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Beyond current air quality standards: studies of ambient ultrafine air pollution and its effects on mortality and hospital admissions in Germany

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Introduction – Air pollution: particles and gases

Gases

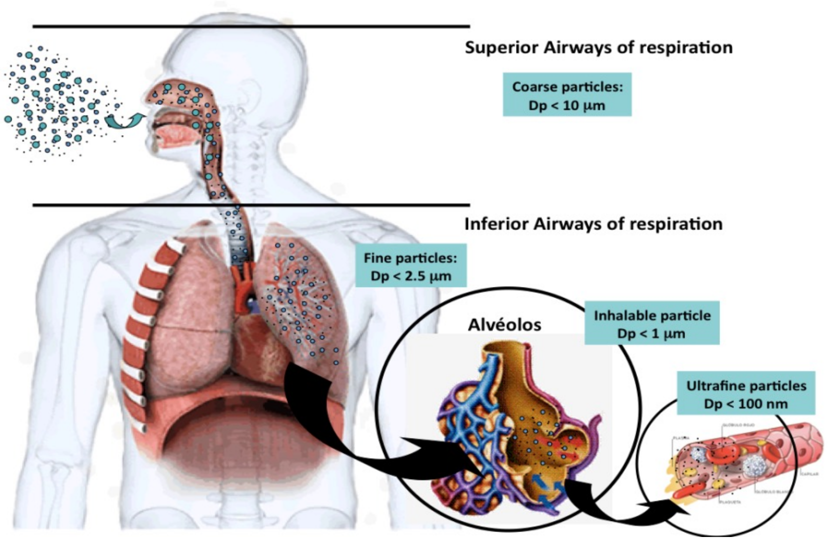
- NO_2, O_3 ,SO_2, CO

Particles (e.g., particulate matter [PM])

- Classification mainly by size
- Composition influences toxicity

Sources

- Natural: Volcanic eruptions, photochemical processes
- Anthropogenic: Traffic, industry, agriculture



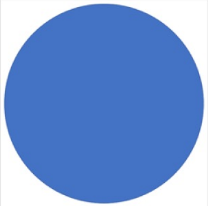
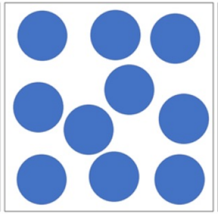
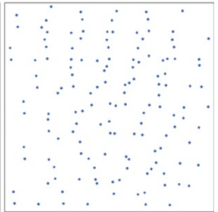
Introduction – What are Ultrafine Particles?

- Ultrafine particles (UFP):
  diameter of ≤ 100nm (≙ 0.1 µm)

- Different particle properties/metrics
  → Different health effects?

- Toxicological evidence relatively high, epidemiological evidence still heterogeneous

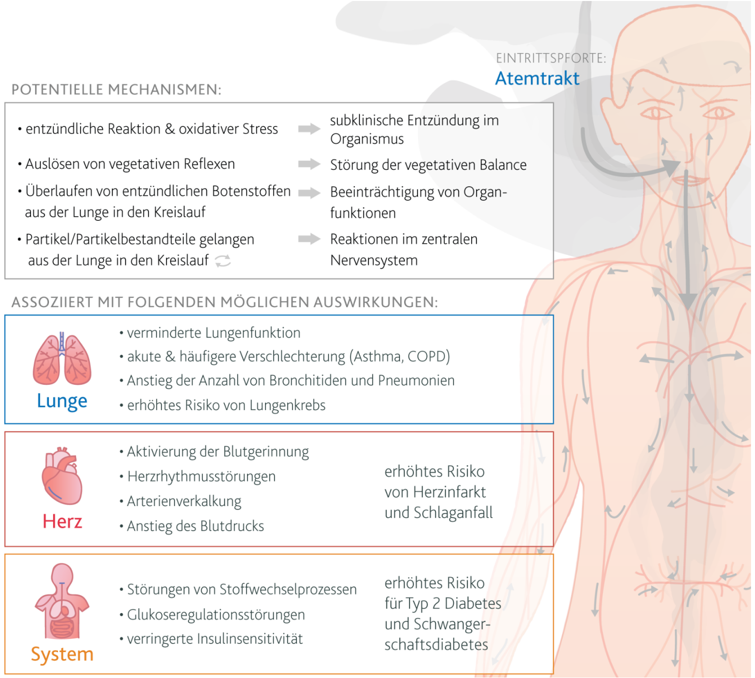
→ More data and epidemiological assessments needed!

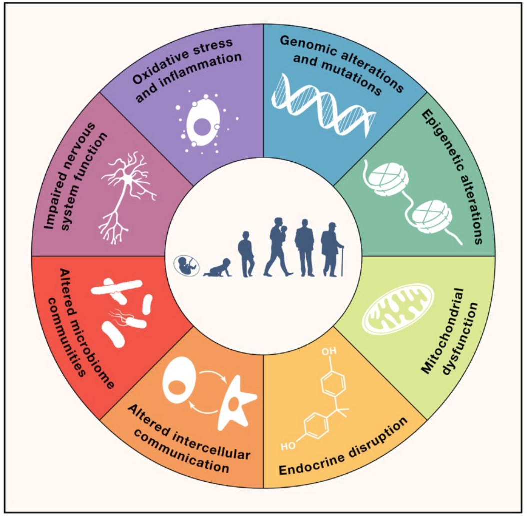
	10 µm (Coarse)	2.5 µm (Fine)	0.1 µm (Ultrafine)
			
Total mass	**1**	**1**	**1**
Particle number	**1**	**64**	**1,000,000**
Surface area per particle	**1**	**0.0625**	**0.0001**
Total surface area per mass	**1**	**4**	**100**
	• Filtered in proximal airway • May irritate skin, mucosa	• Reaches peripheral airway • Cannot enter systemic circulation	• Higher adsorbed toxic material on surface • May enter systemic circulation

HEI Review Panel on Ultrafine Particles 2013; Kwon et al. 2020

Introduction – Biological mechanisms

- 1. Autonomic regulation
- 2. Inflammation
- 3. Translocation





Stone et al. 2017; Schulz et al. 2019; Peters, Nawrot, Baccarelli 2021

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Introduction – UFP and WHO AQG

Statement WHO AQG 2021:

„[…] consensus in the GDG that the body of epidemiological evidence was not yet sufficient to formulate an AQG level.“

→ Good practice statements

Box 4.2. Good practice statement – UFP

The GDG decided to formulate the following four good practice statements on UFP to guide national and regional authorities and research towards measures to reduce ambient ultrafine particle concentrations.

1. Quantify ambient UFP in terms of particle number concentration (PNC) for a size range with a lower limit of ≤ 10 nm and no restriction on the upper limit.
2. Expand the common air quality monitoring strategy by integration of UFP monitoring into existing air quality monitoring. Include size-segregated real-time PNC measurements at selected air monitoring stations in addition to, and simultaneously with, other airborne pollutants and characteristics of PM.
3. Distinguish between low and high PNC to guide decisions on the priorities of UFP source emission control. Low PNC can be considered < 1000 particles/cm3 (24-hour mean). High PNC can be considered > 10 000 particles/cm3 (24-hour mean) or 20 000 particles/cm3 (1-hour).
4. Utilize emerging science and technology to advance approaches to the assessment of exposure to UFP for application in epidemiological studies and UFP management.

UFP are very very small, unregulated, and little is known about their health effects

Methods – Exposure

- Multi-center epidemiological time series study between 2010 and 2017

- Six stations that were part of the former German Ultrafine Aerosol Network (GUAN)

- Daily mean concentrations:
  I) UFP (10-100nm) and PNC (10-800nm)
  II) Size fractions (e.g., 10-30nm, 30-100nm, …)
  III) Other pollutants (e.g., $PM_{2.5}$)

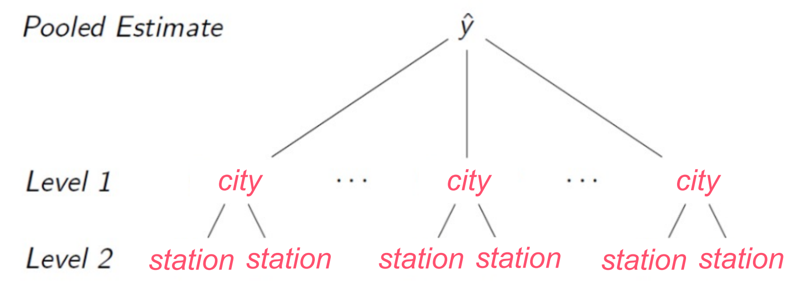
- Daily counts of cause-specific mortality and hospital admissions

Methods – Statistics

- Two-stage modeling design:
  I) Station-specific confounder adjusted Poisson regression
  II) Novel multi-level meta-analytical approach for environmental research

- Two-pollutant models

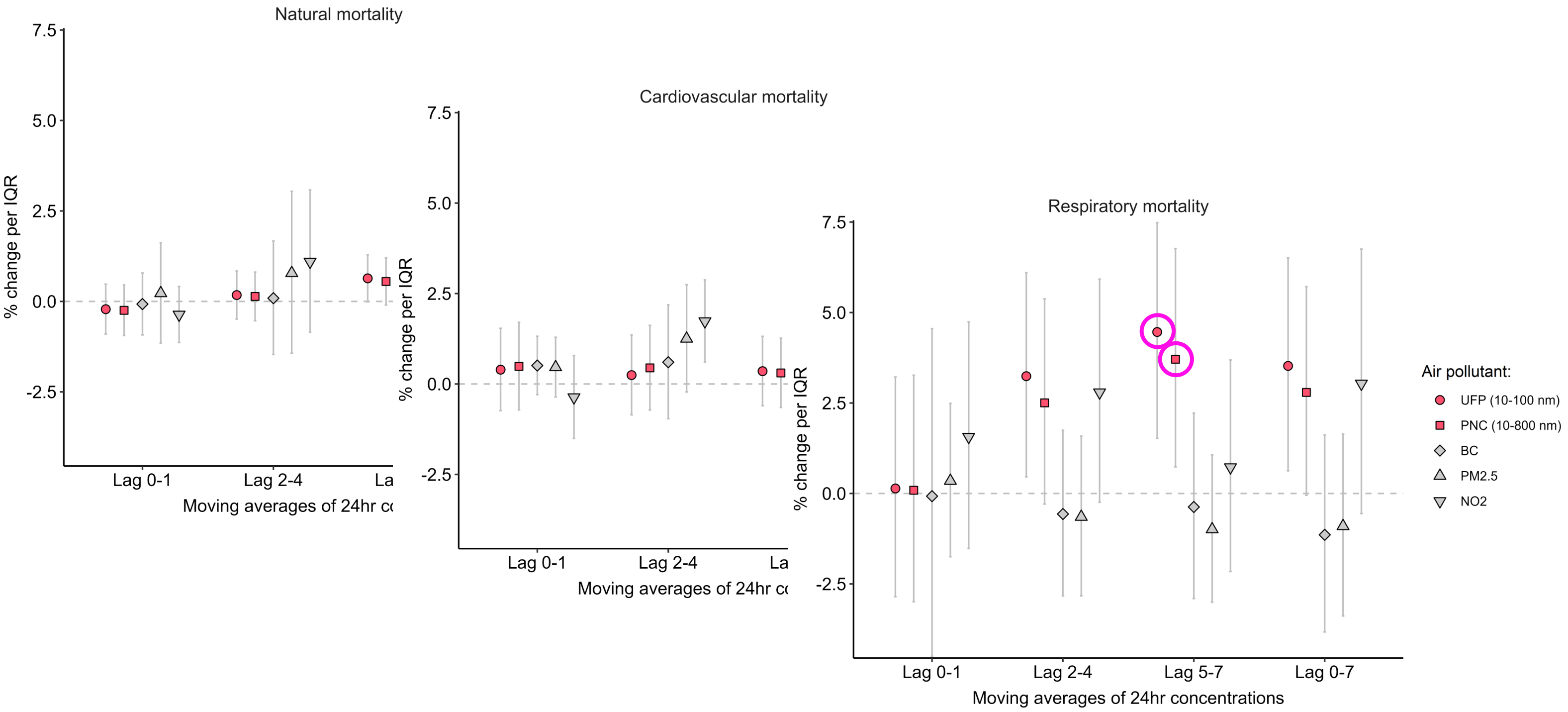
- Effect modification by



- Sensitivity analyses (e.g., different model parameters, additional variables)

Confounding variables
Time trend
Day of the week
Public holidays
Vacation periods
Relative humidity
Influence of low temperatures
Influence of high temperatures

Results I – UFP affects respiratory mortality



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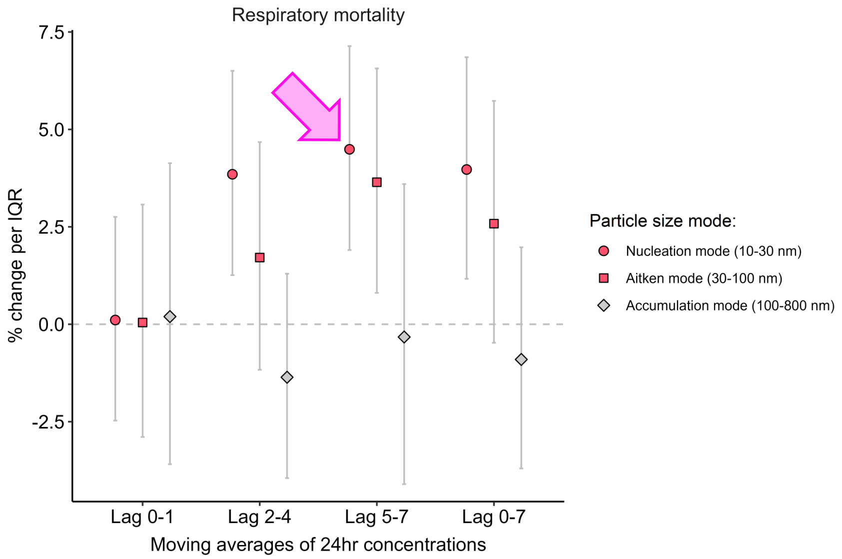
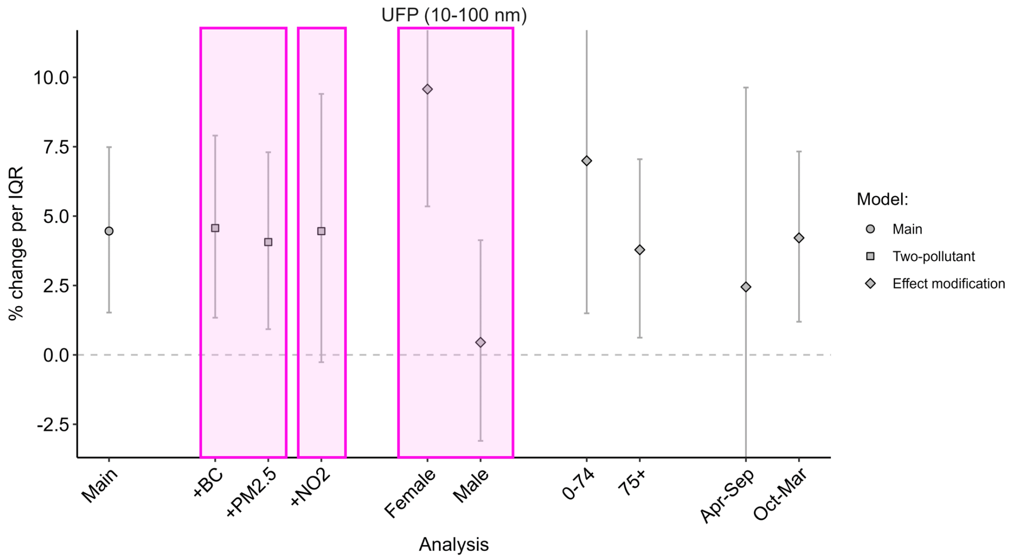
Results I – UFP affects respiratory mortality

… especially for smaller particle size fractions



Results I – UFP and respiratory mortality

Stable effects for particulate co-exposure, higher risk for women



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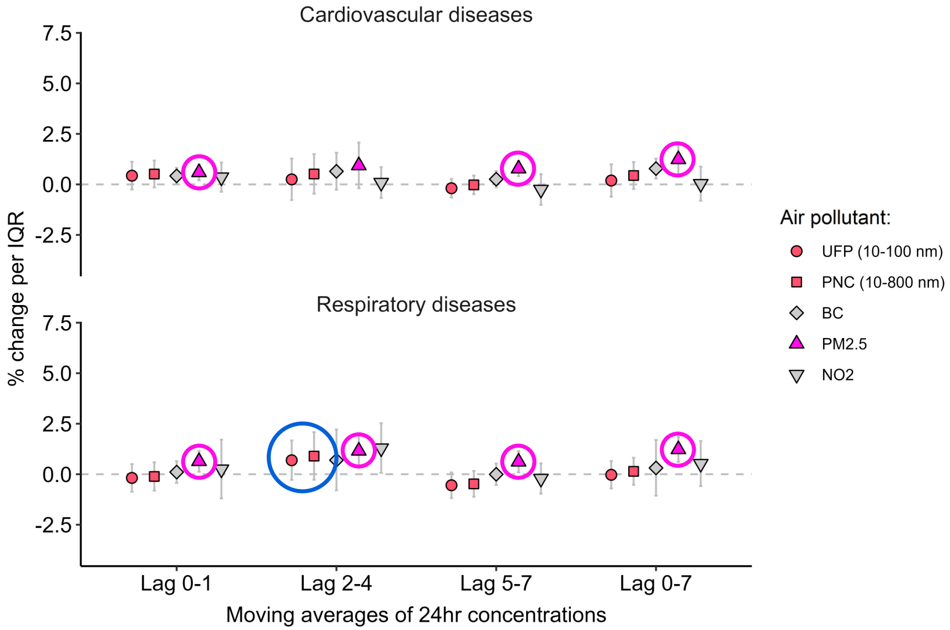
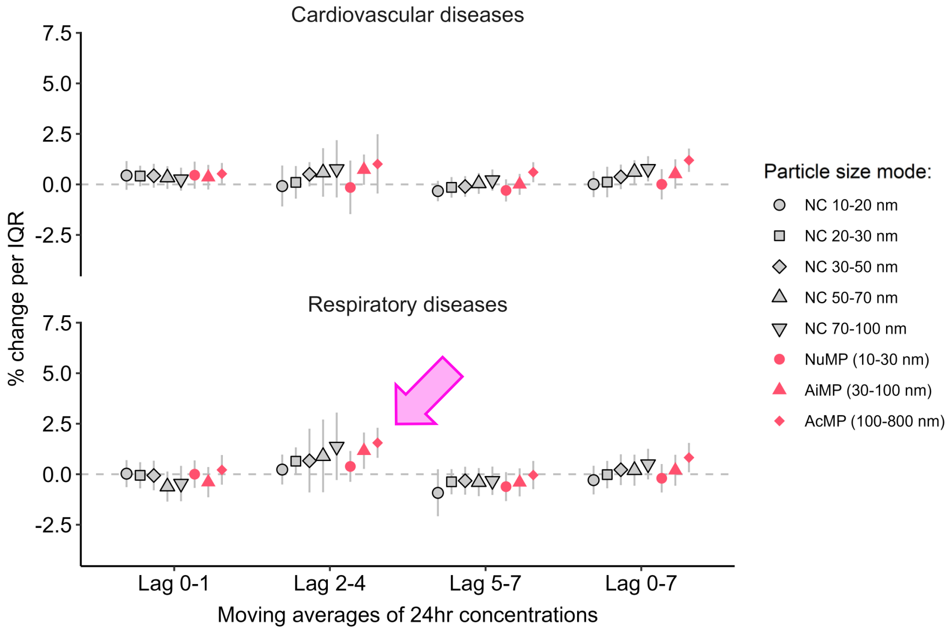
Results II – No clear effects of UFP & PNC on hospital admissions



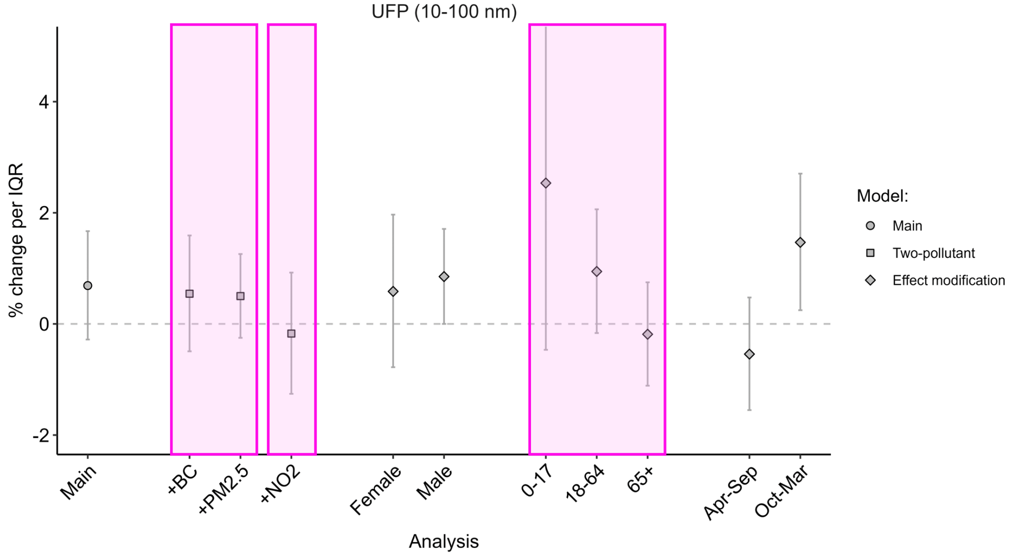
Results II – No clear effects of UFP & PNC on hospital admissions

… although higher risks for larger particle size fractions



Results II – UFP and respiratory hospital admissions

Stable effects for particulate co-exposure, higher risk in the cold season



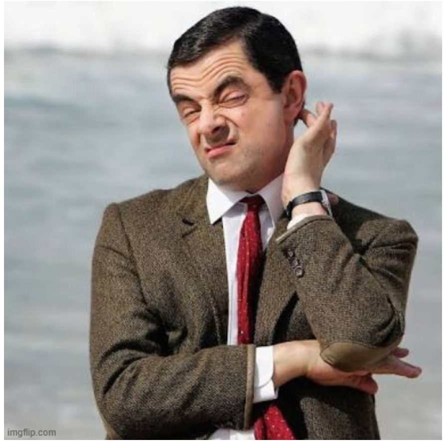
Delayed and size-dependent associations → Respiratory endpoints

Discussion – Evidence

- The evidence remains inconsistent, and the available evidence is difficult to assess consistently

- Source-specific & chemical composition analyses are needed!
  → In larger epidemiological context
  → Disentangle NO_2-relationship

- Regulatory air quality monitoring:
  → Not sufficient to assess overall PM risk adequately using current monitoring standards (e.g., $PM_{2.5}$)



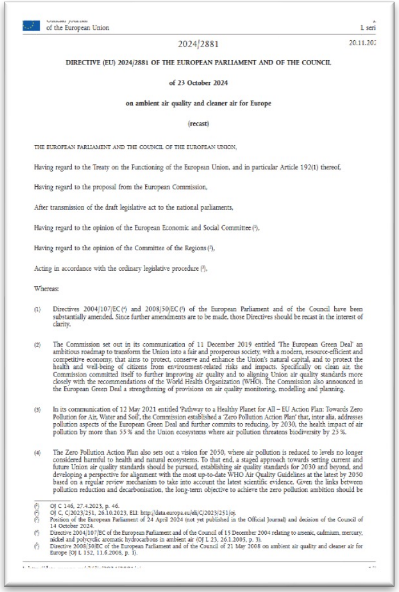
Discussion – New EU Ambient Air Quality Directive

- Published in on 20.11.2024; compliance by 11.12.2026

- According to Article 10:
  MS < 10 million inhabitants: one urban background **(PNC + PNSD + BC)**
  MS > 10 million inhabitants: one **urban background** per 10 million **(PNC + PNSD + BC)**

  MS 10.000 < 100.000 km^2: one rural background **(PNC + BC)**
  MS > 100.000 km^2: one **rural background** per 100.000 km^2 **(PNC + BC)**

- According to Annex III (D.)
  One sampling point for UFP (**PNC**) every 5 million inhabitants where high UFP concentrations (industry, airport, domestic heating) are likely to occur.



Official Journal of the European Union — L series

2024/2881 — 20.11.2024

DIRECTIVE (EU) 2024/2881 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 23 October 2024

on ambient air quality and cleaner air for Europe

(recast)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty on the Functioning of the European Union, and in particular Article 192(1) thereof,

Having regard to the proposal from the European Commission,

After transmission of the draft legislative act to the national parliaments,

Having regard to the opinion of the European Economic and Social Committee [1],

Having regard to the opinion of the Committee of the Regions [2],

Acting in accordance with the ordinary legislative procedure [3],

Whereas:

(1) Directives 2004/107/EC [4] and 2008/50/EC [5] of the European Parliament and of the Council have been substantially amended. Since further amendments are to be made, those Directives should be recast in the interest of clarity.

(2) The Commission set out in its communication of 11 December 2019 entitled 'The European Green Deal' an ambitious roadmap to transform the Union into a fair and prosperous society, with a modern, resource-efficient and competitive economy, that aims to protect, conserve and enhance the Union's natural capital, and to protect the health and well-being of citizens from environment-related risks and impacts. Specifically on clean air, the Commission committed itself to further improving air quality and to aligning Union air quality standards more closely with the recommendations of the World Health Organization (WHO). The Commission also announced in the European Green Deal a strengthening of provisions on air quality monitoring, modelling and planning.

(3) In its communication of 12 May 2021 entitled 'Pathway to a Healthy Planet for All – EU Action Plan: Towards Zero Pollution for Air, Water and Soil', the Commission established a 'Zero Pollution Action Plan' that, inter alia, addresses pollution aspects of the European Green Deal and further commits to reducing, by 2030, the health impact of air pollution by more than 55 % and the Union ecosystems where air pollution threatens biodiversity by 25 %.

(4) The Zero Pollution Action Plan also sets out a vision for 2050, where air pollution is reduced to levels no longer considered harmful to health and natural ecosystems. To that end, a staged approach towards setting current and future Union air quality standards should be pursued, establishing air quality standards for 2030 and beyond, and developing a perspective for alignment with the most up-to-date WHO Air Quality Guidelines at the latest by 2050 based on a regular review mechanism to take into account the latest scientific evidence. Given the links between pollution reduction and decarbonisation, the long-term objective to achieve the zero pollution ambition should be

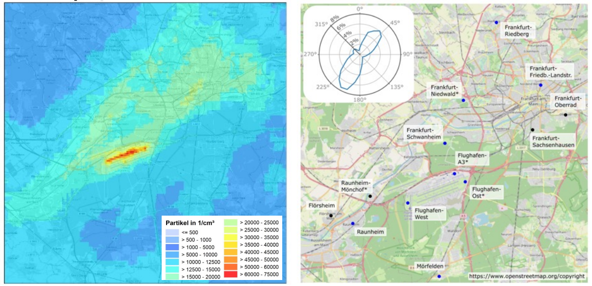
[1] OJ C 146, 27.4.2023, p. 46.
[2] OJ C, C/2023/251, 26.10.2023, ELI: http://data.europa.eu/eli/C/2023/251/oj.
[3] Position of the European Parliament of 24 April 2024 (not yet published in the Official Journal) and decision of the Council of 14 October 2024.
[4] Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air (OJ L 23, 26.1.2005, p. 3).
[5] Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe (OJ L 152, 11.6.2008, p. 1).

Example Germany (83 million, 357.000km^2): 8 urban background and 3 rural background for Article 10, plus 16 UFP monitors (particle number concentration only, no PNSD) where high concentrations occur for Annex III.

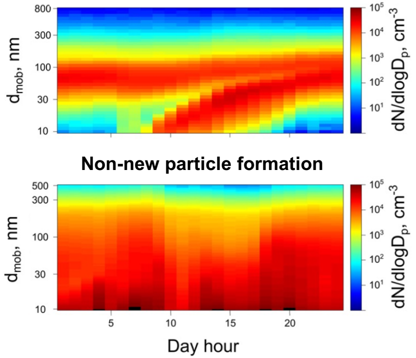
Outlook – Future perspectives

- Implementation of new monitoring infrastructure under revised EU AAQD
- Combination of approaches (e.g., source, chemistry, “classical” EPI metrics)
- Looking at exposure hotspots (e.g., airports)
- Application of new analytical approaches to enhance source apportionment (e.g., using AI methods)
→ New particle formation in times of climate change

Total exposure burden



New particle formation



… also a big thank you to:

- Dr. Susanne Breitner-Busch
- Dr. Alexandra Schneider
- Dr. Josef Cyrys
- Prof. Dr. Annette Peters
- Dr. Susanne Bastian
- Karen Meyer

Thank you.

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Discussion – Strengths & Limitations

Strengths:

- Carefully designed multi-city study over eight consecutive years
- Urban background and traffic/roadside stations
- Multiple sensitivity analyses
- Thorough adjustment for meteorological parameters and time trend

Limitations:

- No source-specific information
- Exposure misclassification → UFP have higher spatial variation than fine PM
- Larger number of analyses
- Rather low number of deaths (especially for RM)

Appendix – Measurement devices

Station	Type	Height of inlet above ground	Mobility particle size spectrometer	Size range	Thermo-denuder	BC instrument	BC cut-off
LMI	Portable cabin	4m	TDMPSS – TROPOS-design	5-800nm	no	MAAP	PM_{10}
LWE	Portable cabin	4m	TDMPSS – TROPOS-design	10-800nm	no	MAAP	PM_{10}
LTR	Portable cabin	~16m	TDMPSS – TROPOS-design	5-800nm	yes	MAAP	PM_{10}
DDN	Portable cabin	4m	TMPSS – TROPOS-design	5-800nm	no	MAAP	PM_1*
DDW	Portable cabin	4m	MPSS – TROPOS-design	10-800nm	no	MAAP	PM_1
AFH	Portable cabin	4m	TDMPSS – TROPOS-design	5-800nm	yes	Aethalometer	$PM_{2.5}$

Appendix – Descriptions

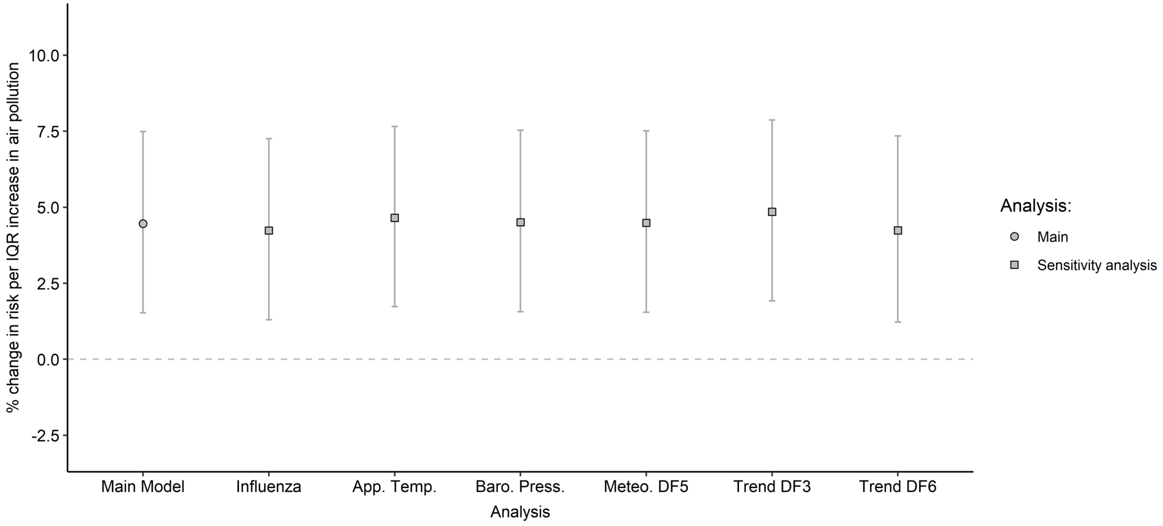
Variable	LMI	LWE	LTR	DDN	DDW	AFH
Station characteristic	traffic/roadside	urban background	urban background	traffic/roadside	urban background	urban background
Air pollutant						
UFP (10-100nm, particles/cm^3)	10,123 (5,156)	4,520 (3,003)	4,838 (3,154)	8,637 (4,366)	4,791 (3,156)	5,655 (3,514)
PNC (10-800nm, particles/cm^3)	11,922 (5,866)	5,748 (3,482)	6,054 (3,686)	10,292 (4,975)	6,186 (3,902)	6,909 (4,017)
BC (µg/m^3)	2.0 (1.3)	0.8 (0.8)	0.7 (0.8)	1.5 (1.1)	0.7 (0.8)	1.4 (1.0)
NO_2 (µg/m^3)	43.0 (17.0)	16.0 (11.0)	-	33.0 (14.0)	18.0 (12.0)	17.7 (12.3)
$PM_{2.5}$ (µg/m^3)	13.6 (12.1)	9.6 (10.5)	-	12.3 (11.6)	10.9 (12.3)	10.2 (10.3)
Meteorological parameter						
Temperature (°C)	11.4 (12.1)	9.7 (11.7)	-	11.3 (12.5)	11.6 (12.4)	9.9 (12.2)
Relative humidity (%)	71.8 (19.6)	75.3 (18.6)	-	70.9 (16.8)	71.8 (17.3)	79.2 (20.3)
Barometric pressure (hPa)	1016.0 (10.0)	1016.0 (10.0)	-	1016.0 (10.0)	1016.0 (10.0)	961.4 (9.0)

Appendix – Count data

Variable	Leipzig	Dresden	Augsburg
Mean population 2010-2017	542,918	534,382	279,159
Total counts of natural mortality	43,250	36,106	20,712
Total counts of cardiovascular mortality	19,880	15,756	8,854
Total counts of respiratory mortality	2,559	2,143	1,426
Mean daily natural mortality (SD)	14.8 (4.1)	12.4 (3.7)	7.1 (2.7)
Mean daily cardiovascular mortality (SD)	6.8 (2.7)	5.4 (2.4)	3.0 (1.7)
Mean daily respiratory mortality (SD)	0.9 (1.0)	0.7 (0.9)	0.5 (0.7)
Total counts of cardiovascular disease HA.	118,265	97,508	59,230
Total counts of heart disease HA.	81,323	68,711	40,582
Total counts of cerebrovascular disease HA.	14,955	14,121	9,434
Total counts of respiratory disease HA	51,383	45,271	38,396
Total counts of LRTI HA.	17,801	14,489	13,467
Mean daily cardiovascular disease HA. (SD)	40.5 (16.7)	33.4 (12.4)	20.3 (8.7)
Mean daily heart disease HA. (SD)	27.8 (11.2)	23.5 (8.9)	13.9 (6.3)
Mean daily cerebrovascular disease HA. (SD)	5.1 (2.6)	4.8 (2.4)	3.2 (2.0
Mean daily respiratory disease HA. (SD)	17.6 (7.8)	15.5 (6.6)	13.1 (7.0)
Mean daily LRTI HA. (SD)	6.1 (3.4)	5.0 (3.0)	4.6 (2.9)

Appendix – UFP and respiratory mortality – SENSI

Change of model parameters:

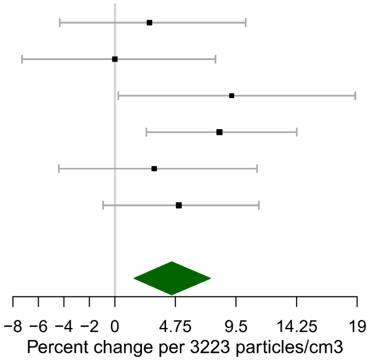


Appendix – UFP and respiratory mortality – SENSI

Forest plots:

resp_mort − PNC_10_100

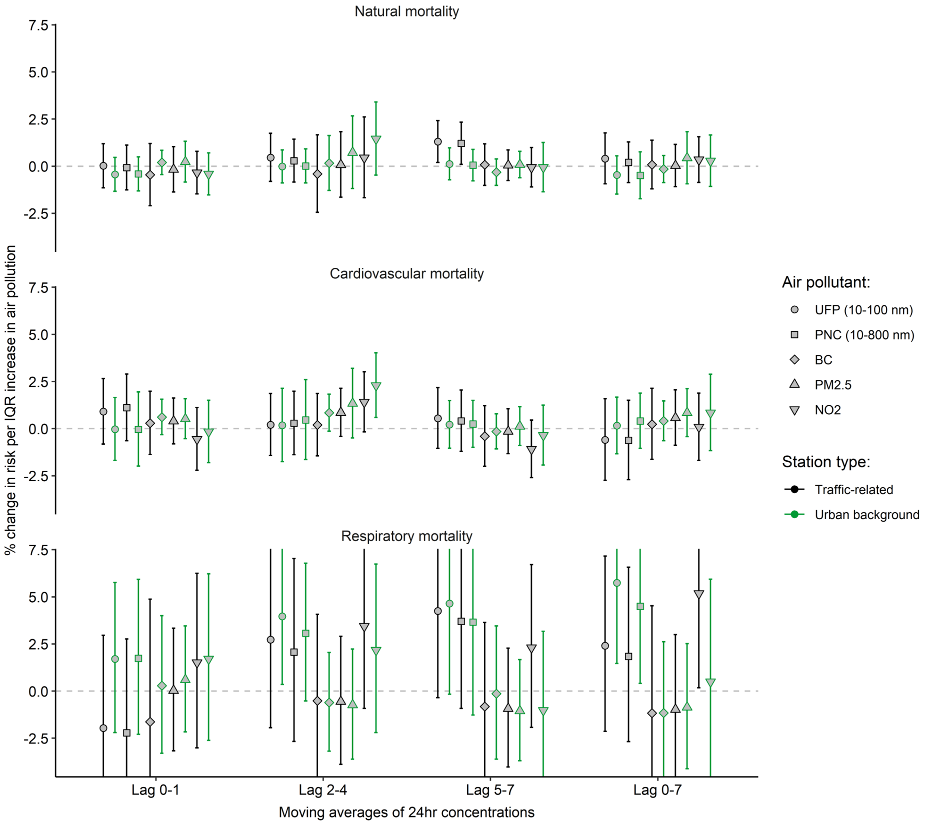
Station	Lag	% Change [95% CI]
Augsburg−Hochschule	lag5_7	2.72 [−4.31, 10.26]
Dresden−Winckelmannstr.	lag5_7	0.01 [−7.28, 7.88]
Leipzig−West	lag5_7	9.16 [0.27, 18.84]
Leipzig−Tropos.	lag5_7	8.20 [2.47, 14.26]
Dresden−Nord	lag5_7	3.08 [−4.39, 11.14]
Leipzig−Mitte	lag5_7	5.01 [−0.92, 11.29]
Random−effects model, REML		**4.46 [1.52, 7.48]**



Heterogeneity: $I^2 = 4.9\%$ p = 0.385

Appendix – UFP and respiratory mortality – SENSI

Urban background vs. Traffic/Roadside stations:



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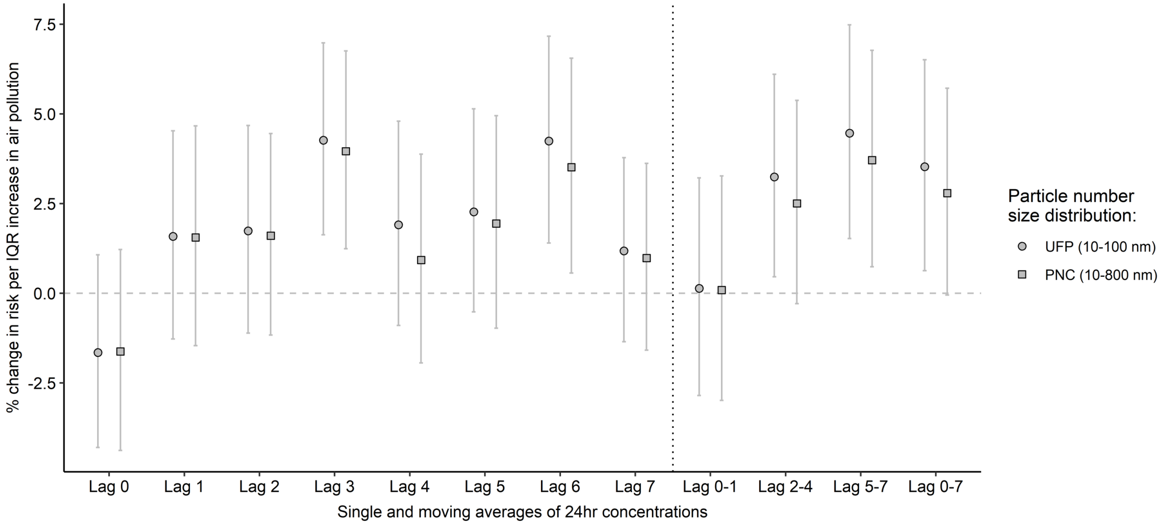
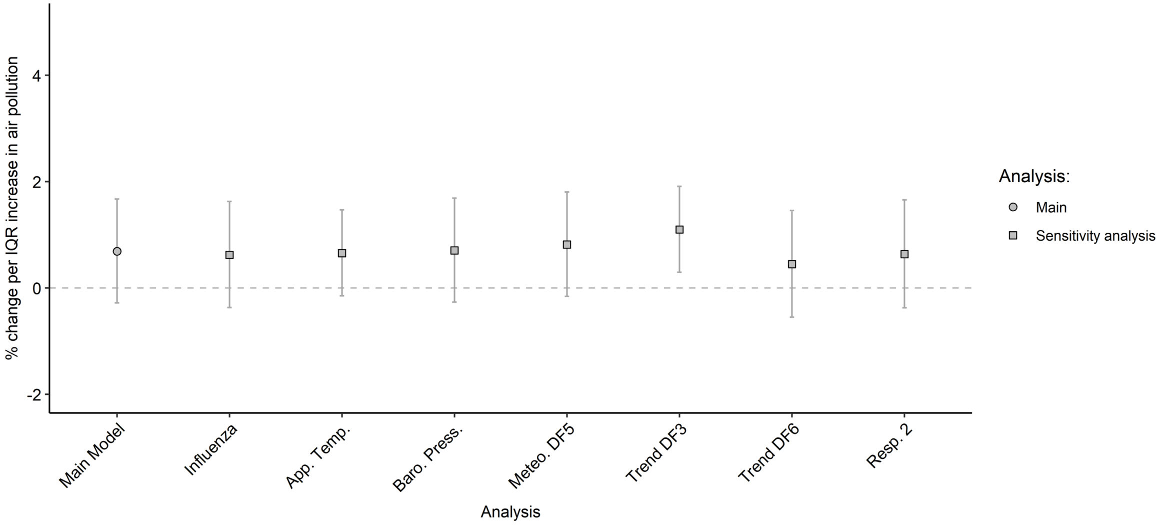
Appendix – UFP and respiratory mortality – SENSI

Single and moving averages:



Appendix – UFP and respiratory hospital admissions – SENSI

Change of model parameters:



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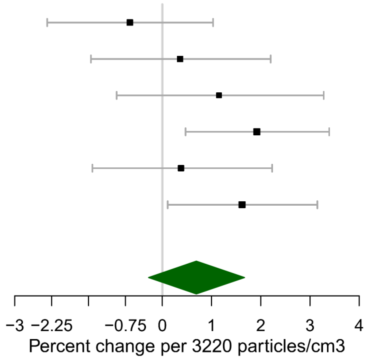
Appendix – UFP and respiratory hospital admissions – SENSI

Forest plots:

resp_kh − PNC_10_100

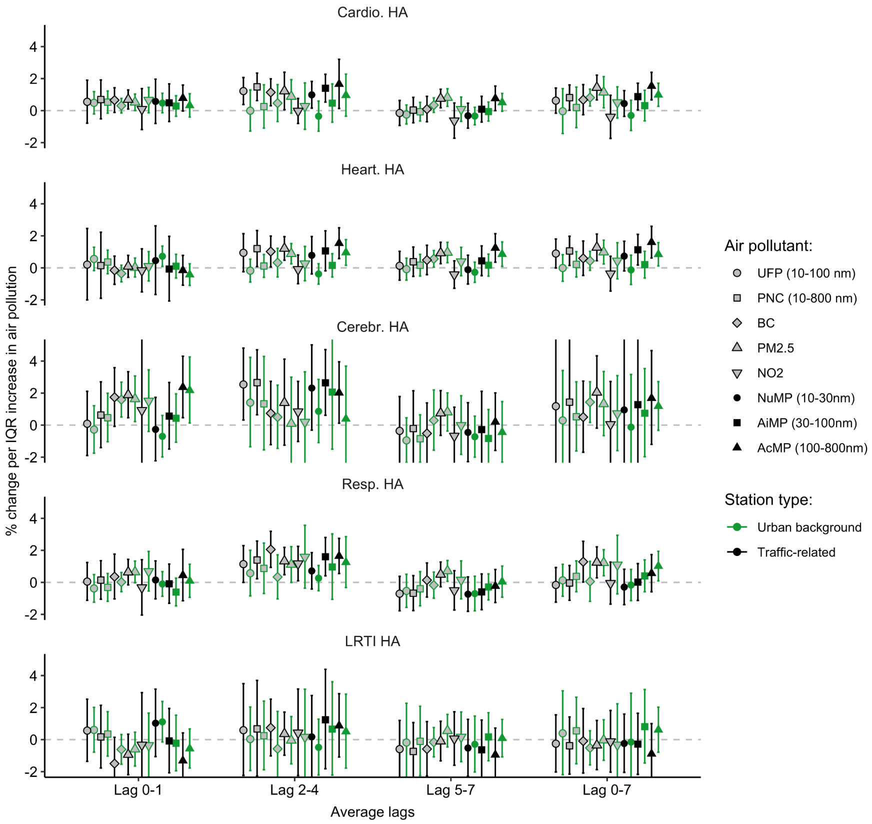
Station	Lag	% Change [95% CI]
Augsburg−Hochschule	lag2_4	−0.66 [−2.34, 1.03]
Dresden−Winckelmannstr.	lag2_4	0.36 [−1.45, 2.20]
Leipzig−West	lag2_4	1.15 [−0.93, 3.28]
Leipzig−Tropos.	lag2_4	1.92 [0.47, 3.39]
Dresden−Nord	lag2_4	0.38 [−1.42, 2.23]
Leipzig−Mitte	lag2_4	1.62 [0.11, 3.15]
Random−effects model, REML		**0.69 [−0.28, 1.67]**



Heterogeneity: $I^2 = 25.1\%$ p = 0.246

Appendix – UFP and respiratory hospital admissions – SENSI

Urban background vs. Traffic/Roadside stations:



Appendix – UFP and respiratory hospital admissions – SENSI

Single and moving averages: