeling, and economic valuation frameworks.

Methodology

Health impacts were quantified using established exposure–response functions (ERFs) derived from recent systematic reviews and epidemiological studies. The number of excess cases (e.g., mortality, morbidity) was calculated based on pollutant concentrations, baseline incidence rates specific for all countries across the EU-27, population data, and relative risks (RRs). Key inputs included modelled $PM_{2.5}$ data, gridded population data (Eurostat GEOSTAT), and country-specific health statistics.

Although $PM_{2.5}$ is consistently linked to adverse health outcomes, the evidence for component-specific effects, particularly secondary inorganic aerosols (nitrate, sulphate, ammonium), remains inconclusive. Consequently, current best practice, endorsed by WHO, EPA, and other expert bodies, applies a uniform risk estimate to all $PM_{2.5}$ mass. This study followed that guidance as the literature review of recent studies as well as the results from the PAREMPI project did not provide sufficiently robust or conclusive evidence to justify conducting a health impact assessment based on an alternative toxicity scenario.

ULUND researchers used high-resolution exposure data and country-specific mortality to estimate attributable health outcomes across the EU-27. Incidence rates and ERFs were sourced from a recent systematic review (Forastiere et al., 2024) covering a range of conditions including cardiovascular and respiratory diseases, dementia, autism, diabetes, and cancer.

External Cost Assessment

Monetary valuation of health impacts was based on the European Commission's standard Value of a Statistical Life (€4,570,100) for premature mortality and disease-specific cost estimates for morbidity outcomes. Morbidity costs included direct healthcare expenditures, long-term care costs, productivity losses, and other societal impacts where relevant.

Key Findings

Premature Mortality

Exposure to secondary aerosols (SecA) was estimated to be associated with approximately **111,000 premature deaths annually across the EU-27**. When traffic-related contributions to secondary aerosol formation were excluded, the estimated mortality burden decreased to approximately **88,000 deaths**, indicating that around **21% of SecA-attributable mortality is linked to traffic emissions**.

Morbidity Outcomes

Secondary aerosol exposure was also associated with a substantial burden of non-fatal disease, including an estimated annual incidence of:

- **186,000 childhood asthma cases**
- **204,000 chronic obstructive pulmonary disease (COPD) cases**
- **591,000 dementia cases**
- **101,000 type 2 diabetes cases**
- **104,000 stroke cases**
- **44,000 lung cancer cases**
- **206,000 acute myocardial infarctions**
- **23,000 autism spectrum disorder cases**

Economic Impact

The economic cost of SecA-attributable premature mortality alone was estimated at approximately **€508 billion annually across the EU-27**. Excluding traffic-related contributions reduced this estimate to approximately **€405 billion annually**. In addition, SecA-related morbidity generated substantial societal costs through healthcare utilization, long-term care needs, reduced quality of life, and productivity losses, further increasing the overall economic burden.

Implications

These findings highlight the considerable public health and economic burden associated with exposure to secondary aerosols in Europe. The results support the need for targeted air quality policies and emission reduction strategies, particularly those addressing precursor emissions from traffic and other combustion sources. They also underscore the importance of considering particulate matter composition and source-specific contributions when assessing health risks and designing mitigation measures.

2. Methods

Health impact assessment (HIA) of air pollution quantifies the adverse health effects attributable to exposure in a given population, using established epidemiological relationships. The core of the methodology involves estimating the number of excess cases (e.g., premature deaths, hospital admissions) by integrating pollutant exposure levels, population data, baseline health statistics, and exposure–response functions (ERFs) derived from cohort or time-series studies.

The standard formula for HIA is:

$$\Delta Y = Y_0 \times (e^{\beta \times \Delta x} - 1) \times P$$

where:

ΔY = number of attributable cases (e.g., deaths),

Y_0= baseline incidence rate of the health outcome,

β = =concentration-response coefficient (ln(RR)/ Δx,

Δx = change in pollutant concentration (e.g., µg/m³ of $PM_{2.5}$),

P = exposed population,

RR= relative risk associated with a unit change in pollutant concentration.

External cost evaluations then monetize these impacts using economic values such as:

- Value of a Statistical Life (VSL): commonly used for premature mortality,
- Value of a Life Year (VOLY): used in burden of disease and cost–benefit analyses.

These values are derived from stated preference studies or revealed preference methods and may be adjusted for local context or policy guidelines. Sensitivity analyses are crucial to account for uncertainties in the ERFs, exposure estimates, population projections, and economic valuation.

2.1 Population exposure

To assess the populations exposure GIS (Geographical Information System) analyses were applied combining modelled annual levels of $PM_{2,5}$ for 2018 in combination with a population grid retrieved from Eurostat (GEOSTAT 1 km^2 population grid - Version 2018; 13 April 2021) using the software QGIS Desktop 3.42 and ArcMap 10.5.1.

(Source: European Commission (Eurostat, Joint Research Centre and DG Regional Policy - REGIO-GIS.)

2.2 Exposure–Response Relationships for Secondary Aerosols (SecA)

Within the PAREMPI project, researchers at Lund University (ULUND) have explored whether conventional exposure–response functions for $PM_{2.5}$ are appropriate for use in health impact assessments involving SecA, or if current evidence justifies adopting component-specific risk estimates. This has been done in order to produce estimates under different scenarios.

While the association between fine particulate matter and mortality is well established, findings related to individual $PM_{2.5}$ components, such as secondary aerosols, remain inconsistent and uncertain, a point emphasized in several systematic reviews (Achilleos, Kioumourtzoglou et al. 2017, Yang, Ruan et al. 2019). The discussion below summarizes the most relevant literature and expert evaluations.

2.3 Scientific Evidence

Systematic reviews and recent cohort studies have provided mixed evidence on the health effects of individual $PM_{2.5}$ components, particularly secondary inorganic aerosols (SIA) such as nitrate, sulphate, and ammonium. For instance, Yang et al. (2019) reported a 2.6% increase in mortality per interquartile range (IQR) of nitrate (~2.3 µg/m³), while Karimi & Samadi estimated a 3% increase (Karimi and Samadi 2023). However, SIA as a group was not significantly associated with mortality in the latter study. Cohort studies in North America and Europe have produced conflicting results. In California, long-term exposure to nitrate and sulphate was associated with elevated cardiovascular and all-cause mortality in a cohort of teachers, though these associations were not replicated in a subsequent study (Ostro, Hu et al. 2015). Canadian registry-based studies observed stronger associations with total $PM_{2.5}$ than with its individual components, although including component proportions improved model performance (Crouse, Philip et al. 2016). In the southeastern U.S., Wang et al. found lower relative risks for sulphate, nitrate, and organic carbon, suggesting that these components may be less harmful. Yet, a later satellite-based study from the same region found an increased mortality risk linked to nitrate, but not sulphate (Wang, Shi et al. 2017). Similarly, Hao et al. (2023) reported that nitrate had a modest risk ratio (RR 1.023 per IQR increase), exceeding that of elemental carbon or organic matter, but falling below sulphate and ammonium (Hao, Wang et al. 2023). Findings from Nordic cohorts suggest a potential role of SIA in cardiovascular mortality, although the evidence for total mortality is less consistent (Hvidtfeldt, Sørensen et al. 2019, Nilsson Sommar, Andersson et al. 2021).Despite growing interest, a major limitation in identifying component-specific effects lies in the availability and resolution of exposure data. Few studies have monitored specific $PM_{2.5}$ constituents across multiple sites, limiting the capacity to assess spatial variability—a key factor in long-term exposure assessments. Moreover, strong inter-correlations among components complicate the separation of individual health effects. Commonly analysed constituents include secondary inorganic particles (nitrate, sulphate, ammonium), organic and elemental carbon, and trace metals. Exposure assessments frequently rely on land-use regression models or chemical transport models. While these methods offer improved spatial resolution—especially compared to earlier gridded models with resolutions from 1×1 km to 30 km—they introduce higher uncertainty and misclassification. Consequently, associations between individual components and health outcomes often lack precision or statistical significance, even when $PM_{2.5}$ overall is robustly linked to adverse effects.

2.4 Evaluations by Expert Bodies

Major public health agencies, including the World Health Organization (WHO), the U.S. Environmental Protection Agency (EPA), the UK's Committee on the Medical Effects of Air Pollutants (COMEAP), and France's ANSES—have consistently concluded that current evidence does not justify the use of component-specific exposure–response coefficients for $PM_{2.5}$. In their most recent evaluations, WHO's 2021 Air Quality Guidelines, the U.S. EPA's 2022 scientific review, and COMEAP's 2022 report all acknowledged potential toxicity differences among PM components but emphasized that the available evidence lacks the robustness required to support component-specific health effect estimates.

As a result, most health impact assessments treat all $PM_{2.5}$ mass equally, regardless of its chemical composition. Specifically, assessments typically do not differentiate between secondary inorganic aerosols (SecA) and other sources of $PM_{2.5}$. Nevertheless, some research indicates that the health risk associated with regional background $PM_{2.5}$ often dominated by secondary aerosols, may be lower per µg/m³ than that from local sources. For example, Turner et al. and Segersson et al. found that locally generated PM was more strongly associated with health outcomes than background PM (Turner, Jerrett et al. 2016, Segersson, Johansson et al. 2021).

In cases where exposure assessments specifically target SecA components, such as nitrate, using regionally derived risk estimates may be more appropriate. Yang et al. reported a 1.1% increase in mortality per µg/m³ of nitrate exposure, higher than the risk typically assigned to background $PM_{2.5}$ mass (Yang, Ruan et al. 2019). However, this differentiation has rarely been implemented in practice. To date, only one published health impact assessment has explicitly applied a separate risk estimate for nitrate (Hang, Meng et al. 2022).

In PAREMPI, preliminary toxicity findings are qualitatively assessed and discussed in conjunction with aged PM composition, which varied across measurement campaigns involving cars, heavy-duty trucks, marine engine and aviation turbine simulations. For example, organic compounds were predominant in the exhaust from an older diesel vehicle, jet fuel combustion, and during operation with distillate marine fuel. In contrast, aged PM was primarily composed of nitrate and ammonium species under conditions with elevated NH_3 levels were injected in the exhaust, while sulfate species dominated with high-sulfur marine fuel. Despite the compositional differences, overall exhaust toxicity remained low. Trans-epithelial electrical resistance (TEER), a strong indicator of cell barrier integrity and permeability, was largely preserved, and oxidative stress responses were minimal. However, transcriptomic profiling revealed changes in gene expression, indicating that certain biological pathways were responsive to the exhaust exposures. These responses were observed for particulate matter having different compositions, dominated by either organic or inorganic compounds. The initial PAREMPI results suggesting toxicity responses for different PM compositions have not provided evidence to warrant revising current health impact approaches. Given the observed harmful effects of both organic and inorganic PM components, indicative PAREMPI results are in line with the recommended exposure–response coefficients for total PM2.5.

For this study, we therefore solely use the HR of 1.095 per 10 mikrog/m3 increase, found in the update of the WHO AGQs from 2021 (Orellano, Kasdagli et al. 2024).

In the HIA calculations in PAREMPI, ULUND has employed country specific age-standardised mortality for the whole of EU-27, as well as country specific mortality. Incidences for the following health outcomes from the review done by Forastiere et al. for total SecA $PM_{2.5}$ (Forastiere, Spadaro et al. 2024), see Table 1.

Table 1. Relative Risk Estimates for Disease Incidence from Long-Term Exposure to $PM_{2.5}$ and NO_2.

Pollutant	Health Outcome (Incidence)	ICD-10 Codes	Age Group (Years)	Classification	Relative Risk (95% CI) per 10 µg/m³	Exposure Range (µg/m³)
$PM_{2.5}$	Asthma in children	J45	0–18	A	1.34 (1.10–1.63)	5–38
	Chronic Obstructive Pulmonary Disease (COPD)	J41–J44	30+	A	1.18 (1.13–1.23)	5–26
	Ischemic Heart Disease (IHD) Events	I21–I22	30+	A	1.13 (1.05–1.22)	5–65
	Stroke	I60–I64	30+	A	1.16 (1.12–1.20)	5–36
	Type 2 Diabetes	E11–E14	30+	B+	1.10 (1.03–1.18)	5–79
	Dementia	F00–F03, G30	60+	B+	1.46 (1.20–1.78)	5–25
	Autism Spectrum Disorders (ASD)	F84.0–F84.9	2–12	B+	1.66 (1.23–2.25)	5–30
	Lung Cancer	C34	30+	A	1.16 (1.10–1.23)	5–44

Notes:

- **Classification**: 'A' indicates a reliable quantification of health effects is possible in an HRA; 'B+' denotes that HRA is possible, but there is greater uncertainty around the reliability of the CRF compared to those included in list A.
- **Exposure Range**: Represents the range of mean exposures in the studies from which the relative risks were derived. Applying these CRFs outside these ranges may introduce additional uncertainty.
- **Systematic Review References**: Detailed references can be found in the original article.

2.5 External cost evaluations

In the PAREMPI project, we adopted the European Commission's standard Value of a Statistical Life (VSL) of €4,570,100 for estimating mortality-related external costs, reflecting the current benchmark used in EU policy assessments and ensuring consistency with cost-benefit analyses in the environmental and public health sectors. For morbidity outcomes, external costs per case were based on existing European cost estimates, including values from the VALESOR tool: The Valesor tool | Valesor. These estimates encompass both direct costs (e.g. healthcare and social care expenditures) and indirect costs (e.g. productivity losses and informal care).

The unit cost estimates applied in the analysis were €121,800 per ischaemic heart disease (IHD) event, €782,660 per lung cancer case, and €624,990 per stroke case. Corresponding estimates were €65,400 per diabetes case, €614,880 per dementia case, and €61,040 per chronic obstructive pulmonary disease (COPD) case. For childhood asthma, a unit cost of €188,970 per case was applied.

No cost estimate for autism spectrum disorder was available in the VALESOR tool. Given the substantial uncertainty surrounding the economic valuation of autism spectrum disorder, ULUND applied no external cost estimate for this outcome.

3. Results

The total annual number of deaths and morbidity outcomes attributable to SecA across the EU-27, as well as per country, are presented in Table 2. According to estimates from ULUND, approximately **111,000 premature deaths** per year in the EU-27 can be attributed to SecA exposure. This In addition, secondary aerosols exposure was associated with substantial morbidity, including an estimated (Table 2):

- 22,940 autism spectrum disorder (ASD) cases
- 206,301 acute myocardial infarctions
- 43,681 lung cancer cases
- 104,049 stroke cases
- 100,921 type 2 diabetes cases
- 591,001 dementia cases
- 203,945 chronic obstructive pulmonary disease (COPD) cases
- 185,818 childhood asthma cases

The corresponding numbers excluding traffic are seen in Table 3. The societal costs SecA attributed mortality amounts to approximately €508 billion annually, and €405 billion annual excluding traffic according to ULUND's estimate (Table 4).

Table 2. Estimated population weighted exposure to total secondary aerosols (SecA) from various sources, including traffic, across the EU-27 and attributed mortality and morbidity. Abbreviations: ASD – Autism Spectrum Disorders; AMI – Acute Myocardial Infarction; COPD – Chronic Obstructive Pulmonary Disease.

	SecA (µg/m³)	Deaths	ASD	AMI	Lung cancer	Stroke	Diabetes	Demens	COPD	Asthma child
Austria	10,4	2647	581	4745	927	2743	1616	7285	6189	3862
Belgium	10	3455	810,2	5173	1528	2802	2921	9736	7503	5511
Bulgaria	6	2341	216	3944	355	2655	1469	2794	2097	1983
Croatia	7,5	1099	158	1792	405	1087	1047	2048	1716	1474
Cyprus	6,1	154	39	130	52	76	206	287	267	282
Czechia	11,2	4021	924	10268	1130	4018	4756	8312	6653	6973
Denmark	6,8	1103	276	1177	590	867	883	2063	2686	1973
Estonia	4,3	199	40	785	61	165	155	428	222	280
Finland	3,3	568	98	1325	190	699	624	1531	1107	900
France	6,4	11917	2827	27404	5830	10133	8631	289994	24558	24326
Germany	11,1	26406	5554	56326	10735	28224	23033	101180	64498	32950
Greece	5,8	2187	364	2789	940	2782	1628	7113	5002	2432
Hungary	8,5	3374	531	8064	1377	2824	3073	5474	5248	4059
Ireland	3,3	477	147	660	200	255	387	801	938	1192

Italy	9,3	16476	3783	28282	7232	14082	16585	82178	42421	23003
Latvia	4,9	427	58	983	85	507	245	662	370	484
Lithuania	5,7	646	92	1744	137	840	318	1027	620	669
Luxembourg	9,3	141	34	129	51	78	122	203	270	279
Malta	4,7	67	15	79	20	45	87	153	620	102
The Netherlands	10,7	5284	1305	8028	2791	4372	4315	14264	270	6154
Poland	7,7	11015	1872	14594	3821	8155	10801	17239	13260	39575
Portugal	4,6	1308	216	968	428	1146	1780	4109	2834	2128
Romania	6,4	5327	719	10169	1170	6028	2922	7252	6056	8057
Slovakia	9	1954	351	3660	388	1708	1403	2358	1982	2595
Slovenia	9,4	599	129	1339	258	469	577	1413	1011	1403
Spain	5,2	6641	1416	9096	2586	5876	9973	16661	1639	9222
Sweden	4,6	1420	385	2648	394	1413	1364	4436	3908	3950
EU-27		**111257**	**22940**	**206301**	**43681**	**104049**	**100921**	**591001**	**203945**	**185818**
For dementia, we have used the population above 65 years of age, for childhood asthma, the population 15 years or younger. For autism the whole population. For COPD, stroke, diabetes, AMI, lung cancer and Acute Myocardial Infarction, assuming 70% of the population is 30 years or older across the EU.										

Table 3. Estimated population weighted exposure to total secondary aerosols (SecA) from various sources, excluding traffic, across the EU-27 and attributed mortality and morbidity. Abbreviations: ASD – Autism Spectrum Disorders; AMI – Acute Myocardial Infarction; COPD, Chronic Obstructive Pulmonary Disease.

Country	SecA (µg/m³)	Deaths	ASD	AMI	Lung cancer	Stroke	Diabetes	Demens	COPD	Asthma child
Austria	8,1	2047	424	3655	712	2105	1249	5420	4740	2905
Belgium	7,8	2614	580	3899	1148	2105	2209	7151	5624	4044
Bulgaria	5,2	2009	181	3380	303	2272	1260	2361	1793	1684
Croatia	6,4	933	131	1519	343	920	888	1715	1450	1235
Cyprus	5,4	138	34	116	46	68	184	253	238	250
Czech Republic	8,7	3048	652	7743	849	3017	3602	6035	4982	5102
Denmark	5,8	945	231	1006	504	740	756	1731	2292	1673
Estonia	3,8	181	36	710	55	149	140	383	201	254
Finland	3,0	513	88	1195	172	630	563	1374	998	809
France	5,3	9854	2272	22612	4802	8347	7134	23521	20206	19833
Germany	8,3	19574	3850	41557	7889	20741	17062	71522	47274	23688
Greece	5,2	2013	332	2565	864	2557	1498	6481	4596	2215
Hungary	7,0	2830	432	6749	1150	2359	2577	4501	4379	3352
Ireland	2,8	398	121	549	166	212	323	665	780	986
Italy	7,3	12583	2623	21468	5461	10633	12655	59083	31918	16776
Latvia	4,3	365	49	840	73	433	210	561	316	410
Lithuania	4,8	551	77	1486	117	715	271	864	527	567
Luxembourg	6,9	107	25	97	38	58	92	148	202	206
Malta	4,8	66	14	77	20	44	85	149	121	100
Netherlands	8,5	4129	966	6248	2166	3392	3370	10747	8548	4698
Poland	6,4	9092	1498	12018	3141	6703	8912	13942	10886	32165
Portugal	4,0	1115	181	824	364	975	1516	3462	2408	1800
Romania	5,3	4441	585	8463	972	5010	2435	5945	5028	6642
Slovakia	7,8	1620	281	3026	320	1409	1162	1910	1633	2115
Slovenia	7,5	479	99	1068	205	373	462	1095	803	1098
Spain	4,4	5730	1199	7838	2226	5058	8603	14182	14569	7892
Sweden	4,0	1244	331	2316	345	1234	1195	3834	3413	3444

For dementia, we have used the population above 65 years of age, for childhood asthma, the population 15 years or younger. For autism the whole population. For COPD, stroke, diabetes, AMI, lung cancer and Acute Myocardial Infarction, assuming 70% of the population is 30 years or older across the EU.

Table 4. Estimated societal costs due to total secondary aerosols (SecA) from various sources, including traffic, across the EU-27. Abbreviations: ASD – Autism Spectrum Disorders; AMI – Acute Myocardial Infarction; COPD – Chronic Obstructive Pulmonary Disease.

Outcome	Estimated cases with traffic	Cost (Billion EUR)	Estimated cases without traffic	Cost (Billion EUR)
Deaths	111 257	508	88 616	405
ASD	22 940	3.4	17 294	2.6
AMI	206 301	25	163 024	20
Lung cancer	43 681	34	34 451	27
Stroke	104 049	65	82 259	51
Type 2 diabetes	100 921	7	80 413	5
Dementia	591 001	363	249 036	153
COPD	203 945	12	179 924	11
Asthma	185 818	35	145 942	28

4. Limitations

Uncertain Toxicity of SecA: It remains unclear whether the health effects of SecA are comparable to those of other $PM_{2.5}$ components, such as black carbon (BC). While several studies have examined associations between SecA and including components and mortality (with large heterogeneity in results), there is a significant lack of studies regarding morbidity outcomes, including cardiovascular and respiratory diseases.

Assumptions in Health Impact Assessments: Due to limited component-specific evidence, current health impact assessments typically assume that the toxicity of SecA is equivalent to that of total $PM_{2.5}$, such as here. This may lead to either overestimation or underestimation of health risks, depending on the true toxicity profile of SecA.

Limited Demographic Data: A lack of detailed population statistics—such as age-specific population distributions (e.g., population aged 30 years and older) for EU-27, hampers efforts to accurately estimate disease burden and exposure impacts across subgroups.

Unclear Source Contributions: The relative toxicity of different sources (e.g., traffic, agriculture, industry) remains poorly characterized. This limits the ability to develop targeted mitigation strategies and to assess the health implications of source-specific exposures. Although emissions from shipping and aviation were not assessed as separate source categories within the PAREMPI project, these sectors contribute to the formation of secondary particulate matter and therefore to population exposure across the EU-27. Their contribution is implicitly reflected in the analysis of secondary aerosols, and should be acknowledged when interpreting the estimated health and economic impacts.

Influence of Meteorological and Regional Factors: The considerable heterogeneity observed in the literature may be explained by variations in aerosol composition, meteorological conditions (e.g., temperature, humidity, wind patterns), and population susceptibility. These factors are not consistently accounted for in existing studies, making it difficult to generalize findings across regions.

Country-specific estimated costs. A key limitation in our analysis is the use of EU-wide average values for the Value of a Statistical Life (VSL) and estimated costs per case. While this approach ensures comparability across countries and simplifies the estimation process, it introduces uncertainty due to the substantial variation in economic conditions, healthcare costs, and societal preferences across EU member states. Country-specific valuations would more accurately reflect national contexts and improve the precision of health impact cost estimates. However, due to data availability and consistency issues, we opted for harmonized EU-level estimates. This choice enables cross-country comparison but may under- or overestimate the true economic burden in individual countries.

5. Discussion

ULUND has estimated that the societal costs of SecA across the EU amount to approximately €367 billion annually. Although these estimates carry inherent uncertainties—due to variations in exposure, health outcomes, and cost assumptions—they underscore the urgency of identifying and implementing cost-effective mitigation strategies.

Strategies to Minimize Societal Costs:

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

2. Stricter Emissions Standards and Enforcement
Strengthening and enforcing Euro emission standards can effectively curb traffic-related emissions of SecA precursors. Retrofitting older diesel vehicles with NO_x abatement technologies (e.g., selective catalytic reduction systems) presents an additional cost-effective option.

3. Urban 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.

4. Fuel and Technology Shifts
Promoting cleaner fuels (e.g., hydrogen, sustainable biofuels) and accelerating the adoption of low-emission vehicle technologies, including hybrid powertrains, can reduce SecA precursor emissions across the transport sector.

5. Agricultural Synergies
As ammonium—an important SecA component—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.

6. Public Health Co-Benefits
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.

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