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Emissions of ultrafine particles from civil aircraft: dependence upon aircraft type and passenger load

Brian Stacey^{1,2}, Roy M. Harrison^{1,3✉} and Francis D. Pope¹

Very high concentrations of ultrafine particles (UFP) were measured at Heathrow Airport London. Exposure to UFP is strongly linked to adverse health effects and guidance for exposure limits has recently been provided by the World Health Organization (WHO). Using 1 s resolution UFP measurements and aircraft GPS data, measurements were assigned to individual aircraft and their operating mode, and this information was used to model UFP emission rates. In all cases, the highest emission rates were associated with departing aircraft, with rates for larger aircraft higher than smaller aircraft. Emission rates per passenger is influenced by the number of passengers carried, especially for arriving aircraft. Calculated emission rates are significantly higher than stated literature values, due to the inclusion of condensable particles in the measurements. These condensable particles are specifically not included in the regulated emission rates. Measured UFP concentrations within the airport boundary (and therefore not accessible to the general public) exceed the WHO guidance, indicating that UFP concentrations outside of the airport boundary could also be of concern. Assessing population exposure close to airports will be of increasing importance in future.

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INTRODUCTION

There is increasing evidence that exposure to Ultrafine particles (UFP, defined here as particles that are smaller than 100 nm in diameter) is associated with adverse health outcomes^{1–10}. However there are very few definitive studies and a scarcity of robust measurement data to assess their concentrations and sources. As a result, to date, there are no limits or target values to minimise exposure to UFP. The automotive industry implements an assessment of UFP emissions for EURO 6/VI vehicles¹¹ (maximum permitted particle number concentration per km), but this only relates to particles >23 nm and only for particles which are involatile at 350 °C. While the nature of road traffic exhaust emissions as they cool and interact with the ambient environment has been documented^{12,13}, the behaviour of emissions from aircraft is less well characterised or understood.

There is growing interest in measurements of UFP close to airports. London Heathrow Airport is the busiest two runway airport in the world and the largest in the UK. Measurements of NO_x and PM have been made at the airport continuously since 1993 and at 5 separate locations currently. Recent studies^{14–18} have shown that high numbers of very small particles dominate the environment around airports, and conclusively point to aircraft as the dominant source of these particles. Our previous two studies^{14,15} explored the relationship between UFP at the airport and the three UK monitoring stations, showing that UFP from aircraft are smaller in size than those generated by road traffic, present in higher numbers, and emitted in larger numbers during departures. Stacey et al.¹⁵ provided evidence to suggest that larger aircraft had higher UFP emissions than smaller aircraft. The emissions from Heathrow are readily detectable not only in a local residential area¹⁹, but also in central London²⁰, and this phenomenon is seen in other cities around the world²¹.

The research we present here is unique in the sphere of ambient air quality measurements in an airport environment. We

are not aware of any other published data that utilises full particle size distribution data sampled at 1 Hz, coupled with exact aircraft type and location data at 1 Hz, along with 1 min meteorological measurements. Over 10GB of data was collected over a 7 week period in 2019, allowing large clusters of measurements from various wind directions, aircraft types and operating modes to be evaluated. The proximity of the monitoring location to a heavily used runway has historically been very difficult for academic researchers to secure. The airside location used for this study is 170 m downwind of the busiest 2 runway airport in the world – for understandable security reasons, airport operators do not usually grant access for monitoring in these locations. The data we have collected and the analysis we present offer a unique perspective on UFP measurements and projected emission rates from civil aircraft.

RESULTS

Overview

For this study, we make use of a UFP analyser (Cambustion DMS500) operating at 1 s resolution at the station closest to the northern runway (LHR2), together with 1 s resolution GPS aircraft movement data, 1 min resolution meteorology, PM and Black Carbon (BC) data plus 10 s NO_x data, to look in detail at the UFP emissions from aircraft, both departing and arriving.

The map in Fig. 1 shows the operating modes of the two runways. Monitoring in 2019 was undertaken at the LHR2 station, 170 m from the centre line of the northern runway.

Results and analysis

For analysis of aircraft emission rates, only periods where aircraft were departing or arriving on runway 27 R were considered. Data were further screened, based on aircraft position on the runway and for unsuitable weather conditions.

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The 2019 measurement data confirms many observations made previously at airports:

- Smallest particles dominate particle number concentrations
- Highest concentrations of the smallest particles come from the airport (Fig. 3)
- Departure measurements are higher than arrival measurements (Fig. 4)
- Higher measurements from larger aircraft
- Highest PM and BC measurements were not associated with airport wind directions

These points are presented in Figs. 2, 3 and 4 and Table 1, and provide clear evidence, repeated at an increasing number of airports, including airports in Zurich, Boston, Los Angeles, Amsterdam and Lisbon, as well as earlier studies at Heathrow^{19,22–26}, that airport activities are a major source of particle number concentrations. However, we have been able to take our research further, to study plumes from individual aircraft.

The 1 s resolution of the DMS500, combined with 1 s precise aircraft location and identification and 1 min meteorology, allowed us to measure an exhaust plume and identify the associated aircraft with absolute confidence. We believe this level of detail is unique to our research; other studies have relied on manual observation of aircraft to assign peak measurements and positioning of monitoring equipment in often less than ideal

locations. Our study benefitted from a long campaign duration with no interfering sources, which allowed the data to be screened to provide the most robust analysis.

Emission rates of particle numbers from individual aircraft were estimated by associating high resolution NO_x measurements with stated ICAO NO_x emission rates²⁷ and then using this association to calculate total particle number emission rates using the PNC measurements. It was not possible to arrange the operation of a CO_2 analyser for this study, as these data would have provided a stronger relationship with the UFP emission rates. The method we used for evaluating aircraft NO_x contribution is explored further in Section 4.5. The calculations we have used assume that NO_x and PN measurements are exclusively associated with combustion. While this is broadly true for NO_x concentrations, the particles that we measured will have undergone many transformations, physical, chemical, new formation and dilution in their transportation to the monitoring station. However, the ICAO particle number emission rates²⁷ are measured at the jet exhaust and are solely associated with particles that are non-volatile at 300 °C. In addition to the particles formed as a result of the combustion of the fuel, studies by Ungeheuer et al and Fushimi et al.^{28,29} have identified unburned lubrication oil is present as semi-volatile nucleation and Aitken sized particles in varying proportions in aircraft exhaust. This monitoring study focuses solely on the particle count and size distribution; it is not possible to estimate the separate semi-volatile and non-volatile contributions or particle composition from the measurements made at Heathrow.

Table 2 presents a comparison of stated ICAO particle number emission rates with calculated values from the measurements. The ICAO particle number emission rates are quoted for non-volatile particles. The calculated total particle number emission rates are estimated from the relationship between ICAO NO_x emission rates and our measured NO_x and PNC attributed to each aircraft. Both arithmetic and geometric mean data are presented. Measured PNC includes volatile and semi-volatile particles, as well as the non-volatile particles assessed in the ICAO tests. As the data approximated to a log-normal distribution, Geometric Standard Deviation (GSD) values for the calculated emission rates are provided in brackets, which, in combination with the geometric mean data, show the wide variation in measurements. The behaviour and transportation of the plume to the analyser inlet, the quantity of lubrication oil nebulised by the engine and the exact operation of the departing / arriving aircraft will have had a material effect on the measurements. Other studies, e.g. SCOPE11³⁰, have explored estimating relationships between measurements of smoke number and particle number emissions. These focus on non-volatile particles to establish emissions indices (EI) relationships – this was not considered for this study, which was targeted to include measurements of all volatile and non-

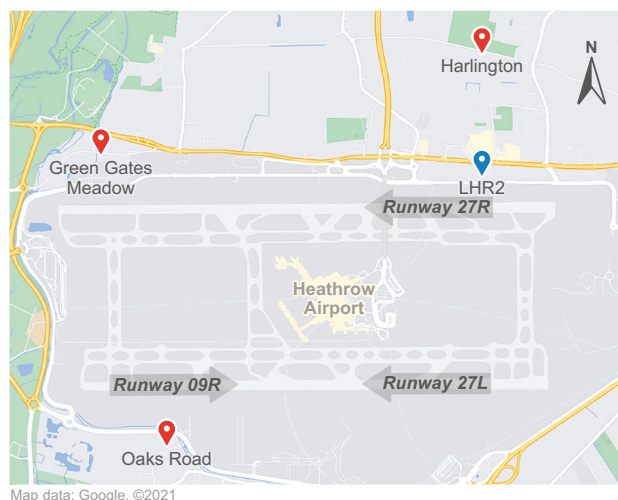


Fig. 1 Map of Heathrow Airport with active monitoring station locations. LHR2 (marked in blue) is the location used for UFP measurements.

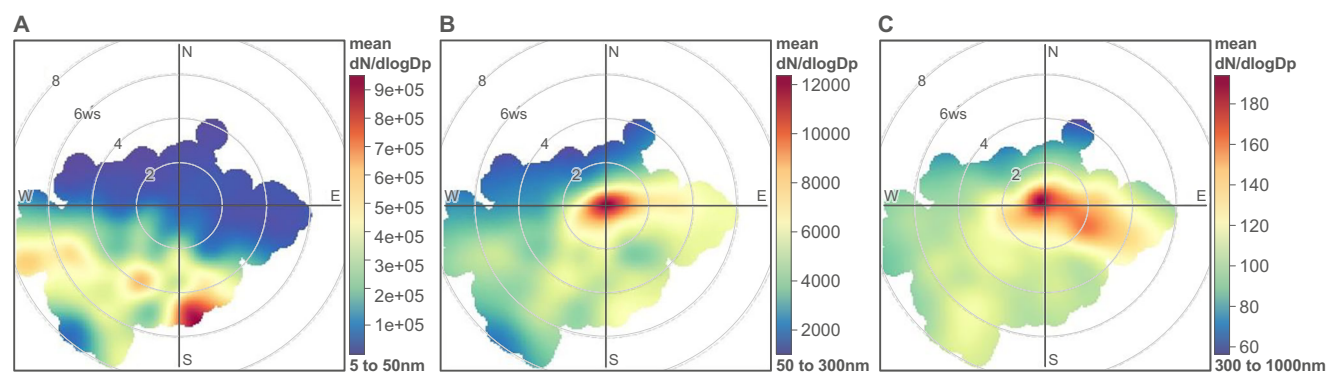


Fig. 2 Polar plot of average particle size distribution. Polar plots of average particle size distribution **A** 5–50 nm particles, **B** 50–300 nm particles, **C** 300–1000 nm particles. The plots show how concentrations are associated with wind direction. Scale is specific for each particle size range, from low (blue) to high (red). Distance from the centre is representative of wind speed.

volatile particles. Additionally, only 1 min of data from other analysers was available, which was not considered to be fast enough to allow unique identification of individual plumes, or correlation with the 1 s UFP measurements. As a result, and noting that the sources of UFP from jet aircraft will not just be from combustion, the evidence presented here offers new insight into aircraft engine exhaust.

We have not used the 100% thrust ICAO emission rate values for our analyses. Following informal discussions with airline pilots from Virgin Atlantic and British Airways, it was discovered that operating procedures for take-off are often different to the assumptions made when using the ICAO database. These airlines experiment with thrust settings for take-off and climb modes to

improve fuel economy. The pilots independently stated that they rarely departed at 100% thrust, using reduced settings, resulting in a longer take off, but reduced fuel use. They said that these operating procedures were reviewed and updated monthly. For this reason, emission rates for the ICAO 85% thrust setting have been used in these comparisons.

Figure 5, Table 2a and Table 2b show a number of different key points. Firstly, and most obviously, the estimated total particle number emission rates are mostly many times higher than the ICAO data for non-volatile particle number emission rates for all aircraft types, both for arrival and departure. This strongly suggests that both volatile and semi-volatile particles contribute to the emissions from aircraft, at least once the exhaust has cooled and mixed in the time taken in transportation of the plume from the runway to the measurement station.

Emission rates from all aircraft are higher for departing aircraft than arriving aircraft. Average emission rates for departing short-haul aircraft are 6–7 times higher than the average short-haul emission rates for the same aircraft during landing. Average emission rates for departing long-haul aircraft are 10–24 times higher than the average long-haul emission rates for the same aircraft during landing.

Previous studies at Heathrow^{14,15} identified that the particle size distribution from airport related wind directions had a smaller size mode than from other wind directions. While the absolute concentrations are much higher when winds are from the airport, the shift in particle size distribution was not repeated in 2019: the peak particle size was ~12 nm, irrespective of wind direction. It is not immediately clear why this should be the case, though it is likely that the different measurement techniques and calculation protocols are the primary cause. Further investigation of the relationships between different instrument types would be beneficial.

The information gathered about UFP for each aircraft type allows us to investigate the data in several different ways. A valuable metric is to look at UFP emission rates per passenger. For this investigation, assumptions are made about the typical seating configurations for each aircraft type. Data from www.caa.co.uk, presenting (on average) the number of passengers in aircraft in September and October 2019, was used to adjust the emission rates per passenger. This Passenger Load Factor (PLF) for each aircraft type is presented in Table 3. The assumption that aircraft are always loaded in this way, together with data screening to remove data where departing and arriving aircraft were not successfully detected (usually by excluding measurement data below 4000 #/cm³), will contribute to the uncertainty of the data presented. However, given the size of the measurement dataset, it is most likely that the observed differences between aircraft types are genuine.

Table 3 and the plots in Fig. 6 highlight a number of key points. The Boeing 777 aircraft have the highest emission rates per passenger for both arriving and departing aircraft. This is probably due to the age of the fleet in operation at Heathrow. The lowest emission rates from arriving aircraft are seen from the short haul aircraft (A32x, 737, 757), although the relative differences between the majority of aircraft types are small (less than a factor of 4). The

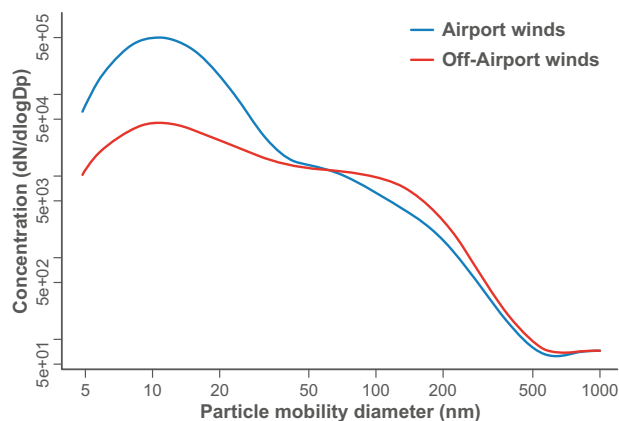


Fig. 3 Survey average concentrations for UFP. The data are split to assess concentrations from on-airport and off-airport wind directions.

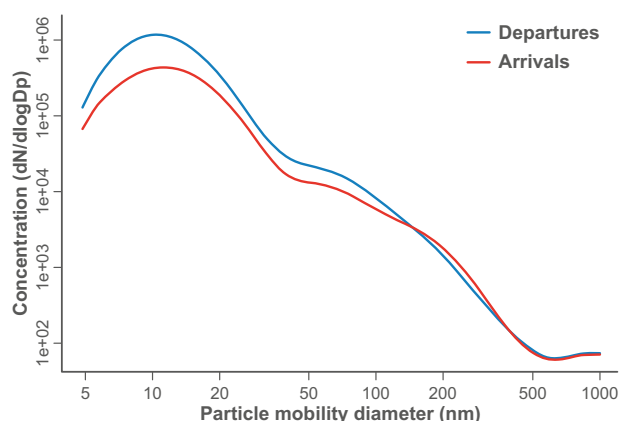


Fig. 4 Survey average concentrations for UFP particle size distribution. Data are split to show the differences associated with departing and arriving aircraft.

Table 1. Representation of particle size distributions separated by direction.

Survey concentrations	PM ₁₀ µg/m ³	PM _{2.5} µg/m ³	BC µg/m ³	UVPD µg/m ³	Particle Number Count (PNC) #/cm ³
Average	10.4	6.1	1.8	0.4	40517
Northerly winds	13.9	7.9	2.1	0.4	8511
Southerly winds	8.5	5.1	1.6	0.4	58464

Northerly winds do not originate from the airport, southerly winds are from the airport. UFP concentrations are clearly much higher from winds associated with the airport.

Table 2. ICAO and calculated total particle emission rates for arriving aircraft.

Aircraft type	ICAO non-volatile PN (#/second per aircraft)	Calculated Average PN (#/second per aircraft)	Calculated Geometric Mean (#/second per aircraft) (GSD)	Ratio geom : ICAO
a:				
Short to Medium Haul				
Airbus A319	5.13E + 14	3.970E + 15	2.13E + 15 (3.46)	4.2
Airbus A320	1.78E + 15	3.379E + 15	2.24E + 15 (2.79)	1.3
Boeing 737	2.44E + 14	4.193E + 15	2.54E + 15 (2.55)	10.4
Boeing 757	No data available	4.566E + 15	3.99E + 15 (1.71)	n/a
Medium to Long Haul				
Airbus A330	2.00E + 15	1.382E + 16	8.63E + 15 (2.51)	4.3
Airbus A340	No data available	8.945E + 15	4.19E + 15 (3.63)	n/a
Airbus A350	3.44E + 15	9.907E + 15	7.13E + 15 (2.47)	2.1
Airbus A380	7.36E + 15	1.097E + 16	6.96E + 15 (2.52)	0.9
Boeing 747	No data available	7.305E + 15	4.26E + 15 (3.05)	n/a
Boeing 767	No data available	9.894E + 15	7.05E + 15 (2.09)	n/a
Boeing 777	No data available	2.074E + 16	1.11E + 16 (3.04)	n/a
Boeing 787	1.49E + 15	1.083E + 16	6.23E + 15 (2.97)	4.2
b:				
Short to Medium Haul				
Airbus A319	1.41E + 15	9.021E + 16	2.144E + 16 (7.03)	15.2
Airbus A320	3.12E + 15	3.262E + 16	1.066E + 16 (4.27)	3.4
Boeing 737	2.64E + 15	2.873E + 16	7.937E + 15 (4.77)	3.0
Boeing 757	No data available	3.098E + 16	1.429E + 16 (3.72)	n/a
Medium to Long Haul				
Airbus A330	2.32E + 15	1.172E + 17	4.592E + 16 (4.26)	19.8
Airbus A340	No data available	1.173E + 17	2.939E + 16 (6.41)	n/a
Airbus A350	2.04E + 15	2.296E + 17	8.743E + 16 (4.76)	42.9
Airbus A380	4.84E + 15	1.780E + 17	6.658E + 16 (4.19)	13.8
Boeing 747	No data available	1.745E + 17	4.393E + 16 (5.09)	n/a
Boeing 767	3.50E + 15	1.309E + 17	3.978E + 16 (5.19)	11.4
Boeing 777	No data available	3.312E + 17	9.699E + 16 (4.07)	n/a
Boeing 787	6.84E + 14	1.669E + 17	5.776E + 16 (4.74)	8.4
Airbus A32x refers to all versions of the A320 and A321 series of aircraft. Airbus A318 results are not reported due to the very small sample collected during this part of the campaign.				
a: ICAO emissions rate data quoted for engines at 30% thrust, summed for the number of engines on the aircraft.				
b: ICAO emissions rate data quoted for engines at 85% thrust, summed for the number of engines on the aircraft.				
GSD Geometric Standard Deviation, reported in brackets.				

lowest emission rates per passenger from departing aircraft are seen from short haul aircraft, e.g., 737 and A32x. Long haul aircraft have emission rates per passenger at least twice as high as the short haul aircraft. The 787, despite being a modern design, carries relatively fewer passengers and thus a higher PNC emission rate per passenger for both arrival and departure.

Using the data from Table 3, a departing long-haul aircraft emits between 2.1 and 7.6 times more particles per second per passenger than an average departing Boeing 737. In contrast, emission rates per passenger from the Boeing 747 are lower than all other aircraft types. While emission rates for aircraft in cruise are not presented here, these basic calculations highlight the complexity of aircraft emissions at airports and why a clear policy for measurement and mitigation has not yet been agreed.

DISCUSSION

This study demonstrates that emissions of UFP from aircraft are a major factor in local air pollution concentrations and emissions near airports^{23,24}. Measurements from individual

aircraft show that total particle number emission rates per passenger carried are lower for larger aircraft, but calculations show that these aircraft also emit significantly more particles per second. The study also shows that volatile and semi volatile particles, condensing and nucleating as the engine exhausts cool and mix, comprise the majority of the total particle numbers that the general public will be exposed to downwind of the airport.

In September 2021, the World Health Organization (WHO) published updated guidelines for global air quality³¹, which includes a “good practice” statement about UFP exposure levels. “High” levels of UFP constitute concentrations above 10,000 #/cm³ for a 24 h average, or above 20,000 #/cm³ for an hourly mean. The average results for this survey in 2019 indicate that UFP concentrations downwind of the airport are likely to challenge this guidance, especially if they are adopted into target or limit values in future legislation. Note that the LHR2 monitoring station location is airside, inside the airport boundary fence where there is no access for the general public. As such, LHR2 is not considered to be representative of

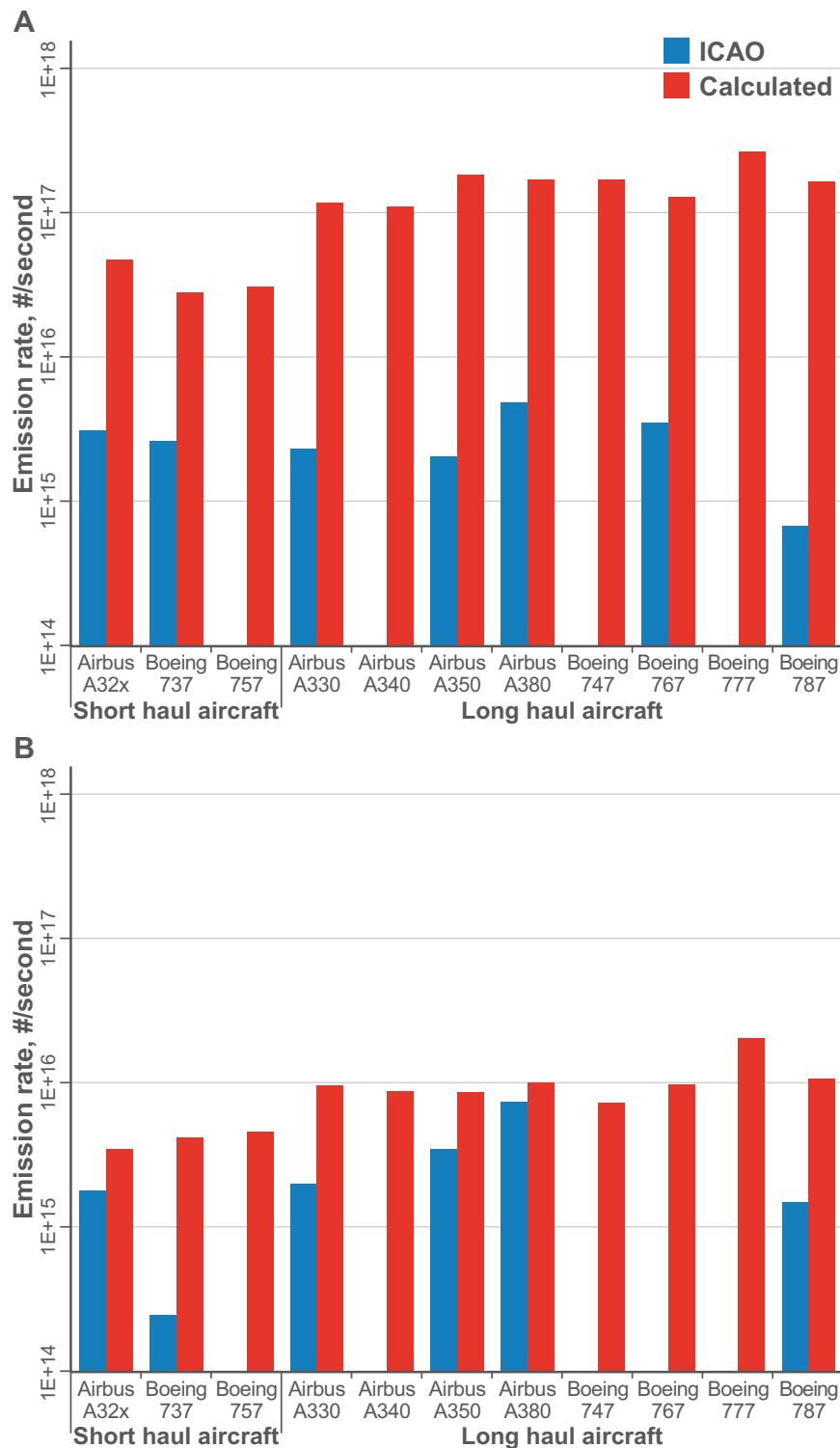


Fig. 5 Bar charts of calculated average and literature Departure and Arrival particle number emission rates. Bar charts of calculated average and literature **A** Departure, and **B** Arrival particle number emission rates. ICAO emission data are unavailable for A340, B747, B757, and B777 departures, as well as A340, B747, B757, and B777 arrivals.

population exposure. Its location provides valuable information for investigating the dispersion, dilution and transformation of UFP emissions further downwind of the airport. The data also highlight the need to monitor beyond the airport boundary as particles emitted from Heathrow are detectable in central London, some 25 km away²⁰.

METHODS

Here we present information about the analysers used, quality control processes, data synchronisation, procedures for data analysis and method used for estimation of UFP emissions. We made use of R, R Studio and the OpenAir suite of tools³² to analyse the relationships between different aircraft types and operating modes.

Table 3. Calculated Total Particle Number emission rates, per passenger for each aircraft type, calculated from Geometric Mean data.

Aircraft type	Estimated maximum passengers	Reported Passenger Load Factor (PLF), %*	PLF Adjusted passenger numbers	PNC per passenger, Departures, #/sec	PNC per passenger, Arrivals, #/sec
Short to Medium haul					
Airbus A319	140	88.5	124	1.729E + 14	1.720E + 13
Airbus A32x	175	89.2	156	6.833E + 13	1.437E + 13
Boeing 737	180	93.3	168	4.724E + 13	1.512E + 13
Boeing 757	210	92.9	195	7.328E + 13	2.047E + 13
Medium to Long haul					
Airbus A330	290	83.1	241	1.905E + 14	3.582E + 13
Airbus A340	350	83.1	291	1.010E + 14	1.439E + 13
Airbus A350	330	81.4	269	3.250E + 14	2.650E + 13
Airbus A380	550	86.6	476	1.399E + 14	1.461E + 13
Boeing 747	420	85.1	357	1.231E + 14	1.194E + 13
Boeing 767	220	88.5	195	2.040E + 14	3.616E + 13
Boeing 777	330	82.2	271	3.579E + 14	4.085E + 13
Boeing 787	275	85.7	236	2.445E + 14	2.642E + 13

Airbus A32x refers to all versions of the A320 and A321 series of aircraft.

*Passenger Load Factor Data obtained from www.caa.co.uk.

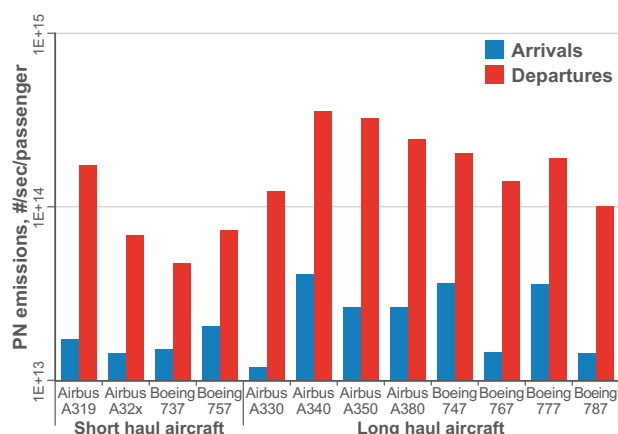


Fig. 6 Bar chart plot of geometric mean emission rates per passenger. Data presented for arriving and departing aircraft from results provided in Table 3.

Air sampling

The monitoring station used for this study is located in the north eastern corner of Heathrow Airport. The station and measurement data can be viewed online³³. The monitoring station is 170 m from the middle of the northern runway, positioned in the prevailing wind from the runway and main terminal areas. The station has been used to measure NO_x and PM continuously since 1993 and for two UFP measurement studies in 2016^{14,15}.

Instrumentation used for the survey

The equipment used at Heathrow Airport for this survey is presented in Table 4.

Quality control processes

The PM, BC and NO_x analysers are all operated according to QA/QC procedures used in the UK national network programmes (QA/QC)³⁴. All analysers are audited and serviced twice yearly with additional traceable calibration standards. The results from these calibrations, services and audits are all used in the process of data ratification. The procedures used to process the raw data are those

used in the UK national monitoring networks, which are fully documented²⁴.

15 min data from the PM, BC and NO_x analysers are downloaded every hour and stored in the cloud. This provisional data is also published in near real time at <https://heathrowairwatch.org.uk> (accessed March 2022). 1 min data from the PM and BC analysers were stored in the analyser internal storage facilities and downloaded to USB sticks every week.

There is currently no ambient monitoring legislation regarding the performance of UFP analysers. The DMS500 was calibrated for both particle counting and sizing using monodisperse soot particles generated at the ISO17025 accredited calibration facilities at the Ricardo Energy and Environment laboratory. In all cases, the sizing capability of the DMS500 was within 1 size bin of the reference standard and within 2% for particle counting (in the range 5e + 03 to 1e + 05). There are no recognised test procedures to assess the capability of the DMS500 analyser (or indeed any other analyser with a classifier) to correctly resolve a polydisperse sample, but the philosophies of Wiedensohler et al.^{35,36} for implementing robust QC to UFP measurements were employed for this study.

There are a number of differing philosophies about how to collect samples for UFP measurements. The few ambient monitoring stations in operation across the UK sample at ambient temperature with a nafion dryer to minimise the impact of water on particle size. It should be noted that water is unlikely to have a significant effect on particles smaller than 50 nm diameter³⁷. The majority of studies of aircraft exhaust emission-related UFP to date have focussed on non-volatile particles, sampling exhaust gases at high temperatures to keep volatile / semi-volatile particles in the gas phase. These differences in sampling methodologies, combined with many different techniques and sampling durations used for studies, means that detailed comparisons of number concentrations between different study programs need to be approached with caution. This was further discussed in the Stacey review of UFP monitoring¹⁶. The DMS500 was configured to undertake regular automatic baseline reprofiling during operation. This operation generally occurred for up to 1 min at three minute intervals. Data validation of the UFP data involved the removal of auto zero data, and screening of data where particle number concentrations were below the limit of detection (for the purposes of this study, all measurements were removed when 10 nm

Table 4. List of monitoring apparatus used for the survey at the LHR2 monitoring station.**Equipment installed**

Cambustion DMS500 Fast Particulate Spectrometer UFP analyser, configured to sample at 1 Hz, 5–1000 nm particle range in 37 different size bins (64 channels per decade), GDI fuel profile algorithm for measurement deconvolution

API T200 NO_x analyser, 15 min average measurements of NO_x, NO and NO₂

FIDAS 200 PM analyser, 1 min average measurements of PM₁₀, PM_{2.5} and PM₁

Magee AE33–7 Black Carbon analyser, 1 min average measurements of Black Carbon (BC) and Ultra Violet Particulate Matter (UVPm)

Lufft WS-600 weather station (Wind Speed / Wind Direction / Temperature / Pressure / Relative Humidity / Precipitation), 1 min average measurements

Praxis Urban NO₂/NO sensor system, 10 s sampling from Alphasense electrochemical cells

particles were below 1000 #/cm³), and where instrument meta data suggested a fault in the measurement process.

The 10 s NO and NO₂ data from the Praxis sensor system required significant processing for baseline drift and temperature sensitivity before any investigation could begin. Once the data had been screened, it was aggregated into 15 min averages and compared against 15 minute average data from the reference NO_x analyser at the monitoring station. The averaged sensor data showed excellent agreement for both NO and NO₂, providing confidence that the 10 s data could be used to establish relationships between measured NO_x from individual aircraft and stated emission rates.

Data synchronisation

1 s of data from the DMS500 was adjusted to agree with the time from the internet (obtained using a mobile phone and verified using <https://time.is>). 15 min average measurements from the NO_x, PM, BC and Meteorology devices are continuously time synchronised from a similar internet clock source. For processing the 1 min PM and BC data the analyser internal clocks were checked for accuracy every week against the mobile phone and measurement data time was corrected when necessary.

High resolution data for individual aircraft movements and runway operating modes was gratefully received from the Aircraft Operations Team at Heathrow Airport. Every second the position, speed, altitude (for aircraft less than 20 metres above ground level) and identification of every moving aircraft on the airfield is recorded. The accuracy of the time stamp is verified using an internet clock source. For the purposes of this study, only aircraft that were on the northern runway, or on the entrances to the northern runway, were included in the analysis of measurement datasets. It is possible that aircraft taxiing to and from the runway will also contribute to measurements when they are directly upwind of the monitoring station, but the distance and lower thrust settings of these aircraft should minimise this potential impact. During westerly winds, the airport operates the two runways in fixed modes. For half of the day, departures are restricted to one runway and arrivals on the other runway. At approximately 14:00 local time, the operation modes are switched, allowing analysis of AQ measurements during arrivals and departures closest to the monitoring station.

For analysis of arriving and departing aircraft, only data associated with winds in the clockwise sector between 100 and 260 degrees, between the hours of 05:00 and 23:00 BST and only during dry weather were included in the analysis. The position of the aircraft on the runway, together with wind speed and direction was then used to determine the time required for the exhaust plume to arrive at the monitoring station. This delay was then fitted to the measurement data to align the measurements to the aircraft. The aircraft type and position meta data were then added to the measurement database to allow a detailed investigation of measurements. Typically, an aircraft departs or arrives at the airport every 90 s.

Data analysis

Data were extensively processed and manipulated using the R and RStudio suite, coupled with OpenAir tools²² for imaging and data sorting. Data analysis was undertaken using a staged and increasingly detailed approach:

- Clustering the full dataset according to wind directions. Similar analysis of this data has been explored in earlier studies^{14,15}, which identified a clear source of the finest particles from the airport. Undertaking this analysis of the 2019 data and comparing it to previous studies provided reassurance of the validity of the DMS500 data.
- Removing unnecessary data:
 - between the hours of 23:00 and 05:00 (when there is no aircraft activity),
 - during periods of rainfall,
 - when aircraft were departing easterly. Operations when aircraft departed easterly were removed, because aircraft only arrive on the northern runway during easterlies, exit the runway more than 2 km from the monitoring station and are therefore assumed to have a minimal contribution to the AQ measurements at the station. Until 2021, aircraft did not normally depart in an easterly direction on the northern runway,
 - data from wind directions clockwise from 260 degrees to 100 degrees. The remaining sector approximates to the zone of Airport contribution to air pollution concentrations.
- Separating the datasets according to runway operating modes, specifically when departing and arriving on the northern runway. Similar analysis of earlier data^{14,15} showed that arriving aircraft emit far fewer particles than departing aircraft. Examination of the 2019 data from the DMS500 confirmed this observation.
- Separating the datasets according to whether an aircraft was on or approaching the northern runway.
- Separating the runway movements into individual aircraft types for both arrivals and departures.

Estimation of UFP emissions from NO_x data: The UFP measurements made with the DMS500 include all types of particles. This will include particles that are emitted and those formed by condensation or coagulation during the advection, cooling and dilution of the exhaust plume as it is transported to the monitoring station. ICAO emissions rate data specifically exclude the latter particles formed from semi-volatiles, and this has a material impact on the comparisons. For the estimation of UFP emission rates from individual aircraft types, a series of processes were undertaken:

- Verification of the baseline and temperature corrected 10 s NO and NO₂ sensor data, once aggregated to 15 min, using the

reference NO_x analyser.

- Sensor “NO_x” data created from the sum of the sensor NO and NO₂ measurements and verified again using the reference NO_x data.
- Separation of the runway only, dry weather NO_x data using the procedures described in the data analysis above.
- Subtraction of background NO_x concentrations, using the nearby Oaks Road monitoring station. The average 15 min background NO_x concentration was subtracted from every 10 s measurement, assuming that background NO_x concentrations would not change significantly during this time.
- 10 second NO_x data was incorporated into the 1 s master dataset, again assuming that there was minimal variation in the NO_x concentrations during the 10 s period.
- NO_x measurements were assigned to individual aircraft and clustered into groups as per the UFP methodology for both departing and arriving aircraft.

Once the NO_x measurements / aircraft correlation had been established, the results were compared against the stated NO_x emissions rates in the ICAO database²⁷ (this assumes 85% thrust settings for departing aircraft and 30% thrust settings for arriving). The average NO_x emission rates for each aircraft group were used, rather than further breaking down the results into individual engine types. Where there are significant differences in emission rates, outlier engine types and associated measurements were excluded from the analysis. For the estimation of emission rates per passenger, we had to decide on a representative value for the number of passengers carried in each aircraft. The manufacturers state a range of seat numbers possible and this will depend on how each company chooses to configure their aircraft. For example, an Airbus A380 can be configured to carry anywhere between 500 and 850 passengers. In practice, the majority of A380s purchased were configured with three classes and approximately 550 passengers, thus we assumed 550 passengers for all A380 aircraft at Heathrow. Similar judgements were made for passenger numbers for the other aircraft types, though the range of minimum and maximum passenger numbers was correspondingly smaller. In order to make the emission rates per passenger comparison, we obtained the relevant Passenger Load Factors (PLF) for Heathrow from <https://caa.co.uk>.

Emission rates for Particle Number Concentrations (# / sec) for both departing and arriving aircraft and aircraft type were then calculated using the measured NO_x data, measured PNC data and the ICAO stated NO_x emissions rates, according to the following equation:

$$\text{PNC emission rate (\#/s)} = \text{NO}_x \text{ emission rate (g/s)} \times \text{PNC (\#/m}^3\text{)} / \text{NO}_x \text{ (g/m}^3\text{)} \quad (1)$$

DATA AVAILABILITY

Data supporting this publication are openly available from the UBIRA eData repository at <https://doi.org/10.25500/edata.bham.00000749>.

CODE AVAILABILITY

No codes were used to support this study.

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AUTHOR CONTRIBUTIONS

B.S. designed and implemented the measurement campaign, collected and processed the data, undertook the analysis and interpretation of the data and wrote the paper. R.M.H. and F.D.P. provided direction for the analysis and interpretation, reviewed and edited the manuscript.

COMPETING INTERESTS

The authors declare no competing interests. The employers of author Brian Stacey (Ricardo) are contracted by Heathrow Airport Limited (HAL) to provide air quality

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ADDITIONAL INFORMATION

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