

Air Quality Support for Review of ANPS

Ultra-fine Particulates Literature Review

Department for Transport

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1. Introduction

Ultrafine particles (UFPs) are generally defined as airborne particles with diameters ≤ 100 nanometres (nm). In recent years UFP emissions from airports have become a topic of interest particularly in relation to large airports close to residential areas such as London Heathrow and Amsterdam Schiphol airport. In 2018, the Department for Transport (DfT) published the Airports National Policy Statement (ANPS). The ANPS outlines a policy framework for decision-making on applications for any nationally significant airport in South-East England. The 2018 ANPS (hereafter referred to as “the ANPS”) was informed by information available at that time. The ANPS did not consider UFP concentrations when it was produced, therefore the Department for Transport (DfT) has commissioned AECOM to produce a review of the existing literature around UFPs, including sources, impacts on human health and potential research gaps.

Less is known about UFPs than more traditional air quality pollutants such as NO_x, and Particulate matter (PM₁₀ and PM_{2.5}), with monitoring of UFPs being significantly less widespread and no legally binding objective concentrations.

This review discusses the challenges of UFP monitoring, the links between UFP exposure and adverse health effects, and also aviation related UFPs with a spotlight on London Heathrow, before highlighting some knowledge gaps and research recommendations.

2. Background

UFPs are characterised by a high surface area-to-mass ratio that enhances their ability to absorb and transport toxic substances, such as polycyclic aromatic hydrocarbons (PAHs), transition metals, and organic compounds (Kwon, et al., 2020). This property increases their biological reactivity and toxicity compared to larger particles, allowing UFPs to penetrate deep into the pulmonary alveoli in the lung and translocate into the bloodstream, potentially reaching organs such as the brain, heart, and placenta (Kwon, et al., 2020) (Morales-Rubio, et al., 2019). The volatility of UFPs is also a key property in terms of their potential to harm human health (Takegawa, et al., 2023). UFPs are both primary (directly emitted into the atmosphere by sources such as traffic and aviation), and secondary (formed from chemical reactions in the atmosphere such as nucleation).

UFPs are measured as Particle Number Concentration (PNC) rather than as a mass. There are many sources of primary UFPs, many of which are anthropogenic, including emissions from the energy, industry, and transport sectors, and from domestic and commercial heating. Evidence suggests that airports are also a contributing source of UFP concentrations. Studies at Heathrow Airport have concluded that UFP size distributions are dominated by particles smaller than 20 nm (Maisol, et al., 2017) (Stacey, et al., 2020). Exposure to UFP concentrations can therefore be elevated in the vicinity of major airports. Another study at Heathrow determined that at a location 1.2km away from the airport, UFP concentrations were ~10 times higher than background concentrations elsewhere in London (Maisol, et al., 2017). Rivas et al. (2020) found that nucleation-mode particles in the urban background of London (North Kensington) and Helsinki were directionally dependent, coinciding with winds from major airports (Heathrow and Helsinki-Vantaa), confirming that aviation emissions can impact city-scale UFP levels.

Aircraft engines are the predominant source of UFPs at airports, with emissions varying by engine type, operational phase, and fuel composition (Stacey, et al., 2023) (Maes, et al., 2025). During take-off, engines operate at high thrust, producing intense bursts of UFPs, often in the sub-25 nm range (Maes, et al., 2025). Taxiing and landing also contribute, but with different emission profiles due to lower engine loads and temperatures (Blanco, et al., 2025). Ground support equipment (GSE), such as baggage tugs, fuel trucks, and auxiliary power units, also emit UFPs, but their contribution is generally much smaller compared to aircraft engines (Hudda, et al., 2016).

The chemical composition of airport-related UFPs includes elemental carbon (soot), organic carbon, sulphate, silicon, and trace metals such as nickel, copper, zinc, and lead, reflecting the combustion of aviation fuel and the use of specialized lubricants (Saitoh, et al., 2019) (Takegawa, et al., 2023). Jet engine lubrication oils have been identified as a significant source of UFPs, contributing unique organic signatures that can be used as tracers for aircraft emissions (Fushimi, et al., 2019).

Whilst UFPs are recognised as important pollutants by the World Health Organization (WHO) and the UK Government, neither has implemented exposure limits and UFP concentrations remain unregulated. UFPs were discussed in the WHO Global Air Quality Guidelines (AQG) document published in 2021 (WHO, 2021):

“As yet, insufficient data are available to provide recommendations for AQG levels and interim targets for specific types of Particulate Matter, notably Black Carbon/Elemental Carbon, UFP and Sand and Dust Storms. However, due to health concerns related to these pollutants, actions to enhance further research on their risks and approaches for mitigation are warranted.”

A Good Practice Statement is provided in Section 4 of the WHO AQG, which outlines measures for types of particulate matter which do not have a specific AQG level. The Good Practice Statement measures relevant to UFPs are:

- “1. Quantify ambient UFP in terms of 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 integrating UFP monitoring into the 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 < 1 000 particles/cm³ (24-hour mean). High PNC can be considered > 10 000 particles/cm³ (24-hour mean) or 20 000 particles/cm³ (1-hour mean).*

4. Utilize emerging science and technology to advance approaches to the assessment of exposure to UFP for their application in epidemiological studies and UFP management”

In 2024, the European Union published the Ambient Air Quality Directive (European Union, 2024), which states that monitoring of UFPs is mandatory, and should be established at ‘supersites’ (urban background and rural locations with long-term data for multiple pollutants). It is advised that, where high levels of UFPs are anticipated, one monitoring site is established for every 5 million inhabitants. Where high levels of UFPs are not expected, one monitoring site should be established for every 10 million inhabitants in urban background locations, and for every 100,000 km² in rural locations.

In 2018, a report titled Ultrafine Particles in the UK was prepared by the Air Quality Expert Group (AQEG) for the Department for Environment, Food and Rural Affairs (Defra) (AQEG, 2018). The report concluded that, due to improvements in fuels and exhaust fume filtering technologies, UFP concentrations in the UK had significantly reduced over the previous decades, however contributions from sectors including aviation and shipping were not fully quantified due to a lack of monitoring. Therefore, the main recommendation of the report was to increase the national monitoring network. Since the report was released, the Defra UFP monitoring network has been expanded to five locations, which are discussed in section 3.

A literature review was conducted by Defra to gather the latest information on monitoring techniques, health effects, and sources of UFPs (Department of Environment, Food, and Rural Affairs, 2026) (to be published shortly). Whilst the review highlighted that traffic sources are a dominant source of UFPs, it also recognised aviation as a primary source of UFPs.

3. Monitoring of UFPs

Monitoring of UFPs is generally less widespread than monitoring of other particulate size fractions, such as PM_{2.5} and PM₁₀. Defra maintains a small network of five UFP monitors in the UK, of these, one is located in Edinburgh, and the rest are in the South of England. One site, Horley, is located close to Gatwick Airport. Monitoring approaches for UFPs present a unique challenge due to the high temporal and spatial variability of emissions, the need for high-resolution instrumentation, and the lack of standardised regulatory requirements (Stacey, 2022). However, monitoring of UFPs has been outlined as a mandatory requirement in the revised Ambient Air Quality Directive (European Union, 2024).

The literature review undertaken by Defra (Department of Environment, Food, and Rural Affairs, 2026) explored the current UFP monitoring network within the UK, which consists of the five Defra sites that form part of the Defra PCN Network, and two additional University sites in Manchester and Birmingham. It was outlined that 14 sites would be required to meet the density described in the Ambient Air Quality Directive (European Union, 2024), and in Section 2 above.

UFP concentrations are typically reported as PNC (Stacey, 2022), which differs from particulate matter concentration which is usually reported as $\mu\text{g}/\text{m}^3$. This is due to the constraints of mass-based monitoring methods for UFPs. Mass-based monitoring methods fail to illustrate spikes in smaller classifications of UFPs (<40nm) as despite a sharp increase in PNC, the mass will remain relatively unaffected as it's dominated by the larger particles. This is one of the reasons mass-based monitoring methods do not tell the full story and why particle number-based monitoring methods are preferred when analysing UFP concentrations.

The challenges in monitoring UFPs are described in the literature review undertaken by Defra (Department of Environment, Food, and Rural Affairs, 2026). These include differing monitoring techniques (which may lead to inconsistent data comparisons), a risk of sampling losses with smaller particles (less than 10nm), and differences in particle size detections across different instruments.

Whilst there aren't currently any legally binding objectives, the WHO Good Practice Measures detailed in section 2 provide an indicative guide to low 24-hour mean PNCs and high 1-hour and 24-hour mean PNCs (WHO, 2021). These are displayed in Table 1.

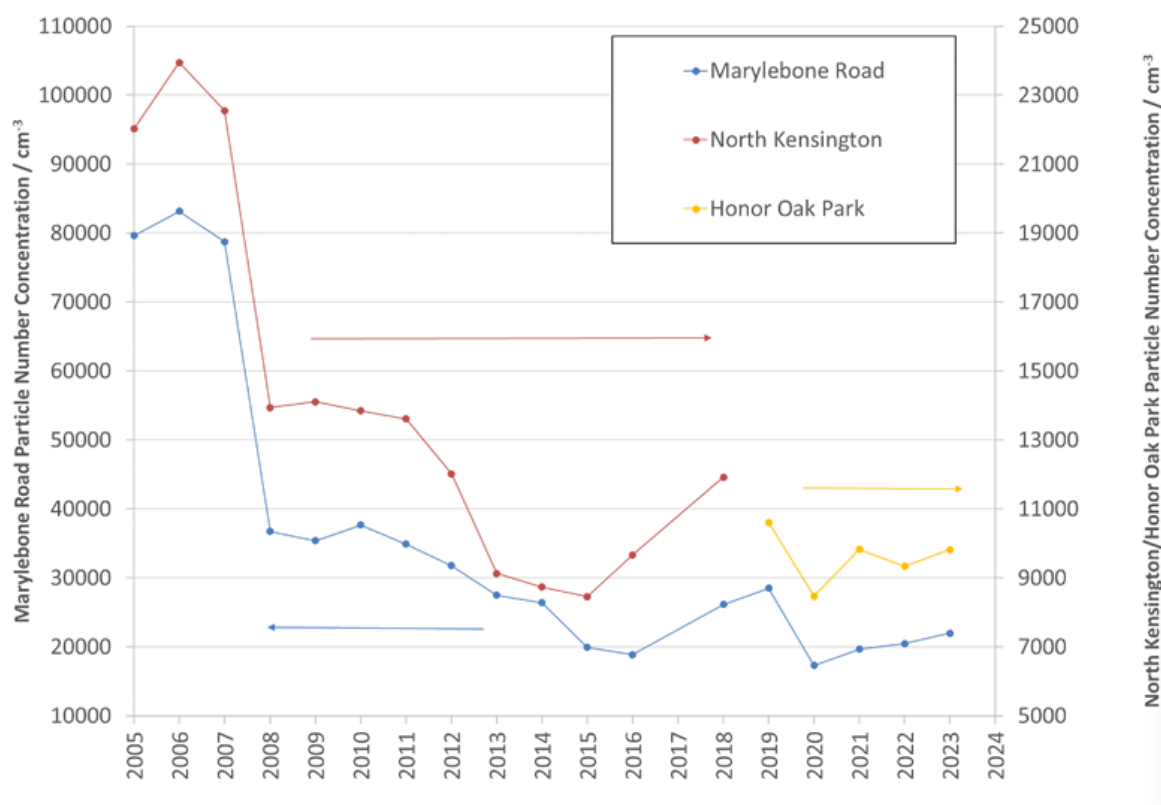
Table 1 WHO Good Practice Statement PNCs

UFP Level	Exceedance Criteria	Description
Low PNC	< 1000 particles / cm^3 (24-hour)	Typically observed in environments not affected by human activity
High PNC	> 10,000 particles / cm^3 (24-hour)	Typical or high exposure found in urban areas
High PNC	> 20,000 particles / cm^3 (1-hour mean)	

Source: WHO global air quality guidelines (WHO, 2021)

UFP monitoring data is not readily available, however annual mean PNCs have been published in various reports and is available from Defra. The figure below shows UFP monitoring results in London between 2005 and 2023 to show recent trends (Ciupek, et al., 2023).

Figure 1 Long-term particle number concentrations annual trends at all London sites. The London North Kensington site moved to London Honor Oak Park in November 2018. (Ciupek, et al., 2023)



Note: The arrows in the chart indicate which axis the data is referring to.

Source: Ciupek, K. et al., 2023. Airborne particle concentrations, particle numbers, and Black carbon in the United Kingdom – Annual Report

4. Health Effects of UFPs

A wide range of health impacts have been linked to exposure to UFPs. Many studies have analysed UFPs' role in birth outcomes and mortality rates from natural, circulatory, and respiratory causes, and both in the general population and in the immediate vicinity of airports. Outcomes of studies into the impacts of UFPs vary, with some claiming direct links between concentrations and human health and others concluding that there is no significant relationship.

One study, based on a 50 x 56 km area surrounding Amsterdam Schiphol Airport, found no association between short-term exposure to UFP from aviation sources and natural, circulatory, or respiratory mortality (Ndiaye, et al., 2026). Alternatively, many studies have found links between airport related UFP emissions and multiple types of cancer including squamous cell carcinoma (SCC) lung cancer, malignant brain cancers, and glioma (Bookstein, et al., 2025) (Wu, et al., 2021) (Ji, et al., 2023). UFP emissions from airport and non-airport sources have also been linked to effects on lung function and inflammation in adults with asthma and neurodegeneration and sleep disorders (Habre, et al., 2018) (Calderón-Garcidueñas, et al., 2023).

Research suggests that UFP emissions from aviation sources may have other human health-related impacts, such as effects on birth outcomes and on the health of children living close to major airports. A study conducted around Amsterdam Schiphol Airport analysed approximately 286,000 singleton births from 2006–2018, focusing on mothers who had lived for at least six months of their pregnancy within a 50 × 56 km area surrounding the airport (Jacobs, et al., 2025). The study found suggestive evidence for associations between exposure to aviation-related UFPs during pregnancy and pregnancy outcomes. However, no links between UFP exposure and infant mortality, low Apgar scores, and low birth weight were identified. Another study on pregnant women, this time living downwind of Los Angeles International Airport (LAX), produced results suggesting that emissions from aircraft play an etiologic role in preterm births (Wing, et al., 2020).

A different study around Amsterdam Schiphol Airport focused on the health effects on older children, of 7–11-years-old, living in the vicinity of the airport. It found that PNC of sizes indicative of aviation and other combustion sources were independently associated with an increase of respiratory symptoms and bronchodilator use (Lenssen, et al., 2024).

In summary, research suggests that UFPs are highly penetrative, biologically reactive pollutants that can affect the cardiopulmonary system, brain, metabolism, and foetal development. Short-term exposure is suspected to trigger inflammation and respiratory symptoms, while long-term exposure is increasingly suspected to contribute to chronic cardiovascular and systemic diseases. A consistent conclusion into the study of the health effects of exposure to UFPs is that more research is required to substantiate the findings made to date.

5. Sources of UFPs from Aviation

Airports are significant sources of UFP emissions, with multiple studies having recorded elevated UFP concentrations in the vicinity of major airports. A study near Heathrow Airport determined that UFP concentrations were ~10 times higher than background concentrations at a location >1km from the Airport's boundary (Maisol, et al., 2017). A study near LAX Airport identified that a primary contributor to UFP PNCs at two sites up to 2 km downwind of that airport was from arriving aircraft on their approach to land (Alvarado, 2018). A study in Tianjin, China, also found that UFP PNCs remained much higher than the background concentrations beyond 400 m from that airport's runway (Ren, et al., 2016).

Airport UFP emissions primarily originate from aircraft operations and associated ground activities. Jet engine exhaust fumes during ground operations, particularly taxiing and ground-idle thrust, is a dominant contributor to UFP levels. Taxiing alone accounted for approximately 49% of total UFP concentrations at Barcelona-El Prat Airport, with a mode diameter of around 17 nm (Ridolfo, et al., 2024). Take-off operations also produce significant UFP emissions, as evidenced by near-runway measurements at Amsterdam Schiphol Airport, where PNCs peaked at 10^6 particles cm^{-3} , with dominant particle sizes below 25 nm (Maes, et al., 2025). Other aviation sources of UFPs include GSE and jet engine lubrication oils (Hudda, et al., 2016) (Toyota, et al., 2024).

Both arriving and departing aircraft have been found to contribute greatly to UFP concentrations, however there are conflicting studies on which element of the Landing and Take-off Cycle contributes more. A study at Amsterdam Schiphol Airport found that plumes from departing aircraft exhibited high PNC (Maes, et al., 2025). However, studies conducted near LAX (Alvarado, 2018) demonstrated that arriving aircraft, particularly on prevailing-wind runways, were the primary drivers of UFP surges. Departing aircraft, while significant, had a comparatively lower impact on UFP concentrations in surrounding communities. Auxiliary power units (APUs), which are used to provide power to aircraft while on the ground, also contributes to UFP emissions. Research has shown sharp increases in UFP levels when APUs are in operation, highlighting this under-regulated source as a key area for mitigation (Michaelis, et al., 2021) (Williams & Trembath, 2021).

GSE operating on aprons also contribute to UFP emissions. These sources produce distinct modal peaks, typically with particle sizes greater than 20 nm, which are distinguishable from the signatures associated with jet engines (Artous, et al., 2024). Secondary formation processes, such as photonucleation, also play a role in UFP generation at airports. At El Prat Airport, Spain, photonucleation contributed approximately 17% of PNC, while similar nucleation events have been reported at Heathrow, Venice, and Narita airports (Ridolfo, et al., 2024) (Takegawa, et al., 2020) (Maisol, et al., 2017).

Particle Size Characteristics

The size distribution of UFPs near airports is dominated by nucleation mode particles (<30 nm). These size distributions vary depending on the operational phase and atmospheric conditions. At Barcelona-El Prat, dominant modes ranged from 13–23 nm during photonucleation and take-off operations, with taxiing producing particles with a mode diameter of approximately 17 nm (Ridolfo, et al., 2024). Near Amsterdam Schiphol, particle sizes below 25 nm were prevalent, with concentrations peaking at 10^6 particles cm^{-3} approximately 200 metres downwind of the runway (Maes, et al., 2025).

At Narita Airport, particles smaller than 10 nm accounted for more than 50% of the total PNC in plumes, with emission indices peaking in this size range (Takegawa, et al., 2020). Similarly, at Tianjin Airport, the dominant particle mode was approximately 16 nm, with an inverted U-shaped response to wind speed (Ren, et al., 2016). Community-scale studies near Heathrow Airport identified an "airport signature" characterised by particles smaller than 20 nm, with concentrations up to 10 times higher than the urban background at distances of 1.2 km from the airport (Maisol, et al., 2017).

Chemical and Physical Signatures

The chemical composition of UFPs near airports provides valuable insights into their sources and formation mechanisms. Metallic elements such as iron, aluminium, chromium, copper, and molybdenum are commonly enriched in UFPs emitted from jet engines. At Barcelona-El Prat, these elements were found in higher concentrations within the UFP fraction compared to urban background levels, with aluminium showing the largest enrichment (Ridolfo, et al., 2024). Similar findings have been reported in studies analysing jet fuel and lubrication oil, which contain trace metals that may be incorporated into emitted particles (Saitoh, et al., 2019). Organic toxicants, including polycyclic aromatic hydrocarbons (PAHs) and benzene, toluene, ethylbenzene, and xylene

(BTEx), are also present in airport-related UFPs (Rodríguez-Maroto, et al., 2024) (Rodríguez-Maroto, et al., 2025).

Lubrication oil derived compounds, such as pentaerythritol esters (PEEs), trimethylolpropane esters (TMPEs), and tricresyl phosphate (TCP) homologues, have been identified as molecular markers linking UFPs to jet engine operations. These compounds are produced through evaporation and condensation processes during engine operation, as confirmed by laboratory experiments that replicated UFP formation by evaporating jet oil (Toyota, et al., 2024) (Ungeheuer, et al., 2021).

Spatiotemporal Dynamics

The dispersion and concentration of UFPs around airports are influenced by meteorological conditions, such as wind speed and direction, and the proximity of exposure to the sources of emissions. Downwind UFP peaks often persist several km from runways, with concentrations decreasing with distance due to atmospheric dispersion (Alvarado, 2018) (Maisol, et al., 2017). Diurnal patterns in UFP levels are closely tied to flight schedules, with peaks occurring during periods of high aircraft activity (Maisol, et al., 2017).

Meteorological factors, such as wind speed, play a critical role in UFP dispersion. Moderate wind speeds create an inverted-U response in Particle Number Concentrations, balancing dispersion and plume interception (Ren, et al., 2016). Variability in UFP emissions across different aircraft and engine types further complicates the spatial distribution of particles. At Amsterdam Schiphol, PNCs did not correlate linearly with thrust or size, highlighting the influence of specific aircraft and engine models on emissions (Maes, et al., 2025).

6. UFPs at Heathrow

Studies consistently demonstrate that UFP concentrations near Heathrow are dominated by particles with a modal peak below 20 nm, a size range distinct from urban background environments in London, where the mode is typically closer to 30 nm. This unique fingerprint is strongly associated with airport activities, particularly aircraft operations. For instance, a study that conducted two seasonal monitoring campaigns at a site 1.2 km from the airfield found that Heathrow's emissions accounted for approximately 30–35% of total UFP PNCs (Maisol, et al., 2017). These emissions were characterised by a distinct modal structure peaking below 20 nm, underscoring the significant impact of airport operations on local air quality. Other contributors included road traffic emissions (24–36%), resuspended road traffic emissions (16–21%), and urban accumulation from London (around 10%). Secondary sources, while contributing less than 6% to particle number concentrations, dominated particle volume, accounting for more than 50% of the total volume concentration.

Further studies reinforced these findings, emphasising the distinct size distribution of UFPs at Heathrow compared to urban and rural locations. Studies have observed that, unlike classical air pollutants, UFP concentrations at Heathrow were higher than those at urban background sites in London, specifically particle numbers in the sub-30nm size range, but are lower than at traffic dominated locations (Harrison & Stacey, 2019) (Stacey, et al., 2020). However, the size distribution at Heathrow was markedly different, with particles smaller than 30 nm observed in far greater numbers. This highlights the unique contribution of airport emissions to local air quality, distinct from other urban sources.

Studies have used high-resolution measurements synchronised with aircraft GPS data to attribute emissions to individual aircraft and operating modes (Stacey, 2022). They found that larger aircraft departing from the runway recorded higher UFP emissions, with emission rates influenced by the number of passengers carried, particularly for arriving aircraft. The inclusion of condensable particles in these measurements resulted in significantly higher emission rates than those reported in the literature, as regulated metrics typically exclude condensable fractions (Stacey, et al., 2023). This discrepancy underscores the need for regulatory frameworks to align with real-world measurements.

The role of aircraft size and engine design in UFP emissions was further explored in a study that found that larger and older aircraft were associated with higher UFP emissions (Stacey, et al., 2021). While newer engine designs showed some improvements, the benefits were not always sufficient to offset the higher emissions from larger aircraft. Additionally, non-exhaust sources, such as tyre abrasion during landing, were identified as contributors to UFP concentrations, with UV-active black carbon (UVPB) spikes observed near landing aircraft.

7. Knowledge Gaps and Research Recommendations

Despite significant progress in understanding UFP emissions at airports, several knowledge gaps remain. Current emissions inventories primarily focus on the landing and take-off (LTO) cycle, leaving emissions during climb, cruise, and descent phases poorly quantified (Owen, et al., 2022). High uncertainties in measuring particles smaller than 10 nm highlight the need for standardised methods and instruments (Takegawa, et al., 2020).

The partitioning of volatile and non-volatile particles and their evolution through nucleation, condensation, and resuspension processes require further investigation to improve dispersion models (Owen, et al., 2022). Additionally, epidemiological studies linking UFP composition to health outcomes for airport workers and surrounding communities are limited. Real-world testing of mitigation technologies, such as low-particle combustor designs, alternative fuels, and electric ground support equipment, is essential to evaluate their effectiveness in reducing UFP emissions.

The establishment of a large-scale, UK-wide, standardised monitoring network is key in understanding the impact of UFPs, particularly in areas surrounding major airports. It is difficult to fully assess knowledge gaps and research recommendations without the understanding that a large-scale UFP monitoring network would provide.

8. Conclusions

The study of UFPs in the context of aviation emissions is still an emerging topic, however it highlights their significant impact on air quality and public health, particularly in areas surrounding major airports. UFPs, characterised by their small size and high surface area, exhibit unique chemical and physical properties that enhance their ability to penetrate biological systems and contribute to adverse health outcomes. Research has consistently demonstrated that airports, including Heathrow, are major sources of UFPs, with emissions dominated by aircraft operations and, to a lesser extent, GSE and APUs. These emissions are distinct from urban background sources, as evidenced by the smaller particle sizes and unique chemical signatures associated with aviation activities.

Despite advancements in monitoring and understanding UFP emissions, several critical knowledge gaps remain. Current regulatory frameworks lack specific guidelines for UFP concentrations, and existing monitoring networks are limited in scope. Furthermore, the health impacts of UFP exposure, particularly in vulnerable populations such as pregnant women, children, and airport workers, require further investigation. The variability in emissions across different aircraft types, engine designs, and operational phases underscores the need for more comprehensive emissions inventories and standardised measurement techniques.

To address these challenges, future research should focus on establishing standardised monitoring methods in order to introduce a large-scale, UK-wide monitoring network. This will allow for the expansion of epidemiological studies, development of effective mitigation strategies, and development of the knowledge required to establish legislative objective UFP concentrations. Innovations such as alternative fuels, low-particle combustor designs, and electrification of ground support equipment hold promise for reducing UFP emissions. Additionally, aligning regulatory frameworks with real-world measurements and integrating UFP monitoring into existing air quality strategies will be essential for mitigating the environmental and health impacts of aviation-related UFPs.

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