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# Evaluation of Aircraft Emissions at London Heathrow Airport

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**ABSTRACT**

A study to monitor Ultrafine Particles (UFP) at Heathrow Airport was undertaken in the autumn of 2017. The campaign followed on from a similar study in 2016, which put UFP at the airport into context with nearby measurements. The objective of the 2017 study was to undertake UFP monitoring at higher time resolution (60 second scans) and in a narrower particle size range (6 to 100 nm). High resolution data from the NOx, PM and Black Carbon analysers on site was also collected during the survey. Measurements were made at the runway station, LHR2 to attempt to characterise individual aircraft using the runway. Nucleation mode particles are again seen to predominantly originate from the airport, with highest concentrations associated with departing aircraft. While there is some correlation of nucleation particles with NOx and BC, these pollutants, together with PM mass and Aitken mode particles, also show strong associations with winds from off-airport directions. There is some evidence that BC emissions from landing aircraft are enriched in UV-active BC (UVPM), most likely as a result of tyre abrasion upon landing. Comparison of UFP measurements with the 2016 survey was not possible because of the differences in configuration of the SMPS for the two surveys. This observation demonstrates the importance of documenting SMPS configuration, to determine if comparison between published data is possible. Analysis of the 1 minute measurement data with associated aircraft departure information was used to group the data by aircraft type. Larger aircraft departing from the runway recorded higher measurements of nucleation particles and NOx compared to smaller aircraft, while emissions of BC, UVPM and $NO_2$ appear to be dependent upon the age of the engine design, rather than the size of the aircraft.

## 1. INTRODUCTION

Heathrow Airport is the busiest two-runway airport in the world. In 2017, the airport handled over 78.0 million passengers and approximately 471,000 aircraft movements (https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/investor/reports-and-presentations/financial-results/2017/2017-FY-Heathrow-SP-results-release.pdf). The airport is located in a complex environment: bounded by the M25 and M4 motorways on two sides, and by the outskirts of London on a third side.

The history of AQ measurements at Heathrow Airport, together with review of UFP at airports and the results of our UFP study at Heathrow Airport in 2016 are extensively discussed in Stacey (2019) and Stacey et al (2020)

An increasing amount of research has been undertaken close to airports, to better understand the nature of ultrafine particles (UFP) emitted from aircraft. The literature review by Stacey (2019) collected the most relevant literature at the time into a single document. Prior research undertaken and referenced in this review, together with a research study of UFP measurements undertaken at Heathrow Airport in 2016 by Stacey et al (2020), informs the direction of research and analysis throughout this paper. More recently studies by, for example Henry et al (2019), Lopes et al (2019), Bousiotis et al (2019) and Rivas et al (2020) have supported the work of others that UFP from airports and aircraft can be observed many kilometres downwind of an airport. Fushimi et al (2019) found that a significant proportion of UFP measured at Narita Airport consisted of unburned jet lubrication oil.

Similarly, the impact of UFP on health has been increasingly studied in recent years. Bendtsten et al (2019) reported that the UFP sampled at two airports in Denmark is comparable in toxicity to UFP from diesel exhaust. Habre et al (2019) found observable health impacts in sensitive receptors downwind of Los Angeles International Airport (LAX), while Wing et al (2020) also identified a link between exposure to aircraft-related UFP and pre-term birth in the region of LAX

For the first time, a panel of experts (Cassee et al, White paper, 2019) has put forward a proposal to regulate exposure to concentrations of UFP. In terms of mitigation, both Cassee et al (2019) and De Jesus et al (2019) found that reducing emissions of $PM_{2.5}$ was not likely to have any significant effect on measured concentrations of UFP.

The Stacey et al (2020) study showed that UFP concentrations at Heathrow in 2016 were clearly influenced by aircraft activity and wind direction. The smallest particles were associated with winds from the airfield, and the particle size distribution of the airport-derived airmass was clearly different to typical urban roadside, urban background and rural distributions. The study focussed on ensuring comparability with the reference monitoring stations, which report measurements every three minutes. At this time resolution, it is not possible to use the data to identify individual aircraft, which depart or arrive on average every 90 seconds at Heathrow.

A follow-up campaign was therefore devised to measure UFP, and where possible the other pollutants at the monitoring station, at a faster time resolution to evaluate individual aircraft emissions and the relationships between aircraft, UFP and other pollutants. This paper builds on the 2016 report and presents the results of the 2017 study.

## 2. METHODS

### 2.1 Monitoring Location

This measurement campaign was designed to undertake rapid measurements of UFP and the conventional pollutants at Heathrow to further explore the local nature of these pollutants in the context of aircraft movements at the airport.

The network of air quality monitoring stations at Heathrow Airport is presented in Figure 1:

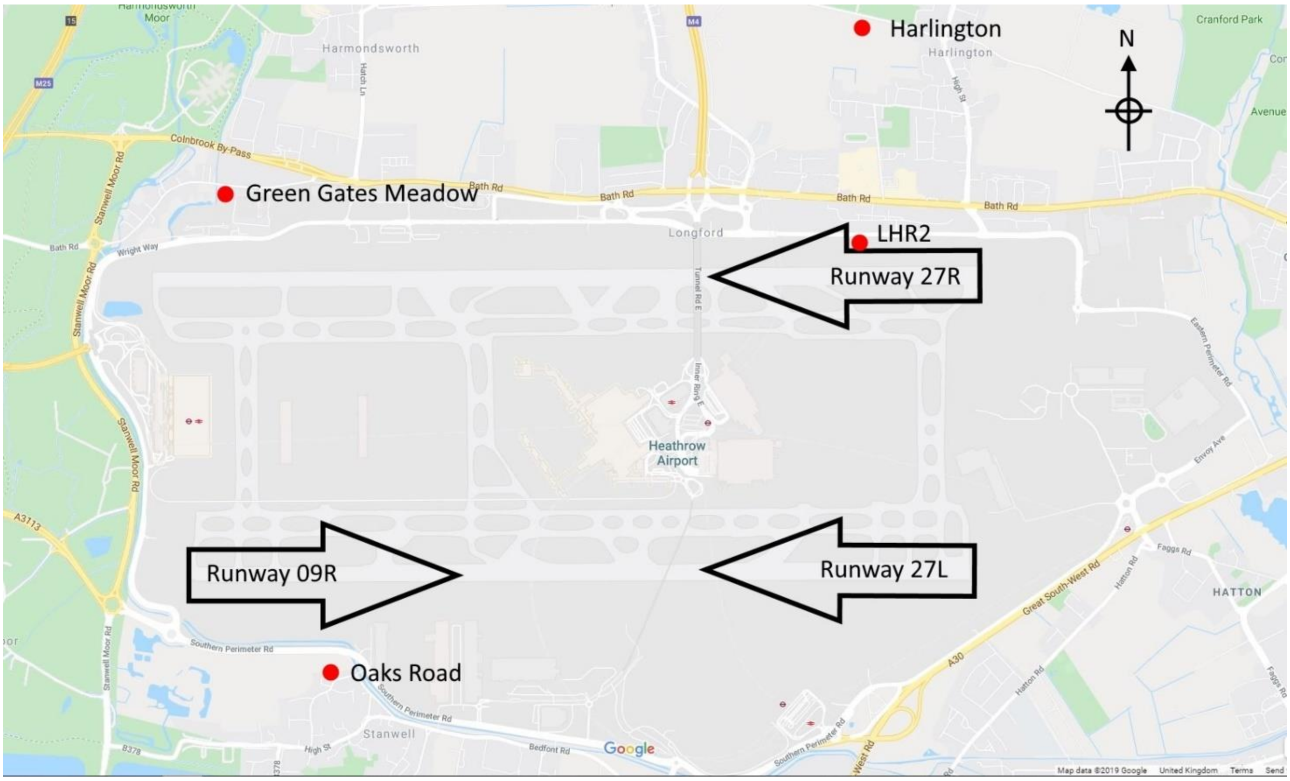


**Figure 1**. Locations of Heathrow monitoring stations. Runway 27R, Runway 27L and Runway 09R denote the three operating modes of the airport, indicating here the runway assigned for departing aircraft. Note that aircraft never depart in an easterly direction on the northern runway.

Because of the dominant south-westerly nature of the winds in the UK, the LHR2 monitoring station is ideally positioned to measure aircraft exhaust plumes. This location was also one of the two monitoring stations used in 2016 and fully described in Stacey et al (2020).

### 2.2 UFP Measurement Campaign

Measurement of UFP at the LHR2 monitoring station was undertaken between 4$^{th}$ October and 7$^{th}$ November 2017.

The following equipment was used:

- Butanol based TSI Model 3776 CPCs (TSI inc., MN, USA) to count particle numbers (the 3776 is more effective at detecting smaller particles than previous TSI CPCs - D50 2.5nm).

- TSI Model 3082 with long DMA (Model 3081) classifier and soft X-ray neutraliser. Automatic on-board software correction was enabled for diffusive losses and multiple charge. Analyser operation and data storage controlled by the Model 3082 running AIM v10.2.0.11. Data was downloaded weekly from the 3082 to a USB stick for subsequent analysis.

The operating methodology of the TSI Scanning Mobility Particle Sizer (SMPS) and Condensation Particle Counter (CPC) has been extensively described in literature, for example by Wiedensohler et al. (2012) and Wiedensohler et al. (2018). The only difference from the recommendations of Wiedensohler et al. (2012) was the absence of a dryer. This is considered advantageous due to minimising diffusive losses of particles while having little effect upon the size distribution of largely hydrophobic nanoparticles subject to a significant Kelvin effect.

The SMPS instrument was configured to sample in the range 6.38nm to 98.2nm, 64 channels per decade. Sampling was programmed to run for 1 minute, sweeping up in size for 45 seconds, and returning down for the remaining 15 seconds.

The instrument was set up to be operated continuously for the entire measurement campaign; unattended automated operation 24 hours per day. Because of the proprietary nature of the TSI software and only a short window of opportunity to deploy the analysers, remote communication to the analysers was not undertaken. The monitoring station was visited weekly to ensure correct operation and take remedial action if required.

Calibration of the CPC and SMPS followed identical procedures and used facilities described in Stacey et al (2020) but within the narrower particle size range used for the 2017 survey.

The 6-100nm configuration of the SMPS in 2017 differs significantly from the setup used at Heathrow in 2016 by Stacey et al (2020) and in the UK National Particles network. Both the Heathrow 2016 and National Network configurations are described in the Stacey et al (2020) paper and are not documented further here. Comparisons of the 2016 and 2017 datasets will be explored in the results, but will be significantly influenced by the differences in configurations used in 2016 and 2017 and, to an extent, the differing meteorology.

The other analysers deployed at LHR2 are described fully in Stacey et al (2020), but were additionally configured to collect 1 minute average data.

### 2.3 Data Analysis

The plots and analysis undertaken in this paper make extensive use of the R and R Studio programs (R Foundation for Statistical Computing, Vienna, Austria, and R Studio Inc, MA, USA) and the OpenAir suite of analysis tools (Carslaw and Ropkins, (2012))

In accordance with the processes defined in Stacey et al (2020) for the 2016 datasets, Nucleation particles are defined as particles smaller than 25 nm, Aitken particles are defined as particles between 26 and 100 nm.

Particle number concentrations are reported in units of particles /$cm^3$, and are calculated from individual size bin data from the SMPS, with no decade adjustment applied.

Measurements from the black carbon aethalometers are reported using identical procedures as reported in Stacey et al (2020)

### 2.5 Measurement Quality Assurance and Quality Control

Processing of the data was undertaken using the same QA/QC procedures described in Stacey et al (2020). While the Heathrow study UFP data reported here uses the same quality assurance and quality control procedures used for the national network datasets and the 2016 study, the differences in configurations in 2017 (including flow rates, size ranges, sample time, software), will have a significant impact on the ability to make direct comparison between the two surveys. These differences will be discussed later.

For measurements of $NO_x$, $PM_{10}$, $PM_{2.5}$, BC and meteorology, the measurements at Heathrow are managed, collected and processed following guidance described in https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1902040953_All_Networks_QAQC_Document_2012__Issue2.pdf. Information about these analysers is also provided in the Supplemental Information, Tables S1 and S2.

# 3. RESULTS

## 3.1 Overall Summary

Timeseries data for the hourly measurements at LHR2 are presented in Figure 2 below. One minute data for all pollutants are available in the DOI, and are presented graphically in Supplemental Information, Figure S1. Hourly averaged measurements of $NO_x$, $PM_{10}$, $PM_{2.5}$ and BC are also accessible through the http://heathrowairwatch.org.uk webpages. The 1 minute averaged data from these analysers will be used to explore associations and differences to typical ambient environments.

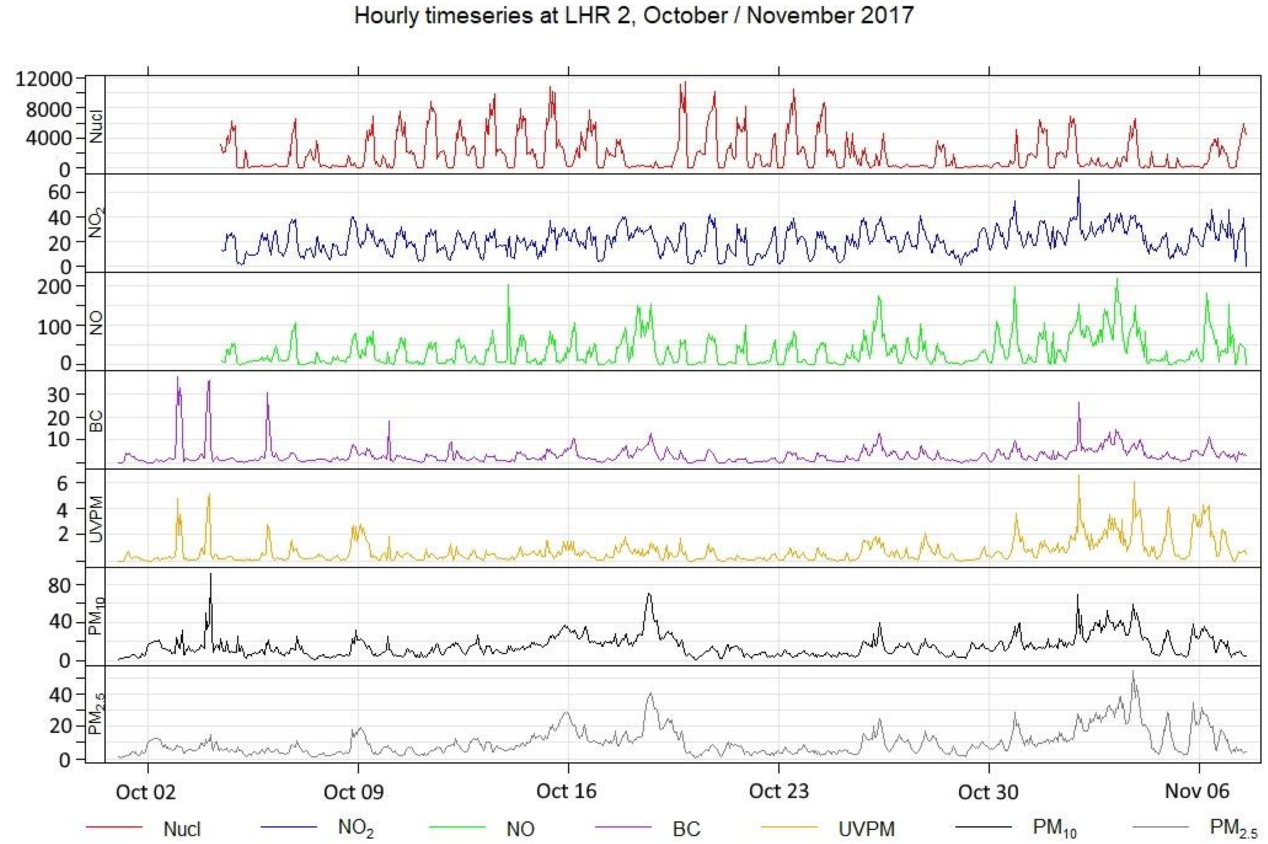


**Figure 2** – Hourly timeseries data at LHR2, October and November 2017. Reported concentrations are ppb for NO and $NO_2$, ug/m$^3$ for $PM_{10}$, $PM_{2.5}$, BC and UVPM, and particles/cm$^3$ for nucleation particles (labelled Nucl on the plot).

It can be seen from Figure 2 that the nucleation concentrations appear to be weakly correlated with $NO_2$ and BC (all data $r^2$ 0.2 to 0.3), but the relationship for nucleation particles is poor with $PM_{10}$ and $PM_{2.5}$ (all data $r^2$ less than 0.01)Concentrations of nucleation particles clearly undergo a diurnal cycle and, as observed in 2016 (Stacey et al (2020)), increase coincident with periods when aircraft are active. The average particle size distribution for the 2017 survey reaches a maximum number concentration at 12.2 nm.

Diurnal plots are presented in the SI (SI figs S26 to S33). Concentrations of NOx, Nucleation and Aitken particles follow the expected diurnal profiles, where highest concentrations are experienced between 06:00 and 21:00. In contrast, diurnal concentrations of PM, BC and UVPM are highest between the hours of 18:00 and 02:00, coinciding with traditional periods of domestic heating, and the increase in the evening due to the road traffic rush hour. The diurnal profiles for PM follow the typical profile of regional monitoring (presented in the SI), suggesting that airport measurements are strongly influenced by off-airport airmasses.

## 3.2 Dependence of Airport Measurements on Meteorology

The meteorology for the 2017 survey was dominated by south westerly winds, ideal for assessing the contribution of the airport and aircraft emissions at the LHR2 monitoring station. The wind rose plot for the survey is presented in the SI, figure S34

Polar plots of the hourly average data are presented in the SI, figures S2 to S10. As with the 2016 survey, nucleation particles are almost exclusively associated with winds from the airport. Aitken particles are strongly associated with winds from the airport, but there is also contribution from easterly and northerly wind directions. NOx, $PM_{10}$ and $PM_{2.5}$ polar plots are very similar to those seen at other monitoring stations across the south east of England, and mostly not from the direction of the airport, reflecting the diverse sources of these pollutants in the UK. The polar plots for BC and UVPM show some influence from the airport, but also when winds are low and immediately west of the station. There was a construction depot next to the monitoring station during the survey, active between 23:00 and 04:00, and it is likely that this has influenced the data. For the purposes of aircraft analysis, this period is not included in analysis in any case. Imagery of the construction depot is presented in the SI, figure S11

## 3.3 Relationship Between Pollutants

Following exact time synchronisation of all measurement datasets, bivariate regression analysis was undertaken using the polarPlot function in openAir. This analysis was used to identify which wind directions were associated with the closest correlation between pollutants. These plots are provided in the SI, figures S12 to S25.

The plots show very strong ($r^2$ greater than 0.8) correlation between Nucleation and Aitken particles from the direction of the airport, much weaker when winds are from northerly directions. The weak correlation ($r^2$ less than 0.4) between Nucleation and Aitken particles from the north clearly indicates that nucleation particles mostly originate from the airfield. Nucleation particles from the airport are also closely correlated with BC ($r^2$ above 0.8).

Nucleation particles from the airport show some correlation with UVPM and NOx ($r^2$ between 0.5 and 0.9) , but correlation is weak ($r^2$ less than 0.4) for Nucleation particles with either $PM_{10}$ or $PM_{2.5}$.

$PM_{10}$ and $PM_{2.5}$ correlation with NOx is mostly weak ($r^2$ less than 0.5) for most wind directions, though there are clusters of good correlation ($r^2$ above 0.8) to the north and one to the south that could be associated with the nearby runway. $PM_{10}$ and $PM_{2.5}$ correlations with UVPM ($r^2$ above 0.8) are strongly associated with some airport wind directions and speeds, as well as from directions north of the monitoring station, suggesting a multitude of sources contributing to PM and UVPM in the area. The correlation immediately to the south closely mirrors the PM/NOx correlation, further suggesting the influence of the runway as a contributor to local measurements.

NOx and BC correlation is good to strong ($r^2$ between 0.6 and 1.0) for most wind directions except for the NW sector. Correlation between NOx and UVPM is strong ($r^2$ above 0.8) for wind directions associated with the airport.

### 3.4 Dependence of Measurements on Airport Operation

As previously stated, Heathrow operate the two runways in a rotating system when aircraft depart and arrive in a westerly direction. During any typical day, aircraft land on runway 27R for half the day, before swapping and landing on runway 27L. Aircraft depart on the other runway, allowing complete independence of departure and arrival schedules. From a monitoring perspective, this is very useful, because it raises the possibility to assess emissions from departing and arriving aircraft.

It needs to be remembered that the measurements at the monitoring station will be impacted by cooling, dilution and interaction with other sources, but this is mitigated to some extent by the proximity of the station to the runway and the absence of any other sources between the aircraft and the monitoring station. In addition, especially for gaseous and mass-based PM measurements, while the background concentrations will contribute to the reported measurements, their contributions are not removed from the datasets. This has been considered during the analysis. Aircraft movement information for the 2017 survey was again provided by Heathrow Airport Limited.

The 2016 survey found that average concentrations of Nucleation particles was highest when aircraft were departing closest to the monitoring station.
The table below provides average concentrations measured at the airport in October / November 2017 in various operating modes:

| Pollutant / Operation | Overall (902 hours) | Depart 27R (320 hours) | Depart 27L (308 hours) | Depart 09R (45 hours) | Overnight (229 hours) |
|---|---|---|---|---|---|
| Nucleation, # / $cm^3$ | 1813 | 3625 | 1328 | 422 | 141 |
| Aitken , # / $cm^3$ | 205 | 317 | 191 | 127 | 81 |
| BC, $\mu g/m^3$ | 3.22 | 3.61 | 2.34 | 4.47 | 3.61 |
| UVPM, $\mu g/m^3$ | 0.71 | 0.85 | 0.49 | 0.58 | 0.83 |
| $PM_{10}$, $\mu g/m^3$ | 15.1 | 14.4 | 13.5 | 28.4 | 15.5 |
| $PM_{2.5}$, $\mu g/m^3$ | 10.0 | 9.7 | 8.9 | 18.6 | 10.2 |
| NOx, ppb | 52.9 | 76.5 | 39.2 | 71.5 | 33.4 |
| NO, ppb | 32.6 | 50.1 | 20.6 | 48.8 | 20.1 |
| $NO_2$, ppb | 20.3 | 26.4 | 18.7 | 22.7 | 13.2 |

**Table 1** – average concentrations in different airport operating modes.

The table clearly shows that:

- Highest particle numbers are associated with aircraft departing from runway 27R, closest to the monitoring station. On average, Nucleation particle concentrations are 3 times higher than those seen for aircraft landing on runway 27R (departing on 27L), ~8.5 times higher than operations in easterly winds (departing on 09R) and 25 times higher than when the airport is closed overnight.
- For Aitken particles, the differences are less marked: when aircraft are departing on 27R, average concentrations are 1.7 times higher than departures on 27L, 2.5 times higher than departures on 09R and 3.9 times higher than overnight concentrations. Additionally, concentrations of Aitken particles show a significant baseline that appears to be independent of airport operating mode, confirming that emissions of Aitken particles from the airport are produced in far smaller quantities when compared to emissions of Nucleation particles.
- PM concentrations are highest during easterly winds (departing on 09R). This is certainly the influence of longer range transport of PM from London and beyond.
- BC concentrations are also highest during easterly winds, but average concentrations are higher for aircraft departing on 27R compared to landing on 27R. This is also true for UVPM.
- UVPM concentrations are elevated overnight, confirming that domestic heating is a likely additional source in the area.
- Average NOx, NO and $NO_2$ concentrations are all higher when aircraft depart on 27R compared to landing on 27R (departing on 27L). But high average NOx and NO concentrations are also recorded during easterly winds, reflecting the influence of emissions from London on these local measurements.

The observation that departing aircraft emit higher numbers of UFP compared to arriving aircraft appears to contrast with work by other researchers, eg. Hudda et al (2017), Shirmohammadi et al (2017), which suggest that arriving aircraft have a significant effect on UFP concentrations directly under the flight path. However, other studies, including Keuken et al (2015) have shown that elevated UFP concentrations can be attributed to airports even 40km from the airport and not under flight paths.  It is therefore possible that ground level dispersion of UFP emissions from aircraft movements has not yet been fully considered in modelled and measured approaches to the assessment of UFP from aircraft and further investigation of the possible impact mechanisms is warranted.

### 3.5 Examination of Fine Temporal Resolution Data

The monitoring station at LHR2 is 170m from the centre of the northern runway.  Under favourable meteorology, plumes from aircraft departing and landing impact on the monitoring station, raising the possibility that these plumes can be further analysed and characterised by, for example, aircraft type, engine type, aircraft landing and aircraft departing.

On average (https://www.heathrow.com/file_source/Company/Static/PDF/Investorcentre/Heathrow-(SP)-FY2016-results-release-(FINAL).pdf), an aircraft departs from the airport every 90 seconds between 06:00 and 23:00 every day.  The SMPS/CPC configuration at LHR2 was set to provide a full particle size sweep every minute, allowing the possibility to investigate whether to uniquely assign a single measurement to an individual aircraft.   Some structure in the PN measurements can be observed which bears excellent correlation to the runway operations.  The plot in Figure 3 presents the stacked timeseries collected on 20 October.

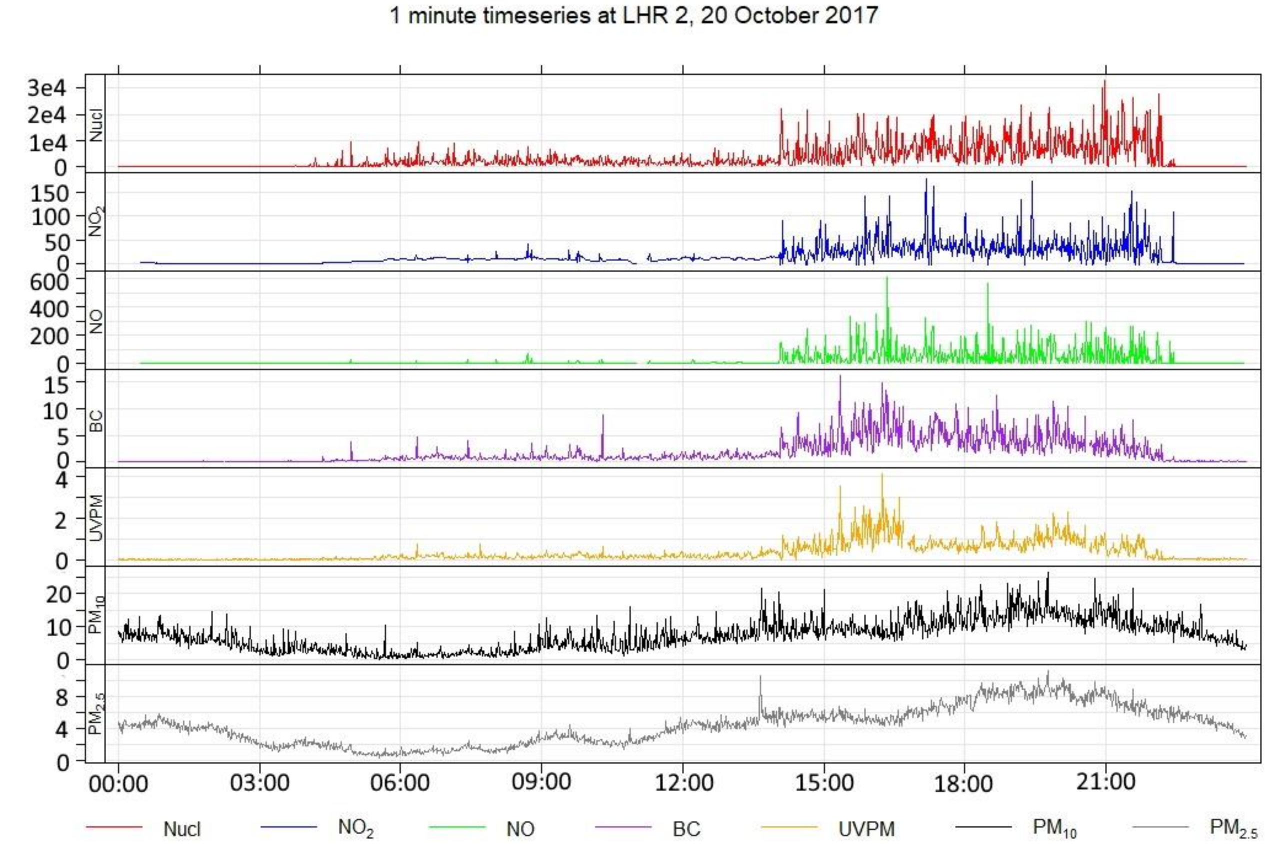


**Figure 3.** Stack timeseries plot, LHR2, 20 October

On this day, aircraft were landing on 27R during the morning period, and departing from 27R in the afternoon period. The elevated Nucleation particle count during departures is very clear in this plot and mirrors the observations seen in the 2016 survey. The plot also shows very clear correlation of NOx, BC and UVPM with particle number concentrations, lower for arriving aircraft and higher for departing aircraft – as would be expected for the different thrust settings in these two modes of engine operation.

Correlation of the above pollutants is less obvious for $PM_{10}$ and $PM_{2.5}$, which do not follow the abrupt change in scale when the aircraft operating mode changes. The level of detail seen in the 1 minute data allows some unexpected observations to be made. The plot in Figure 4 shows the stacked timeseries for 16 October:

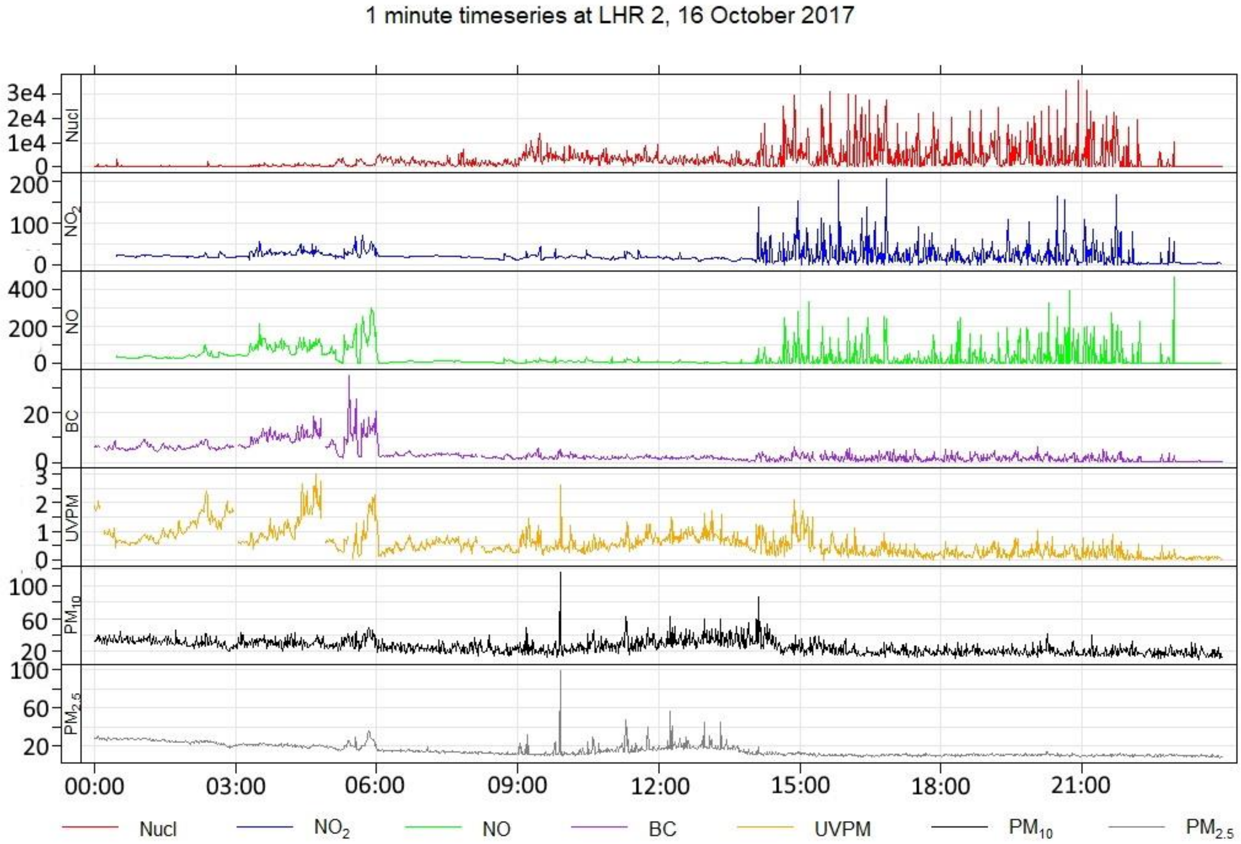


**Figure 4.** Stack timeseries plot, LHR2, 16 October

Aircraft movements on 16 October followed the same pattern as 20 October and the trends between pollutants is, by and large, similar. Closer inspection reveals some subtle differences:

- $PM_{10}$ and $PM_{2.5}$ concentrations are higher during the morning arrival mode than the afternoon departure mode.
- BC and UVPM concentrations do not follow each other at all throughout the airport operating day. Prior to 06:00, the agreement between them is reasonable, though the effect of non-aircraft sources (e.g. overnight domestic heating) is observable in the data. UVPM concentrations are high between 09:00 and 15:00 (during arrivals), compared to concentrations after 15:00. In contrast, BC concentrations between 09:00 and 15:00 are lower than measurements after 15:00. On examination of the meteorology between 09:00 and 15:00, recorded wind directions were between 170 and 220 degrees. This is the sector where air sampling captures the point where the majority of aircraft touchdown on the

runway, leading to the possibility that tyre smoke from landing aircraft was transported from the runway and measured at the station during this period. Tyre smoke from landing aircraft is a blue-grey colour and likely to be in the fine particle range, as the tyres are subjected to great stress from the acceleration and weight of the aircraft. The correlation between $PM_{2.5}$ and UVPM, together with the absence of correlation with NOx and Nucleation particles, associated with exhaust emissions, further supports this observation.

- Winds from 0:00 to 06:00 originated from the north east and east of the monitoring station, suggesting off-airport emissions contributed to the elevated levels of NOx, BC and UVPM during this period. The NOx, BC and UVPM measurements at LHR2 are very similar to measurements made at other monitoring stations in the area.

The SMPS/CPC setup provides detailed information about the PSD every minute. This detail is not necessary for analysis, as the breakdown into nucleation and Aitken particle number concentrations demonstrates how the particle size distribution is dominated by fine particles. For completeness, an animation of the 1 minute PSD data from 20 October is provided in SI Animation S1. This animation clearly shows three distinct modes:

- Period when aircraft are not operating (0:00 to 06:00 and 23:00 to 0:00)
- Period where aircraft are landing (06:00 to 14:00)
- Period where aircraft are departing (14:00 to 23:00)

The animation also shows just how dependent the measurements are on aircraft movements. There are many periods of both high emissions, associated with aircraft, and relatively “quiet” periods, coinciding with reduced aircraft activity. This is the first time that we are aware of that airport UFP measurements have been reported in this way, clearly illustrating the nature and effect of the aircraft activity.

### 3.6 Correlation of UFP with aircraft movements

As part of normal airport operation, Heathrow Airport Limited keep a log of all aircraft ground movements. Records of aircraft type, time of departure or arrival and the relevant runway used were provided at 1 minute resolution. This allows analysis of Nucleation mode particles to be closely associated with exhaust plumes by tying together aircraft location, wind speed and direction, time taken for the plume to arrive at the measurement station and the associated pollution data. By knowing what aircraft is being measured, clustering of Nucleation particle concentrations by aircraft type is also possible.

For the purposes of this investigation, only aircraft departing on 27R were examined, and only when winds were from the 105 to 265 degree sector – i.e. when the exhaust plume would be transported to the monitoring station. Reviewing the timeseries data for the entire survey, there were a selection of days when concentrations of Nucleation particles were highest, providing the strongest potential to assign peak concentrations to individual aircraft. The comparison was therefore further restricted to include only departures on 9-16, 19-21, 23 and 31 October 2017. During this time, 5127 aircraft departed from Runway 27R, clustered into the following groups:

| Aircraft type | Number of aircraft | Number of aircraft successfully identified | Percentage of total successfully identified |
|---|---|---|---|
| Airbus A31x / A32x series | 2408 | 1188 | 49% |
| Airbus A33x series | 191 | 113 | 59% |
| Airbus A34x series | 72 | 52 | 72% |
| Airbus A35x series | 42 | 21 | 50% |
| Airbus A380 series | 315 | 200 | 63% |
| Boeing 737 series | 137 | 69 | 50% |
| Boeing 747 series | 308 | 202 | 66% |
| Boeing 757 series | 39 | 15 | 38% |
| Boeing 767 series | 307 | 196 | 64% |
| Boeing 777 series | 732 | 477 | 66% |
| Boeing 787 series | 442 | 274 | 62% |
| Others | 134 | 70 | 52% |

| | | | |
|---|---|---|---|
| Total | 5127 | 2877 | 56% |

**Table 2** – Departing aircraft on Runway 27R, separated by type, on selected days in October 2017. “successfully identified” represents the number of aircraft where measured nucleation concentrations were elevated above the prevailing background concentrations at the expected arrival time of the plume at the monitoring station.

Initial review of the assignment of peaks revealed that a large number of departures were poorly identified by the analysers. A higher proportion of heavier aircraft, with an expected higher fuel use during takeoff, are successfully identified when compared to lighter aircraft (for example 72% of all A340 aircraft were identified, vs 49% of all A31x/A32x). By way of example of the problem of identification, Figure 5 shows Nucleation particle concentrations over a one hour period on one day.

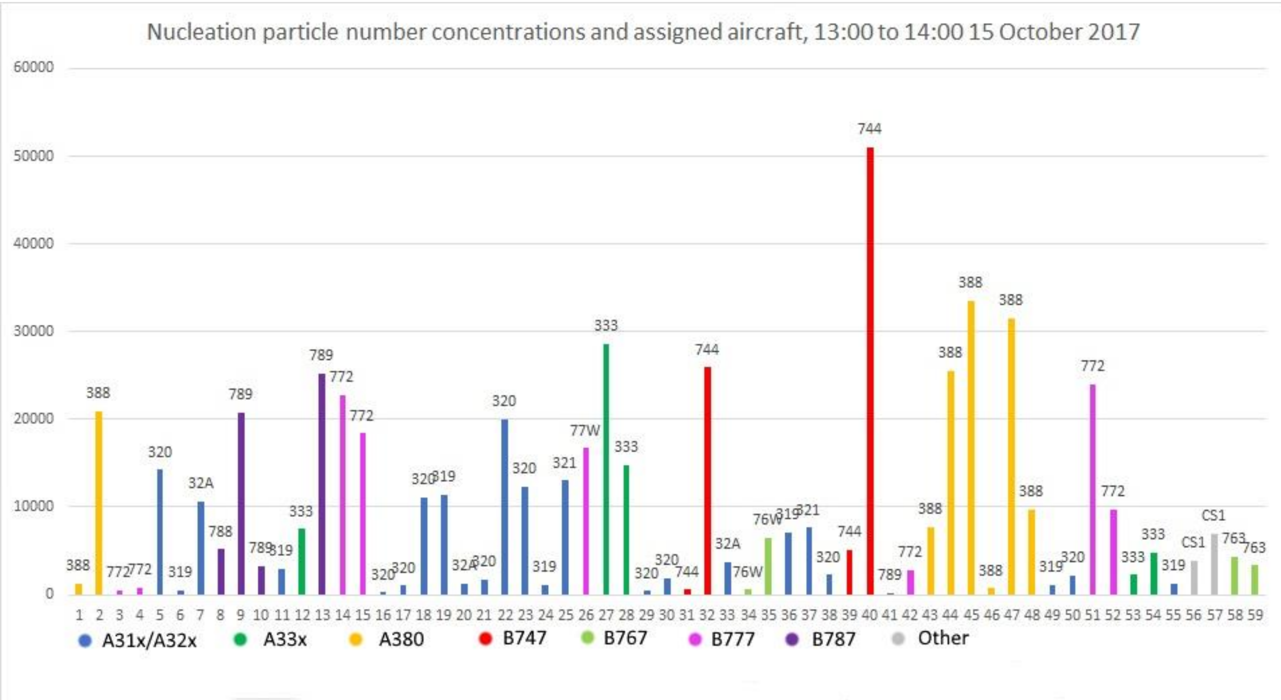


**Figure 5** – Nucleation concentrations recorded for aircraft departures, 13-14:00 15 October 2017. The aircraft type is labelled at the top of each bar, and colour coded according to the legend.

It is clear from this plot that a significant number of nucleation peaks are very low when compared to other similar aircraft. There are a number of possible reasons for this:

- The departure time of the aircraft is reported at the start of the minute the aircraft “throttles up”. It was not possible to determine the exact position of the aircraft on the runway, so assumptions are made about when the emission plume will arrive at the monitoring station.

- High time resolution meteorological data was not available for this survey. All calculations for plume transportation were made using 15 minute averaged wind speed and direction data
- The dataset has not been screened for rainfall. A proportion of plumes will have been negatively impacted during periods of rainfall, but high resolution rainfall data was not available to identify and filter out these periods.
- The 1 minute scan of the SMPS from 6 to 100 nm means that if the exhaust plume arrived at the monitoring station midway through the scan, it is possible that the SMPS would miss the Nucleation particles completely from a departing aircraft.
- It is also possible that, when wind direction was closer to 260 degrees, that the plume from a departing aircraft would be detectable for a longer period, due to the increased distance from the monitoring station, leading to the possibility that the SMPS would record a single aircraft plume over multiple minutes.

Because of the number of mis-assigned plumes, the data were further screened by rejecting identifications when Nucleation particle number concentrations were lower than 4000/cm$^3$. Using this restriction, 44% of the departures were removed from the analysis. The table below summarises the results from these screened identifications.

| Aircraft type | # Aircraft assessed | Nucleation particles, #/cm$^3$ / RSD, % | BC, ug/m$^3$ | UVPM, ug/m$^3$ | NO, ppb | $NO_2$, ppb | $PM_{10}$, ug/m$^3$ | $PM_{2.5}$, ug/m$^3$ |
|---|---|---|---|---|---|---|---|---|
| Airbus A31x / A32x series | 1188 | 8060 / 47% | 4.18 | 0.80 | 42.1 | 27.9 | 13.1 | 8.5 |
| Airbus A33x series | 113 | 11438 / 59% | 3.87 | 0.64 | 85.0 | 41.8 | 12.4 | 8.0 |
| Airbus A34x series | 52 | 10859 / 60% | 4.50 | 0.51 | 91.0 | 31.2 | 12.4 | 8.0 |
| Airbus A35x series | 21 | 12266 / 45% | 3.34 | 0.54 | 99.7 | 39.9 | 11.4 | 7.0 |
| Airbus A380 series | 199 | 13578 / 64% | 3.98 | 0.66 | 107.9 | 34.7 | 13.2 | 8.3 |
| Boeing 737 series | 69 | 7719 / 46% | 3.57 | 0.73 | 39.4 | 24.8 | 14.3 | 9.2 |
| Boeing 747 series | 202 | 12734 / 63% | 4.12 | 0.72 | 95.6 | 40.0 | 13.0 | 8.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Boeing 757 series | 15 | 7063 / 45% | 4.80 | 0.67 | 70.9 | 32.3 | 13.9 | 8.9 |
| Boeing 767 series | 196 | 10438 / 57% | 4.59 | 0.79 | 84.0 | 38.6 | 12.7 | 8.4 |
| Boeing 777 series | 477 | 12422 / 56% | 3.56 | 0.69 | 112.3 | 38.3 | 12.7 | 8.3 |
| Boeing 787 series | 274 | 12406 / 56% | 3.14 | 0.64 | 84.1 | 35.1 | 12.3 | 7.9 |
| Others | 70 | 8078 / 47% | 3.31 | 0.72 | 36.2 | 26.0 | 12.9 | 8.6 |
| **All departures** | **2876** | **10266** | **3.94** | **0.73** | **71.9** | **33.0** | **12.9** | **8.4** |

**Table 3** – Summary of average concentrations, separated by aircraft type, screened for Nucleation particle measurements greater than 4000 particles / cm$^3$. The relative standard deviation (RSD) for nucleation particles is presented to demonstrate the wide variation in the measurements recorded.

The Nucleation particle number data are further assessed in the box and whisker plot in Figure 6:

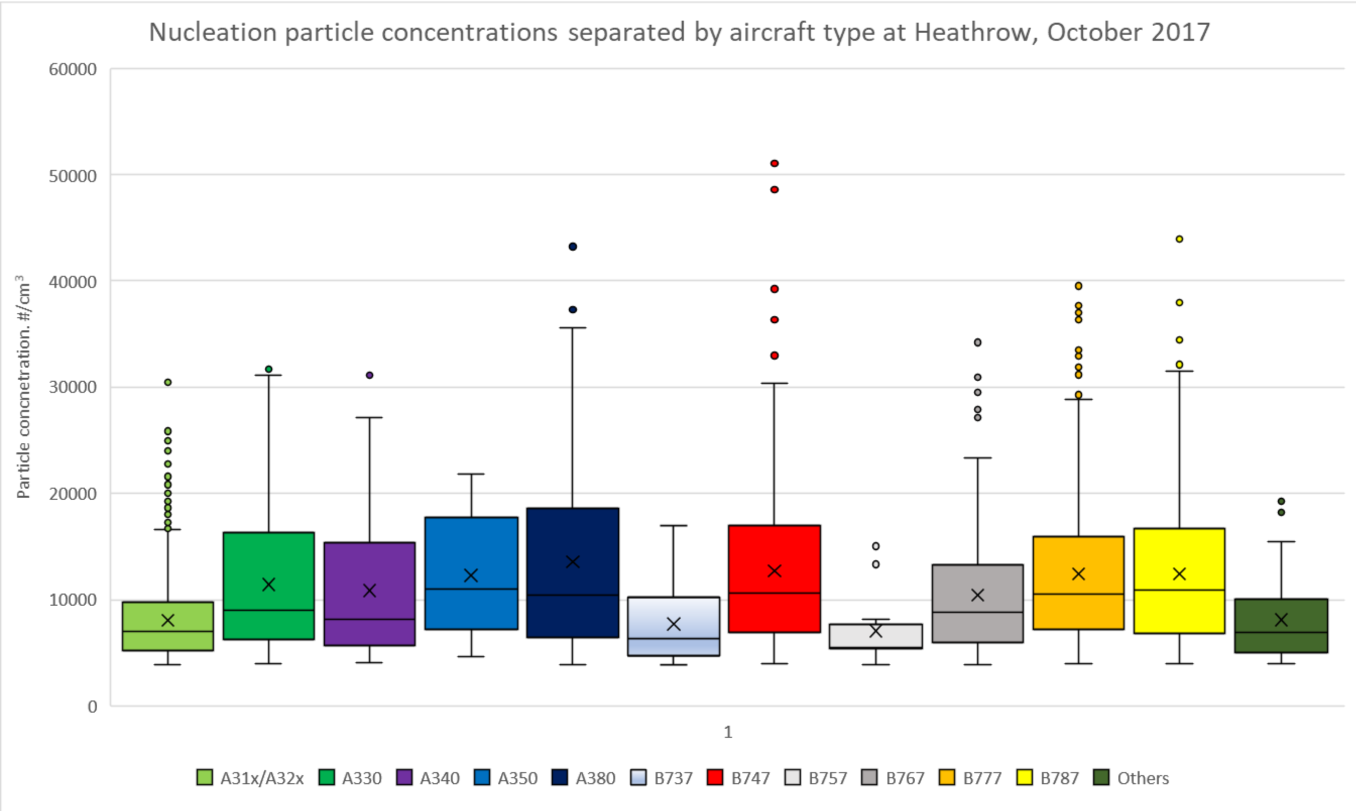


**Figure 6** – Box and whisker plot, separating nucleation measurements by individual aircraft type. Average concentrations are represented by a X, median by a line within the box. The box upper and lower limits represent the 25th and 75th percentiles while the whiskers present the 0 and 100% boundaries. Note that the lower whisker ignores data screened by rejecting all results below 4000 particles/cm$^3$. Outliers are represented by individual dots.

Bearing in mind the varying sample sizes for each aircraft type, the average data in the above table and figure confirms the following:

- Smaller aircraft emit fewer nucleation particles than larger aircraft

- Total NOx concentrations are highest from largest aircraft
- $NO_2$ concentrations follow a similar pattern to NOx – larger aircraft generally emit higher concentrations than smaller aircraft, though it is likely that the newer fleet of heavy aircraft have lower $NO_2$ emissions – measured $NO_2$ from Boeing 747 aircraft is higher than Airbus A380 aircraft, for example. More investigation is required to get a fuller understanding of this observation.
- There is no clear trend in the BC data. Average BC emissions from the Boeing 787 were the lowest recorded for any aircraft type, suggesting that the newer design of this engine may be better for these emissions.
- There is no clear trend in the UVPM data, though average measurements appear to be lower for newer aircraft types – Boeing 787 vs Boeing 767 for example.
- Measurements of $PM_{10}$ and $PM_{2.5}$ appear to be completely independent of aircraft type. Average $PM_{10}$ concentrations recorded during departures of Boeing 747, Airbus A380 and 31x/32x aircraft are essentially identical. This further confirms that background mass concentrations of PM dominate measurements – any additional contribution from aircraft is not likely to be significant.

Further investigation of the nucleation particle count data for each aircraft group was undertaken, using a simple correction to normalise the measurements with respect to wind speed. The data were examined before and after correction, using both the relationship between relative standard deviations within aircraft type and exploring the ratio of average concentrations between aircraft types. Unfortunately, a systematic improvement in the relative standard deviation of each clustered group was not observed, suggesting that the relationship between emissions from aircraft and measured downwind concentrations is more complex than a simple adjustment for one parameter.

### 3.7 Comparison of 2017 particle size distribution with 2016 dataset

A similar study to investigate UFP at the airport was undertaken at Heathrow in the autumn of 2016 by Stacey et al (2020), in direct comparison with other monitoring in the south east of England. The 2016 study configured the TSI SMPS/CPC identically to the comparator monitoring stations, the 2017 study investigated a smaller particle range at a faster time resolution to identify individual aircraft UFP contribution.

There were significant differences identified in the particle distributions and counts between the two datasets, which were a direct consequence of the differences in how the analyser was configured for each campaign. As a result, direct comparison between the 2016 and 2017 data is not possible; this is discussed further in the SI.

## 4. CONCLUSIONS

An extensive campaign to monitor UFP at London Heathrow Airport was undertaken in the autumn of 2017. The primary objective was to examine high temporal resolution data to investigate the relationship between individual aircraft and measured concentrations of UFP, $PM_{10}$, $PM_{2.5}$, NOx and BC.

The SMPS analyser was specifically configured for fast response (1 minute scans) and within a much smaller size range (6-100 nm particles) than in our 2016 campaign. This change in configuration caused a shift in measurements, both in magnitude and peak particle size, meaning that comparison with historic and current UFP data in the UK was impossible.

This study, within 170 metres of a busy runway, shows that nucleation mode particles predominantly originate from the airport, with highest concentrations associated with departing aircraft. This observation is in contrast with some other research, which suggests that UFP concentrations downwind of airports is dominated by aircraft emissions being transported to ground level by wing tip vortices from arriving aircraft.

There is some correlation of nucleation particles with NOx and BC, and these pollutants, together with PM and Aitken particles, also show strong associations with winds from off-airport directions, not associated with nucleation particles. There is some evidence that BC emissions from landing aircraft is higher in UV-active BC, most likely as a result of tyre abrasion upon landing.

Analysis of the 1 minute measurement data with associated aircraft departure information was used to group the data by aircraft type. Larger aircraft departing from the runway recorded higher measurements of nucleation particles and NOx compared to smaller aircraft, but emissions of BC, UVPM and $NO_2$ appear to be more dependent upon the age of the engine design, rather than the size of the aircraft.

## DATA AVAILABILITY

Data supporting this publication are openly available from the UBIRA eData repository at https://doi.org/10.25500/00000535

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**Brian Stacey:** Conceptualisation, methodology, software, validation, formal analysis, investigation, resources, data curation, writing – original draft, writing – review and editing, visualisation, project administration

**Roy Harrison:** Supervision, writing – review and editing

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