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Airborne Ultrafine Particles: Real-life Exposure Patterns, Epidemiological Evidence and Regulatory Responses in Switzerland and Beyond

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Abstract: Ultrafine particles (UFP) exhibit large spatial and temporal contrasts, and distinct physicochemical properties that enable deep lung penetration and systemic translocation, posing potential health risks. Despite mechanistic evidence from toxicological studies, large-scale epidemiological evidence remains limited due to sparse monitoring and complex exposure assessment. Switzerland has contributed substantially to UFP research through measurement campaigns, mobile monitoring, and modelling studies, which improved understanding of spatial and temporal exposure contrasts. Emerging findings suggest associations between long-term UFP exposure and cardiovascular indicators, though epidemiological evidence for short-term associations with mortality and morbidity remains weak. Ongoing Swiss and European projects aim to refine high-resolution spatiotemporal models, assess population-level health impacts, and inform future air quality standards and regulatory frameworks for UFPs.

Keywords: Air pollution · Epidemiology · Health effects · Particle number concentration · Switzerland · Ultrafine particles

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1. Introduction

Much like clinical studies that compare the effects of a drug to a placebo, environmental epidemiology studies rely on exposure contrasts to assess the impact of pollutants on health. These

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contrasts can be spatial – for example, comparing people living in areas with high versus low concentrations of ultrafine particles (UFP) – or temporal, where individuals are healthier during periods of lower recent exposure compared to periods of higher exposure. Sometimes, studies leverage both spatial and temporal contrasts.

Studying associations between UFP and health presents several major challenges: (1) UFP concentrations are highly variable across both space and time, (2) they originate from numerous anthropogenic and natural sources, which affects their composition, size and surface characteristics and hence their toxicity and (3), in the absence of regulations for ambient concentration, UFPs are routinely measured at only a few locations.[1] Within Switzerland, UFP levels are measured by the NABEL network (Nationales Beobachtungsnetz für Luftfremdstoffe [Switzerland's National Air Pollution Monitoring network]) at five distinct locations routinely, which provides long-term continuity. However, the ability of these sites to capture spatial variability is limited, considering that not all are representative for locations where people actually live.

Although *in vitro* and animal studies have provided important mechanistic insights,[2] large-scale epidemiological studies on health effects of UFPs remain limited due to challenges in exposure assessment, the lack of standardized monitoring, and difficulties in distinguishing UFP effects from those of co-pollutants.[3] Due to their nanoscale size and low mass, UFPs possess an extremely large surface area-to-mass ratio, enabling them to adsorb toxic substances more effectively than larger particles.[4] Unlike coarse or fine particles, UFPs can penetrate deeply into the alveolar regions of the lungs.[5] There, their large surface area increases interactions with epithelial cells, exacerbating oxidative stress and inflammation, and impairing normal clearance mechanisms.[5] Furthermore, UFPs can translocate across biological barriers following inhalation, enter the bloodstream, and reach distant organs – including the brain and heart – by crossing the blood–brain and blood–heart barriers.[2] Health effects of these particles would therefore make sense from a mechanistic perspective. Indeed, review studies[3b] demonstrated short-term effects of exposure to UFP, including mortality, emergency department visits, hospital admissions, respiratory symptoms, and effects on pulmonary/systemic inflammation, heart rate variability and blood pressure.[3a] As long-term health effects, all-cause, cardiovascular issues, ischemic heart disease and pulmonary mortality were evaluated.[6]

This article highlights how Swiss research has contributed to understanding real-life exposure patterns and short- and long-term health effects of UFP exposure, through original and importantly, through systematic reviews, which situate this work within the broader international context. We focus particularly on projects which have measured and modelled the spatial and temporal exposure contrasts of UFPs, and their relationship with respiratory, cardiovascular, and neurological diseases. We offer an outlook on ongoing and future UFP-related epidemiological research in Switzerland. We further reflect on the scientific and regulatory challenges involved in establishing robust exposure metrics, setting health-based guidelines, and integrating UFPs into existing air quality frameworks in Switzerland and beyond.

2. Real-life Exposure to Ultrafine Particles

Because UFPs are not routinely monitored, significant gaps remain in understanding their real-world distribution. This has prompted growing interest in measuring UFP exposure in real-world environments, enabled by new measurement technologies. The studies presented here focus on assessing UFP variability across different Swiss settings, characterizing both outdoor and indoor exposure. They consider major sources such as urban traffic, airports, and common human activities.

2.1 *Particulate Matter Monitoring in the BRISKA Study*

To estimate the carcinogenic and non-carcinogenic health risk from ambient air pollution in the Basel area, particulate matter (PM), including UFPs, was measured in 1997 at various locations in the city of Basel within the framework of the Basel Risk Assessment Study of Ambient Air Pollutants (BRISKA). Whereas PM_4, PM_{10} and TSP (total suspended particles) were measured over one year at seven locations,[7] UFPs with diameters of 0.018 up to 0.421 μm were measured at three road traffic sites with different traffic intensities for *ca*. 28 hours.[8] Average particle number concentrations ranged from 5,690 to 19,300 per cm^3 at these three traffic sites, and hourly UFP particle number concentrations were highly correlated with hourly traffic counts for heavy duty traffic (0.67–0.86) and moderately correlated for light duty traffic (0.43–0.59).

2.2 *Use of Portable Samplers in the Tri-Tabs Project*

The Tri-Tabs study (Project Tri-national Traffic, Air, Bruit et Santé) used the then newly developed miniDiSC (miniature diffusion size classifier) instruments, which were portable and allowed for short-term on-site UFP measurements.[9] Data were collected in three seasons (spring, summer, winter), at 43 sidewalks for 20 minutes each, and at 17 residential sites where measurements were taken over two-week periods. The larger number of monitoring sites enabled the development of the first statistical models to relate the observed variability in UFP concentrations to factors such as local traffic flow, presence of traffic lights, building height, population density, land use, season, and meteorological conditions including temperature and wind speed. The study demonstrated that short-term mobile measurements can effectively address sparse spatial coverage while the number of long-term UFP monitors is limited.

2.3 *Mobile Measurements on Zurich Trams*

A first application of mobile monitoring of UFPs was carried out by putting GPS-enabled miniDiSCs on top of trams and integrating data transmission *via* GSM and WLAN in Zurich and several other Swiss cities.[10] The high spatial and temporal variability of the PNC (particle number concentration) was also noted in this project, and mobile sensor data were combined here with geo-statistical interpolation (Kriging) and land use regression to help explain this variability and create detailed pollution maps. Challenges included that spatial coverage was limited to the tracks on which the trams drove, and while insightful, the resulting interpolated maps are based on snapshots of data that cannot be generalized for the long-term. Land use regression modelling is mentioned as a promising way of comprehensively assessing long–term exposure.

2.4 *SAPALDIA Indoor-outdoor Comparison*

Building on these advances in UFP monitoring, the SAPALDIA study expanded this work through long-term, population-based assessments that combined repeated outdoor and indoor measurements across multiple Swiss regions with modelling approaches.

Indoor–outdoor measurements in 80 homes found a mean indoor PNC of ~7,800 particles/cm^3, with considerable variability in indoor–outdoor ratios.[11] The measured indoor PNC was generally lower in rural compared to urban homes. Correlations between indoor and outdoor PNCs were often weak, especially in winter, reflecting the influence of ventilation behaviour, building characteristics, and indoor sources such as cooking and human activity, which could contribute over 50% of indoor PNC.[11,12]

Modelling analyses showed that outdoor PNC was a poor predictor of mean indoor concentrations due to highly variable indoor emissions. Models relating indoor to outdoor concentrations performed better for median values when information on window use was incorporated.[12]

2.5 *Long-term Within-city Contrasts in Zurich*

A further long-term monitoring study assessed the Lung-Deposited particle Surface Area concentration (LDSA) at five urban, two suburban and three rural locations in Zurich, Switzerland in 2021 and 2022.[13] The project assessed the reliability of relatively low-cost sensors for long-term monitoring, and durability for deployment within a long-term real-time network. The results highlighted the strong influence of the wind direction and the upwind or downwind position of the measurement sites relative to local sources such as major roads, restaurants and the nearby Zurich airport.[13] The 'Net4cities' project is currently expanding this measurement effort to 54 sites in Europe.[14]

The focus on LDSA as the main exposure metric in these projects is so far uncommon. Given the high surface-to-mass ratio of UFPs, LDSA serves as an intuitive proxy for potential particle reactivity with lung tissue surfaces, which has been noted as the main driver for toxicity in many studies.[15] Nevertheless, PNC has emerged as the more popular metric, likely partially because of the larger number of instruments on offer at the time.[15] For lack of an agreed-upon standardized metric or method to quantify UFPs,[4] because previous projects demonstrated a strong correlation between LDSA and PNC in outdoor environments (in Switzerland),[16] and likely for time series longevity, the continued measurement of PNC has remained most common, and has been defined as the preferred metric in the European Ambient Air Quality Directive.[17] The perception that PNC is easier to measure than LDSA holds for condensation particle counters (CPCs) or mobility particle size spectrometers (MPSS), which enlarge tiny aerosol particles through vapor condensation to make them optically detectable. The measured signal in these instruments is therefore proportional to the particle number concentration (in each size bin, for MPSS). This principle, however, does not apply to instruments based on other measurement techniques – specifically electric diffusion charging – where the measured charge is instead proportional to the lung-deposited surface area (LDSA).[18] Considering the relatively high cost, maintenance requirements, and temperature conditioning needed for CPCs, low cost instruments based on electric diffusion charging make LDSA an attractive, and 'scalable' metric.

2.6 *Long-term Measurements Around Zurich Airport*

Similarly, a long-term measurement campaign (2020–2023) in a residential neighbourhood in Kloten, near Zurich airport, emphasized the substantial contribution of airport operations to PNC, particularly during the day, and under westerly or north-westerly winds (*i.e.* from the direction of the airport).[19] Because flight traffic was largely halted during the Covid-19 pandemic, but road traffic was less affected, the relative contributions to the total PNC could be estimated. Air traffic was found to contribute approximately 48% (11,500 particles/cm^3) of the total PNC, while local street traffic contributed 24% (5,800 particles/cm^3). Peak 10-minute average concentrations reached up to 500,000 particles/cm^3, indicating that airports have a disproportionately large impact on UFP pollution compared to other air pollutants such as NO_2 or larger particulate matter.[19]

2.7 *MARKOPOLO Indoor-outdoor Work*

The ongoing 'MARKOPOLO' (Markers of Pollution) indoor/outdoor study aims to investigate how building characteristics and household activities, such as heating, cooking, and ventilation, affect indoor air quality, with a specific focus on ultrafine particles.[20] In total, 60 households will be monitored twice for one week. Unlike the earlier SAPALDIA project, which focused on average concentrations, MARKOPOLO applies real-time measurements to capture short-term changes in air pollution. By combining these continuous data with residents' reported activities, the study will enable detailed analysis of how household behaviours influence indoor air quality. This high-resolution approach makes it possible to study the impact of indoor UFP sources on air quality and assess short-term peaks in particle concentrations, providing a more dynamic understanding of indoor exposure than previously available.

3. UFP Exposure Assessment and Modelling for Epidemiological Studies

Routine networks offer a limited number of places where we have good long-term data, and with limited representation of the typical places in which people live. The need to measure in more places and better capture and assess spatial contrasts was quickly recognized as a need for epidemiological applications.

3.1 *SAPALDIA Measurement and Modelling Study*

The SAPALDIA campaign in 2011 and 2012 was among the first to measure PNC and LDSA, in addition to other pollutants, in Basel, Geneva, Lugano, and Wald at a total of 67 sites for a week each, as well as reference sites, assessing the contrasts between areas, sites and seasons. Both PNC and LDSA showed strong, between and within-area spatial variation, seasonal patterns, and correlation with other pollutants, especially NO_2 and $PM_{2.5}$ absorbance.[16] The median of the average PNC at the participating residences was ~10,800 particles/cm^3,[21] and concentrations were markedly higher in winter than in summer.[16,21] Further analyses showed a rapid decrease of the mean PNC as a function of the distance between the measurement site and the nearest major road, with the most striking contrast between 0 and 100 meters, and falling to background around 500 meters.[21] Diurnal PNC profiles show a clear effect of morning and evening rush hours, during which contrasts between street sites (where concentrations increase sharply) and background sites (where concentrations did not increase so markedly) get larger.[21] This highlights traffic as a dominant driver of UFPs in both space and time. Land use regression models were developed which integrated measured concentrations and environmental predictors, such as road density, traffic volume, built-up area, altitude, green space and blue space.[22] While the study developed national land use regression models for most other pollutants, multi-area models were insufficiently able to capture area contrasts between the different study areas, suggesting that capturing regional variability constitutes a major contribution, and accounting for it in models is not trivial.[22]

3.2 *EXPANSE Mobile Measurement and Modelling*

Between 2018 and 2019, the 'EXPANSE' project, with SwissTPH as one of its partners, conducted harmonized mobile monitoring of ultrafine particle number concentrations (PNC) across nine European cities, including the region surrounding Basel, Switzerland, *via* two seasonally distinct daytime campaigns (warm *vs* cold season), generating a large, comparable dataset for mapping intra-urban contrasts and building Europe-wide and area-specific exposure surfaces.[23] EXPANSE provided high-resolution spatial patterns for the Basel region, and an external evaluation which highlighted that pooled models performed better in some study areas than in others. Separate modelling efforts were made for the contributions from nearby traffic only, and the total PNC including the background. While in most other cities in Europe, models which focused on nearby traffic emissions performed best, in Switzerland, in contrast, models which included the background concentration performed better. Likely, these are better able to reflect complex topography and elevation gradients which contribute to major concentration variability in Switzerland. Overall, pooled multi-city models captured moderate-to-high variability when evaluated against independent, longer-term historical measurements from across Europe, such as those of SAPALDIA,[16] and the maps include a Basel panel illustrating sharp within-city contrasts. The novelty lay in a continent-wide, harmonized mobile UFP dataset that enabled pooled mapping at the 25 × 25 m scale, alongside an explicit attempt to separate local on-road and background components for broader application in epidemiology. Remaining needs include improved inclusion of temporal predictors and explanation of temporal patterns, reduced overprediction at off-road sites, and further tests of model transferability over complex terrain such as that found in Switzerland.

3.3 *High-resolution Spatiotemporal Modelling in MARKOPOLO*

The new MARKOPOLO project extends previous Swiss UFP mobile measurements and modelling to a national scale.[20] Funded by the EU and the Swiss State Secretariat for Education, Research and Innovation (2025–2029), this project will assess associations between UFP exposure and population health by linking modelled UFP exposure with the Swiss National Cohort for population-level epidemiological analyses (Fig. 1). The Swiss TPH currently performs a multi-season, nationwide mobile UFP measurement campaign in Switzerland. Complemented by continuous fixed-site monitoring by the NABEL network, the data will be used to develop daily mean UFP concentration surfaces at 25 × 25 m resolution, from 2025 back to 2010. The modelling approach will move beyond standard land use regression models by incorporating temporally varying predictors, such as meteorological variables (*e.g.* wind speed, precipitation, temperature), a chemical transport model,[24] and diurnal, weekly, and seasonal patterns, to improve characterization of spatiotemporal variability. Anticipated outputs include high-resolution exposure maps suitable for linkage to health data to study both long-term and acute effects of exposure in a multi-pollutant setting (see part 4).

Fig. 1. Mobile UFP measurement platform 'AirView' (all electric KIA e-Soul) by Utrecht University, the Netherlands. Photo taken during a measurement campaign in Santa Maria in Calanca, Grisons, Switzerland. Photo: Eric Twomey.

4. Swiss and International Epidemiological Studies on Short- and Long-term Health Effects

Due to the shortage of wide-area, large scale exposure models, epidemiological studies on the health effects of UFPs have been scarce in Switzerland, both for short- and for long-term health effects, based on personal measurements of exposure,[25] or exposure models.[26]

4.1 *Short-term Health of Highway Maintenance Workers*

Repeated personal exposure measurements of 18 highway maintenance workers focussed on the relationship between simultaneous air pollution and noise exposure and short-term cardiovascular and respiratory health effects.[25a,27] The study measured personal exposure to ultrafine particles in addition to NO_2, CO, O_3, $PM_{2.5}$ and noise over the course of 50 work shifts.[27] Activities like mowing, lumbering, electrical maintenance in tunnels, and pavement repair yielded mean PNC's of >60,000 particles/cm^3.[27] Overall, mowing was the predominant activity, in which the workers engaged 50% of their time. Researchers further assessed blood pressure, proinflammatory and prothrombotic blood markers, lung function, and fractional exhaled nitric oxide approximately 15 hours after each work shift.[25a] While noise and $PM_{2.5}$ exposure during highway maintenance work were associated with blood pressure, heart rate variability and several blood markers, there were no associations with respiratory symptoms, or with LDSA – the marker for ultrafine particles, especially after adjustment for co-pollutants.[25a] While exposure in these studies was assessed very precisely, and repeatedly, the main challenge was the relatively small number of observations compared to the number of possible exposure–health associations tested.

4.2 *Pre-clinical Markers of Cardiovascular Health in the SAPALDIA Study*

Besides extensive exposure measurements and modelling, the SAPALDIA study analysed carotid intima-media thickness in relation to multiple air pollutants, including UFPs.[26] Intima-media thickness is a pre-clinical marker for atherosclerosis and cardiovascular disease risk, and was available for 1,503 people aged ≥ 50. The study considered long-term exposure to ultrafine PNC and LDSA as modelled previously.[22] In addition, PM mass and gaseous air pollutants were also considered. The study found that long-term outdoor exposure to ultrafine particles (both PNC and LDSA) was associated with greater carotid intima-media thickness, suggesting increased cardiovascular risk. The associations were modest and of similar magnitude to that from fine particulate matter ($PM_{2.5}$), but stronger in people already at higher cardiovascular risk: people with diabetes and those with lower education. Although the study suggested that LDSA might be a better marker for the health-relevance of UFPs than PNC, based on a two-pollutant model, the strong correlation between both metrics must be acknowledged, limiting the ability to truly disentangle the two metrics.[26]

4.3 *EXPOsOMICS Associations Between Personal, Indoor and Outdoor Concentrations and Health*

The EXPOsOMICS study measured short-term personal and outdoor exposure to ultrafine and fine particulate air pollution[28] in association with blood pressure and lung function in healthy adults,[25c] involving Swiss participants (among others) in an international collaboration.

This produced mixed results: neither UFP exposure in the 2-h preceding health test, nor the 24-h mean personal, residential, and central site UFP exposures were associated with blood pressure or lung function.[25c] There were positive associations between $PM_{2.5}$ and systolic blood pressure: about 1.4 mmHg increase per interquartile range (IQR) increase in $PM_{2.5}$ across personal, residential outdoor, or central site exposure metrics.[25c] Personal soot exposure and dose were positively associated with diastolic blood pressure: roughly 1.2 mmHg (personal soot exposure) and 0.9 mmHg (dose) per IQR increase.[25c] The magnitudes of the effects were modest (in the order of ~1 mmHg), but could be relevant at the population level considering the ubiquitousness of the exposure. Repeated samples from 157 adults further showed no association between UFP and DNA-methylation, a marker for epigenetic regulation and genomic stability. The study identified associations between 24-hour exposure to $PM_{2.5}$ air pollution and DNA methylation, but found no associations with UFP exposure.[25b]

4.4 *MARKOPOLO and the Brain-lung-heart Axis*

In vitro and animal studies have demonstrated that UFPs can cross cellular and biological barriers, transgress from the lungs into the bloodstream and brain, and induce cellular oxidative stress and vascular inflammation – mechanisms consistent with a 'brain–lung–heart axis' of toxicity, which is the central focus of the MARKOPOLO project that started in 2025.[20] UFPs have been shown to penetrate epithelial cells by non-phagocytic mechanisms,[2] accumulate in brain tissue causing neuroinflammatory and amyloidogenic changes,[3,4] and elicit systemic inflammatory responses affecting multiple organs.[5] These mechanistic pathways are currently being corroborated and expanded through coordinated toxicological and exposure studies within the MARKOPOLO consortium across Europe. Swiss TPH will use the daily 25 × 25 m UFP exposure surfaces developed through the MARKOPOLO UFP model to conduct epidemiological analyses within the Swiss National Cohort. Amongst others, associations between UFP exposure and overall mortality, neurovascular and neurooncological diseases like strokes and brain cancer will be investigated. First, all-cause mortality will be analysed to describe broad associations with long-term UFP exposure, using survival models with standard individual and area-level covariates and multipollutant adjustment (*e.g.* $PM_{2.5}$, NO_2). Second, to examine brain tumour mortality, we will apply Cox proportional hazard regression to study whether long-term UFP exposure is associated with malignant brain tumour deaths, similar to a recent study by Lloyd *et al.* (2024), who found that in Montreal and Toronto, ~13% of brain cancer cases can be linked to UFP exposure. We aim to extend this study by using health data from a larger cohort over a longer period and linking it with a higher resolution UFP exposure model. Third, for short-term effects, we will evaluate short-term UFP exposures as a potential trigger of fatal strokes using a time-stratified case-crossover design and multi-pollutant models. A health impact assessment will estimate attributable health and economic burdens of UFP exposure in Switzerland. MARKOPOLO will help clarify whether UFPs exert independent long- and short-term health effects beyond co-pollutants and identify priorities for future research and policy.

5. Reviews from Switzerland

The Swiss Documentation Centre Air Pollution and Health (locally known as Dokumentationsstelle Luftverschmutzung und Gesundheit, LUDOK) is hosted at the Swiss TPH since its establishment in 1985, and has contributed to numerous reviews on the short- and long-term health effects of air pollutants, including UFPs.[3b,29]

A recent meta-analysis by Bergmann *et al.*[5] concluded that while the number of studies on the association between short-term UFP concentrations and mortality has increased substantially in recent years, current evidence does not yet clearly support a consistent association for effects on natural, cardiovascular and respiratory mortality. The authors emphasize the need for harmonized UFP monitoring and improved exposure characterization to advance epidemiological analyses and policymaking. A further review by Bergman *et al.*[9], reviewing 85 studies, found weak evidence for a positive association between long-term UFP exposure and non-accidental mortality, finding further associations with myocardial infarctions, strokes, brain tumours, and childhood autism incidence. Meta-analyses for hypertension, diabetes incidence, cancers, and myocardial infarction incidence were robust to adjustment for co-pollutants $PM_{2.5}$ and NO_2, though the authors noted that overall, less than half the studies adequately adjusted for co-pollutants.

A recurring theme across these reviews is the considerable heterogeneity in both exposure assessment and epidemiological study quality. Limitations include inconsistent use of multipollutant models, differences in spatial and temporal resolution of exposure estimates, and varying methodological rigor, warranting the need for more standardized and high-resolution UFP exposure assessment and epidemiological studies.

Beyond peer-reviewed literature, LUDOK has contributed to several reports and policy documents that bridge scientific findings and public health decision-making. These include the Swiss Federal Commission for Air Hygiene (EKL) Report on Air Quality,[30] the German translation of the Health Effects Institute Special Report on Traffic-Related Air Pollution,[31] and the policy white paper 'Ambient Ultrafine Particles: Evidence for Policymakers'.[15] Together, these efforts contribute to evidence-based recommendations for future UFP guidelines in Switzerland and beyond.

6. Legislation of Ultrafine Particle Concentrations

Based on the epidemiological evidence so far, the application of the precautionary principle applies to ultrafine particles: to limit exposure and potential harm where possible, despite scientific uncertainty about health effects. In the meantime, the WHO recommends to expand air quality monitoring of UFPs, and advance approaches for exposure assessment to aid subsequent epidemiological studies.[32]

At present, the Swiss Federal Commission for Air Hygiene (Eidgenossische Kommission für Luftreinhaltung, EKL) has not proposed guideline values for additional, previously unregulated air pollutants.[33] However, it supports the recommendations outlined in the WHO 2021 Air Quality Guidelines concerning soot and ultrafine particles (UFPs), emphasizing that their emissions should be minimized as far as possible.

Similarly, the European Union has acknowledged the health relevance of these pollutants.[17] Although there are still no binding limit values for soot or UFPs in EU legislation, recent revisions of the Ambient Air Quality Directives include commitments to improve monitoring of UFPs in air quality networks.[17] Globally, many countries have yet to regulate key air pollutants such as $PM_{2.5}$, ozone, and nitrogen dioxide[34] – although the WHO issued guideline values for these pollutants already in their 2005 edition of the air quality guidelines, which were further tightened in the 2021 update.[32] This underscores the importance of international guidelines like those from the WHO, which provide a science-based foundation for countries developing or updating their air quality standards.

7. Conclusions and Outlook

While Switzerland has contributed in a major way to UFP exposure measurements and modelling efforts, no large Swiss epidemiological study has so far demonstrated associations between long-term exposure to UFPs and severe health effects like mortality or morbidity, and few Swiss studies on short-term and pre-clinical endpoints exist. Internationally, the number of original studies has substantially increased between the reviews conducted in 2019[3b] and those published in 2025.[3a,6] Meta-analyses do not clearly support short-term effects of UFPs on mortality, independent from other co-pollutants, and so far there is weak evidence for long-term effects. This highlights the need for further hands-on measurements, dedicated UFP modelling to assess spatial and temporal exposure contrasts and highly powered epidemiological studies.

By far, the most often used UFP metric in epidemiological studies is PNC, but linking this to specific disease outcomes has been more limited in Switzerland than for other pollutants like $PM_{2.5}$ and NO_2, for which effects on respiratory and cardiovascular health are well-established. A major challenge is the correlation among pollutants and exposure metrics (*e.g.* $PM_{2.5}$, NO_2, PNC, LDSA). This makes it difficult to clearly disentangle which pollutants or metrics are causally responsible for any association with health. It is therefore all the more important that we do not let contrasts we know exist for other pollutants inform PNC models with the idea to apply to epidemiology and tease out the singular causal effect of PNC. While illustrative for a nice continuous UFP surface, such models are of little use for epidemiological purposes if based largely on $PM_{2.5}$, NO_2, or other related air pollutants.[35] Though absolute concentrations and units may be different, if they essentially all have similar variability, this does not allow epidemiology to disentangle health effect attributable to either exposure.

Although LDSA is considered the main driver of toxicity in toxicological experiments, PNC is more commonly measured, and is most prominently referenced in the new EU Ambient Air Quality Directive.[17] Because LDSA is proportional to particle number concentration multiplied by the mean particle diameter, the two are often well correlated in short-term, co-located measurements and in settings with similar, omnipresent sources and size distributions. Over long periods, however, relative source contributions may change, and environments dominated by smaller particles (*e.g.* from airports) or larger particles (*e.g.* wood-burning) may have similar PNC but different LDSA. For applications in environmental epidemiology – particularly those focusing on short-term exposure variability and traffic-related emissions – it may therefore matter little which metric is used.[26] As a result, epidemiological studies struggle to determine which metric is most health-relevant; an area where toxicological studies are better positioned to provide clarity.

Future modelling efforts for UFPs, for which traffic has traditionally been a major source, will be challenged by the anticipated electrification of street traffic. Electric vehicles currently represent 14% of the Swiss car fleet, but this will increase sharply due to the European Union's 2035 mandate to phase out the sale of new internal combustion engine (ICE) cars. While the proportion of 'classic' tailpipe emissions from ICE vehicles is expected to diminish, non-tailpipe emissions will become relatively more important.[36] Moreover, electric vehicles tend to be 20% heavier than their ICE counterparts, which could lead to an increase in the rate of abrasion of tires, breaks and road surfaces.[36] Microplastics constitute a sizeable fraction of these abrasion particles, which are also high in metals such as barium, copper, iron, and zinc, and are known to be elevated near major roads.[37] In addition, other sources of combustion will become more prominent predictors in future models for UFPs and other air pollutants.

Since most studies have so far focused on ambient outdoor exposure at the home, focus points for further studies might be indoor sources and personal exposure beyond the home. As a lot of our time is spent indoors, and high-exposure environments can contribute a lot to the total, identification of hotspots and targeted reduction of concentrations in these areas may have a relatively large impact on exposure. Furthermore, in the absence of a pre-established relationship between UFPs and health in general, likely vulnerable populations can only be assumed based on sensitivities previously identified for other pollutants, such as for children and elderly, but there is little evidence for similar vulnerabilities for UFPs.

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