AIRPORTS COUNCIL INTERNATIONAL

ULTRAFINE PARTICLES AT AIRPORTS

Current understanding of ultrafine particle emissions and concentrations at airports in 2018

ABOUT ACI EUROPE

ACI EUROPE, the voice of Europe's airports, is the European region of Airports Council International, the only worldwide professional association of airport operators. ACI EUROPE represents close to 500 airports in 45 European countries. Member airports handle over 90% of commercial air traffic in Europe, welcoming more than 2 billion passengers each year.
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For further information, contact:
marina.bylinsky@aci-europe.org

Cover photo: Amsterdam Airport Schiphol

FOREWORD

The data in this publication is a result of a coordinated effort by the airports represented in the Environmental Strategy Committee of ACI EUROPE (Airports Council International). ACI EUROPE would like to thank all the airports involved in this study for their time and dedication, in particular Zurich Airport's Environmental Department which contributed significantly to the execution and completion of the study.

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1. MANAGEMENT SUMMARY

In the light of growing concerns in relation to ultrafine particles (UFP) and their potential health impacts, the professional association of European airports, ACI EUROPE, has performed its first study on UFP at airports in 2012. New knowledge has been gained on UFP since this date, including through dedicated measurement campaigns and analysis by and at European airports.
To take account of this work, ACI EUROPE has decided to update its 2012 study, with a focus on UFP measurement and the different factors that influence UFP concentrations at and around airports.

This scope of the study reflects the commitment of the European airport industry to better understand and address the impact airport-related activities can have on UFP concentrations on and around airports. It must however be noted that these activities are not the only nor the main sources of UFP in general.

The main conclusions of this study can be summarized as follows:

- It is important to distinguish between particulate matters (PM; usually specified in a mass concentration) and ultra-fine particles (usually specified in a number concentration). The latter do only comprise particles of a size below 100 nm. Measurements of particulate matters within a larger size range do thus cover UFPs, but do not exclusively address them and their specifics. Furthermore, mass and number concentrations are not necessarily correlated. Hence caution is needed when deriving conclusions on UFPs from studies addressing PM (usually PM2.5 or PM10).
- Contrary to PM2.5 and PM10, there is currently no specific standard for the measurement of UFP. The type and set-up of measurement devices for UFP thus play a significant role for the results; factors such as frequency of the measurement (scan time) or distance between air inlet and measurement point can influence results at exactly the same location and in identical ambient conditions by an order of one or two. Any study results thus need to be put into the context of the underlying measurement characteristics. This also implies that caution must be used when comparing results of studies using different measurement methodologies.
- UFP concentrations depend on a variety of criteria such as emission sources, measuring location (distance to source), time of day and meteorological conditions. Consequently, short-term measurements at single locations may drastically over- or underestimate the average UFP concentrations at airports. Only long-term measurement campaigns with several monitoring locations at an airport can provide a robust view of the UFP behaviour at the airport.
- Compared to other combustion emissions sources (fossil fuel combustion vehicles and machinery), aircraft engines tend to emit UFP of a smaller size and higher number concentrations. Consequently, several studies point to an association between aircraft take-offs and landings and high number concentrations in the vicinity of the airport. However, these high concentrations seem to be rather short-term and also tend to rapidly decrease with growing distance from the airport. On the contrary, UFP from other combustion sources tend to be of bigger size but lower concentrations, which however tend to be maintained over a longer period of time, as for instance shown by the London Heathrow and Zurich Airport case studies.
- Wind direction and wind speed have a significant influence on particle number concentrations.
- Concentrations of other pollutant species such as Black Carbon (BC) or Nitrogen Oxides (NOx) are not necessarily correlated with UFP number concentrations. Therefore, results from studies on these pollutants should not be used to extrapolate concentrations of UFP, and vice versa, as this might lead to under- or overestimations.

As far as health impacts of UFP are concerned, while there is a growing scientific consensus that particulate air pollution (covering different sizes of PM) in urban environments may lead to an increased risk of respiratory and cardiovascular disease, the knowledge base on UFPs specifically is still limited. Studies at Copenhagen and Amsterdam Schiphol Airports presented in this report did not show correlations between exposure to UFP and adverse health impacts and concluded that further research is needed. In this respect, it must be noted that the particle number concentration as measurement parameter alone is not a sufficient metric to infer dose-effect relationships, as they encompass particles of various species with different physical and chemical properties that can have different impacts on health. Hence, the understanding of these properties of different types of UFP is key and a central area for future research.

This ACI EUROPE study also highlights the progress made by the aviation industry to address its UFP emissions. This refers in particular to the adoption a new aircraft engine standard for non-volatile particulate matters (nvPM) by the International Civil Aviation Organisation (ICAO) as well as a series of mitigation actions carried out by airports, for instance by modernizing their ground support equipment, using electric vehicles, low-carbon fuels or renewable energy. Airports also play a key role in collaborating with their airline partners and air navigation service providers to optimize aircraft movements on the ground and during landing and take-off so as to reduce emissions. The industry is encouraged to continue and enhance its efforts in this field.

2. INTRODUCTION

2.1 BACKGROUND

General concern over ultrafine particles (UFP) has risen in society over the past years. In general, the emission of UFP is however not a recent phenomenon and also part of natural processes. Many today's activities, products and processes are associated with the emission of ultrafine particles. This includes, but is not limited to, aviation related activities. Science and industry have therefore worked hard on improving the knowledge and understanding on characteristics, metrics, assessments, impacts and mitigation of ultrafine particles.

2.2 ACI EUROPE INITIATIVE

Airport Council International – European Region (ACI EUROPE) as the airports' industry association has been very active since the beginning of the discussions on UFP at airports, which started approximately in 2010. Already in 2012, ACI EUROPE developed and published a comprehensive study on UFP with the information available at the time.

ACI EUROPE promotes the knowledge and information dissemination of this topic among airports worldwide and is thus publishing this report to provide airports with updated information on UFP, based on the latest research on this area.

2.3 ABOUT THIS REPORT

This report discusses the current knowledge on ultrafine aerosols in aviation and specifically at airports. It is acknowledged that this is a point in time study only and there may well be more information available which is not included or referenced in this study.

The study comprises the following sections:

- Section 1 provides a short management summary
- Section 2, this section, introduces the topic and delivers the background
- Section 3 discusses some scientific background of ultrafine particles with their characteristics and main sources. The section also briefly introduces impacts as far as it is deemed feasible for the understanding of this report.
- Section 4 puts aviation related UFP emissions in the context to other UFP emission sources.
- Section 5 describes the current regulatory framework, both on the side of aircraft and non-aircraft related emissions and the concentrations on ambient air.
- Section 6 contains a range of more recent airport studies where ultrafine particle measurement campaigns have been conducted and draws some conclusions.
- Section 7 delivers detailed descriptions of characteristics and requirements for the measurement of ultrafine particles at and around airports and provides recommendations on how to do it.
- Section 8 focusses on the mitigation options for the relevant airport emission sources that are potentially available and that are often implemented by airports.
- Section 9 takes a view to the future with what is to be expected in the coming years.
- Section 10 contains the annexes with abbreviations and references.

3 SCIENTIFIC FRAMEWORK OF ULTRAFINE PARTICLES

3.1 GENERAL CHARACTERISTICS

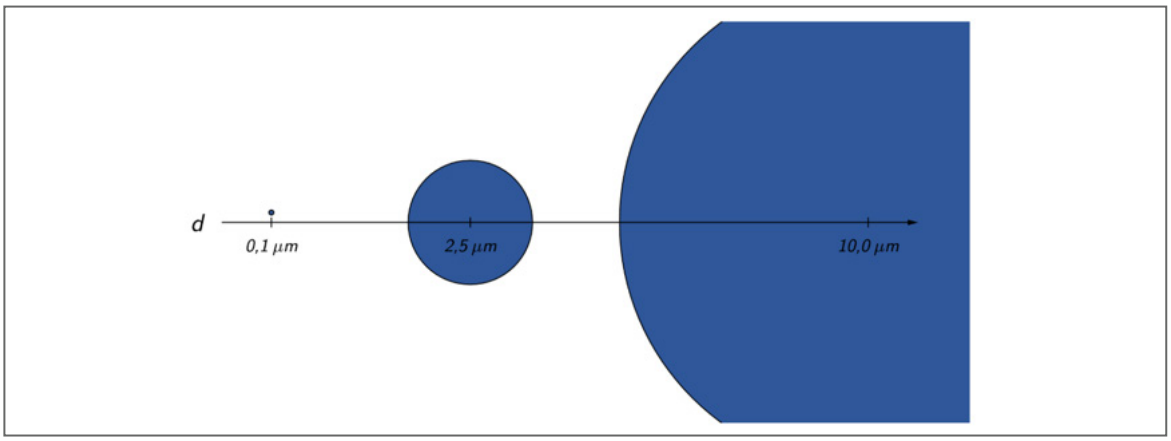
Particles up to a diameter of 100nm (=0.1 µm) are called ultrafine particles.

At the exhaust plane of any combustion engine, particulate emissions mainly consist of ultrafine soot or black carbon emissions. Such particles are called primary "non-volatile" particulate matter (nvPM). They are present at high temperatures in engine exhaust and they do not change in mass or number as they mix and dilute in the exhaust plume behind a source, just their concentration changes. The geometric mean diameter of these particles is for aircraft extremely small and ranges roughly from 15nm to 60nm (0.06 Microns).

Additionally, gaseous emissions from engines can also condense to produce new particles (i.e. volatile particulate matter – vPM), or coat the emitted soot particles. Other gaseous species react chemically with ambient chemical constituents in the atmosphere to produce the so-called secondary particulate matter. Volatile particulate matter is dependent on precursor emissions, which are controlled by gaseous emissions and the fuel composition (e.g. sulfur content).

The following figure illustrates the difference between UFP and the largest possible particles of the two other most commonly addressed PM sizes, PM2.5 (with size below 2,5 µm and PM10, with size below 10 µm):

FIGURE 1: ILLUSTRATION OF ULTRA-FINE PARTICLE SIZE

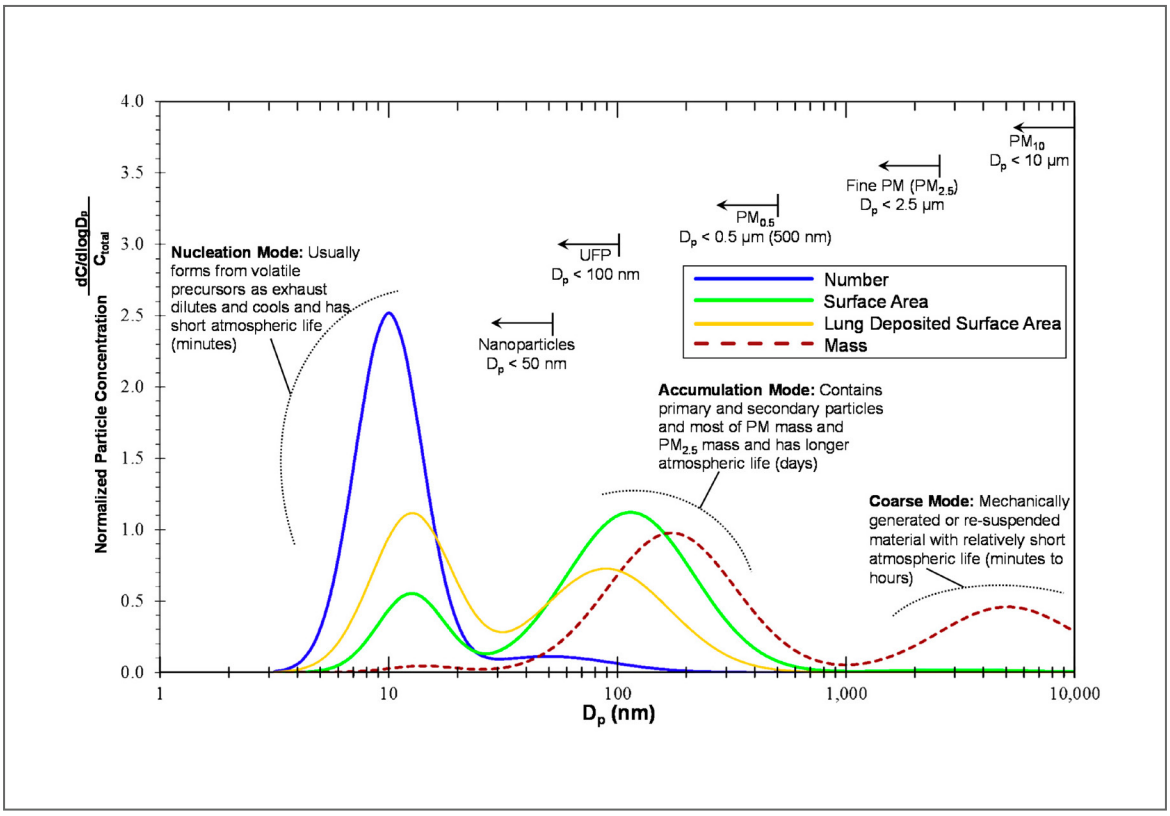


OVERVIEW OF PARTICLE SIZE RANGES AND PROCESSES

Particle numbers and diameter vary depending on the formation and ageing process they go through. The following figure illustrates the formation of primary particles through high temperature combustion and indicates at which stages UFP occur (see size range in red)[1]. Depending on physical and chemical properties, particles grow and coagulate until they reach a potential sedimentation property.

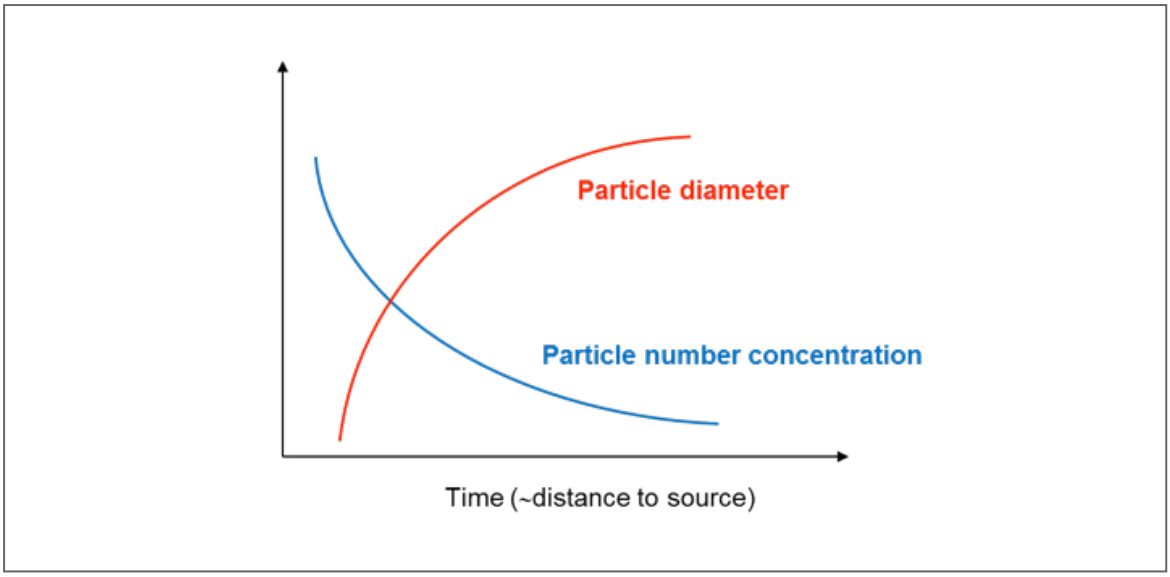
1. See Annex for some definition of terms

FIGURE 2: PARTICLE MODES AND THEIR CHARACTERISTICS (BALDAUF ET AL., 2016)



The transport and conversion of particles is dependent on many factors, e.g. meteorology, reactivity of compounds/solubility, background concentration of gases/ aerosols and conversion processes after emission. The following figure shows the very generic evolution of the average particle diameter and the particle number concentration over time or the source distance respectively.

FIGURE 3: DYNAMICS OF PARTICLES OVER TIME (SWISS AGENCY FOR ACCIDENT INSURANCE (SUVA), 2012)

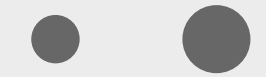
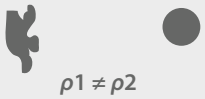


PARTICLE MEASUREMENT

Due to their small size, UFP cannot be detected by traditional techniques for PM2,5 and PM10 measurements that rely on measuring mass. Instead, they are measured in terms of particle number which is typically determined per cubic centimetres (cm-3) of air (particle number concentration).

While the number of particles is the relevant metric, the mobility diameter of particles is likewise of importance as it can be both an indicator for source apportionment and a metric for the evaluation of impacts. However, there are many different types of diameters that can be used to describe the size of a particle. The following table demonstrates the various diameter types and their use in measurement devices.

TABLE 1: PARTICLE DIAMETER TYPES

SHAPE TYPE	DIAMETER DEFINITION
	**Geometrical Diameter:** With regard to the "vertical" diameter, both particles have the same size.
 $n = 1.66$ $d = 41$ nm $n = 1.33$ $d = 50$ nm	**Optical Diameter:** Based on their refraction properties, both particles have the same size because of their different refraction indices *n*. –> Optical particle measurement
 $\rho 1 \neq \rho 2$	**Mobility Diameter:** With regard to their diffusion, both particles are of the same size. –> Diffusion battery (EDB), electrical mobility analyser (SMPS)
 $\rho = 4$ g/cm³ $d = 1$ µm $\rho = 2$ g/cm³ $d = 2$ µm	**Aerodynamic Diameter:** With regard to their sedimentation speed, both particles are of the same size. -> Electric low pressure impactor

In relation to scope, measurements can address total UPF concentrations (covering both nvPM and vPM) or only nvPM. This depends on the objectives of a measurement campaign. Focusing on nvPM usually allows for a better understanding of emissions from different types of combustion sources and their behaviour. Total UFP numbers relate more to the understanding of concentrations, which can then also be used as input for health impact studies.

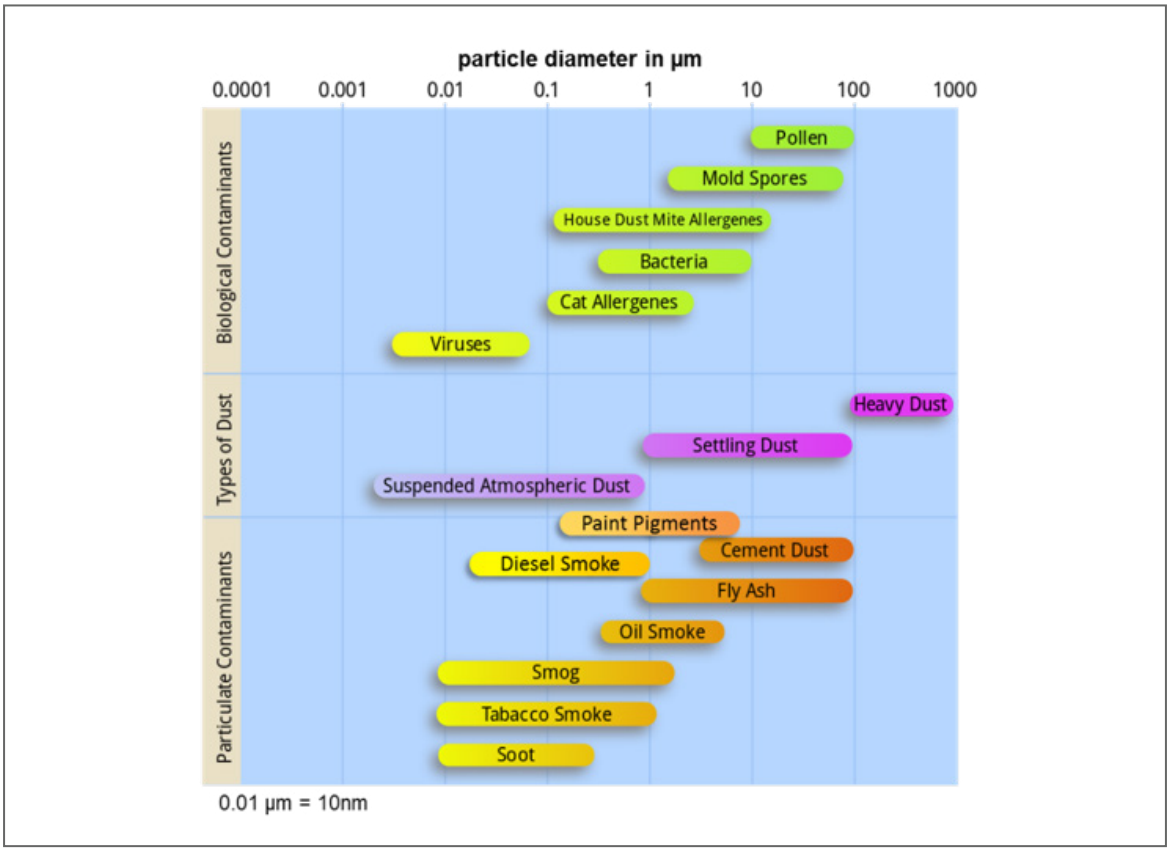
It must be noted that there is currently no dedicated standard that would deliver information specifically on the number of UFP and their size distribution. Practitioners therefore often include particles of larger sizes as well when measuring UFP. As illustrated in Figures 2 and 3, concentrations of smaller particles are usually comparatively higher than those of larger particles formed over time after emission. In any measurement that covers particles of very small sizes, the concentration of larger particles will therefore be comparatively low. As put by Kumar et al, "[particles smaller than 300 nm diameter contribute over 99% of total PN emissions (Kumar et al., 2009a). Unlike the lower cut-off size, any upper cut-off size over 300 nm does not influence PN estimates greatly." (Kumar et al., 2014, page 2) Additionally, practitioners are able to distinguish between UFP and the other fraction by measuring the number size distribution.

3.2 SOURCES OF ULTRAFINE PARTICLES

Although airborne particles originate from many natural and anthropogenic sources (which include sand, dust, fires, vehicles, boilers and sea salt), UFP are generated in high number concentration at very high temperatures, such as combustion processes - wood fires, industrial processes, vehicle engines, cooking fumes, and cigarette smoke are all common sources; as are the printer cartridges (carbon black) from copiers, laser printers and welding-fumes.

For illustration purposes, a non-exhaustive selection of various particle emission sources with the corresponding particle sizes are shown in the picture below.

FIGURE 4: DIFFERENT PARTICLE SOURCES AND THEIR SIZES (WIKIPEDIA, AMENDED ACI)[2]



At an airport, the most typical particle sources come from the following sources:

- Aircraft: Particles from main engines, auxiliary power units, brakes and tires.
- Aircraft handling: Particles from ground support equipment, vehicles combustion and tires.
- Infrastructure operation: Diesel and oil smoke from combustion processes, paint pigments from maintenance and pollen from green-field maintenance,
- Landside traffic access: Particles from vehicles combustion and tires and particles from rail services (brakes and rails).

2. https://en.wikipedia.org/wiki/File:Airborne-particulate-size-chart.svg

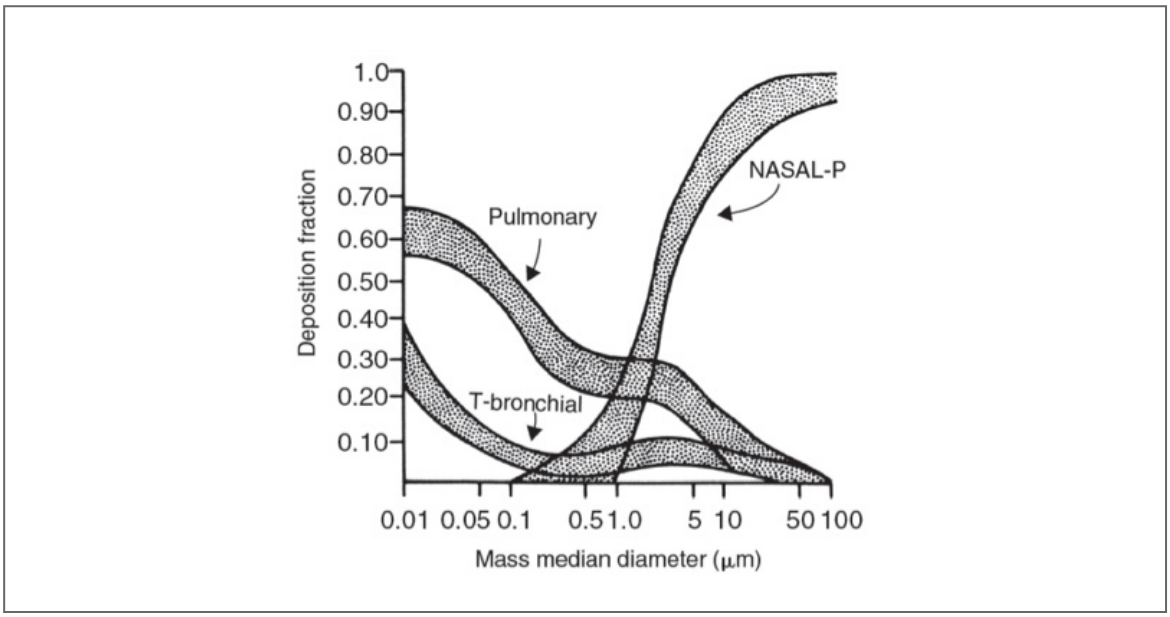
This shows that apart from aircraft, the emissions sources at an airport are not specific to airport-activities, but are also present in other transport sectors and industrial processes such as power generation or construction. For more details, please see section 4.

3.3 IMPACTS

There is a growing scientific consensus that particulate air pollution in urban environments (with PM of of different sizes) may lead to an increased risk of respiratory and cardiovascular disease (see for instance Airport Cooperative Research Program (ACRP), Report 135, 2015). However, there is still uncertainty about an association between exposure to UFP specifically and related health effects. Several aspects are relevant for potential health impacts:

- **Inhalability**: the following figure shows the particle deposition in different areas of the respiratory system as a function of the particle diameter. In general, the smaller the particles, the deeper they are able to penetrate into the respiratory system.

FIGURE 5: PARTICLE DEPOSITION AS A FUNCTION OF PARTICLE DIAMETER (ONLINE ETHICS CENTER, 2010)[3]



- **Exposure time**
- **Physical/chemical property** of particles with respective potential health effects. This includes the surface area of a particle (lung-deposited surface area, LDSA) but also the ageing effects of particles with potential physical and chemical changes. It must be highlighted that emissions and exposure are thus not the only relevant factors for the assessment of health impacts of UFPs. Degrees of toxicity of different UFP species are also crucial.

Two studies have been published by national health agencies or institutes in 2016 to examine potential health effects from aviation related UFP exposure at and in the vicinity of airports.

3. The nasopharyngeal region consists of the nose and throat; the tracheobronchial (T-bronchial) region consists of the windpipe and large airways; and the pulmonary region consists of the small bronchi and the alveolar sacs.

3.3.1 COPENHAGEN AIRPORT

The previous ACI EUROPE Study on Ultrafine Particles at Airports (2012), indicated that statistical evidence had been found that showed acute negative health effects are related to increased levels of airborne particles. These effects can include:

- Increased use of asthma medication
- Asthma attacks in patients having asthma
- COPD (chronic obstructive pulmonary disease) attacks
- Hospital admissions for cardiovascular diseases
- Deaths from heart attacks, strokes and respiratory problems

Partly to follow up on this, the monitoring work stream in the Copenhagen Airport Air Quality Program (see section 6 for more details) has had the focus on the results from a scientific cohort study, which was concluded in 2016 (Lauenborg, Karina, et.al., 2016)[4]. The English summary from this cohort study is replicated below.

INTRODUCTION

Measurements carried out by the Danish Center for Environment and Energy in 2010 showed high concentrations of ultrafine particles (UFP) at Copenhagen Airport (CPH). Especially high levels were measured on the apron, where ground personnel are working. There is a growing scientific consensus that particulate air pollution in urban environments may lead to an increased risk of cardiovascular disease.

However, there is still uncertainty about an association between occupational exposure to UFP and related health effects. It is not possible to predict any health risk among airport employees working outdoors at Copenhagen Airport, based on existing knowledge from urban environments, as the working population is younger and healthier than the general adult population. The overall aim of this project was to examine the association between occupational exposure to UFP and cardiovascular diseases, lung diseases, lung cancer and bladder cancer among airport employees.

METHOD

This study cohort was based on information from company employment registers (SAS, NOVIA, CPH) as well as union member registers (3F Kastrup, 3F København, 3F Mølleåen og Vagt- og Sikkerhedsfunktionærernes Fagforening). The cohort comprised 69,175 men in unskilled positions eligible for follow-up in the period 1990-2012. Based on GPS-measurements and expert assessments we calculated amount of time on apron during a normal working day for each calendar year. This was called apron-years.

We followed the cohort in the Danish National Patient Register, the Danish Register of Causes of Death, and the Danish Cancer Registry for diagnosis of ischemic heart disease (IHD), cerebrovascular disease, asthma, chronic obstructive pulmonary disease (COPD), lung cancer and bladder cancer.

4. http://www.arbejdsmiljoviden.dk/nyt/nyheder/2016/december/19_partikelforurening-paavirker-ikke-lufthavnsansattes

RESULTS

The reference group and the exposed group were almost comparable in relation to register based information and survey day except that a smaller proportion of the exposed group compared to the reference group were current smokers, 27% and 32%, respectively. We found no increased incidence of IHD, cerebrovascular disease, asthma or COPD associated with exposure to UFP among exposed employees at Copenhagen Airport compared to the reference group. In relation to lung cancer and bladder cancer we had too few cases to conclude on an association.

CONCLUSION

It can be concluded, that findings from this project do not provide evidence for an association between occupational exposure to UFP and the incidence of cardiovascular diseases, lung diseases or cancer among airport employees at Copenhagen Airport. This is the first study that examines this association at an airport and more research is needed.

The full report and English summary can be found here:
http://www.arbejdsmiljoviden.dk/nyt/nyheder/2016/december/19_partikelforurening-paavirker-ikke-lufthavnsansattes

3.3.2 SCHIPHOL AIRPORT

Two explorative studies from TNO (Keuken et al, 2015) and RIVM (Bezemer et al, 2015) on UFP concentrations around Amsterdam Airport Schiphol concluded that the UFP concentrations around the airport are comparable with concentrations near road traffic in the city centre. Along with that little is known about the health effects of UFP and the assumption that especially small particles are harmful to human health, was a motivation for RIVM to an explorative study into the health risks of UFP in the Schiphol region. Because a quick response is required and due to the availability of data, the research focuses initially on a possible increased mortality risk in areas around Schiphol airport with increased UFP concentrations. After this first exploration, a comprehensive research will be conducted and is planned to be completed in 2021. During this research, interim results will be published.

In the present study RIVM addressed the following questions:

- What are the mortality rates in the period 2004-2011 in the Schiphol region?
- How do these mortality rates compare with mortality rates of areas in the Schiphol region with limited UFP exposure?
- If there are differences in mortality rates within the Schiphol region and compared to other regions in the Netherlands, how can they be interpreted?

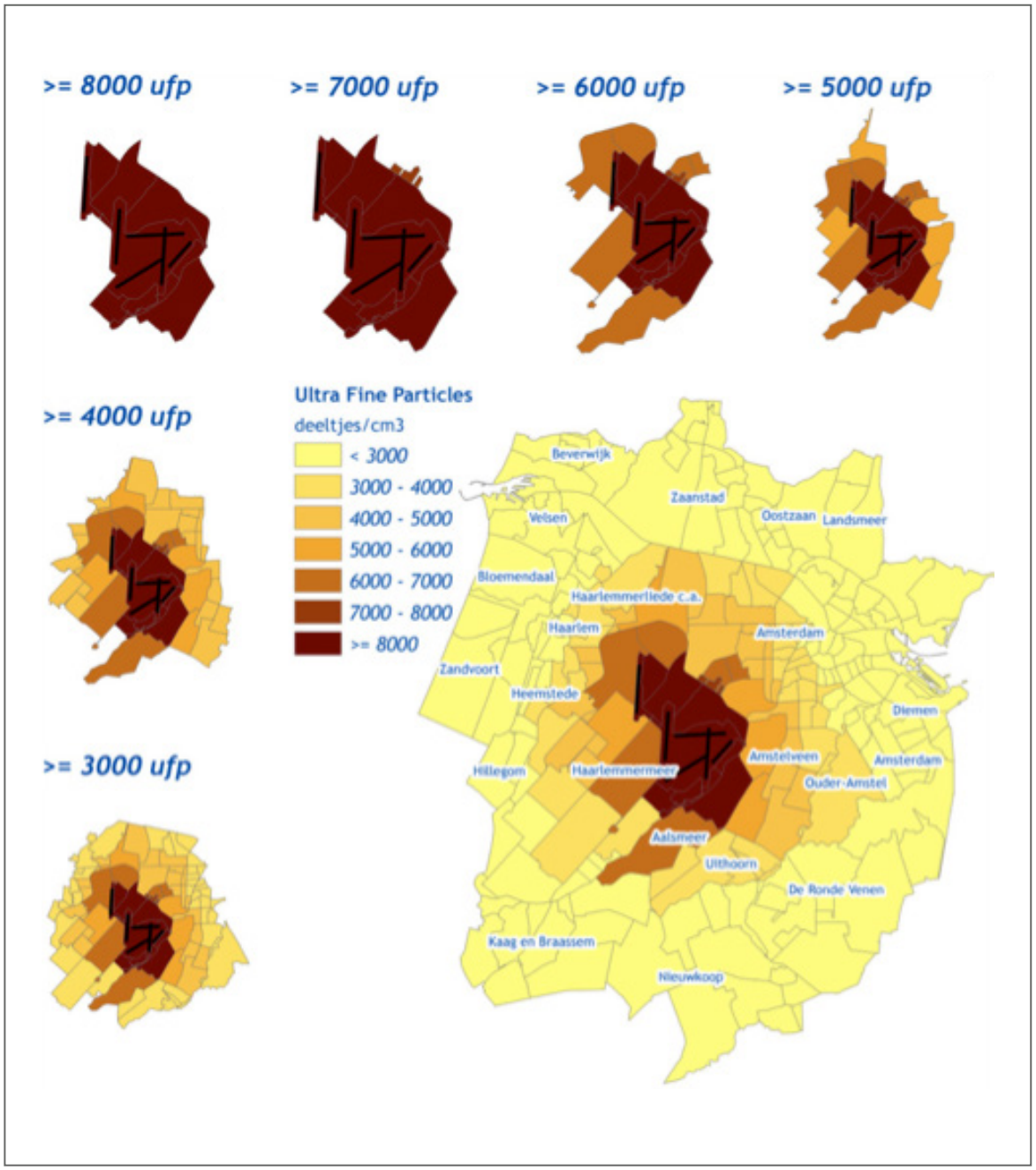
METHODOLOGY

All municipalities within 10 km from any of the runways are involved in this research, a region of approximately 25 by 30 km divided in 247 zip code areas. For this area the UFP concentrations are known from an earlier research (ESC, 2015). Even though in this research UFP concentrations are determined in a short period of time, they are considered representative for the entire period. This assumption is plausible because the UFP concentrations are used to indicate areas with an expected higher or lower concentration instead of the absolute concentration of UFP.

Mortality rates on all-cause mortality and cause specific mortality for cardiovascular disease, respiratory disease and lung cancer from Statistics Netherlands (CBS) are analysed in this research.

For this study, six partly overlapping UFP areas were composed by combining zip code areas based on their modelled UFP concentration contribution by aviation. The smallest UFP area consists of all zip code areas with a contribution of aviation of more than 8000/cm^3 and the largest UFP area of the zip code areas with more than 3000/cm^3. In the area within 10 km to any of the runways the majority of the zip code areas have a UFP concentration contribution of less than 3000/cm^3 (Figure 6).

FIGURE 6: ZIP CODE AREAS AROUND SCHIPHOL AIRPORT INVOLVED IN THE RIVM RESEARCH AND THE MODELLED UFP CONCENTRATION CONTRIBUTION BY AVIATION USED TO DEFINE THE SIX UFP AREAS FOR COMPARISON WITH THE COROP AREAS IN THE NETHERLANDS.



Two comparisons have been performed. First, the hazard rate of all the zip code areas close to Schiphol have been mapped to find a spatial pattern. Second, the UFP areas are compared with COROP areas in the rest of the Netherlands by ranking them based on their hazard ratio. For statistical analysis the Netherlands are divided into 40 COROP areas for which the hazard ratios are known.

The demographic and socioeconomic factors that influence mortality are taken into account in this research. These factors for all areas are: age, gender, country of origin, marital status, standardized household income and moving behaviour. For the zip code areas, education, income and position in the labour market have been taken into account as well.

The UFP cohort consists of habitants who were 30 years or older in 2004 and lived on the same address for at least five years. This has resulted in a sample of 708.818 people. Table 2 shows the mortality rates in the UFP cohort.

TABLE 2: MORTALITY AND UNDERLYING CAUSE OF DEATH DURING THE PERIOD 2004-2011 IN THE UFP COHORT (N=708.818)

MORTALITY AND UNDERLYING CAUSE OF DEATH	NUMBER	AS PERCENTAGE OF	
		UFP COHORT	NATURAL CAUSES
Natural causes	**67.703**	9,6%	100%
Cardio vascular disease	**20.532**	2,9%	30,3%
Respiratory disease	**6.547**	0,92%	9,7%
Lung cancer	**5.361**	0,76%	7,9%

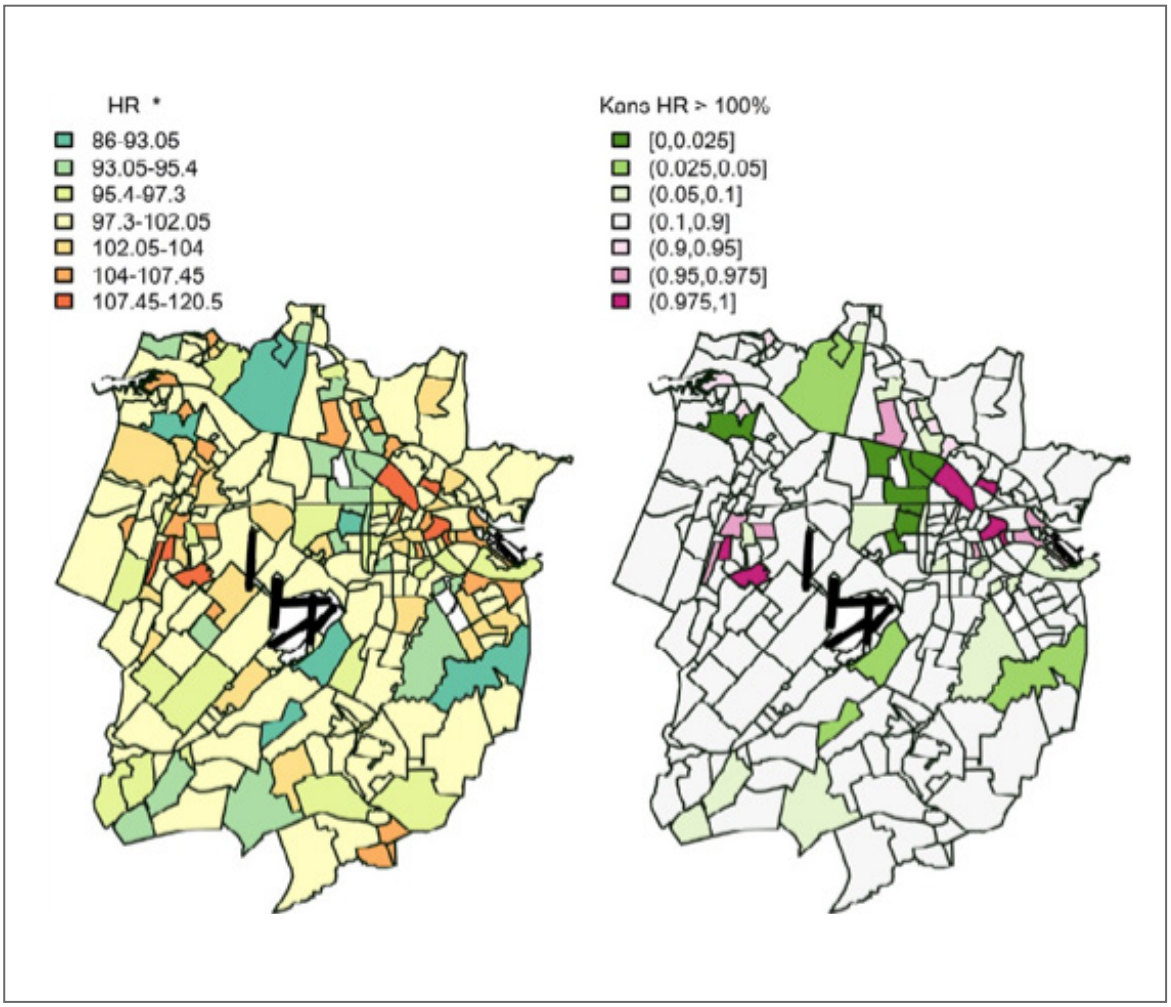
RESULTS

For both analysis the results are presented below.

HAZARD RATIO IN THE RESEARCH AREA

The results are presented in the form of maps with the distribution of the risk. As an example the distribution of the risk of mortality on natural causes is presented in the following figure. In the actual report there are similar figures of the other mortality risks.

FIGURE 7: DISTRIBUTION OF THE RISK OF MORTALITY ON NATURAL CAUSES ACROSS THE RESEARCH AREA EXPRESSED AS HAZARD RATIO (LEFT) AND AS EXCEEDANCE PROBABILITY OF HAZARD RATIO (RIGHT), AFTER CORRECTION FOR DEMOGRAPHIC FACTORS, STANDARDIZED HOUSEHOLD INCOME AND SOCIAL STATUS OF THE ZIP CODE AREA



There is no systematic pattern found in hazard ratios. Some isolated areas have an increased hazard ratio, but about the same number of areas have a reduced ratio. These increases or reductions are rarely statistically significant.

COMPARISON TO MORTALITY RISKS IN THE NETHERLANDS

The results are presented in the form of tables ranking the hazard ratio of COROP areas, both the 40 areas in the Netherlands as well as the 8 areas nearby the airport. These rankings have been done for all six UFP areas from >8000/cm^3 to >3000/cm^3. As an example, the ranking of the risk of mortality on natural causes in relation to the area with UFP contribution from aviation >8000/cm^3 is presented in figure 8 and 9. In the actual report there are similar figures of the other mortality risks.

FIGURE 8: HAZARD RATIO FOR THE RISK OF MORTALITY ON NATURAL CAUSES, THE 95% CONFIDENCE INTERVAL AND RANKING OF 40 COROP AREAS IN THE NETHERLANDS VERSUS ZIP CODE AREAS BASED ON MODELLED UFP CONTRIBUTION OF AVIATION GREATER THAN 8000/CM^3, AFTER CORRECTION FOR DEMOGRAPHIC AND SOCIOECONOMIC FACTORS

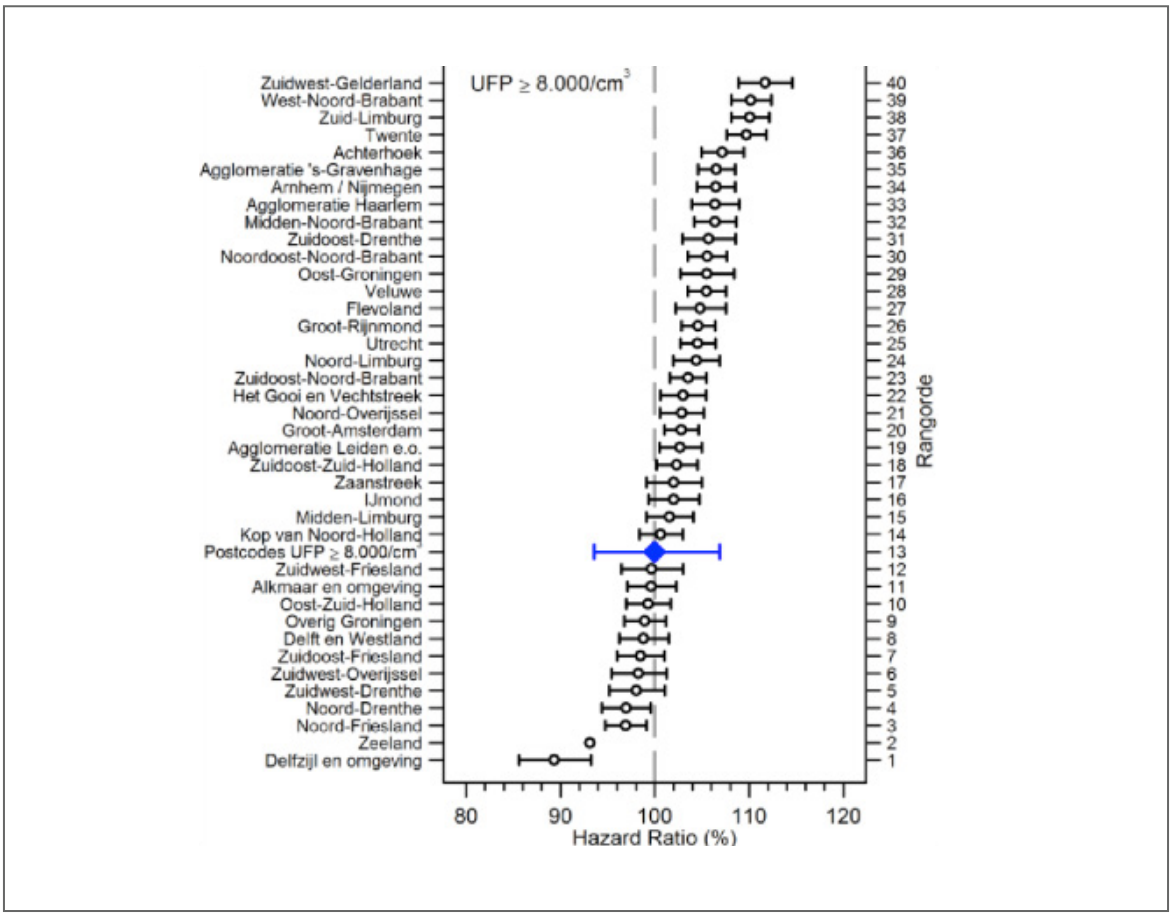
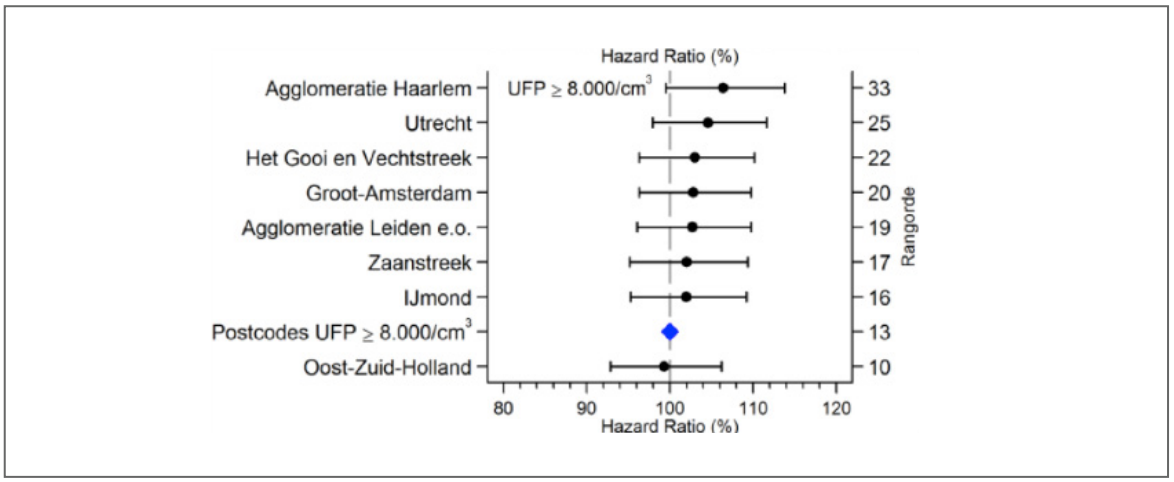


FIGURE 9: HAZARD RATIO FOR THE RISK OF MORTALITY ON NATURAL CAUSES, THE 95% CONFIDENCE INTERVAL AND RANKING OF 8 COROP AREAS NEARBY SCHIPHOL AIRPORT VERSUS ZIP CODE AREAS BASED ON MODELLED UFP CONTRIBUTION OF AVIATION GREATER THAN 8000/CM^3, AFTER CORRECTION FOR DEMOGRAPHIC AND SOCIOECONOMIC FACTORS



The findings show that the risk of natural mortality in the UFP areas near the airport does not differ very positively or negatively from what can be expected based on the mortality risks in nearby COROP areas. Differences are small.

For mortality in cardiovascular disease and for respiratory diseases, the findings are similar to those for natural mortality.

The mortality risk for lung cancer in the various UFP areas is on average slightly higher than the risk found on average in COROP areas in the Netherlands. However, similar to the findings on other mortality risks, the differences are small. Also, there is no statistically significant difference with the mortality risks in the eight COROP areas nearby the airport. In general, the mortality risk for lung cancer was slightly higher than average of the COROP areas. But when comparing the individual UFP areas (from >8000/cm^3 to >3000/cm^3) to the COROP areas, a decreasing risk in the areas with increased UFP levels has been observed - the opposite of what was expected.

The absence of a consistent spatial pattern in the mortality risks or that the mortality risks do not differ significantly from the national average in The Netherlands does not exclude that the UFP concentrations from aviation can lead to an increase in mortality. Further research is needed.

EVALUATION OF MODELLED UFP CONCENTRATIONS

The UFP concentrations in the research area are modelled by converting the modelled PM10 concentrations from air traffic to UFP concentrations, following a conversion factor of approximately 400,000 for the whole area (Bezemer et al, 2015). An expert estimate of the total uncertainty in the PM10 to UFP conversion factor (calculation, measurement and generalization) is approximately 50% in the area near the airport and even higher at further distance. Due to the high degree of uncertainty, this type of calculation should not be used to derive dose-effect relationships. For the present study however, this way of modelling is still useful, because the UFP concentrations are used solely to identify relative differences in UFP concentrations to subsequently select the study areas. In future, additional measurements should be made to improve modelling and to enable studies on dose-effect relationships.

3.3.3 CONCLUSIONS

The studies carried out at Copenhagen and Amsterdam Schiphol Airport confirm that further research is needed to understand any potential health impacts of exposure to ultrafine particles. To enable it, measurements delivering information on particle characteristics such as their chemical composition and different diameter types are required. As it will be shown in Section 7, such information is not delivered by the currently available measurement methods.

Furthermore, health impact studies in relation to UFP must rely on a correct differentiation between UFP emissions and concentrations. To investigate health effects, the concentration of particles is of relevance, which depends on emissions but also other factors that influence the way particles disperse and mix in the air, e.g. meteorology.

4 AVIATION PARTICLE EMISSIONS IN THE CONTEXT OF OTHER SOURCES

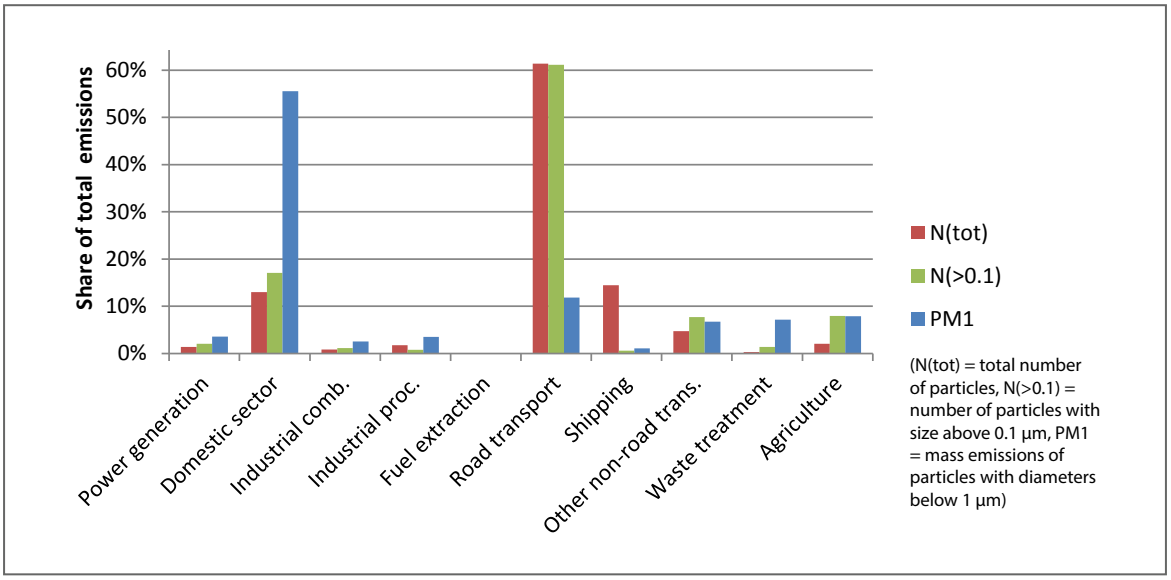
Many natural and human activities lead to the emission of particles, including ultrafine particles. Air transportation is just one of many emission sources. The following table presents a selection of locations where UFP emissions occur. The comparability between the underlying sources is however limited due to limited information on measurement parameters (size-range, total/non-volatile PN, averaging period, source distance, measurement device type) and thus only presents an approximate view of the particle numbers at those locations.

TABLE 3: UFP CONCENTRATIONS FROM VARIOUS EMISSION SOURCES
(BLUE = ACI EUROPE UFP STUDY 2012, ORANGE = DATA FROM STUDIES PRESENTED IN THIS REPORT, BLACK = INTERNET RESEARCH)

LOCATION	PARTICLES/CM^3
Pedestrian area in downtown Rome	**max 120,000**
Kitchens at home	**several times >100,000**
Plastic manufacturer	**88,300**
Range of restaurants in the USA	**average 80,000**
Peace Bridge from USA to CAN (road, 300m away)	**60,000-70,000**
Geneva Pedestrian Area	**62,900**
Stockholm City Street	**56,000**
Zurich Airport (downwind at the fence, Gate 109)	**47,300**
Chemistry laboratory, University in Australia	**21,700**
Brussels Airport (250m away)	**18,000**

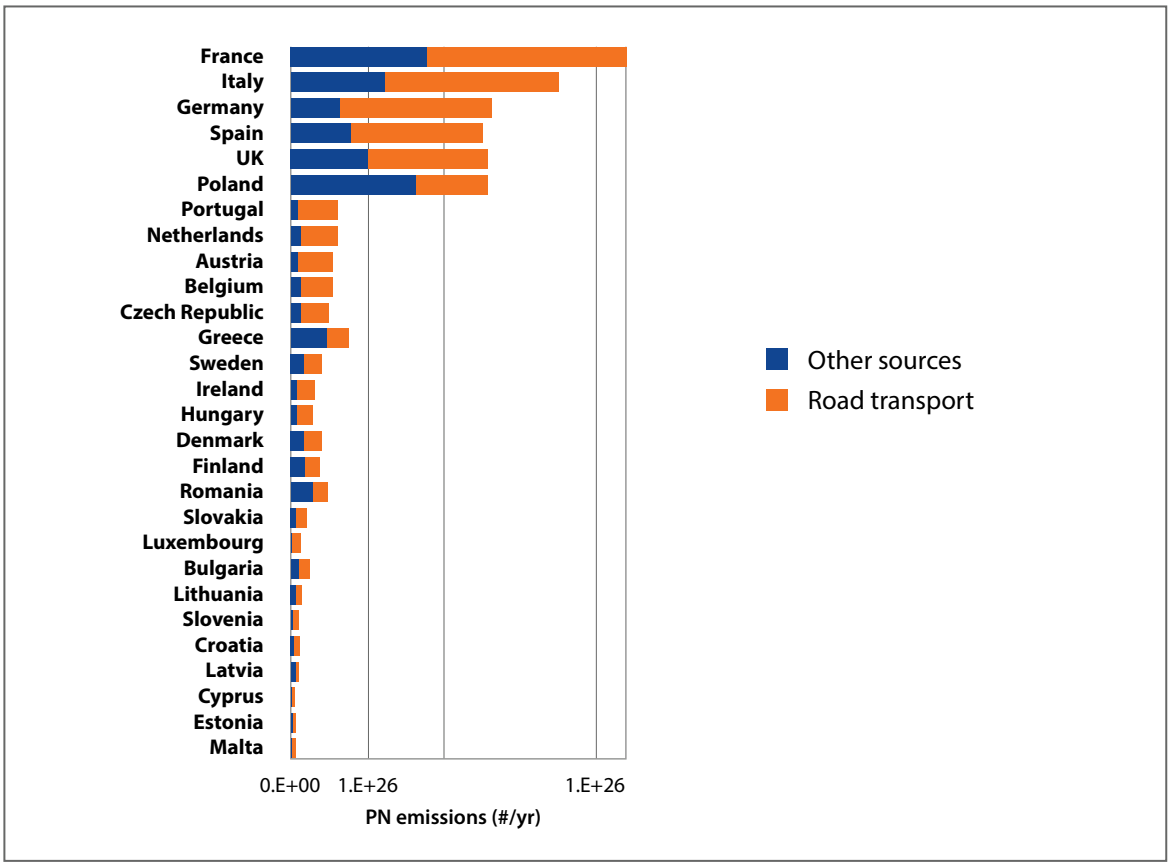
Based on a study by Paasonen et al., the main contributor to the total particle number emissions is road transport: Road transport in 2010 contributed over 60% of the total PN emissions in 28 European states, followed by non-road transport (~ 19% to total PN emissions; including national ship traffic) and domestic combustion (~ 13%). The following picture shows the total number of particle emissions in 28 European countries in 2010 from road transport and other sources. Those other sources include power generation, industrial combustion and processes, domestic, non-road transport, agriculture and waste treatment. (Paasonen et al., 2013, pages 9 and 11)

FIGURE 10: TOTAL EU28 PARTICLE EMISSIONS SPLIT 2010 BY SECTOR (PAASONEN ET AL., 2013)



The contribution from road traffic varied from ~ 32% of total PN emissions in Greece to ~ 97% in Luxemburg. France, Spain, Germany, Italy, UK and Poland are the top six PN emitters in the EU28 and together, their road traffic contributes nearly 3/4 (~ 72%) of the total traffic-induced PN emissions in the EU28. (Paasonen et al, 2013).

FIGURE 11: TOTAL PARTICLE NUMBER EMISSIONS IN EU28 COUNTRIES IN 2010 (PAASONEN ET AL., 2013)



5 UFP REGULATORY FRAMEWORK

The UFP regulatory framework presented below addresses both emissions and concentrations of UFP. Emissions regulation typically addresses nvPM, whereas concentration standards establish limits for total PM numbers, covering both nvPM and volatile PM.

5.1 AVIATION EMISSION REGULATIONS[5]

In 2008, first proposals for the introduction of an ICAO particulate standard for aircraft engines were made, and subsequently a specific plan was developed and agreed at the 8th meeting of ICAO Committee on Aviation Environmental Protection in 2010. That plan comprised consulting with the SAE International E-31 Committee and developing a nvPM standard, first for turbofan engines of rated thrust >26.7 kN. After the development of several prototype test cells and measurement campaigns in Switzerland, the UK and USA, the compiled results led to the publication of the SAE Aerospace Information Report (AIR 6241) in 2013. The AIR6241 report documented the specifications of the standardized nvPM sampling and measurement system.

The new specifications are outlined in the new Appendix 7 of the ICAO Annex 16 Vol. II. The CAEP/10 nvPM standard, introduced in 2016, uses a mass concentration limit that is equivalent to the smoke number regulatory level in the following sense: if an engine passes the current smoke number standard, by design of the regulatory level, it will pass the first nvPM standard.

For each aircraft engine type, the new CAEP/10 nvPM standard mandates the reporting of:

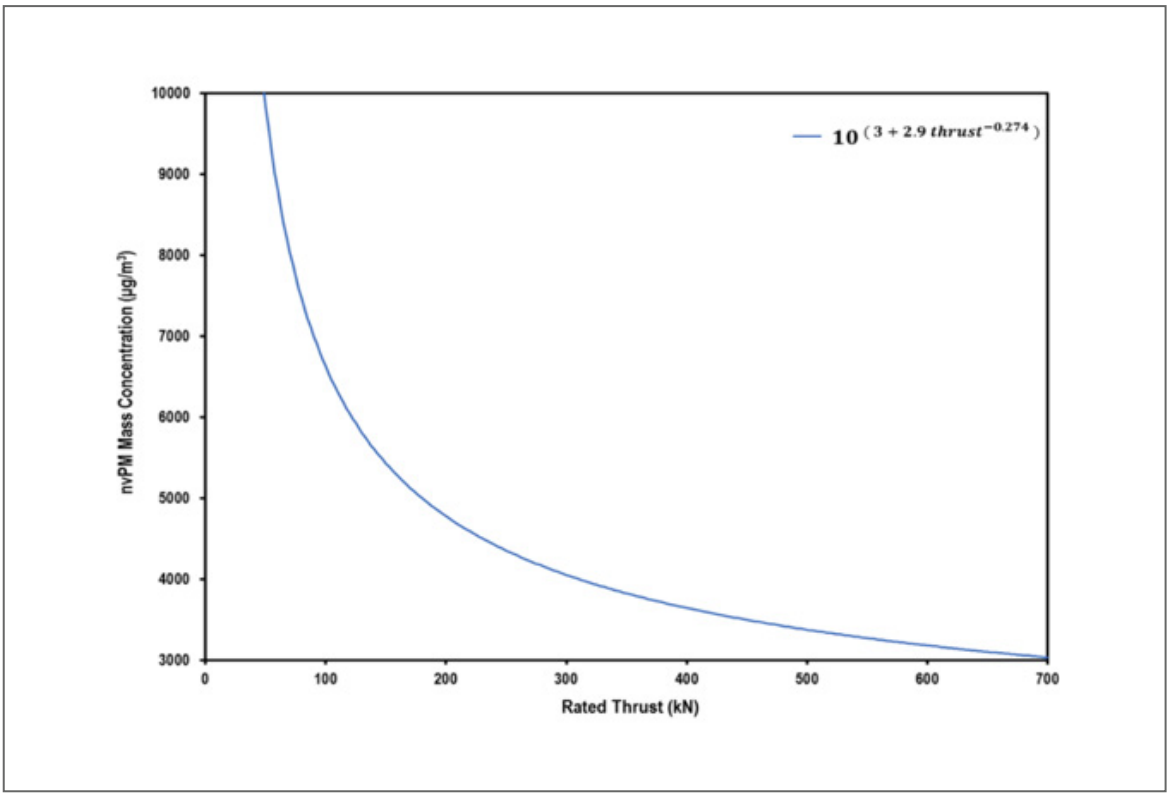
- The fuel flow at each thrust setting of the certification landing and take-off cycle (LTO).
- The nvPM mass and number emission indices (EIs) for the four LTO measurement points.
- Maximum nvPM EI mass.
- Maximum nvPM EI number.
- Maximum nvPM mass concentration.

The new standard applies to all in-production engine types of rated thrust >26.7 kN, on or after 1 January 2020. The reported certified parameters will allow comparisons of engine technology and engine type comparisons for health and climate relevant nvPM emissions. Furthermore, the maximum nvPM mass concentration obtained from the nvPM certification measurement is used to maintain regulation of the non-visibility criteria of the exhaust and provides a pathway for the potential removal of the old smoke number standard for engines of rated thrust >26.7 kN as early as 2020.

The regulatory level for the CAEP/10 maximum nvPM mass concentration was developed based on a statistical relationship between nvPM mass concentration and the smoke number. A graphical representation of the CAEP/10 nvPM regulatory limit for maximum nvPM mass concentration is shown in the following figure.

5. ICAO, 2016

FIGURE 12: AIRCRAFT ENGINE MAXIMUM REGULATORY LIMIT FOR NVPM MASS CONCENTRATION



CORRECTION FOR NVPM LOSSES IN THE STANDARDIZED SAMPLING AND MEASUREMENT SYSTEM

A sampling system for gas turbine nvPM will lose a portion of the particles when they travel through the sampling lines because of the very small size of these particles. Therefore, the nvPM emissions measured at the instruments will be lower than the values at the engine exit plane.

The purpose of emission certification is to compare engine technologies and to ensure that the engines produced comply with the prescribed regulatory limits. The ICAO nvPM sampling and measurement system requirements standardize the particle losses in the system such that engine measurements performed by different engine manufacturers and test facilities can be compared directly.

However, for emission inventories and impact assessments, nvPM emissions at the engine exit should include the particle size dependent losses in the sampling and measurement system.

A standardized methodology to estimate such system losses is described in the new proposed Appendix 8 to the ICAO Annex 16 Vol II nvPM update so that all engine manufacturers can report loss correction factors using the same procedure. The CAEP/10 update to the ICAO Annex 16 Vol.II includes a recommendation that engine manufacturers report the system loss correction factors together with the nvPM emissions data as soon as engine data are certified.

5.2 NON-AIRCRAFT EMISSION REGULATIONS[6]

Emissions of particulate matter (PM), nitrogen oxides (NO and NO2, when measured combined, they are referred to as NOx), unburnt hydrocarbons (HC) and carbon monoxide (CO) are pollutants regulated by "Euro emissions standards". Similar standards are in place in non-EU countries and in other world regions. In general, emission regulations are adopted as part of the EU framework for the type approval of cars, vans, trucks, buses and coaches. Current standards are: for light duty vehicles (cars and vans) Euro 6, while the current standard for heavy duty vehicles is Euro VI.

Emission standards for light-duty vehicles are applicable to all vehicles category M1, M2, N1 and N2 with a reference mass not exceeding 2610 kg (Euro 5/6). EU regulations introduce different emission limits for compression ignition (diesel) and positive ignition (gasoline, CNG, LPG, ethanol,...) vehicles. Positive ignition vehicles were exempted from PM standards through the Euro 4 stage. Euro 5/6 regulations introduce PM mass emission standards, equal to those for diesels, for positive ignition vehicles with direct injection engines.

European emission standards for engines used in new non-road mobile machinery (NRMM) have been structured as gradually more stringent tiers known as Stage I...V standards. Stage I...IV regulations for diesel engines were specified by Directive 97/68/EC and five amending Directives adopted from 2002 to 2012. One of the amending Directives also introduced emission standards for small, spark-ignited non-road engines. From Stage V, Regulation 2016/1628 specifies emission requirements for all categories of compression ignition (diesel) and positive ignition mobile non-road engines, replacing Directive 97/68/EC and its amendments.

TABLE 4: EU VEHICLE AND MACHINERY EMISSION STANDARDS

VEHICLE TYPE	STAGE	DATE	PM (G/KM)	PN (#/KM)	COMMENTS
Passenger Cars (Diesel)	Euro 6	09. 2014	0.005	$6.0x10^{11}$	0.0045 g/km using PMP measurement procedure
Passenger Cars (Gasoline)	Euro 6	09.2014	0.005	$6.0x10^{11}$	Applicable only to engines using DI engines; 0.0045 g/km using PMP measurement procedure
Light Duty Vehicles (Diesel), all Classes	Euro 6	09.2015 (latest)	0.005	$6.0x10^{11}$	0.0045 g/kg using PMP measurement procedure
Light Duty Vehicles (Gasoline), all Classes	Euro 6	09.2015 (latest)	0.005	$6.9x10^{11}$	Applicable only to engines using DI engines; 0.0045 g/km using PMP measurement procedure

6. www.dieselnet.com/standards (07.04.2017)

VEHICLE TYPE	STAGE	DATE	PM (G/KM)	PN (#/KM)	COMMENTS
Heavy Duty Vehicles (Diesel)	Euro VI	01.2013	0.01	$8.0x10^{11}$	Steady-state testing
Heavy Duty Vehicles (Diesel)	Euro VI	01.2013	0.01	$6.0x10^{11}$	Transient testing

NON-ROAD ENGINES	STAGE	DATE	PM (G/KM)	PN (#/KM)	COMMENTS
NRE-v/c-4 (Diesel) 37 ≤ P < 56 kW	Stage V	2019	0.015	$1x10^{12}$	*Ex: Baggage Belt, Ramp Snake.*
NRE-v/c-5 (All) 56 ≤ P < 130 kW	Stage V	2020	0.015	$1x10^{12}$	*Ex: GPU, High Loader, Catering Truck*
NRE-v/c-6 (All) 130 ≤ P < 560 kW	Stage V	2019	0.015	$1x10^{12}$	*Ex. Aircraft push-back tractor*

Regulatory authorities in the EU, USA, and Japan have been under pressure from engine and equipment manufacturers to harmonize worldwide emission standards, in order to streamline engine development and emission type approval/certification for different markets. Stage I/II limits were in part harmonized with US regulations. Stage III/IV requirements were harmonized to a large degree with the US Tier 3/4 standards. However, at Stage V the harmonization has been largely lost — the Stage V PN limits require diesel particulate filters (DPF) on all affected engines, while the US Tier 4 standards can be met without filters.

EU non-road emission standards usually specify two sets of implementation dates: (1) type approval dates, after which all newly type approved models must meet the standard, and (2) market placement (or first registration) dates, after which all new engines placed on the market must meet the standard. The dates listed in the preceding tables are the market placement dates. In most cases, new type approval dates are one year before the respective market placement dates.

5.3 CONCENTRATION REGULATION

The European Commission has endorsed ambient concentration standards for a several gaseous primary and secondary pollutants through several directives, most recent the directive 2008/50/EC on ambient air quality and cleaner air in Europe. Such legislation is backed by similar standards in other parts of the world,[7] which can vary depending on local, national or regional priorities or circumstances. There are particle mass standards, but they refer to PM10 and PM2.5 only. Thus there are currently no standards specific to ultrafine particles.

The European Commission has endorsed several directives related to occupational exposure to chemical agents, e.g. Directive 2009/161/EU - indicative occupational exposure limit values. These limits – similar on countries outside the EC – cover a range of substances found in various occupations; the list usually is not complete. However, the above mentioned Directive comprises the third list (to present). This indicates the dynamics in the manufacturing and service-oriented industry and could allow for further amendments.

The process for establishing ambient concentration standards may vary according to national constitutional or other regulatory requirements. However, it usually involves large scale epidemiological studies on dose – health and ecosystem effects and intensive public and political debates and consensus finding.

5.4 CONCLUSIONS FOR THE AIRPORT INDUSTRY

The main activities at an airport that include combustion engines are the aircraft traffic, aircraft handling operations and the landside access traffic from passengers, staff and visitors. Other airport activities include the operation of the infrastructure like combustion plant, generators, or paint pigments.

With the implementation of EU Regulation 2016/1628 and the expected endorsements of new stringency options for the nvPM standard by ICAO, most combustion emission sources associated with the airport activities will be regulated for particle mass und numbers from combustion processes. The remaining gaps are emissions from generally non-regulated aircraft combustion sources like the auxiliary power units (APU) or small aircraft engines (<26.7 kN thrust). The current regulations support the airport industry's approach to local air quality management by subsequently providing information for emission inventories and mitigation planning.

At the same time, it must be noted that while emission standards relate to nvPM, it is also important to better understand the behaviour of vPM. This concerns both the formation of vPM and the different factors impacting it such as fuel quality, and their concentrations. In this respect, airports can play a role through measurement campaigns, covering both nvPM and vPM. Several of them are already carrying out this type of research, as presented in section 6. As measurements of UFP are very complex, with results potentially varying depending on the equipment used, Section 7 then outlines some points for attention for such activities.

7. ICAO Doc 9889, Airport Air Quality Manual, Chapter 2

6 AIRPORT STUDIES

6.1 INTRODUCTION

Airports must comply with environmental regulations when developing and operating their infrastructure. The same applies to aircraft operators and service providers at airports that operate their equipment. Part of such environmental regulations in local air quality might be related to regular assessments and mitigation.

Following international guidance like ICAO Doc 9889 or others, airports may develop emission inventories, perform dispersion analysis and measure total pollutant concentrations on a voluntary basis. Airports, regulators and research establishments have done work starting in 1999 (US Environment Protection Agency APEX-Studies). More recent focus has turned to specifically monitor and even model UFP at airports and airport regions. In the absence of a dedicated measurement standard for UFP, the decision to perform such work is at the discretion of each airport. If relevant measurements and analysis are carried out, it is important to correctly put them into context of the equipment used, as well as other relevant parameters such as the location, meteorological conditions and measurement frequency.

The following section presents a range of recent airport studies and work done to better understand ultrafine particle concentrations at and in the vicinity of airports. It must be noted that this list of studies is not exhaustive, and that further research has been carried out both in- and outside Europe, including around the airports of Los Angeles (Shiromahammadi et al, 2017: Riley et al, 2016; Hudda et al, 2014; Hudda and Fruin, 2016), Rome Ciampino (Stafoggia et al, 2016), Venice (Maisol et al, 2016), Mytilene in Greece (Psanis, 2017) and Tianjin in China (Ren et al, 2016).

Some studies often cited in public discussions (Schiphol Airport: Bezemer, A., 2015 or Boston Airport: Hudda, N., 2016) have shown some of the challenges associated with regional assessments. In the case of the Schiphol study, an attempt was made to use particle mass information as a correlation to particle number concentrations. In Boston, regional measurements were correlated with aircraft activities. Challenges have been observed when attempting to establish correlations between activity pattern and measured particle number concentrations without considering particle sizes or similar activity pattern of other sources. Another problem is the still disperse measurement quality of equipment. In Schiphol, different measurement methods were in use in different locations during different time periods and the results partially extrapolated to gain a regional concentrations picture.

Therefore it is important to remember that each study follows its own choice of measured substances, location, technical equipment, duration and other parameters. In this respect, it is also important to differentiate between studies that address UFP only, and those covering PM within a larger size range. The latter require particular attention when drawing conclusions for UFP specifically, with the lower cutoff of measurements playing an important role (as outlined in section 3.1). Due to the different methodologies applied, results cannot be compared airport by airport.

6.2 LONDON HEATHROW AIRPORT

In 2016, Heathrow Airport Limited (HAL) sponsored and commissioned a PhD project to investigate concentrations of Ultra Fine Particles (UFP) around the airport. The project, undertaken by Brian Stacey, Ricardo Energy and Environment and supervised by Professor Roy Harrison, University of Birmingham, will attempt to answer a series of questions:

- Do UFP concentrations at an airport differ from typical urban environments?
- Is there any correlation with UFP and other pollutants / meteorology?
- Is it possible to differentiate between different aircraft types / engines?
- Are UFP / other pollutant concentrations different when aircraft are taking off / landing?
- Is it possible to quantify any additional UFP contribution of the airport to the local environment?
- Are there any measurements that can be used as a surrogate for UFP measurements?

To begin to assess this, a monitoring campaign was conducted at 2 locations around Heathrow: one located 170m north of the Northern runway (LHR2), the second approximately 600m south of the Southern runway (Oaks Road). Concurrent measurements of UFP were made at the stations between 30 September and 25 November 2016. The stations used for the campaign also measure Oxides of Nitrogen (NOx), Particulate Matter (termed PM10 and PM2.5), Black Carbon (BC) and Carbon Dioxide (CO_2), allowing detailed profiling of the datasets to be undertaken. Local meteorological measurements were also made at the LHR2 station, allowing directional analysis to be performed on the data.

A second campaign is planned for the autumn of 2017, designed to look in much finer detail at the aircraft taking off and landing on the northern runway.

This initial summary of the data collected to date explores the headline results and context of the UFP measured at the airport.

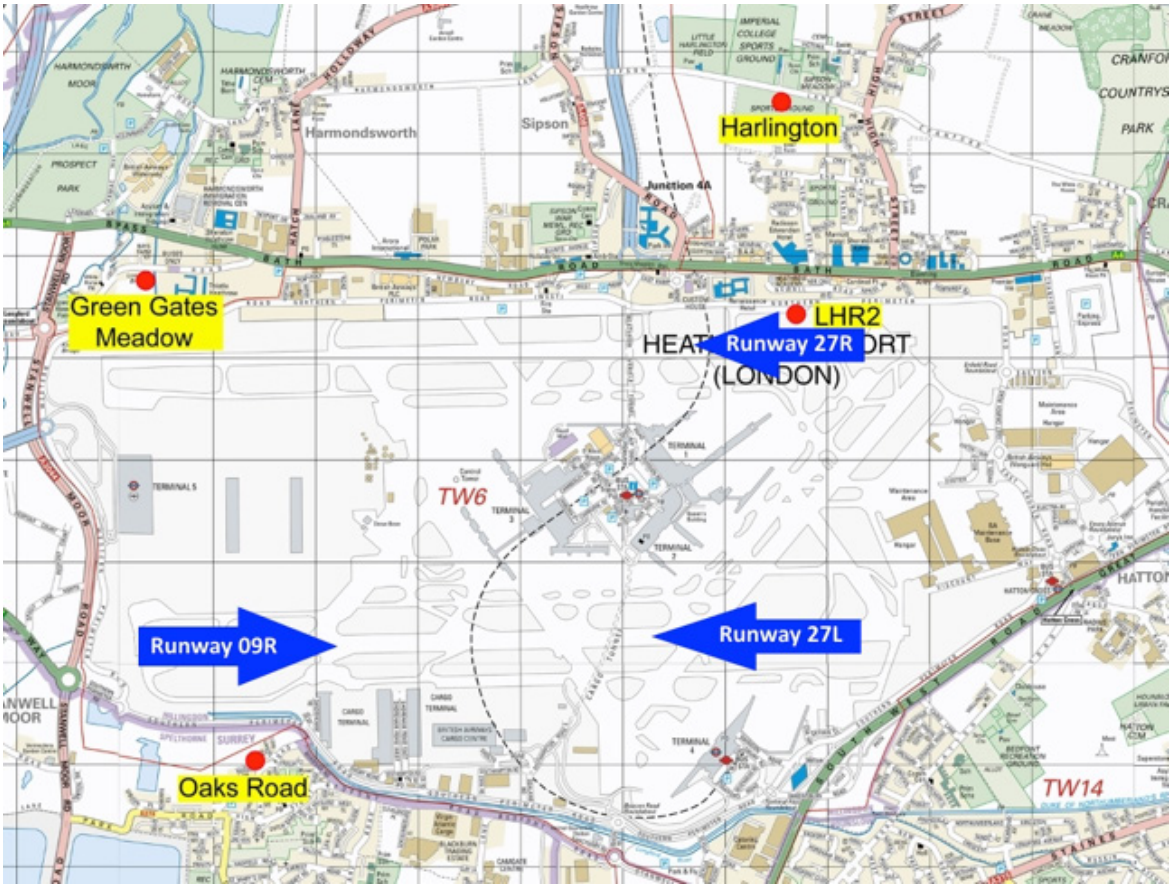
6.2.1 METHODOLOGY

HAL operates four monitoring stations around its perimeter:

- LHR2 – located airside in the north eastern corner of the airfield. It is 170m from the northern runway and less than 20m from the northern perimeter road. It has been in operation continuously since 1993
- Oaks Road – Located in a residential area to the south west of the airport, approximately 600m from the southern runway. It has been in continuous operation since 2001.
- Green Gates Meadow – Located in a residential / commercial area to the north west of the airport, approximately 450m from the northern runway. It has been operating continuously since 2001.
- London Harlington – Located to the north of the airport in a sports field on the outskirts of Harlington Village, approximately 1200m from the northern runway. It has been in operation since 2004.

The locations of these stations are presented in the figure below:

FIGURE 13: LOCATION OF THE MONITORING STATIONS



For this study, LHR2 and Oaks Road were chosen to measure UFP, in order to assess concentrations both upwind and downwind of the airport. Both stations measure NOx, PM10, PM2.5, BC and CO_2, while LHR2 additionally measures a range of meteorological parameters. The NOx, PM and BC analysers are conventional, type tested devices, while the CO_2 measurements are collected with a pervasive IR sensor fitted to the exhaust of the BC analyser.

UFP measurements were made with the following analysers:

TABLE 5: MONITORING STATIONS AND EQUIPMENT

STATION	EQUIPMENT INSTALLED
LHR2	TSI 3082 Scanning Mobility Particle Sizer (SMPS) TSI 3775 Condensation Particle Counter (CPC)
Oaks Road	TSI 3080 SMPS TSI 3775 CPC

The devices were configured to operate identically to the SMPS / CPC analysers used in the UK UFP monitoring network – sweep the size range in 2mins 15 seconds, every 3 minutes. They cover the particle size range from 14.6nm to 661.2nm. The only difference in instrument setup is that the Heathrow analysers were not fitted with a membrane dryer, when compared to the three UK network analysers. This may have an effect when comparing the particle size distributions for the larger particles measured by the SMPSs at Heathrow.

The CPCs were calibrated before and after the measurement campaign at the UKAS accredited ISO 17025 calibration facilities at Ricardo. In all cases, the calibration of the CPCs were within 1% of expected values.

The SMPSs sizing ability were also characterised in the Ricardo calibration laboratory, before and after the campaign. Again, in all cases, the characterisation of the sizers was within 1 size channel of the expected response. Thus the data collected from the UFP analysers was both internally consistent as well as traceable to the UK reference standard.

The initial measurement campaign ran from 30 September to 25 November 2016. In addition to the measurement data collected at the monitoring stations, HAL also provided comprehensive meta data, documenting aircraft movements, types of aircraft, time of landing, time of departure, time of push back from stand and runway operating modes. Thus it will be possible to correlate pollution with how the airport was being operated at the time of any pollution events.

In addition to airport activity, data from the UK national monitoring network can also be used to put the measurements into context. As noted earlier, SMPS/CPC measurements are made at three sites in the south of England: London Marylebone Road (traffic), London North Kensington (background) and Chilbolton (rural). For this campaign, provisional data from all three stations is used to compare against the Airport measurements.

6.2.2 RESULTS

Meteorological data from the US National Oceanic and Atmospheric Administration (NOAA) was used to produce a series of polar plots. These bivariate plots of hourly mean concentrations of nucleation and accumulation mode particles at LHR2 and Oaks Road against wind speed and wind direction data measured at Heathrow should be interpreted as follows:

- The wind speed is indicated by the distance from the centre of the plot; the grey circles indicate wind speeds in 2 ms-1 intervals.
- The pollutant concentration is indicated by the colour (as indicated by the scale).

Nucleation mode particles are predominantly directly emitted from combustion processes and are the smallest particles measured by the SMPS analyser, typically in the range 0 to 50 nm. Accumulation mode particles are usually formed by the combining of many nucleation particles over time. These are typically 100 to 1000nm in size.

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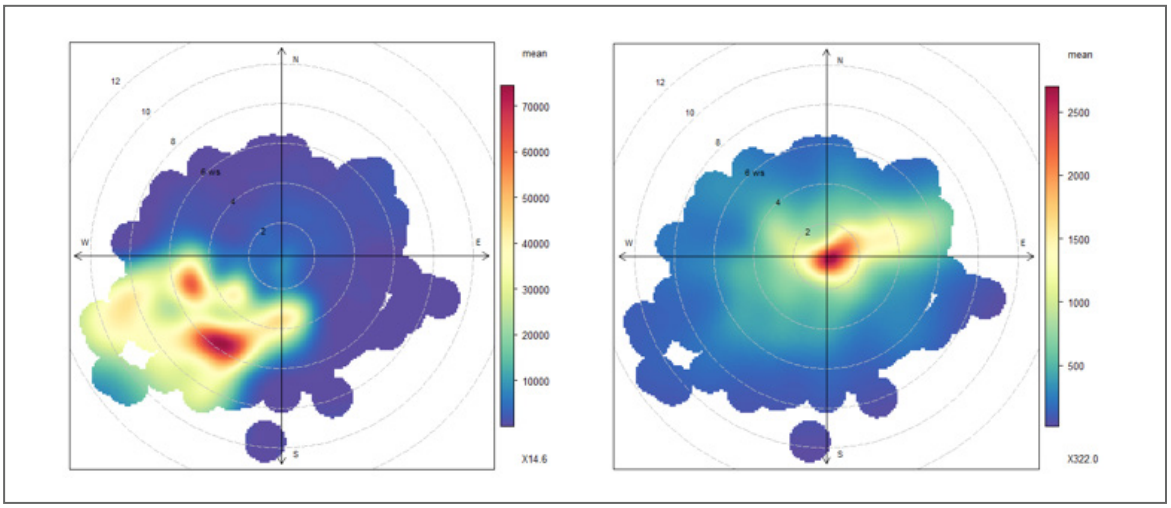
8. Data capture from the SMPS/CPCs at Heathrow did not cover the entire 30 September to 25 November campaign. At LHR2 the analyser configuration was incorrect on installation. Normal operation was established on 7 October and continued without issue for the remainder of the campaign. At Oaks Road the CPC interface with the computer failed on 29 October and was not successfully re-established, despite a number of attempts over the remaining period. Data capture from 30 September to 29 October was 100%.

These plots therefore show how pollutant concentrations varied with wind direction and wind speed. The plots below show concentrations with wind speed and direction at LHR2 for the entire survey period[8]:

FIGURE 14: POLAR PLOT OF NUCLEATION (LEFT) AND ACCUMULATION MODE PARTICLES AT LHR2

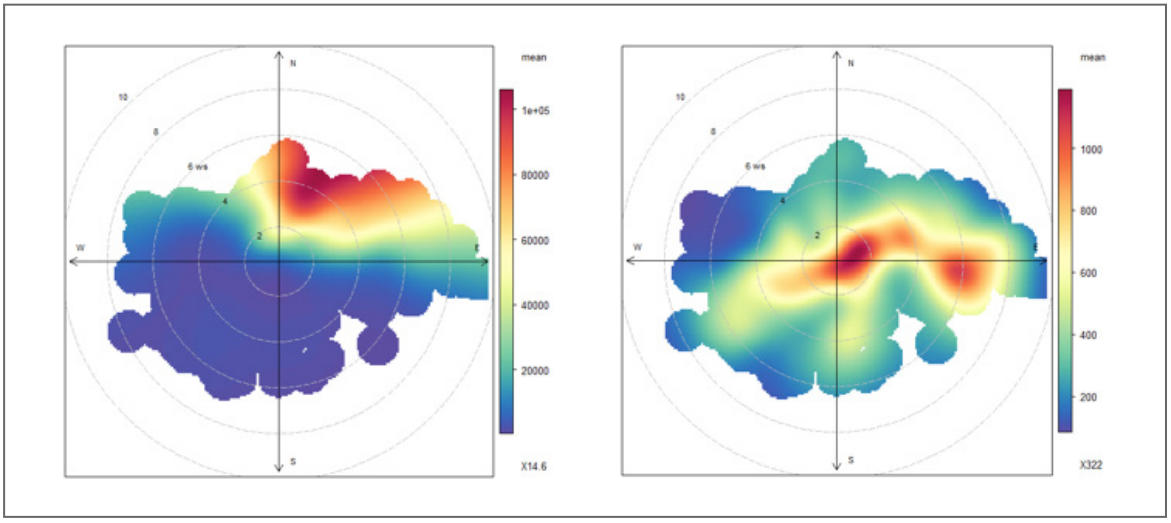


These plots provide a number of observations:

- At LHR2, nucleation mode particles are strongly associated with winds from the South and South East.
- There are a number of strong associations of nucleation mode particles at a range of directions and wind speeds to the south of LHR2, suggesting a number of different sources.
- The accumulation mode particles are strongly associated with very low wind speeds and winds from north of the airport.

The polar plots for Oaks Road for the survey are presented below:

FIGURE 15: POLAR PLOT OF NUCLEATION (LEFT) AND ACCUMULATION MODE PARTICLES AT OAKS ROAD



These plots provide a number of observations:

- At Oaks Road, nucleation mode particles are strongly associated with winds from the North and North West (i.e. the direction of the runway).
- Accumulation mode particles are strongly associated with a wide range of wind speed and directions, suggesting a number of different sources at this location.

The data from LHR2 and Oaks Road can be further disaggregated: Information from HAL about aircraft movements allows the UFP data to be filtered according to where the aircraft depart and land.. There are three normal operating modes at Heathrow, depending on wind direction[9]:

- Take off on Runway 27L, land on Runway 27R
- Take off on Runway 27R, land on Runway 27L
- Take off on Runway 09R, land on Runway 09L

For information, Runway 27R is closest to the LHR2 station, Runway 09R is closest to Oaks Road, as shown in Figure 13. The following observations can be made from analyses at LHR2 and Oaks Road disaggregated by runway operating mode:

- Highest concentrations at LHR2 are associated with aircraft taking off closest to the LHR2 station.
- Concentrations of 14.6nm particles are in the order of 50% lower when aircraft land on Runway 27R compared to when they are taking off on the same runway
- While measured concentrations were much lower at LHR2 when aircraft take off from Runway 09R, a small signal can still be seen associated with strong southerly winds. As the aircraft are already airborne by the time they pass the LHR2 station, this suggests that the emissions can still reach ground level under some conditions. There is also evidence of nucleation mode particles at LHR2 when winds are very low.
- There is no association of 14.6nm particles at LHR2 with westerly winds when aircraft land on Runway 09L. Aircraft have usually vacated the runway well before they approach the LHR2 station.
- Highest concentrations of 14.6nm particles at Oaks Road are strongly associated with winds from the north and east, when aircraft depart from the easterly runway 09R. A significant signal is still seen from aircraft when they depart from the southernmost westerly runway, 27L.

As noted earlier, the UK measures UFP at three locations near to Heathrow:

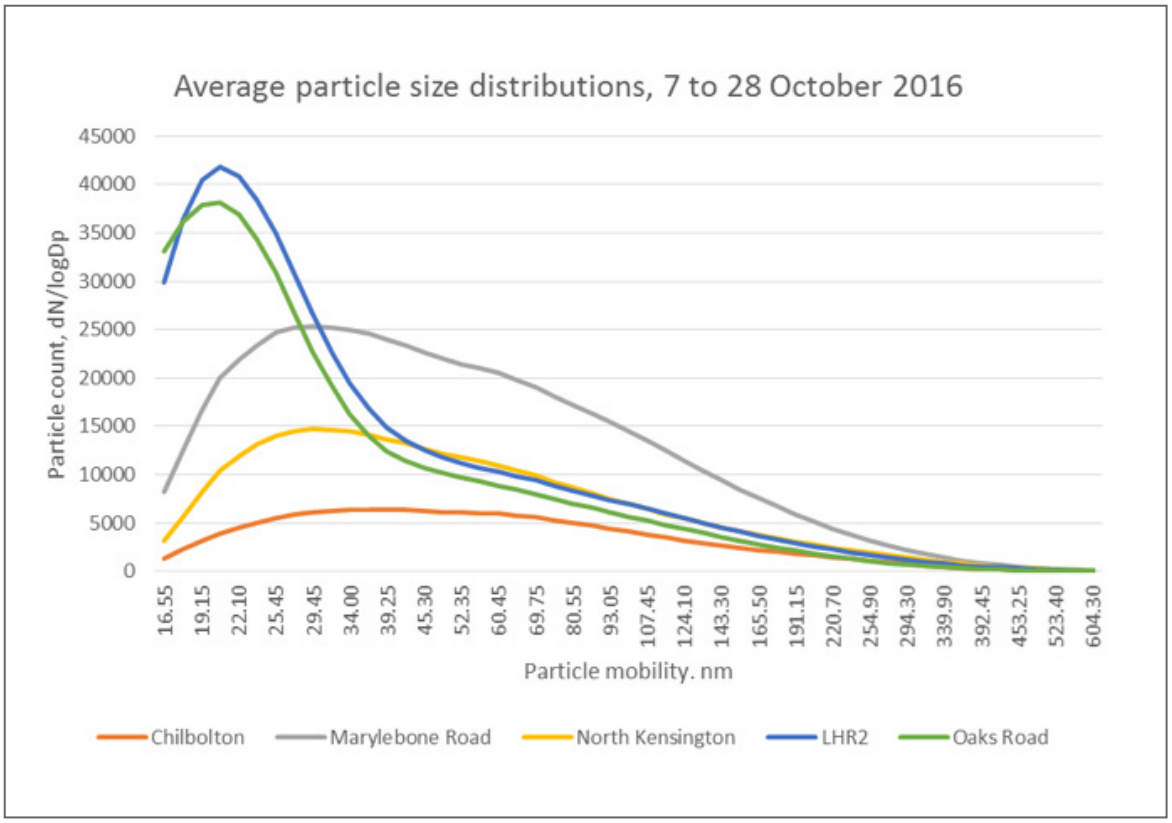
- London Marylebone Road – A traffic station in the centre of London
- London North Kensington – A residential station in West London
- Chilbolton – A rural station 20 miles north of Southampton

The SMPS / CPC analysers at Heathrow were configured identically to these three analysers (with the exception of the dryer fitted to the UK stations), allowing direct comparison of the data to be made. In addition, the Heathrow analysers were calibrated in the UKAS accredited ISO17025 laboratory at Ricardo, further ensuring traceability of the measurements to the national network datasets.

9. Aircraft do not typically depart from Runway 09L at LHR.

The plot below shows the average particle size distributions for all 5 stations for a period where all the analysers were operational:

FIGURE 16: AVERAGE PARTICLE SIZE DISTRIBUTIONS AT HEATHROW AND UK NETWORK STATIONS, OCTOBER 2016

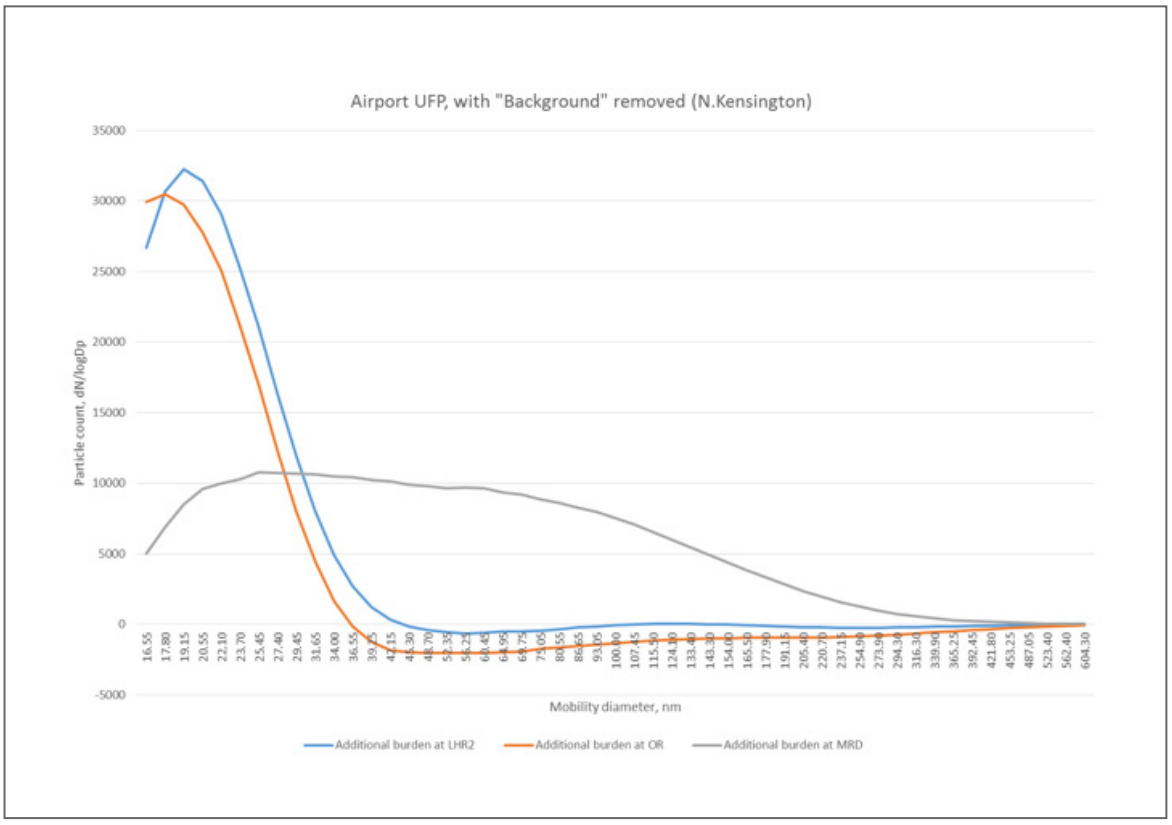


This plot shows, strikingly, that the smallest particles are much more abundant at the Heathrow stations than at any of the other locations. However, once particle sizes are larger than about 40nm, average concentrations at both Heathrow stations are the same or lower than the background North Kensington station.

At Marylebone Road, concentrations of particles larger than 35nm are significantly higher than any of the other stations.

The plot below "normalises" the average particles counts, using North Kensington as the reference

FIGURE 17: AVERAGE PARTICLE SIZE DISTRIBUTIONS "NORMALIZED" TO NORTH KENSINGTON OCTOBER 2016



This plot clearly shows that for particle sizes above 40nm, the Heathrow stations are remarkably similar to North Kensington. For smaller particle sizes, the airport stations have much higher particle counts. The roadside station at Marylebone Road is always higher than North Kensington, and higher than the airport stations for particle sizes larger than 35nm.

The table below shows the average total particle count (the sum of all size counts from 14.6 to 661.2nm) for all stations:

TABLE 6: MONITORING STATIONS AND AVERAGE TOTAL PARTICLE COUNTS

STATION	AVERAGE TOTAL PARTICLE COUNT (DN) PARTICLES / CM^3
Marylebone Road	10,046
LHR2	9,053
Oaks Road	7,964
North Kensington	5,384
Chilbolton	2,637

Average total particle count at Marylebone Road is higher than any other location. The airport sites are both significantly higher than North Kensington, as a direct consequence of the enhanced fine particle concentrations. The rural Chilbolton station experiences particle numbers less than half that of the North Kensington station.

6.2.3 DISCUSSION

This initial assessment of the UFP data collected at Heathrow Airport in autumn 2016 has provided valuable insight into the nature of ultrafine particles at the airport. The following key observations can be made:

- Total particle count between 14.6nm and 661.4nm are highest at London Marylebone Road in London.
- Total particle counts at LHR2 and Oaks Road are higher than the background station at London North Kensington
- Nucleation mode particle numbers (particles between 14.6nm and ~40nm) are significantly higher at LHR2 and Oaks Road than at the London stations.
- Particle number concentrations for particles larger than ~40nm at LHR2 and Oaks Road are remarkably similar to those measured at London North Kensington.
- There is clear evidence that highest concentrations of nucleation particles are associated with aircraft activity, in both departure and landing phases.

This summary represents a very brief snapshot assessment of the over 10 million data points collected over the period 30 September to 25 November 2016. Additional analysis of these data will include:

- Assessment of and correlation with other pollutant measurements made at the stations: Black Carbon, NOx, PM, CO_2, meteorology
- Examination of datasets at much finer time resolution. UFP measurements were made every 3 minutes, other pollutants were recorded at 15 minute intervals.
- Examination of aircraft movement data. Every aircraft landing and departing for the survey period is catalogued.

A follow up study is planned for later in 2017. This will focus on LHR2 and will attempt to collect measurement data at much finer time resolution – ideally 1 minute or less – to allow investigation of individual aircraft movements and emissions.

6.3 BRUSSELS AIRPORT

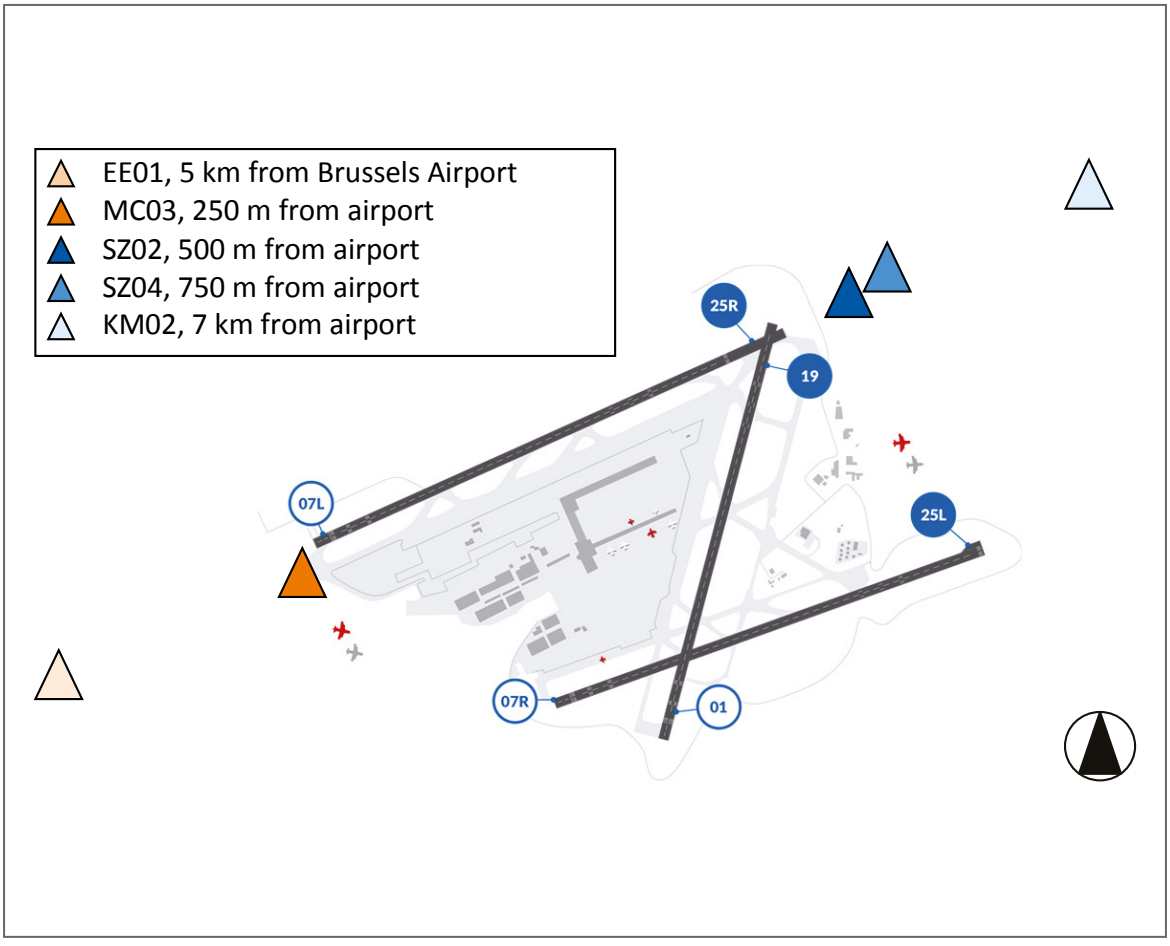
A study "UFP and BC – monitoring in the surroundings of Brussels Airport" (Ultrafine particles and Black Carbon) was performed in 2016 by VITO, commissioned by the Flanders Environment Agency and the Brussels Environment Agency (J. Peters, P. Berghmans, J. Van Laer, E. Frijns with the cooperation of BIM, ECN, ISSeP en VMM).

The objective of the study was to investigate the potential contribution of operations at Brussels Airport to the local air quality at surrounding residential areas. Therefore the concentrations of UFP, black carbon (BC) and nitrogen oxides (NOx) were measured at different locations near the airport and measurements were compared to literature results.

6.3.1 MONITORING PLAN

Five locations were selected as monitoring locations, including one existing air quality monitoring station from the Flanders Environment Agency (VMM). The monitoring stations were located on a transect aligned with runway (25R/07L) at varying distance from the runways. Four of the measurement locations (EE01, MC03, SZ02 and SZ04) are characterized as urban background stations, whereas one location (KM02) is a rural station.

FIGURE 18: MEASUREMENT LOCATIONS AT BRUSSELS AIRPORT



The monitoring was performed for UFP, BC, NOx and PM10. The UFP number concentration was continuously monitored at locations EE01, KM02, MC03 and SZ04 with a scanning mobility particle sizer (SMPS) within different particle size classes of 10-20, 20-30, 30-50, 50-70, 70-100, 100-200 and 200-294 nm. The UFP measurement resolution was five minutes. The BC and NOx concentration was measured at EE01, KM02, MC03 en SZ02 at a resolution of 30 minutes. The PM10 concentration was determined on a daily basis. The monitoring was done during a two month period, i.e. October and November 2015. An overview of the instruments that were used at the different monitoring stations is given in this table:

TABLE 7: MONITORING EQUIPMENT AND PARAMETERS

LOCATION	PARAMETER	MONITOR
Steenokkerzeel SZ04	UFP	TSI SMPS 3936L76
	PM10	Leckel SEQ47/50
Steenokkerzeel SZ02	BC	MAAP 5012
	NOx	NOx TS42i
Diegem MC03	UFP	IfT custom classifier and CPC3772
	BC	Magee AE22
	NOx	NOx 42C
	PM10	Leckel SEQ47/50
Evere EE01	UFP	IfT custom classifier and CPC3772
	BC	Magee AE22
	NOx	NOx TS42C
	PM10	Leckel SEQ47/50
Kampenhout KM02	UFP	TSI SMPS 3936L76
	BC	MAAP 4012
	NOx	NOx TS42C
	PM10	Leckel SEQ47/50

Meteorological data from a nearby meteorological station (Melsbroek) were provided by BIM (Brussels Instituut voor Milieubeheer). Information about LTO operations at Brussels Airport during the two month monitoring period was provided by the Flanders Department of Energy, Nature and Environment (LNE) and is based on flight information and radar measurements of Belgocontrol and Brussels Airport Company.

Before the two months monitoring period, a two week period (14-28/09/2015) of simultaneous measurements at one of the sites (SZ04) was performed to compare the instruments. Based on these simultaneous measurements, the UFP monitoring systems were adjusted and rescaling models were parameterized to increase comparability between the measurements from different instruments. The correspondence of the rescaled simultaneous measurements was excellent, with a difference of less than 3% between most instruments for the majority of UFP size classes.

6.3.2 RESULTS

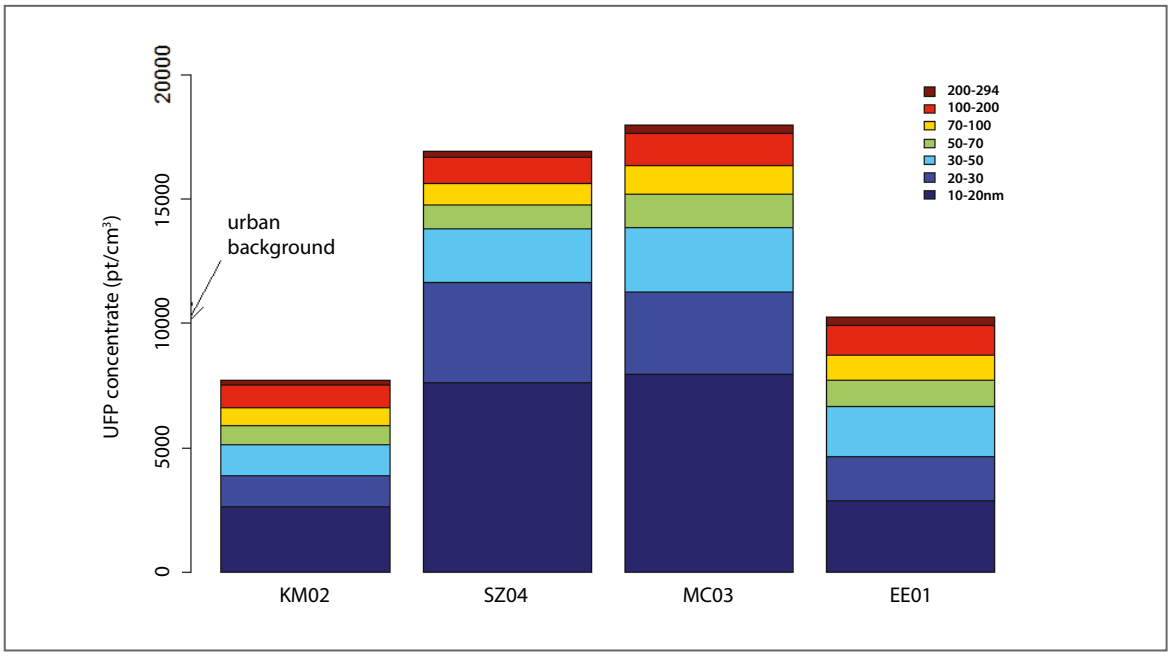
The results presented are mainly focused on the smallest UFP fraction of this study, i.e. 10-20 nm, which is the fraction with the largest contribution to aircraft emissions. Based on the entire measurement period, the average and 99th percentile (P99) number concentrations of UFP of size class 10-20 nm are largely increased at the nearby monitoring stations SZ04 and MC03 compared to KM02 and EE01 stations which are situated further away from the airport.

TABLE 8: MAIN UFP RESULTS BRUSSELS AIRPORT

LOCATION	AVERAGE 10-20NM		P99 10-20NM		DISTANCE TO AIRPORT
	pt/cm³	**ratio**	**pt/cm³**	**ratio**	**km**
Evere (EE01)	2,891	1.1	10,063	0.5	5
Diegem (MC03)	8,119	3.1	68,992	3.5	0.25
Steenokkerzeel (SZ04)	7,776	3.0	74,370	3.7	0.75
Kampenhout (KM02)	2,615	1	19,660	1	7
Ratio [location]/[KM02]; KM02 is a rural background site					

The share of the 10-20 nm fraction in the total 10-294 nm UFP number concentration is much larger near the airport (SZ04 45% and MCO3 45%) in comparison to the more distant locations (KM02 35% and EE01 28%). The UFP concentrations vary between the hours of the day, with the highest concentrations during the morning rush (6 – 10 am local time) and evening rush (4 – 8 pm local time). The number of LTO operations at Brussels Airport shows a similar bimodal pattern.

FIGURE 19: PARTICLE SIZE DISTRIBUTION AT THE MEASUREMENT STATIONS



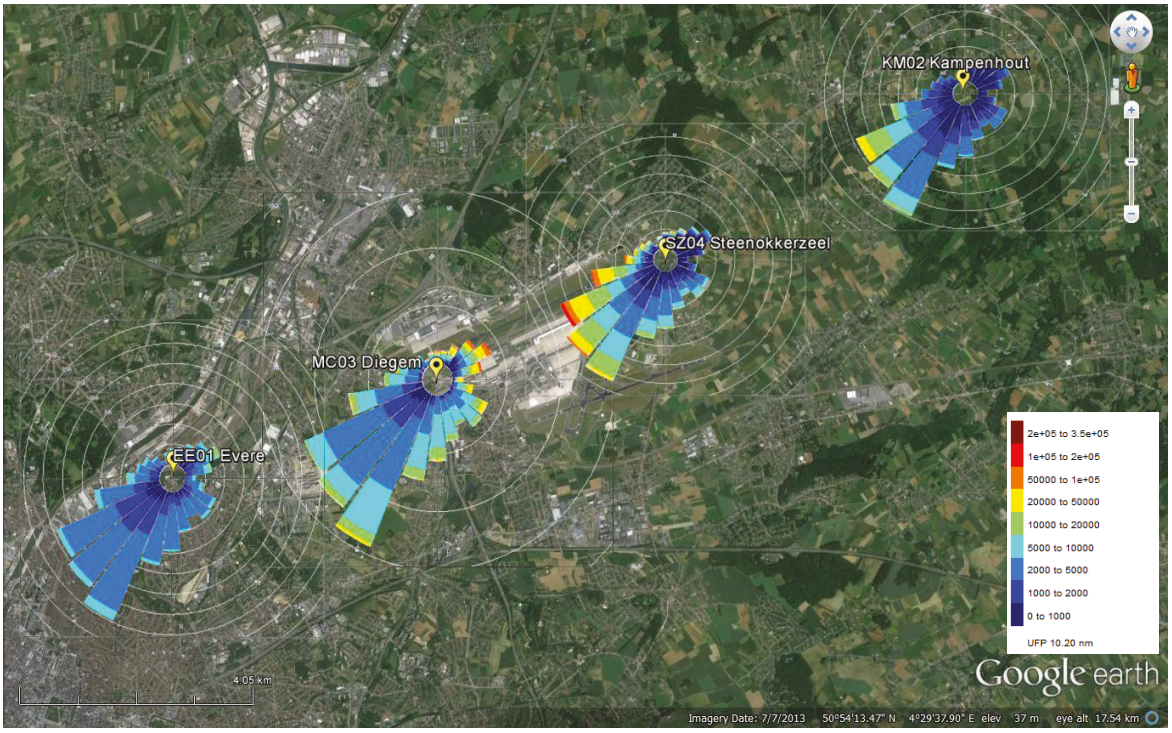
The analysis of UFP concentration measurements in relation to wind direction showed increased UFP concentrations of the 10-20 nm size class at all the monitoring locations when they were situated downwind of the airport. At the nearby stations, the UFP number concentrations of the 10-20 nm size class exceed 50 000 pt/cm^3 during 6-11% of the time for SZ04 and MC03, respectively. For larger UFP classes (> 70 nm) the UFP pollution roses did not show the directionality toward the airport which was observed for the smaller UFP classes.

An additive model was used to account for the contribution of airport operations to the UFP concentration at nearby downwind locations. An overcompensation by this model was inevitable, so the values reported here are probably rather conservative estimates. Under downwind conditions, for 25% of the time an airport contribution to the 10-20 nm UFP particle numbers of 20 000 to 28 000 pt/cm^3 was estimated. For 10% of the time a contribution of more than 44 000 to 58 000 pt/cm^3 was found, and for 5% of the time of 66 000 to 82 000 pt/cm^3. The maximal contribution ranged between 255 000 and 276 000 pt/cm^3.

Flight information was used to further investigate the variability in UFP concentration. A visual inspection of 3D plots of the hourly mean UFP concentration of the 10-20 nm size class, the hourly prevailing wind direction and the hourly number of LTO operations showed a clear gradient of increasing UFP concentration with increasing numbers of LTO operations during downwind conditions, especially at SZ04 which is downwind under the dominant Southwesterly wind direction. At MC03 the gradient is less clear due to a much lower number of measurements under downwind conditions.

The variability of the hourly 10-20 nm UFP concentration in function of meteorology and LTO operations was further analysed using a multiple linear regression model. For the two locations NE of the airport the models explained 60% (SZ04) and 51% (KM02) of the measured variation. The model identified the number of LTO operations at the nearest runway 25R during downwind conditions as the most important independent variable in explaining the variation in UFP concentration at both sites. The analysis revealed a correlation between the UFP concentration in the surrounding area of the airport and aircraft LTO operations.

FIGURE 20: MEASUREMENT RESULTS IN FUNCTION OF METEOROLOGY



The contribution of airport activities to the other measured air pollutants, BC, NOx and PM10, is much less evident. The analysis of BC and NOx concentration profiles in function of wind direction did not reveal higher contributions from the airport than from other (probably mainly traffic) sources. The daily average PM10 concentration was similar at all measurement sites.

6.3.3 CONCLUSION

In urban environments, road traffic is generally the dominant source of primary UFP (10-100 nm). In the area surrounding Brussels Airport, a significant contribution of airport activity to the UFP 10-20 nm number concentration is observed. The contribution decreases with increasing distances, but effects are measurable at a distance of 7 km from the airport. There is a clear relationship between LTO operations, wind direction and distance to the airport and the UFP concentration that is observed at a monitoring site in the area around the airport. In contrast, the airport activity does not have a higher contribution to the BC, NOx and PM10 concentration at the monitoring sites compared to the contributions from traffic at nearby roads and motorways.

6.4 ZURICH AIRPORT

A detailed UFP-study was performed by Zurich Airport in 2016, using a large number of measurement devices. The main objectives of the exploratory study were to determine particle number, diameters and LDSA and their temporal and spatial variability during several weeks of measuring and furthermore to study specific effects of meteorology and aircraft operations.

6.4.1 MEASUREMENT SETUP

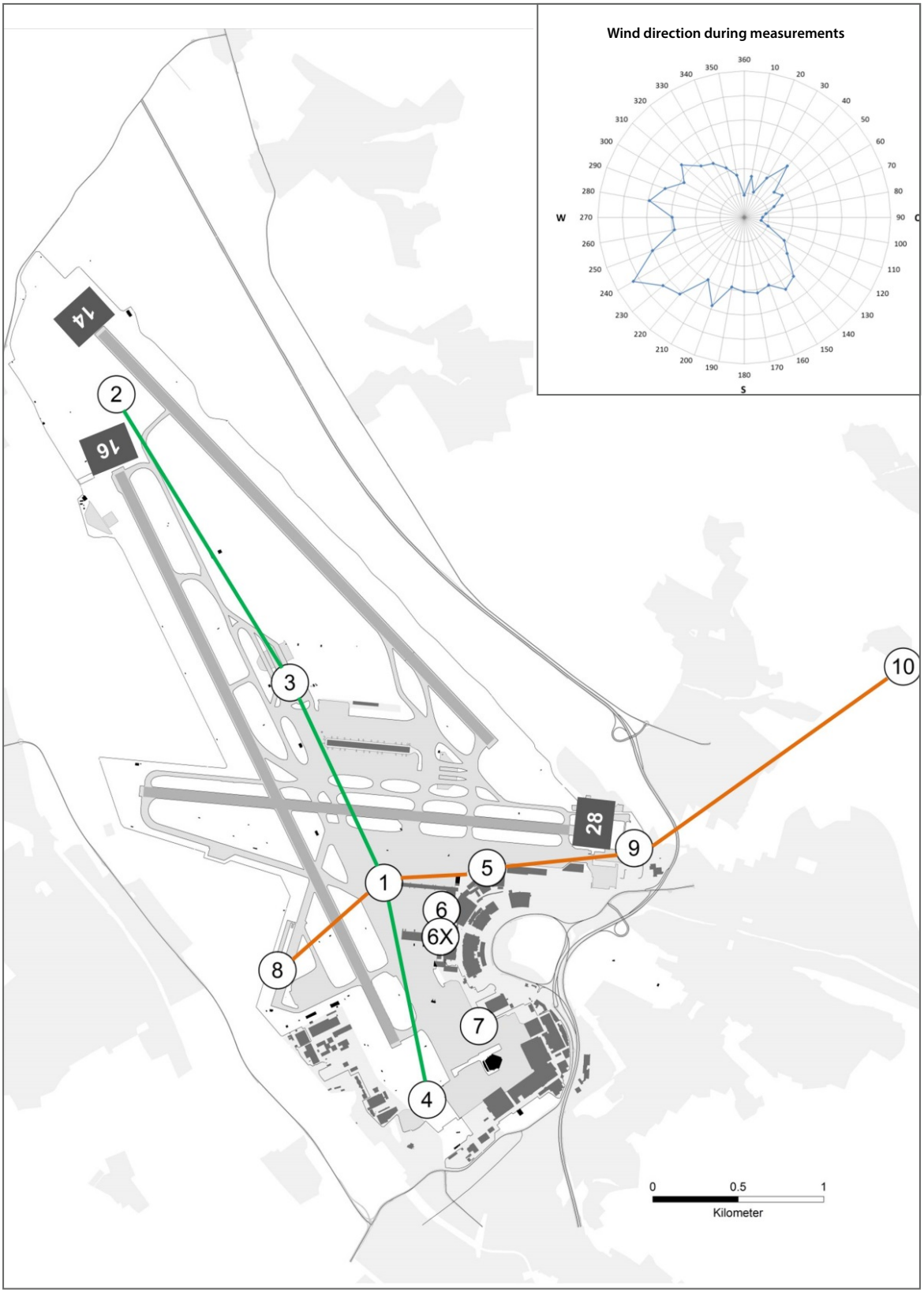
The miniature diffusion size classifier (miniDiSC, Fierz et al. 2011) was selected as a nanoparticle detector in this study because it has some advantages that make it ideal for this type of study: it is relatively compact, needs little power and can operate under a wide range of temperatures; all of which allowed simple installations at the airport. Compared to the standard device for particle number monitoring, the Condensation Particle Counter (CPC), it needs no working fluid and can thus run unattended for longer periods of time; and furthermore, it also measures an average particle diameter which may be useful for source apportionment as discussed above. While the particle concentration range of the device is well suited to this measurement campaign (10^3 - 10^6 particles per cm^3) and the upper limit was sometimes reached, the jet engine particles are quite close to the lower end of the specified diameter range of 10-300nm. Special care was taken in this study to ensure that the devices were operating properly at this outer edge of their specifications.

The measurement locations were grouped into three clusters and the stations placed accordingly: Transect North-South of the main long-haul departure Runway 16 to capture UFP near aircraft operations (stations 1, 2, 3, 4), transect West – East and a background station in line with predominant wind direction (stations 1, 5, 6/6X, 7, 9, 10) and a transect apron North-South (stations 1, 5, 6/6X, 7; see figure 21) to assess aircraft and handling emissions likewise. Station 1 has the same location as the permanent air quality monitoring station that covers NOx, NO_2, Ozone and PM10. In total, ten locations were selected for measurements.

TABLE 9: MEASUREMENT LOCATIONS AND THEIR CHARACTERISTICS ZURICH AIRPORT

NO.	LOCATION	CHARACTERIZATION
1	**Roof Pier A**	Aircraft handling, aircraft taxiing; 350-400m distance to Runways 28 (short haul take-off and landing) and 16 (long-haul take-off)
2	**Meteo Garden**	Aircraft traffic: Landings Runways 14 (180m distance) and 16, take-off long-haul Runway 16 (450m distance)
3	**Stands Papa**	Aircraft taxiing to Runway 16; departing aircraft (400m distance)
4	**End of RWY16**	Departing long-haul aircraft Runway 16 (400m distance; aircraft altitude 200m)
5	**Apron V5**	Airside traffic, aircraft handling, landing and take-off Runway 28 (270m distance)
6/6X	**Apron courtyard**	Airside traffic, aircraft handling, pushback, aircraft idling and taxiing
7	**Stands Charlie**	Airside traffic, aircraft handling, aircraft taxiing
8	**Helipad West**	Airport fence, upwind. Between cantonal road (370m) and Runway 16 (460m distance)
9	**Entrance Gate 109**	Airport fence, downwind. Between motorway A51 (250m distance) and Runway 28 (450m distance)
10	**Cemetery Kloten**	Background, little traffic, (1,900m from airport fence); long-haul overflights (1,500m/ground)

FIGURE 21: ZURICH AIRPORT LAYOUT WITH UFP MONITORING STATIONS AND PREDOMINANT WIND FIELD

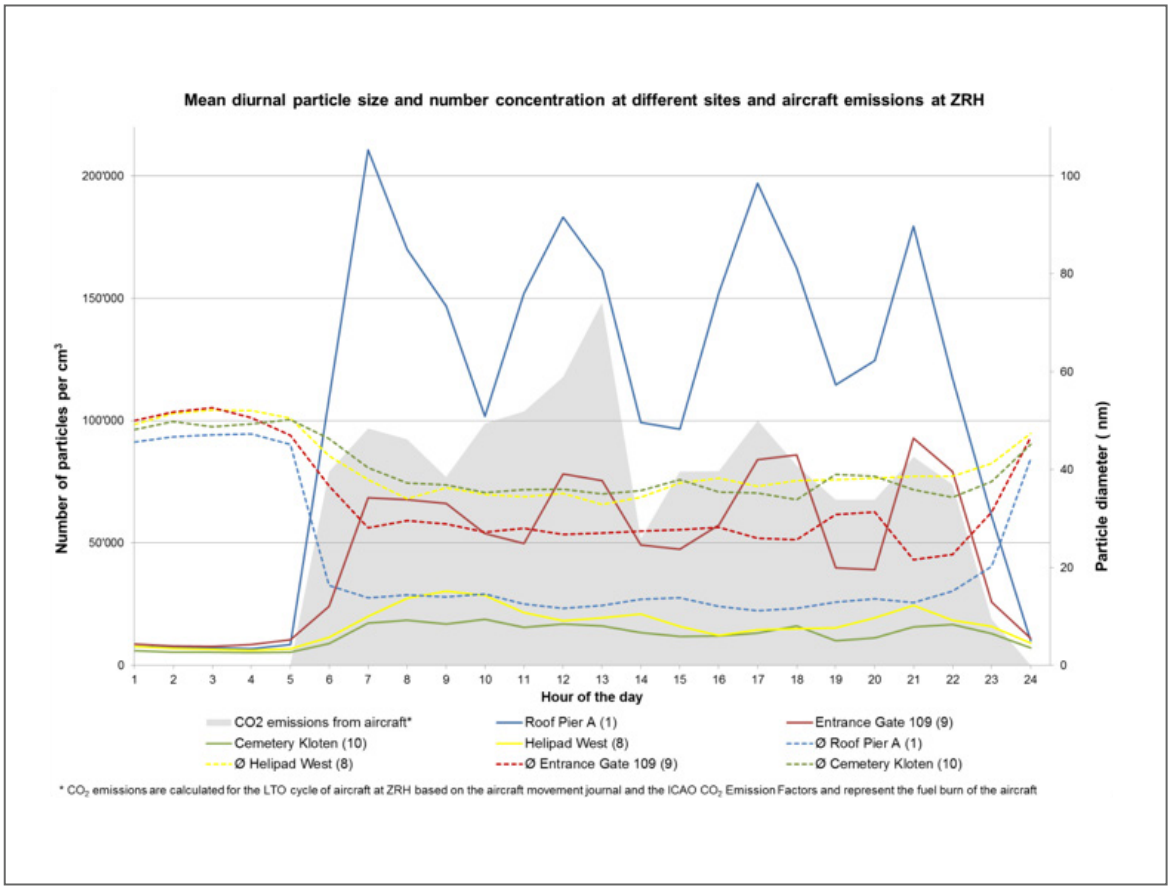


All stations were equipped with a Miniature Diffusion Size Classifier (MiniDiSC) with a data capture frequency of 1s [Fierz, et al. 2011]. All aerosols are being accounted for (volatile and non-volatile) within a size range of 10-300nm. These devices are rather compact and were run on external power, thus being well suited for the campaign at an airport, requiring low maintenance. The systems were all calibrated in parallel, ensuring like-for-like measurements among the devices. The campaign ran from April until June, 2016 (5 weeks) to capture various weather conditions and compensate for some potential monitoring gaps.

6.4.2 RESULTS

The diurnal particle number concentrations and average mobility diameter for monitoring stations along the East-West transect are presented in the following figure. The stations represent predominately upwind (no 8), downwind (no 9), hot spot (no 1) and background locations (no 10). For comparison, the aircraft activity is shown as LTO (landing and take-off) CO_2-emissions (grey area). LDSA values range from 18nm^2/cm^3 at night to 135nm^2/cm^3 during peak time at 0700. The diurnal LDSA pattern also corresponds well with the particle number concentrations.

FIGURE 22: DIURNAL PARTICLE NUMBER AND SIZE DISTRIBUTION AT SELECTED MONITORING SITES, HOURLY AVERAGE (SOLID LINES: PARTICLE NUMBERS CONCENTRATIONS; DOTTED LINES: AVERAGE MOBILITY DIAMETERS; GREY AREA: KG CO_2, NOT SCALED)



Station 1 (Pier A) shows the highest number concentrations at the lowest particle size and at the same time the most distinct diurnal variation in both particle numbers and particle size. This could be expected from the location in the centre of the airport and aircraft activity. Station 9 (Entrance Gate 109) which is located 1,450m downwind at the airport fence compared to station 1 shows half the numbers and twice the size of particles while the station 10 (Cemetery Kloten), 3,300m downwind the airport station 1 shows low particle numbers with high diameters. Station 8 (Helipad West), 1,030m upwind the airport station 1 also shows low numbers with high diameters despite being only 460m distant from the main long haul aircraft take-off runway. However, this station is 370m downwind the cantonal road West of the airport and will thus also be influenced by those emissions.

The variability of the particle number concentrations was very high in two ways. First, the variability between the stations over the same time period at the airport itself spans from the station 8 (Helipad) with 16,000 part/cm^3 (hourly average) to the station 6X (Emergency stairs) with 139,000 (factor of 8.6). The second variability is observed within the station results themselves. Station 5 (V5 Apron) rendered values from 1,400 (minimum) to 786,000 part/cm^3, with a mean of 104,000 part/cm^3 (again hourly averages over the whole campaign duration). Even the background station 10 (Cemetery) showed a span from 1,300 to 100,000 part/cm^3 with a mean value of 12,000 part/cm^3. The lowest values occurred during night-time and the highest values during day time peak hour traffic, as also can be seen in above figure.

The average diameter variability is less pronounced. It is a factor of 1.9 between the lowest (station 1, Pier A, 21.7nm) and the largest (station 2, Meteo Garden, 40.5nm). Within the same station, the variability factor was highest at station 9 (Gate 109) with a low of 7.9nm and a high of 103nm where the average was 33.5nm.

Wind speed and direction were analysed to identify their influence on particle number and size variability. The wind analysis was first done at the same station (2, Meteo Garden) during always the same one hour of activity – between 10:34 and 11:34 – but different wind situations (following figure). Clearly, number concentrations and size and thus the "pattern" vary considerably depending on the wind direction where the measurement location may be upwind, downwind or crosswind to the airport centre. The Northeasterly wind likely shows the influence from landing traffic on Runway 14, while the Northwesterly wind brings background concentrations and Southeasterly wind (factor 10 higher illustrated) shows the impact of departing aircraft on Runway 16 and the influx from the centre of the airport and all activities there.

The second comparison was done along two transects, one being North-South (Runway 16, along the stations 2-3-1-4) and one being West-East (along the stations 8-1-5-9-10). The North-South transect shows similar results for Northerly (330°-30°) and Southerly (150°-220°) winds. The high peaks from Roof Pier A drop by at least two thirds to either airport boundary station (2 and 4). The West-East transect primarily shows the impact of the high activity profile around Pier A und the apron (stations 1 and 5). With Southwesterly winds (220°-280°), peak values are reached at Apron V5 station (5), with Northeasterly winds (30°-90°) at Roof Pier A (1). For both wind directions, peak numbers drop also by two thirds within approximately one kilometre distance and even by 80% within 3km distance.

FIGURE 23: VARIABILITY OF PARTICLE NUMBER AND SIZE DUE TO DIFFERENT METEOROLOGICAL CONDITIONS, BUT SAME ACTIVITY PROFILE (METEO GARDEN, NO 2)

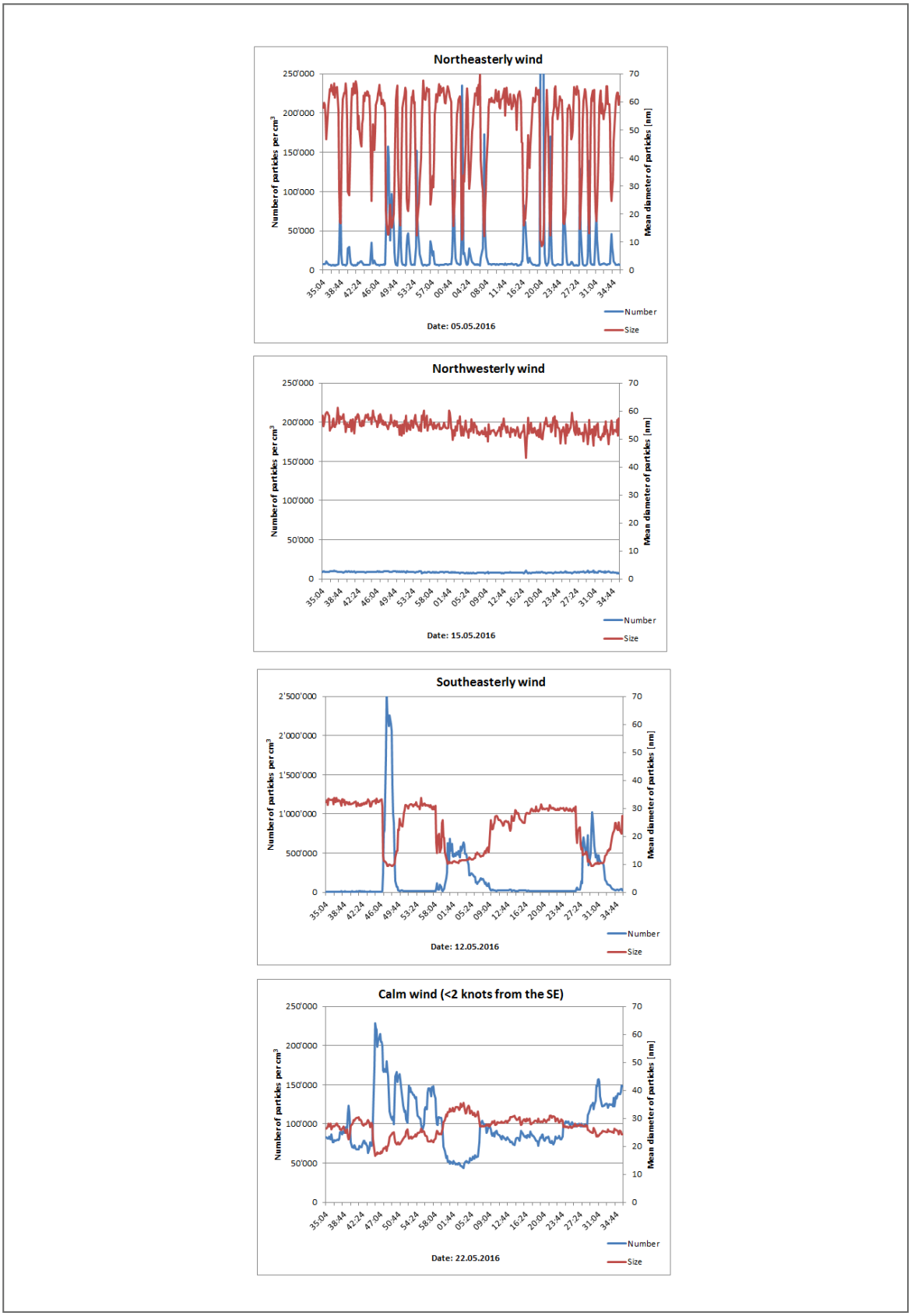
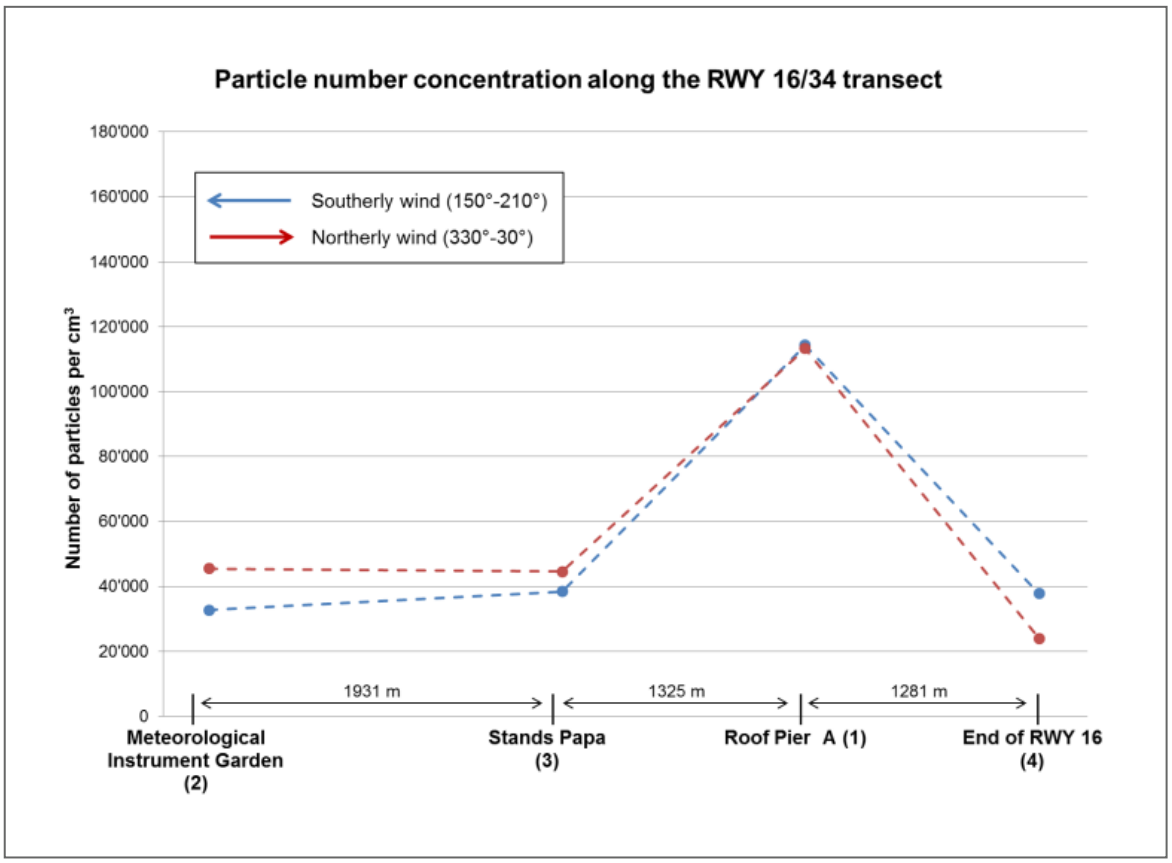
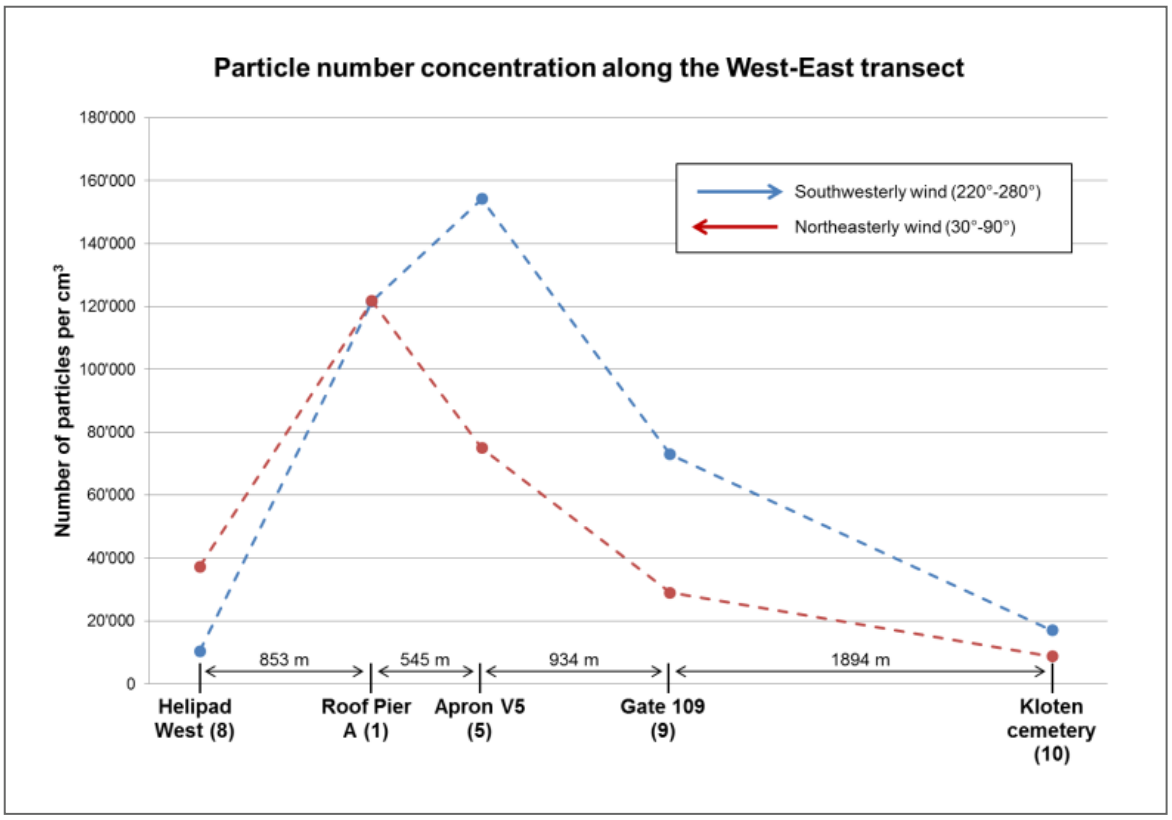


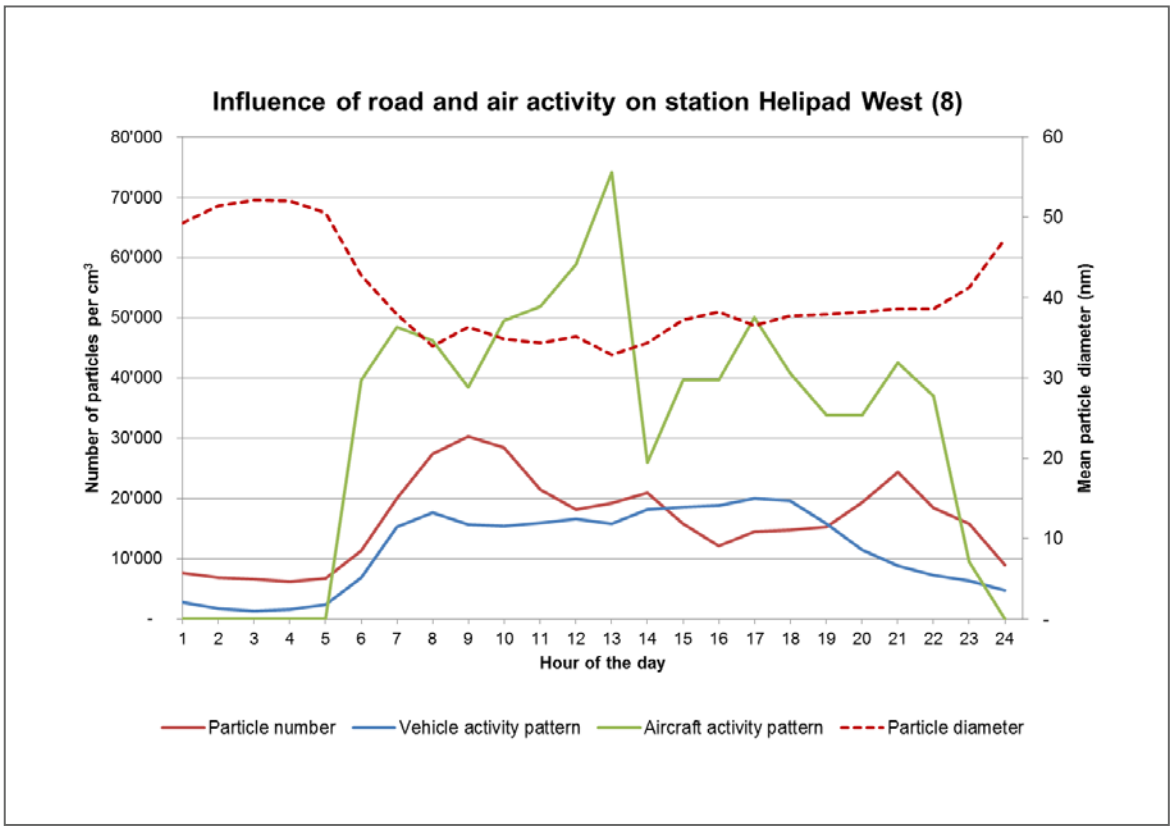
FIGURE 24: PARTICLE NUMBER CONCENTRATIONS ALONG THE NORTH-SOUTH AND WEST-EAST TRANSECTS





Monitoring station 8 (Helipad West) is located between a busy cantonal road (370m) und Runway 16 (460m). For both sources, comparable hourly activity profiles were available and were used in conjunction with particle number concentrations and size at the monitoring station. The following figure shows the diurnal pattern in relation to vehicle and aircraft activity.

FIGURE 25: DIURNAL PARTICLE NUMBER CONCENTRATIONS AND SIZE WITH ROAD AND AIRCRAFT ACTIVITY PROFILES (NO DIMENSION)



The hourly particle number concentrations vary between 7,000 part/cm^3 at night to 30,000 part/cm^3 during the peak time of 08-10 o'clock. Aircraft activity peaks become not visible and the concentration pattern follows more the vehicle activity pattern.

6.4.3 CONCLUSIONS

This study demonstrates the high temporal and spatial variability of UFP concentrations on the airport area, and the importance of wind speed and direction as confounders. It also shows the significant decrease of number concentrations with increasing distance from the source. Short-term measurements at single locations may drastically over- or underestimate the true (average) UFP concentrations at airports.

UFP measurement locations must be chosen carefully, should always be complemented with wind speed and direction measurements, and operated over longer periods of time to cover a representative sample of activity and weather conditions. The extremely small particle sizes observed in this study also indicate that measurement equipment must be chosen carefully.

6.5 COPENHAGEN AIRPORT

Copenhagen Airport is the main airport in Denmark and the largest airport in Scandinavia, with 29 million passengers and 265,784 flights handled in 2016. Copenhagen Airport is operated by Copenhagen Airports A/S (CPH). CPH owns and operates Copenhagen Airport and Roskilde Airport.

FIGURE 26: COPENHAGEN AIRPORT AND THE LOCATIONS OF THE AIRPORT'S AIR QUALITY MONITORING STATIONS (RED STARS): STATION WEST (NO, NO2, PM2.5 AND UFP), STATION EAST (NO, NO2, PM2.5) AND THE APRON STATION, STATION B4 (NO, NO2 AND UFP).

6.5.1 LOCAL AIR QUALITY – THE HEALTH & SAFETY PERSPECTIVE

Like many other airports, CPH has been working with air quality management for a number of years. Focusing on the airport's possible impact on the neighbouring communities, CPH has monitored the air quality at the fence since 2000. The monitoring program has been focusing on particles (PM2.5), NO and NO2. Results have always been well below regulatory limit values.

Based on the air quality monitoring program, CPH was doing quite well in terms of air quality. However, following measurements of polycyclic aromatic hydrocarbons (PAH) at the apron at the Airports in Rome (Cavallo et al., 2006), the air quality in terms of working environment gained more focus among staff as well as management in both CPH and partners at the airport. With the aim of taking a fact-based approach to this challenge, a thorough survey of air pollution related to the working environment of

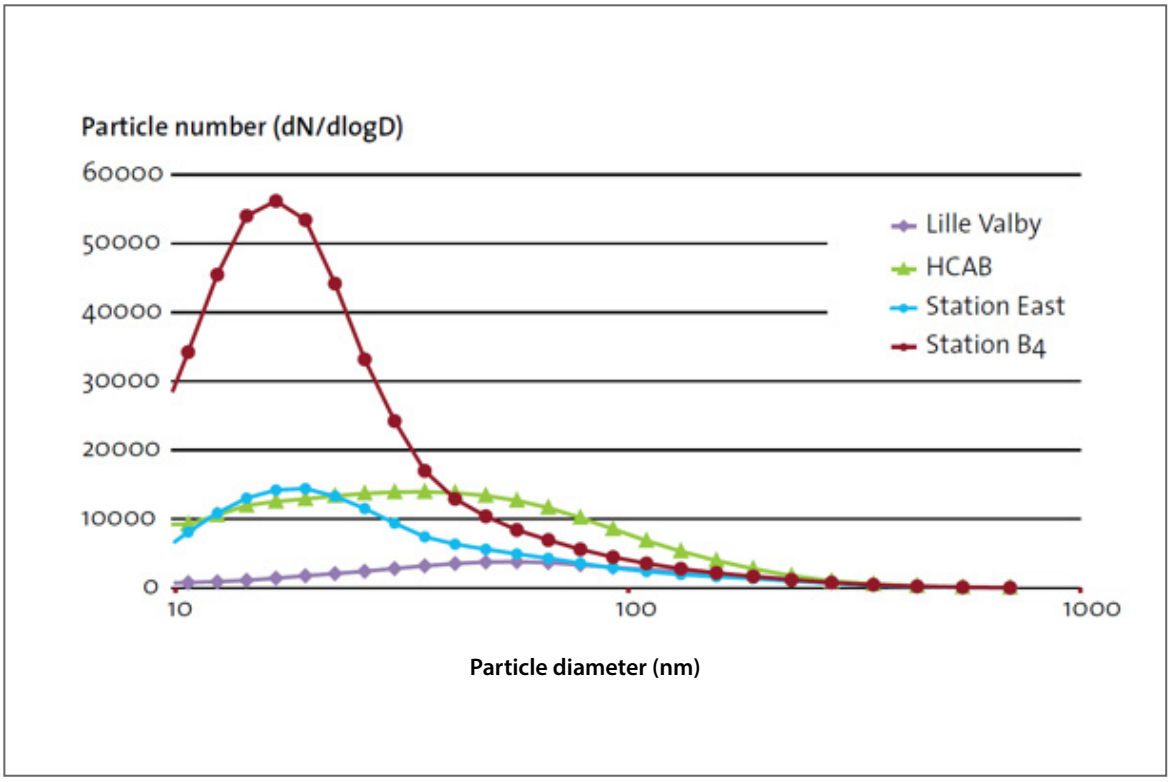
Copenhagen Airport was conducted from 2009 to 2011 by Danish Centre for Environment and Energy, Aarhus University (DCE). The findings are published as a scientific report: Assessment of the air quality on the apron of Copenhagen Airport Kastrup in relation to working environment (Ellermann et al. 2011).

The aim of the survey was to map the air pollution at the apron and to determine the sources of air pollution. Giving the focus on working environment, the emphasis was on determination of air pollution in those areas of the apron where staff is working.

The study led to the main conclusion that for the majority of the investigated air pollutants (nitrogen oxides, PM2.5, PAH, VOC, particulate organic and elemental carbon) the concentrations at the apron are below the comparable levels measured at H.C. Andersens Boulevard (HCAB), one of the busiest streets in Copenhagen (approximately 60,000 vehicles per day). Also, all measured pollutants were below air quality limits for the pollutants, where such exist.

However, the number of particles did not match this picture. The levels measured at the apron showed that the particle number (6 – 700 nm) was about two to three times higher at the apron than at HCAB and 85-90% of the particle number consisted of particles with a diameter between 6 and 40 nm. This particle fraction accounted for the difference between the particle number at the apron and HCAB. The ultrafine particles (particles with a diameter less than 100 nm) originated from the combustion of jet fuel and diesel at the apron. At the outskirts of the airport, the particle number was about 20 – 40 % lower than at HCAB. It is important to note that there is no air quality limit value in Denmark for particle number in ambient air.

FIGURE 27: DCE STUDY ON PARTICLE COUNT. PARTICLE COUNT ON Y-AXIS AND SIZE ON THE X-AXIS AT 4 DIFFERENT LOCATIONS: COPENHAGEN AIRPORT, STATION EAST, STATION B4, HCAB AND LILLE VALBY (RURAL AREA).



6.5.2 THE COPENHAGEN AIRPORT AIR QUALITY PROGRAM

The DCE study made it clear that the most prevalent air pollutant at the apron area was ultrafine particles and on this basis, CPH established the Copenhagen Airports Air Quality Program in its current form. The program is organized across the airport companies with personnel on the apron, with the common goal of minimizing the exposure of ultrafine particles to employees.

The Copenhagen Airport Air Quality Program is managed by CPH, but the strength of the program is really the cross organizational set-up and the fact that representatives in the program include both employees and management, also from handling companies, union representatives, main carriers, ANSPs and authority representatives. The work is voluntary and based on collaboration and an open dialogue between the partners and the success of the program is highly dependent on this partnership.

FIGURE 28: EMPLOYEE DRIVING ONE OF CPH'S ELECTRICAL STAIRS.

The program is organized in three work streams:

- Behaviour
- Ground Support Equipment
- Monitoring

In each work stream a number of various projects and initiatives have been and are being conducted. The scale of these projects varies from time limited awareness campaigns to scientific studies.

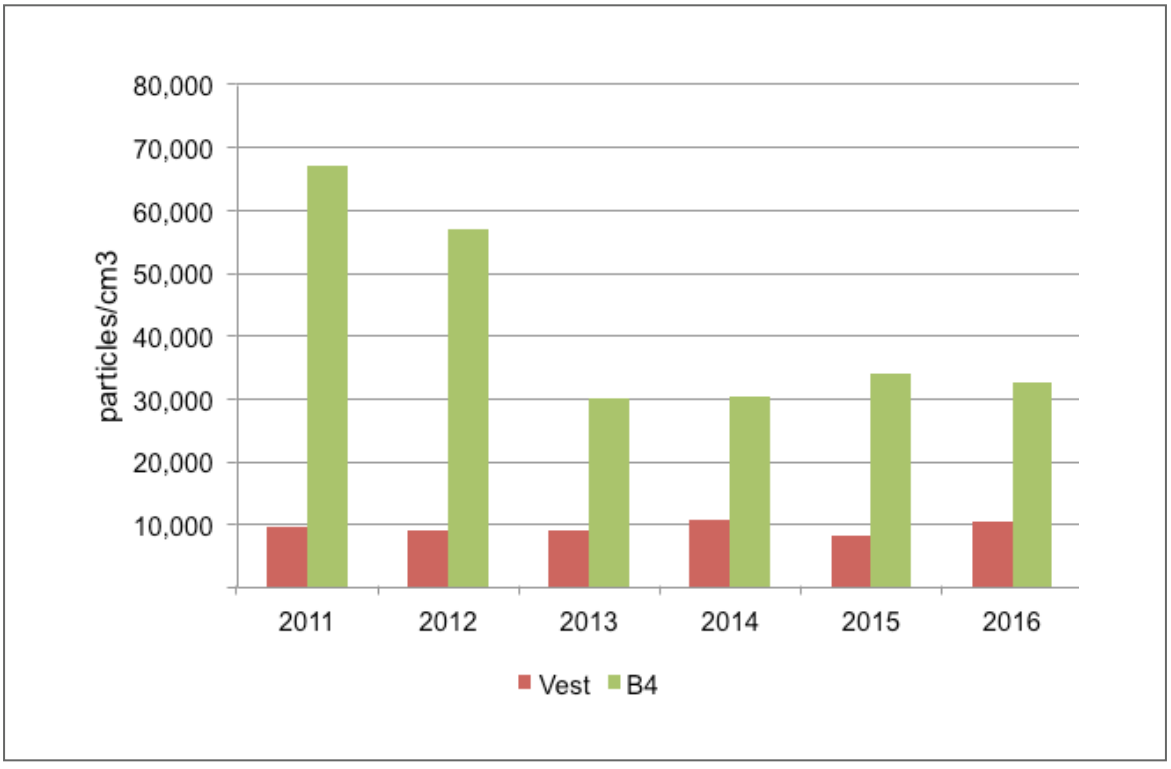
CPH has, on a voluntarily basis, established continuous monitoring stations for ultrafine particles at two locations: At the central apron (B4) and at the western boundary close to residential areas. Measurements started in August 2010 and are done 24/7. This means that CPH has been measuring continuously for 6 years and will continue measurements in order to collect data for documentation of effects from the various remediation initiatives. The stationary measurements are supplemented by ad hoc measurements with handheld devices.

For particle count CPH is using a CPC (TSI model 3775) for the stationary monitoring stations and furthermore using 2 types of handheld equipment, the TSI P-Trak and DiSCmini from Testo. The latter has more or less taken over from the P-Trak when it comes to ad hoc measurements with handheld devices.

6.5.3 ENVIRONMENTAL AND OPERATIONAL RESULTS GO HAND IN HAND

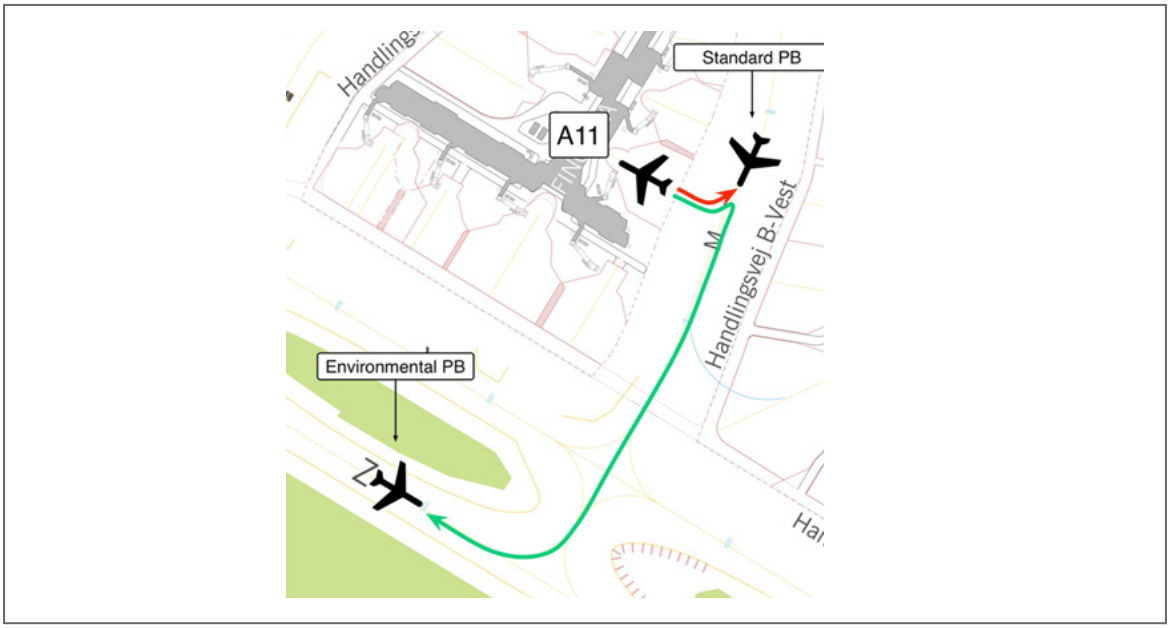
The work within the Air Quality Program goes hand in hand with the CPH Airport Carbon Accreditation at level 3, optimization: A reduction in emission of ultrafine particles will most likely also result in a reduction of CO_2-emissions. Locally, the projects conducted within the frames of the Copenhagen Airport Air Quality Program have resulted in a reduction in annual mean levels of particle numbers at the central apron area of about 50% since 2011.

FIGURE 29: UFP MEASURED (ANNUAL MEAN VALUE) AT THE CENTRAL APRON (B4) AND THE WESTERN BOUNDARY (VEST). SINCE 2011, THE LEVEL AT THE CENTRAL APRON HAS BEEN REDUCED BY ABOUT 50%.



All the conducted projects and initiatives play their part in the reduction. However, the one that really made a difference was a project where the standard push-back procedure was changed and an environmental push-back procedure was implemented, on basis of a test period.

FIGURE 30: NEW AIRCRAFT PUSH-BACK PROCEDURES



The former standard procedure, involving start-up of aircraft main engines in an area between two piers and with a large apron area is now replaced by the environmental push-back procedure involving a longer push of the aircraft to the closest taxiway before start-up of the main engines.

As it turned out, the operational effects have been moderate in general and even positive in some traffic situations, especially for arriving aircraft, since the environmental push-back procedure makes more room for arriving traffic.

These results are characteristic for CPH's work towards better air quality at the aprons: the aim is to minimize the amounts of ultrafine particles emitted without compromising the operational efficiency.

6.5.4 WHAT'S NEXT?

Even though the Copenhagen Airport Air Quality Program has been in place for a number of years, there is still work to be done. There are still active and new initiatives in each of the three work streams:

The "behaviour" work is a continuous process, which among others focuses on behaviour and awareness at the apron area, such as single-engine taxiing, stop of main engines at gate, limiting use of APUs, limiting time of idling with vehicles etc.

In terms of ground support equipment, CPH has set a standard for "green equipment" with yearly targets for the percentage of green equipment in Copenhagen Airport. Again, the focus is on minimizing the particle emissions from the equipment, meaning that for example electrified equipment and diesel equipment with functional particle traps currently both comply with the standard.

The Monitoring work stream will have focus on the start-up of a new, scientific project with the aim of researching the toxicity of ultrafine particles in airports. As outlined in section 3.3, toxicity is an important factor for the assessment of health impacts of UFP. The results of this project are expected to be reported in 2019.

More information: http://dit.cph.dk/wp-content/uploads/2015/07/EN-6-Air-Quality-Air-Quality-Programme.pdf

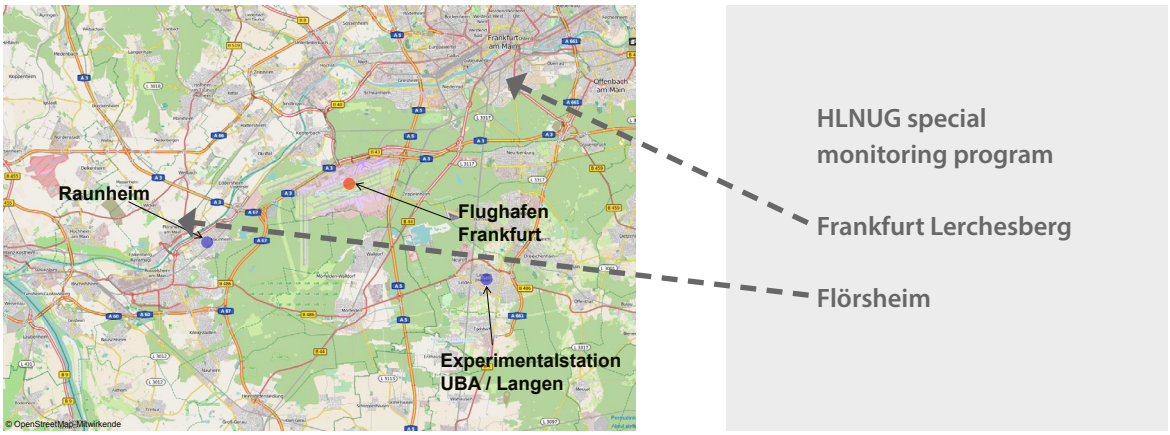
6.6 FRANKFURT AIRPORT

At Frankfurt Airport, continuous air quality monitoring has been conducted since 2002. The results are being published as Annual Air Quality Reports on the Fraport website [Fraport 2017a]. Moreover, a monitoring site of the public network has been in place since 1976, maintained by HLNUG[10] in the city of Raunheim about six kilometers southwest of the airport. Additional temporary measurements were performed below flight paths near the airport in order to detect any particular influence of aircraft emissions resulting from operations on Runway Northwest, after it had been put into service in 2011 (Frankfurt Lerchesberg [Jacobi 2013] and Flörsheim [Jacobi 2014]). With regard to common pollution species regulated by limit values, the influence of air traffic could not be identified in the records.

6.6.1 MONITORING SITES AND EQUIPMENT

First measurements of ultrafine particles (UFP) in the vicinity of the airport were done by the UBA[11] center for quality standards and monitoring methods at Langen from 2010 to 2013. In cooperation with the UBA Langen office, HLNUG started UFP monitoring at Raunheim in 2015. The results have been presented within the framework of several public and non-public sessions. In the present report, we refer to the document published by the FLK[12] [Jacobi et al. 2016]. Information beyond the original diagrams is given by means of corresponding text boxes.

FIGURE 31: POSITIONS OF HLNUG STATION AT RAUNHEIM AND UBA OFFICE AT LANGEN [JACOBI ET AL. 2016]



The Raunheim site is characterized as urban background six kilometres southwest of the airport. A UCPC TSI 3776 is used for the counting of particles (total number of volatile and non-volatile particles), supplemented with Labview software (UBA). The range of particles is 3 – 1000 nm. Size distribution is currently not being recorded. The evaluation for this report covers a period from September 2015 to March 2016.

10. HLNUG: Hessian State Agency for Nature Conservation, Environment and Geology (Hessisches Landesamt für Naturschutz, Umwelt und Geologie), http://www.hlnug.de
11. UBA: Federal Environmental Agency (Umweltbundesamt), https://www.umweltbundesamt.de
12. FLK : Frankfurt Noise Abatement Commission (Fluglärmkommission), http://www.flk-frankfurt.de

6.6.2 RESULTS

Based on the first few months of records, the UFP level at Raunheim seems to be elevated compared to other urban background sites. Table 10 shows some long-term values from German stations.

TABLE 10: COMPARISON OF UFP CONCENTRATIONS, DATA TRANSFERRED FROM SLIDE 10 [JACOBI ET AL. 2016]

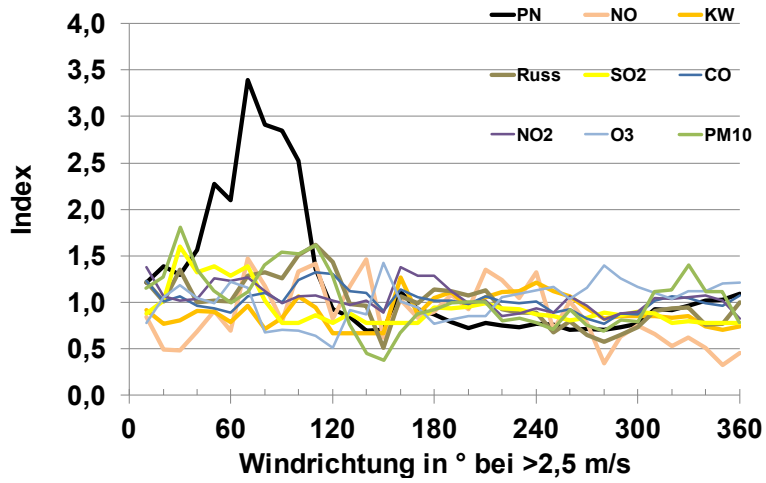
SITE	SITE CHARAC-TERISTICS	Range (nm)	Mean (1/cm³)	Median (1/cm³)	Max.1h-Value (1/cm³)	AVERAGING PERIOD
Raunheim	urban BG	3-1000	16,100	12,300	142,000	09/2015-03/2016
Langen	urban BG	3-1000	12,200	10,500	67,000	2010-2013
Berlin	urban BG	4.5-1000	8,700	7,700	49,000	05/2014-08/2014
Dresden	traffic	5-800	14,923	-	-	2010-2013
Leipzig	traffic	5-800	16,321	-	-	2010-2013
Melpitz	rural BG	5-800	5,651	-	-	2010-2013
BG = Background						

Different time scales and size ranges not being strictly identical, a direct comparison is difficult. For instance, the Raunheim values refer to seven winter months, whereas the Berlin values refer to four summer months. Thus, different results may already arise from the fact of different seasonal atmospheric dispersion conditions and different averaging periods, even if all other conditions were equal. However, the Raunheim mean value[13] rather corresponds to the levels at sites exposed to road traffic and the current 1h-maximum is about twice the 1h-maximum of the multi-annual time series at Langen.

Further evaluation shows a distinct dependence of UFP concentration on wind direction, which is not found with other pollutants in particular if data are selected for wind speed > 2.5 m/s.

13. Considering the first complete monitoring year leads to similar results [Jacobi 2017]

FIGURE 32: UFP DEPENDENCE ON WIND DIRECTION [JACOBI ET AL. 2016]



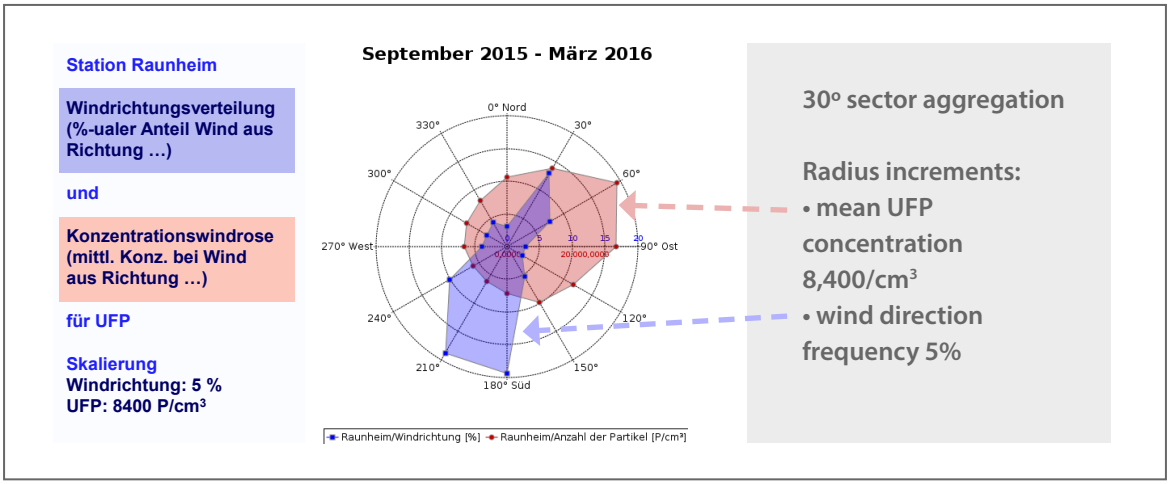
Data selection for wind speed > 2.5 m/s
Index: ratio of 10° sector mean concentration to total mean
"Russ": soot
"KW": non methan hydrocarbons

Elevated values of all species from the northeast and southeast sectors, still present in the total data set (not shown here), no longer occur at higher wind speed. Instead, all curves besides UFP vary more or less irregularly within a range of the 0.5-fold to 1.5-fold of the overall means. In contrast, maximum UFP concentrations up to almost the 3.5-fold of the mean occur with a wind direction from about 70°, i.e. east-northeast (the direction to the airport). While parts of the urban agglomeration, particularly the motorways A3, A67 and the nearby "Mönchhofdreieck" intersection, are located in a northeasterly direction as well, the deviant UFP course rather indicates a non-road traffic emission source.

In general, the effect of increasing concentration values with wind speed is untypical, though it has been reported before with respect to aircraft-related UFP (see Figures 14/15 and [Hudda et al. 2016]). An attempt to explain such behavior was that downwards mixing of pollutants emitted at higher altitude would become more intense during strong wind situations, while ground-level emissions would then disperse faster with increasing horizontal distance. Another reason might be that wind directions are more persistent for higher wind speed than for very low wind speed, when the direction may be subject to considerable orographically induced fluctuations. Thus, the direction of a potential source might just be easier detectable in case of moderately higher wind speed.

In the Frankfurt/Rhine-Main region, northeasterly wind directions are mostly related to high pressure systems with low wind speed and reduced atmospheric mixing, thus presenting a potential for accumulation of pollutants. Such conditions are not very frequent compared to the occurrence of the main south-southwest wind direction sector, see figure 33.

FIGURE 33: FREQUENCY DISTRIBUTION OF WIND DIRECTIONS AND DEPENDENCE OF UFP CONCENTRATION ON WIND DIRECTION [JACOBI ET AL. 2016]

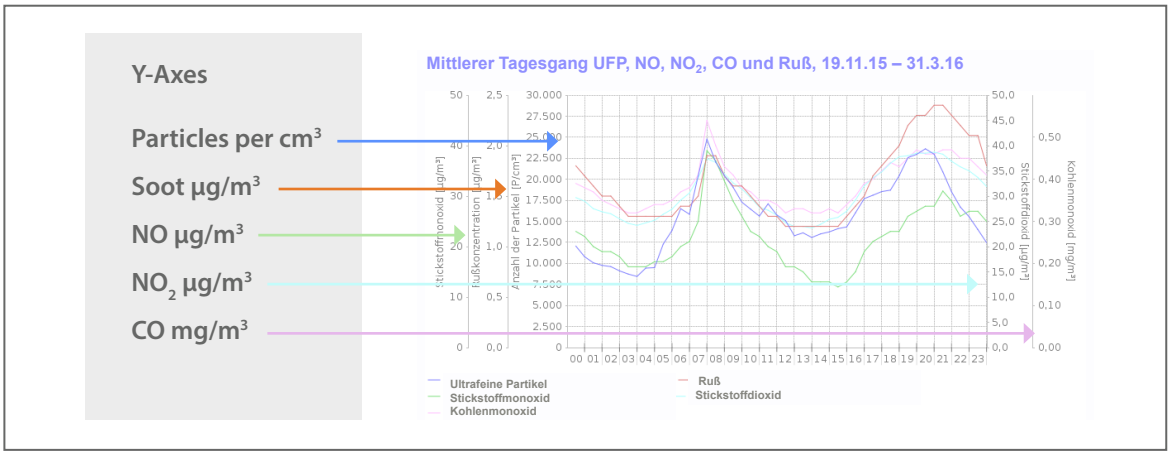


Northeasterly wind direction combined with higher wind speed is even less frequent. Thus, the number of occasions with highly elevated UFP concentration at Raunheim related to these conditions will also be rather small.

This may be the reason why the diurnal variation of the UFP concentration is very similar to the course of the other components, see Figure 34. It is the well-known pattern mainly determined by the morning and evening peaks of road traffic and by the diurnal variation of atmospheric mixing, being reduced during the night and early morning hours and reaching its maximum in the afternoon.

While all other concentrations then decrease to the low levels before the morning rush hour and below, the UFP concentration remains at a slightly elevated level during the afternoon minimum. This seems to correspond to the unusual wind-speed dependence of UFP. It does not necessarily mean direct downwards mixing from any altitude, but rather horizontal advection of polluted air in the presence of a vertically extended kind of "reservoir layer", influenced for instance by descending or ascending aircraft. Secondary particle formation from various precursors and emission sources may also contribute to this effect [Birmili, 2006].

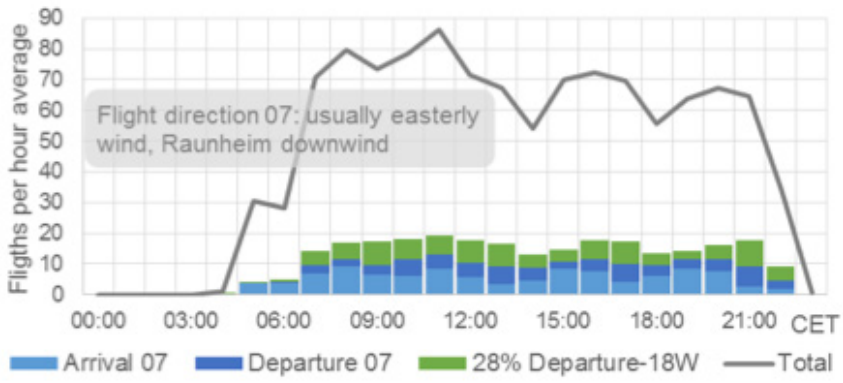
FIGURE 34: MEAN DIURNAL VARIATION OF UFP, SOOT, NO, NO2 AND CO [JACOBI ET AL. 2016]



The two drivers of the diurnal variation of pollution described before, i.e. road traffic and atmospheric mixing, are the most important influencing factors. A relation to air traffic as shown in Figure 35 is not obvious. In particular, the number of aircraft movements during so-called "07 operations" follows a meandering curve throughout the diurnal operation time that cannot be identified in the UFP course.

FIGURE 35: RUNWAY USAGE AT FRANKFURT AIRPORT (TOP) AND MEAN DIURNAL VARIATION OF FLIGHT NUMBERS (BOTTOM), FOR "07 CONDITIONS" (SEE TEXT), © FRAPORT AG

Runway	Arrivals	Departures
Northwest	x	-
Center	(x)	x
South	x	(x)
18 West	-	x



07 operations are largely confined to northeasterly wind directions. In these cases the city of Raunheim is located below the flight path of descending aircraft and – probably more importantly downwind of the remaining final approach and of departures as well[14]. A potential influence of air traffic on the UFP concentration at Raunheim would then be at maximum, but does not become apparent in the mean diurnal variation. However, as a caveat, it has to be taken into account that the mean diurnal variation presented in Figure 34 is not restricted to periods of 07 operations but covers all situations.

14. The number of 18 West departures during 07 conditions is roughly estimated to be 28% of the total 18 West departures according to the percentage of 07 conditions throughout the analysed period.

6.6.3 SUMMARY AND CONCLUSIONS

After the first half year of UFP monitoring the mean concentration at the Raunheim site is about 16,000/cm^3. At other comparable sites, the concentration levels are considerably lower. However, the significance of comparisons is limited due to different particle size ranges and different time scales.

Elevated UFP concentrations at Raunheim are related to east-northeasterly wind directions, i.e. the sector where the airport is located but also parts of the urban agglomeration of Frankfurt and nearby motorways. Furthermore, it is the sector usually associated with stable atmospheric conditions and reduced dilution of emissions. The dependence on wind direction is enhanced with UFP only, not with other pollution species, when data are selected for wind speed > 2.5 m/s. This indicates a major role of UFP transport from a vertical extended layer and/or less fluctuating wind direction from the potential source, e.g. the airport. Regional secondary particle formation may also play a role.

The mean diurnal variation of the UFP concentration largely shows the same pattern as the course of the other components, usually driven by the variation of road traffic and atmospheric stability. Based on current observations and evaluations – which are still limited – a relation to air traffic is at least not obvious.

While detailed source apportionment of UFP concentrations at Raunheim is still challenging an airport influence cannot be ruled out. According to model calculations such influence would be expected, for instance in case of nitrous oxides[15], but this is not detectable in monitoring results because of the dominating contributions of other emissions sources, mainly road traffic.
The particular UFP dependence on wind speed and possibly the slightly higher level of the UFP afternoon minimum represent some special features with respect to UFP compared to other components that may be related to air traffic. However, the frequency of meteorological transport conditions associated with significantly elevated UFP concentrations at Raunheim is relatively low.

For more detailed information, it is envisaged to include the size distribution into the monitoring program and to install an additional station in the most frequent downwind direction of the airport (north-northeast). Furthermore, a UBA project[16] has been launched aiming at model calculations in order to quantify UFP contributions to ambient air concentrations in the vicinity of Frankfurt Airport.

15. Aircraft contribution 2 to 5 µg/m3 to NO2 annual mean at Raunheim of about 30 µg/m3 in total [Fraport 2017b]
16. UFOPLAN Vorhaben 2016, FKZ 3716 5220 00

6.7 BERLIN AIRPORT

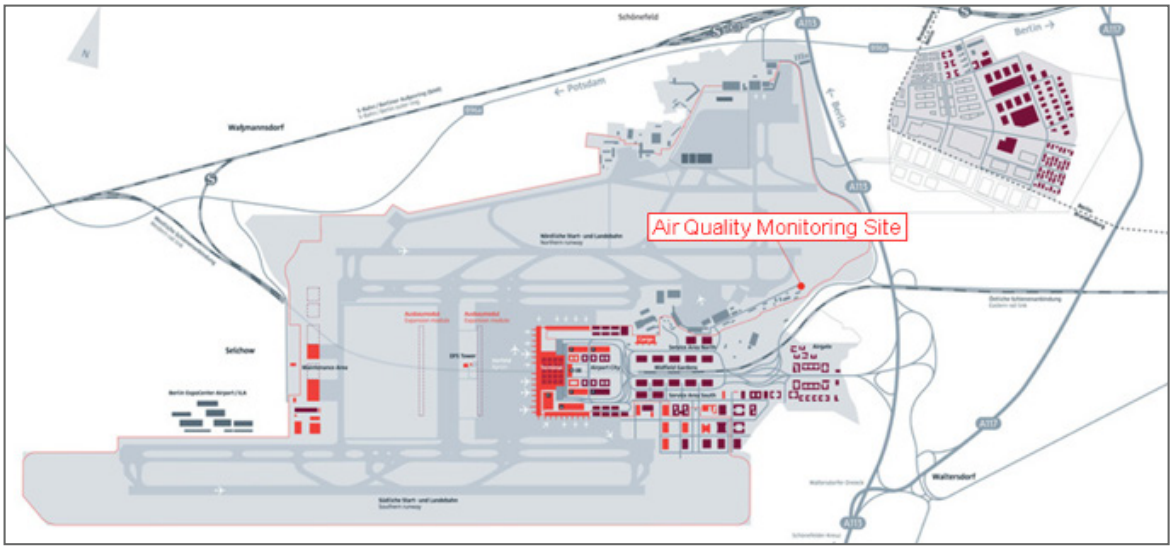
Flughafen Berlin Brandenburg GmbH (FBB) is running an air quality monitoring site at Berlin Schönefeld Airport since 2011 prior to and within the scope of operating Berlin-Brandenburg Airport as a future single airport location.

The air quality monitoring site is located just south to the eastern head of runway 25R (Figure 36). The location was chosen in communication and collaboration with the State Environmental Agency of Brandenburg and is used predominantly to measure the impact of emissions caused by aircraft taking off and landing, vehicle traffic on the ground as well as handling processes on the aprons.

The monitoring programme focuses on gaseous pollutants such as carbon monoxide (CO), nitrogen oxides (NO, NO2, NOx) and ozone (O3) as well as particulates (PM10 and PM2.5) that are all continuously monitored. Additional samples are collected by filters and activated carbon tubes and submitted to the State Laboratory of Berlin-Brandenburg where analysis of BTEX and other volatile organic compounds, polycyclic aromatic hydrocarbons including benzo[a]pyrene as well as quantification of soot as part of PM10 are carried out.

In September 2016 FBB extended its air quality monitoring programme by equipping its air quality monitoring site with a Wide Range Aerosol Spectrometer setting the foundation for continuous measurements of ultrafine particles on a 24/7 basis.

FIGURE 36: BERLIN AIRPORT LAYOUT WITH AIR QUALITY MONITORING SITE. NORTH ORIENTATION OF MAP IS INDICATED AT THE TOP LEFT.



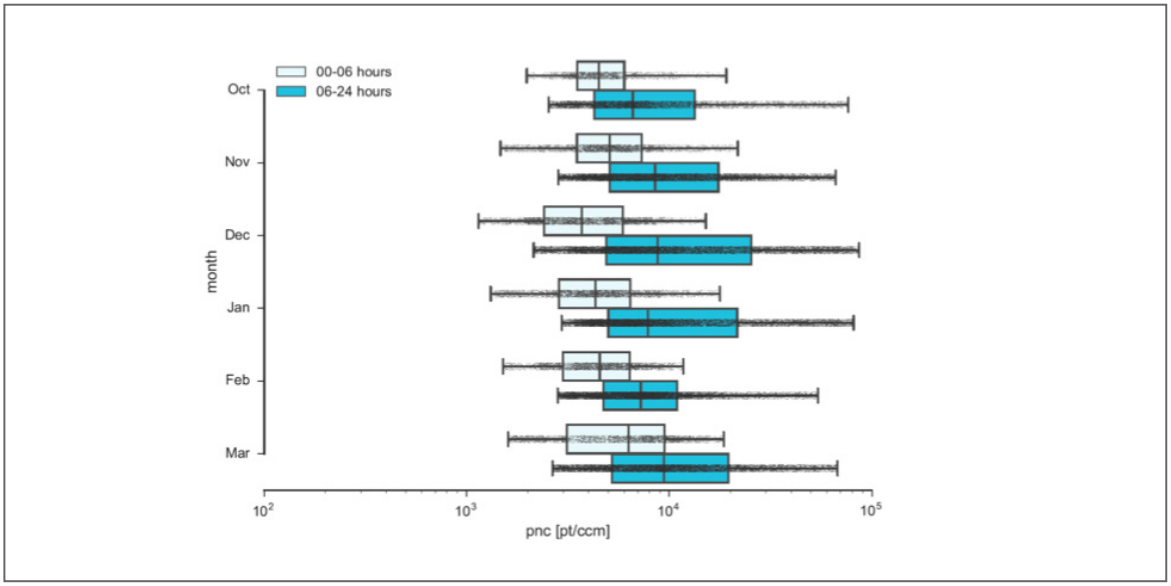
6.7.1 MEASUREMENT SETUP

FBB utilises a Wide Range Aerosol Spectrometer by Grimm Aerosol Technik GmbH & Co KG. The setup thereby combines an EDM 180 device for measuring aerosols within the size range of 250 nm up to 32 µm in optical diameter as well as a SMPS+C, Model 5420 device facilitating a butanol-driven condensation particle counter for measurements of particle number concentration (pnc) below 1 µm in particle size (5-1,100nm). Measurements of particle size distribution can also be realised by retrofitting the SMPS+C with a Differential Mobility Analyser.

6.7.2 PARTICLE NUMBER CONCENTRATION

Measurements of particle number concentration have been continuously carried out from mid-October 2016 to end-March 2017 and are further ongoing. Figure 37 presents first data showing 5th to 95th percentile data distribution of 3-minute-averaged pnc time series consisting of 78,425 part/cm^3 values that are grouped by month as well as night (00-06 hours) and daytime (06-24 hours). Figure 37 thereby shows single observations along with underlying boxplot graphs displaying range, median and interquartile range of grouped data.

FIGURE 37: TIME SERIES DATA ON PNC GROUPED BY MONTHLY NIGHT (00-06 HOURS) AND DAYTIMES (06-24 HOURS) SHOWING 5TH-95TH PERCENTILE.



Distribution of pnc data is right skewed with median values of grouped data below 104 part/cm^3. Pnc levels at daytime are generally higher as well as pnc variability compared to night-time. Daytime median values are elevated by 1.5 to 1.8 times and in December by 2.4 times compared to night-time. Interquartile ranges vary approximately between 2.5·103 to 6.4·103 part/cm^3 at night-time and 6.2·103 to 2.1·104 part/cm^3 at day-time. The 5th to 95th percentile range thereby varies approximately from 1.0·104 to 2.0·104 part/cm^3 at night-time and spans about 4 times wider from 5.1·104 to 8.4·104 part/cm^3 at daytime.

Figure 38 depicts prevailing wind conditions displaying frequency of counts by wind direction and associated wind speeds. Most frequent wind directions bear southerly to west-south-westerly as well as easterly and east-north-easterly headings contributing all at least 10 percent each to the overall distribution. The upmost frequent wind direction thereby bears a WSW heading even accounting for more than 14 percent to the overall observations. Lowest frequencies are observed for the wind directions N to WNW. Remaining wind directions are fairly even distributed. Furthermore a clear disposition to low wind speeds can be observed for north-north-easterly to south-east-southerly wind directions that hardly exceed wind speeds above 2 m/s. Higher wind speeds are monitored for remaining wind directions. Moreover highest wind speeds above 4 m/s generally relate to wind directions with south-west-southern to west-north-western bearings. Particularly at headings W and WSW these conditions account for more than 45 percent and 34 percent respectively of the observations at daytime as well as 23 percent and accordingly 28 percent at night-time. It is noted that the distribution of wind direction and speed is fairly consistent between day and night.

FIGURE 38: WIND ROSES DISPLAYING FREQUENCY OF COUNTS BY WIND DIRECTION AND ASSOCIATED WIND SPEED RANGES. DATA RELATE TO 5TH-95TH PERCENTILE PNC AND ARE GROUPED BY NIGHT (0:00 - 6:00) AND DAYTIME (6:00 - 24:00).

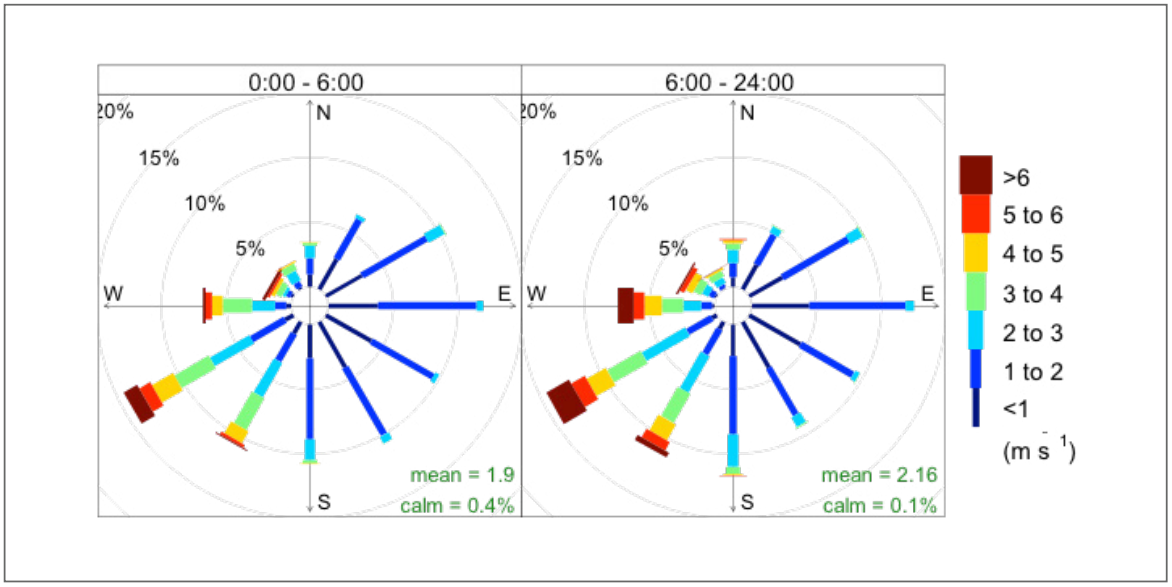
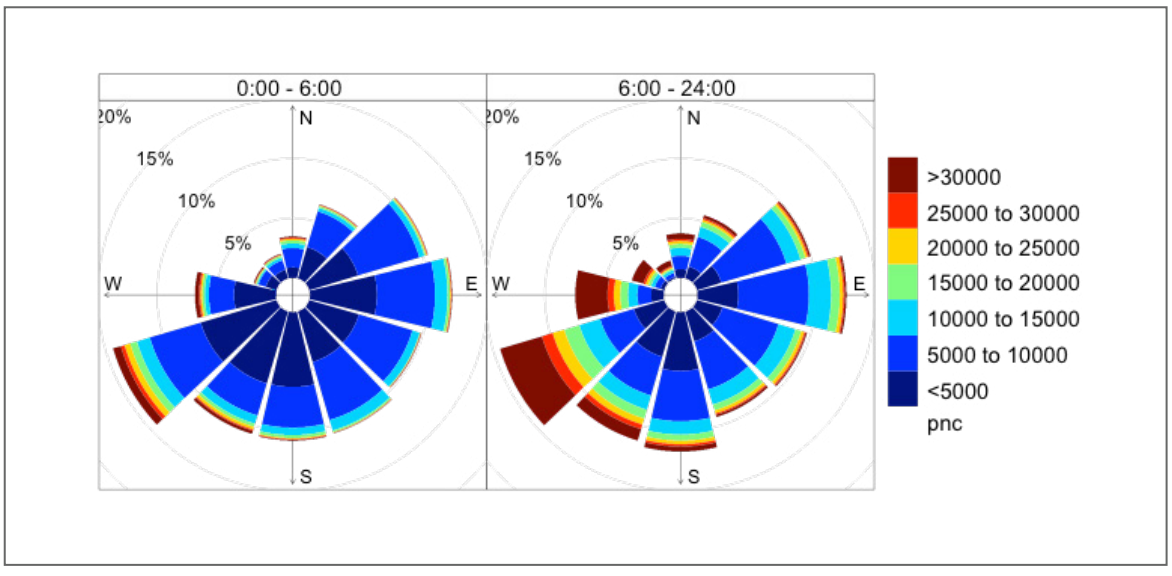


Figure 39 shows frequency of counts by wind direction and associated particle number concentration ranges. Maximum concentration levels can be observed from all wind directions, but are elevated in frequency for westerly wind directions from N to S with highest frequencies for winds directed from W to WSW. Thereby daytime pnc are generally increased for all wind directions compared to night-time. This observation is most pronounced for wind directions from W to SSW.

FIGURE 39: FREQUENCY OF COUNTS BY WIND DIRECTION AND ASSOCIATED PNC LEVELS [PART/CM^3]. DATA RELATE TO 5TH-95TH PERCENTILE PNC AND ARE GROUPED BY NIGHT (0:00 - 6:00) AND DAYTIME (6:00 - 24:00).



6.7.3 CONCLUSIONS

Temporal variance of pnc data by month of year will mainly be affected due to prevailing meteorological conditions and seasonality. Therefore long-term measurements will be required for a profound statistical evaluation. Temporal differences between daytime and night-time pnc can be attributed to diurnal overall emission source activity patterns and can be observed for all wind directions alike.

Elevated pnc levels are monitored for westerly wind directions from N to S with highest frequencies for winds directed from W to WSW. These observations point to airport activity, i.e. runway, taxiway and apron operations but also interim construction site activities. High frequencies of increased pnc levels are reasonable due to onsite monitoring. However, an influence of more distant sources outside the airport grounds, i.e. the motor way as well as rural areas located north to south-east directions can also be observed but to a much lesser extent. This might be due to both, lower wind speeds and greater distance to potential sources of emissions. It is thereby noted that increased pnc levels are generally observed at wind speeds above 3 m/s whereas low pnc levels basically comply with wind speeds below 3 m/s. These observations emphasise findings at Frankfurt Airport (see chapter 4.6.4). Estimation of UFP transport and the undertaking of emission source apportionment will moreover necessitate simultaneous multi-point monitoring at upwind and downwind locations.

6.7.4 OUTLOOK

FBB has acquired a mobile air quality monitoring platform that is equipped with equivalent air monitoring devices including a second Wide Range Aerosol Spectrometer. Measurements of ultrafines therefore can be conducted also outbound the airport grounds in future. Regular calibration of ultrafine particles monitoring equipment will be of future importance as quality assurance is vital for inter-comparability of data sets. First actions hereby involve consultation of Leibniz Institute for Tropospheric Research. UFP monitoring at Berlin Airport will proceed and continuously supplement to a long-term dataset on UFP, also focusing on their size distribution measurements prospectively.

In order to relate to various ultrafine particle emission sources at close-up range, further detailed information on onsite ground traffic activity patterns are needed. Implementation of traffic counters at the air quality monitoring site could present an appropriate future approach.

Moreover further correlation of pnc data to monitored meteorological and other air quality relevant parameters will be examined.

6.8 CONCLUSIONS FROM STUDIES

Particle number counting instruments measuring ambient air particle concentrations usually count all UFP particles, irrespective of their origin and physical or chemical composition. UFP are very different in shape, from liquid droplets to solid complex, non-symmetrical structures. Some sizing instruments report the so called "mobility diameter", which does not take all these characteristics into account. In addition, it is important to distinguish between the measurement of UFP and PM of size ranges including but not limited to UFP.

The most recent airport studies have shown results which lead to the following main conclusions:

- UFP particle number concentrations are subject to a very high temporal and spatial variability.
- Concentration developments are highly dependent on wind velocity and wind direction.
- Particle number concentration is just one metric; likewise important is the particle mobility diameter at the same time and location.
- Aircraft engines tend to emit short-time high numbers of particles of small diameters while other combustion sources (e.g. fossil fuel combustion vehicles and machinery) show lower peak number at larger diameter and over longer periods of time.
- Furthermore, within the plume chemistry and microphysical processes will form secondary, volatile PM. Therefore, there seem to be considerable differences between total PM and non-volatile PM numbers with volatile particle numbers being higher in the size range below 50nm. Studying total PM numbers is important for a comprehensive understanding of UFP concentrations and behaviour.
- High numbers of particle concentrations rapidly decrease with increasing distance from the source.
- The further away from direct identifiable sources measurement samples are taken, the more difficult it becomes to associate the results to specific sources. This both applies for horizontal and vertical distances.
- Short-term measurements at single locations may drastically over- or underestimate the true (average) UFP concentrations at airports

Measurement campaigns and studies covering UFP particle concentrations are not sufficient to relate them to health effects. As particle number counters report total number of particles without any information on chemical composition and without knowledge of health impact of different species, the measured levels of UFP number concentrations are not more than an inventory of the UFP concentrations observed at and near the airport.

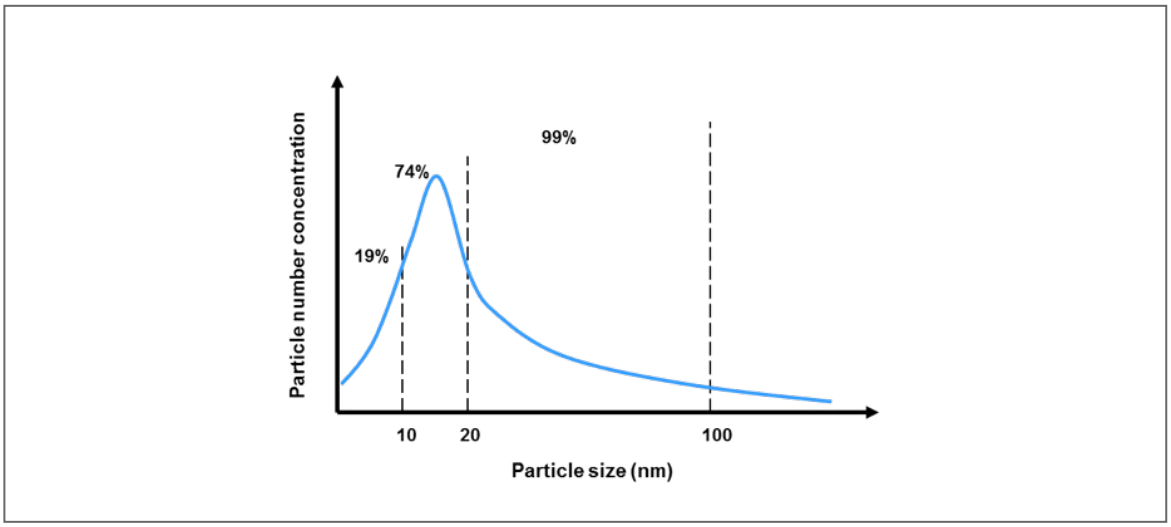
7 MEASUREMENT OF ULTRAFINE PARTICLES

7.1 UFP MEASUREMENT CHARACTERISTICS

Particles from a combustion source are usually emitted with high dynamics (plume velocity and turbulence). Immediately after release, particles are subject to mechanical and chemical processes. There are volatile and non-volatile particles emitted from the exhaust plane. Volatile or semivolatile compounds are known to cause variation in measurements due to condensation and supersaturation. Both types may still be present at the receptor location point (the measurement device). As such, it is often envisaged to remove the volatile particles and measure the non-volatiles only. The removal or separation of the non-volatile particles is performed by means of a catalytic stripper or a thermodenuder.

Measured particle number concentrations of aerosols are also highly affected by the measurement technology. A key specification is the lower detection limit with regard to the particle mobility diameter. In some cases, cut-off limits are set for 23nm (in the case for the certification of automotive vehicles). However, the lower cut-off limit for aero engines has to be much lower (e.g. 10nm or even less). For the purpose of compliance with certification procedures and emission limits, this may not be of particular relevance. When it comes to presenting actual ambient concentrations, particles outside the specified range should not be removed. The following picture illustrates the percentage of particles from a Scanning Mobility Particle Sizer (SMPS) measurement at an airport at various particle size points. Such percentages can differ considerably.

FIGURE 40: PARTICLE NUMBER PERCENTAGES AT SEVERAL DIAMETER POINTS (SPECIFIC AIRPORT EXAMPLE, APRON AREA)

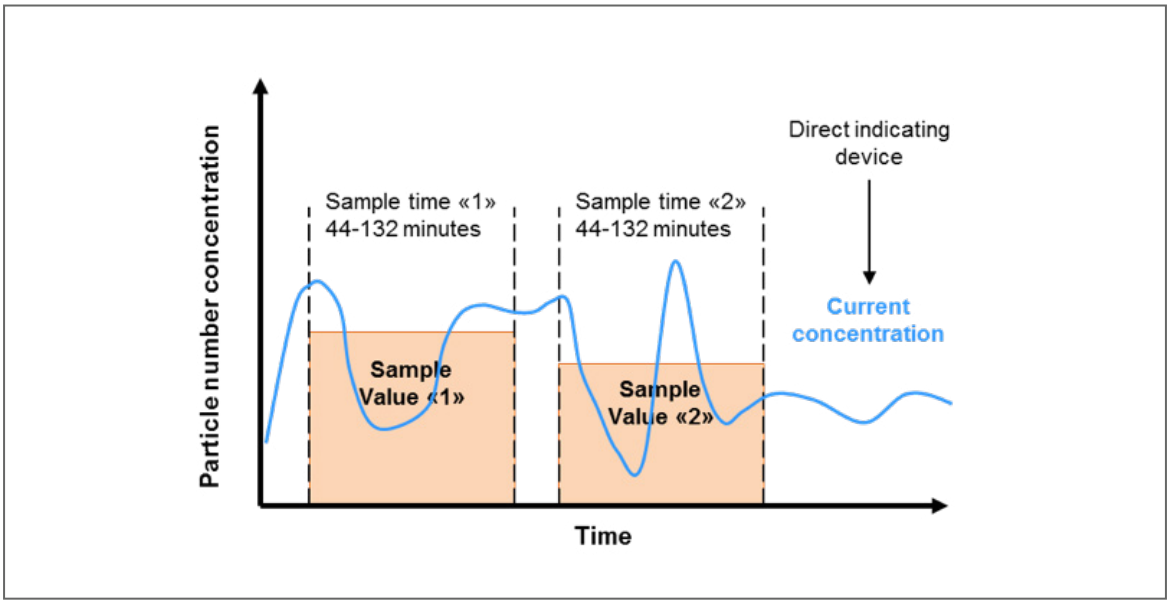


There is usually a distance between the air inlet and the actual measurement point which is covered by the sampling line. Particle losses in the sampling line can be significant; sometimes they are corrected in the device through software. This needs to be considered.

UFP measurement devices have different scan times, depending on the technology used and the parameters measured. While some devices scan the ambient air every second and produce a concentration and a diameter value, other devices might take up to several minutes if they run a full scan

over all particle sizes. The following picture illustrates the difference between a direct indicating device following the current concentration and thus producing significantly different concentrations (higher/lower) than if the data were aggregated over a longer period of time. In this case, peaks and lows may be averaged out. This fact is important when trying to compare values of different integration times.

FIGURE 41: DYNAMIC CONCENTRATION AND INTEGRATION TIME (SUVA, 2012)



The characteristics of the measurement (e.g. the lower detection limit and the line losses in the device) can influence the particle number concentrations by an order of one or two (see section 7.3. for more details). As such, all relevant information on the measurement device has to be recorded and reported alongside the actual results.

7.2 TECHNICAL STANDARDS

A new European Technical Standard (CEN/TS 16976 from the European Committee for Standardisation) has been published in August 2016. This standard describes a method for determining the particle number concentration in ambient air in a range up to about 107 particles/cm^3 for averaging times equal to or larger than 1 minute. The standard method is based on a Condensation Particle Counter (CPC) operated in the counting mode and an appropriate dilution system for concentrations exceeding the counting mode range. It also defines the performance characteristics and the minimum requirements of the instruments to be used. The document describes sampling, operation, data processing and quality assurance/quality control (QA/QC) procedures including calibration.

The lower and upper sizes considered within the standard are 7nm and a few micrometers, respectively. Therefore, it is important to bear in mind that it does not only cover UFP and furthermore, it does not address the question of size distribution of the particles counted. To address this limitation in terms of UFP measurement, the European Committee for Standardisation is working on a technical standard for the determination of the particle size spectra of atmospheric aerosol using a Mobility Particle Size Spectrometer. In the meantime, contrary to PM2.5 and PM10, there is currently no specific standard for the measurement of UFP.

7.3 EQUIPMENT AND TECHNOLOGIES

This section provides on overview of measurement devices that have been used for airport studies in the past. The devices measure UFP starting at their lower detection limit and usually include particles larger than the upper size definition of UFP at 100 nm. The variety of the devices reflects the absence of a uniform standard, and the results of measurements performed with them must consequently be treated with caution. Depending on the objectives of a study, different types of equipment can be appropriate, and therefore, it is not possible to make general recommendations for the use of specific devices.

The table below describes the main characteristics of the devices used for airport-related studies so far.

TABLE 11: MEASUREMENT DEVISE FOR PARTICULATE MATTERS COVERING UFP

NAME	METHOD / DESCRIPTION
SMPS	A Scanning Mobility Particle Sizer (SMPS) is a method to determine the number size distribution of submicron particles. It uses a measurement system consisting of an electric charger, a mobility classifier, a counter, and PC control. Resolution: 2-5 min.
ELPI	The Electrical Low Pressure Impactor is a 12 (14) stage cascade impactor that measures particle number concentrations as a function of aero-dynamic diameter from 6nm-10µm. There is no working fluid required.
CPC	A Condensation Particle Counter (CPC) measures the total airborne number concentrations in a given the particle diameter range. It does not deliver information on particle sizes. Range: 7nm-3,000nm.
miniDiSc	The miniature diffusion size classifier is a portable instrument for nanoparticle measurement. It operates without a working fluid and measures the total number concentrations, the average particle mobility diameter and the LDSA in each scan. Range: 10nm-300nm; Resolution: 1 sec.; Concentration: 1,000-1,000,000 #/cm^3.
P-Trak	The P-Trak is a hand-held instrument to measure the particle number concentrations. It delivers no information on particle sizes. Concentrations: 0-500,000 #/cm^3; Range: 20-1,000nm.

Two types of devices deliver information on both the diameter and number of particles, thus enabling to identify and count particles with less than 100 nm diameter: the Scanning Mobility Particle Sizer (SMPS) and the Electrical Low Pressure Impactor (ELPI). Both devices have the advantage of a high accuracy of measurements, and by providing information on diameter sizes, they can also support source apportionment. They do however also involve high costs and additional maintenance.

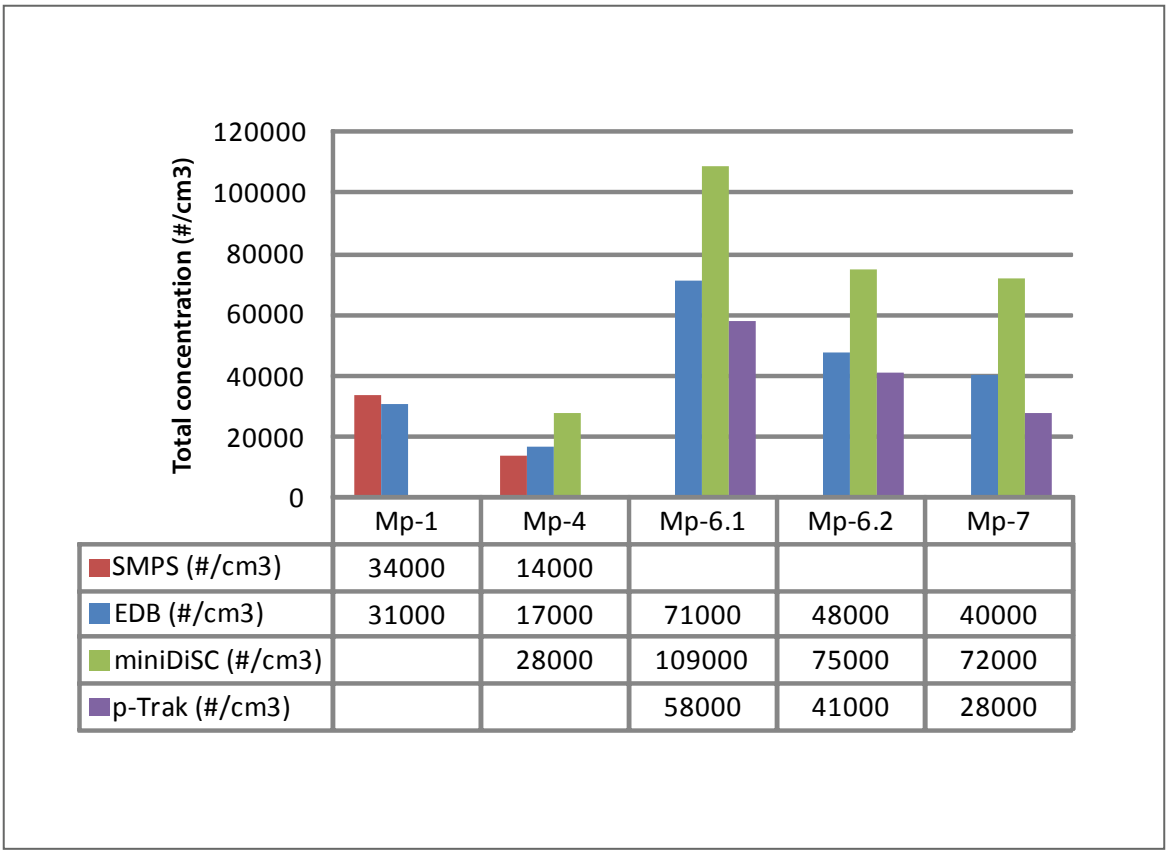
Due to its low cut-off of 7 nm, the Condensation Particle Counter (CPC) allows accurately capturing UFP, but not isolating their number from the one of particles of a larger size, since contrary to the SMPS and ELPI, information on particle sizes is not delivered,

miniDiSc and P-Trak cover a wider range of particle sizes and hence offer less measurement precision than the above mentioned instruments. miniDiSc provides information on the average particle size, however the average particle diameter is not necessarily the one with the highest concentration. The device calculates the mean value based on a monomodal distribution, in most cases the real distribution is bi- or trimodal. P-Trak does not capture any diameter related data at all. Measurements with these devices can therefore mainly be used for orientation purposes but do not provide a comprehensive picture of UFP concentrations at an airport.

Each device is different with regard to its specific measurement technique (volatile/non-volatile, dry/wet, line loss, detection limits, range, etc), parametrization and handling during a campaign. As such, results can vary significantly from device to device. The following figure shows measurement results from a campaign, where several devices have been used simultaneously. For each measurement point (Mp), the devices were operated in exactly the same location and during the same duration and ambient conditions. As can be seen from the results, they can vary by as much as a factor of two.

This has particularly to be considered in attempts to compare different measurement campaigns or in cases where campaigns are being conducted with different measurement devices.

FIGURE 42: VARIABILITY OF MEASUREMENT DEVICES (SUVA, 2012)



	Mp-1	Mp-4	Mp-6.1	Mp-6.2	Mp-7
SMPS (#/cm3)	34000	14000			
EDB (#/cm3)	31000	17000	71000	48000	40000
miniDiSC (#/cm3)		28000	109000	75000	72000
p-Trak (#/cm3)			58000	41000	28000

Consequently, it must also be noted that a single measurement with a one type of equipment does not provide a comprehensive picture of UFP concentrations at the airport. The latter can only be achieved through long-term measurement campaigns at various locations.

7.4 POINTS FOR ATTENTION FOR MEASURING ULTRAFINES

The measurement of ultrafine particles becomes complex when it comes to the need to gain information beyond just the particle number concentration at a given point in time and at a given location. Based on the various studies available and the current knowledge on the behaviour of UFP, any measurement campaigns should take into account the following:

1. The minimum parameters to be measured in parallel are particle number concentrations (1/cm^3), particle mobility diameter (nm), wind speed (m/s) and wind direction (deg). Any other gaseous substances may be measured at the same time to aid the interpretation of the results.
2. The measurement device needs to have a lower cutoff of at least 10nm, better 7nm and has to have an upper particle range of at least 1,000,000 particles/cm^3. In general, the smaller the lower cutoff, the higher the accuracy of UFP measurements. Specifically, it is recommended to use the CEN/TS 16976 as a minimum requirement to perform ambient measurement of ultrafine aerosols when using a CPC.
3. The line-losses or other measurement corrections must be accounted for.
4. It has to be considered, whether the total number of particles should be measured or just the relevant non-volatile particles (nvPM). As mentioned in previous sections, nvPM account only for a part of the total PM numbers which also comprise vPM. Whether total PM or only nvPM should be addressed depends on the objectives of the measurement campaign.
5. Additional information of activities should be recorded at the same time. This includes not only aircraft traffic, but likewise mobile street sources, machinery or any other emission releasing activity (heating, fires, construction sites, etc).
6. As a single station only gives limited information on the dynamics of particle emissions and their sources, it is recommended to operate at least two stations simultaneously in opposite locations of the main activities.
7. A measurement campaign has to last a minimum of several weeks in the same location, and a repetition during winter/ summer time (to take both seasons into account) should be envisaged.

8 MITIGATION

Airports continuously work to reduce gaseous emissions and thus concentration from all sources at the airport. While most emission sources are outside the responsibility of the airport operator, programs like Collaborative Environmental Management (CEM), developed and introduced by EUROCONTROL and supported by all aviation stakeholders assist airport operators in their efforts.

Following international guidance and best industry practices, airports work jointly with their partners (airlines, air navigation service providers and other stakeholders) to evaluate and implement mitigation options as set out in the following table. It is well understood that only the reduction of emission at source will subsequently reduce the concentration of substances in the ambient air. This concerns both nvPM and precursors of vPM. However, other sources in the vicinity of and not related to airports that are not under control of the airport may still contribute far more to the overall regional air pollution.

The choice of actual implementable measures depends on a number of factors like airport location, aircraft activity, services at the airport and others. To this end, above list is an overall list of examples and some measures might not be applicable to some airports.

TABLE 12: LIST OF COMBUSTION PARTICLE EMISSION MITIGATION OPTIONS AT AIRPORTS

GROUP	EMISSION SOURCE	MITIGATION OPTION
Aircraft	**Aircraft taxiing**	Reduce congestion, ease flow of traffic through support software (A-CDM, AMAN, DMAN, CDO, etc)
		Change of fuel properties (lower sulphur and aromatics)
		Support for aircraft taxiing with less than all engines operating (single engine taxi)
		Modify push-back operations of aircraft as to avoid engine start-up procedures in sensitive areas.
	Auxiliary Power Unit (APU)	Provide stationary electricity and Pre-conditioned air
		Impose APU operating restrictions
Ground Handling	**Ground Support Equipment (GSE) and airside vehicles**	Electrify GSE fleet or provide electric charging stations
		Modernise fleet (Stage II to Stage IV)
		Install Diesel Particle Filters (DPF) on diesel GSE
		Change to fuel with lower emissions (clean diesel, low-sulfur fuel, compressed natural gas (CNG), hydrogen)
Airport Infrastructure	**Diesel generators**	Limitation on operating times
		Change to fuel with lower emissions (clean diesel, low-sulfur fuel, CNG, hydrogen)
		Alternative systems (batteries, etc)
	Heating plants	Change to fuel with lower emissions (eco-fuel, CNG)
		Reduce usage through installation of alternative heating systems and development of renewable energy (e.g. geo-thermal, aquifer, solar).
Landside traffic	**Vehicles**	Incentives to use public transportation and car-pooling. Provision of fossil-free fuel stations (electric)
		Prioritizing low emission vehicles (taxi, shuttles)
		"No idling" policies at curbside

9 OUTLOOK AND FUTURE WORK

The understanding of sources, behaviour and effects of ultrafine particles is developing. This includes, but is not limited to aviation.

In the aircraft engine regulatory context, the current ICAO nvPM standard is a first step in the development of a mass and number nvPM standard for aircraft engines. Data from the representative aircraft engines will be used in the development of LTO-based nvPM mass and number metric systems, stringency options, and technology responses. Furthermore, efforts will be undertaken to potentially replace the smoke number with the maximum nvPM mass concentration for aircraft engine certification.

Similar to gaseous and smoke emissions, emission factors for other sources commonly found at airports will also need to be developed to determine characteristic nvPM mass and number emissions. This will give airports the tool to complement their emission inventories. This work, however, includes the consideration of line-loss corrections between the engine exit plane and the ambient air.

Combustion engine regulatory processes will also further advance. Stage V legislation commits the European Commission to produce two reports on future emission regulations for non-road engines:

- By the end of 2018: An assessment of the possibility of adopting measures for the installation of retrofit emission control devices in existing, in-use non-road engines.
- By the end of 2020: An assessment of further pollutant emission reduction potential, and the identification of potentially relevant pollutant types that do not fall within the scope of the Stage V regulation.

In the area of research, a better understanding of the impact of UFP on health can be expected.

To address this, the various planned and completed measurement campaigns – not only at airports – will improve techniques and procedures to better understand spatial and temporal characteristics of ultrafine particles.

10 ANNEX

10.1 TERMS AND ABBREVIATIONS

A-CDM	Airport Collaborative Decision Making
Aggregate	Several things grouped together or considered as a whole.
AMAN	Arrival Manager (Software for the support of arriving aircraft)
APU	Auxiliary Power Unit (kerosene fuelled aircraft built-in turbine for power and air-conditioning production)
CAEP	ICAO Committee on Aviation Environmental Protection
CDO	Continuous Descent Operations
CEM	Collaborative Environmental Management (EUROCONTORL)
CEN/TS	Comité Européen de Normalisation, Technical Specification
CNG	Compressed natural gas
CO	Carbon monoxide
Coagulation	is a process which involves coming together of colloidal particles so as to change into large sized particles.
CPC	Condensation Particle Counter
DLR	German Aerospace Center, Cologne
DMA	Diameter Mobility Analyser
DMAN	Departure Manager (Software for the support of departing aircraft)
EC	European Commission or European Community
EDB	Electric Diffusion Battery
EI	Emission Index
ELPI	Electrical Low Pressure Impactor
GPU	Ground Power Unit
GSE	Ground Support Equipment (diesel, gasoline, CNG or electric driven machinery)
HC	Hydrocarbon
ICAO	International Civil Aviation Organisation
LDSA	Lung deposited surface area
MDG	Modelling and Database Group
NOx	Nitrogen oxides
NRE	Non-road Engines
NRMM	Non-road Mobile Machinery
Nucleation	the initial process that occurs in the formation of solids or liquids from gases
nvPM	non-volatile particulate matter
OHS	Occupational Health and Safety
PM	Particulate matter
PNC	Particle Number Concentration
RIVM	Dutch National Institute for Public Health and Environment
SAE	Society of Automotive Engineers, USA
SMPS	Scanning Mobility Particle Sizer
SUVA	Swiss National Accident Insurance Agency
UFA	Ultrafine aerosols (range of ≤100 nm)
UFP	Ultrafine particles (range of ≤100 nm)
vPM	volatile particulate matter
WG	Working Group

10.2 REFERENCES

1. ACI EUROPE: Ultrafine Particles at Airports. November 2012.
2. Assessment of the air quality on the apron of Copenhagen Airport Kastrup in relation to working environment, Technical report, Ellermann et al. 2011, Danish Centre for Environment and Energy, Aarhus University (DCE), November 2011
3. Baldauf, Richard W. et al. Ultrafine Particle Metrics and Research Considerations: Review of the 2015 UFP Workshop. Environmental Research and Public Health, 2016, 13, 1054.
4. Bezemer, A. et.al. Rijksinstituut voor Volksgezondheid en Milieu (RIVM): Nader verkennend onderzoek ultrafijnstof rond Schiphol. Report 2015-0110.
5. Biernat, Krzysztof (Editor): Biofuels – Status and Perspective. ISBN 978-953-51-2177-0, 2015.
6. Birmili 2006. Birmili, Wolfram: "Räumlich-zeitliche Verteilung, Eigenschaften und Verhalten ultrafeiner Aerosolpartikel (<100nm) in der Atmosphäre, sowie die Entwicklung von Empfehlungen zu ihrer systematischen Überwachung in Deutschland". UMWELTFORSCHUNGSPLAN DES BUNDESMINISTERIUMS FÜR UMWELT, NATURSCHUTZ UND REAKTORSICHERHEIT. Forschungsbericht 203 43 257/05. UBA-FB 000942. Texte 26/06 ISSN 1862-4804. Leibniz-Institut für Troposphärenforschung e.V., Leipzig. 2006
7. CEN/TS 16976. Ambient air - Determination of the particle number concentration of atmospheric aerosol, 2016 (preliminary application, adopted 21.06.2016, limited until June 2019)
8. Danish Ecocouncil (2012): Air Pollution in Airports. Ultrafine particles, solutions and successful cooperation. ISBN 978-87-92044-37-2.
9. ESC: Modelberekeningen aan ultra fine particles rond Schiphol. Op basis van de analyse van metingen. Rapport 2015R001. Erbrink Stacks Consult., Oosterbeek, 2015
10. EASA: Study on sampling and measurement of aircraft particulate emissions SAMPLE – Final Report. EASA.2008.OP.13, October 2009
11. Erbink Stacks Consult: Model Calculations to Ultrafine Particles around Schiphol. Report 2015R001. 2015.
12. Flughafen Zürich AG: Aircraft Ground Energy Systems. December 2013.
13. Flughafen Zürich AG: Diesel Particle Filters for GPU. March 2018.
14. Fraport 2017. Annual Air Quality Reports. http://www.fraport.com/en/responsibility/publications/environmental-statements.html
15. Fraport 2017b. „Luftschadstoffe – Eigenschaften und Anteile". Page 8. http://www.fraport.de/content/fraport/de/misc/binaer/verantwortung/Schallschutz_und_Fluglaerm/luftqualitaet/luftschadstoffe---eigenschaften-und-anteile/jcr:content.file/luftqualitaet-luftschadstoffe-eigenschaften-und-anteile_20160929.pdf; Accessed 2017-03-31 13:46
16. Gidhagen, L. et al: Simulation of NOx and ultrafine particles in a street canyon in Stockholm, Sweden. Atmospheric Environment 28 (2004) 2029-2044
17. http://www.boeing.com/commercial/airports/acaps/777rsec5.pdf (July 2012)
18. http://www.freepatentsonline.com/7549318.html (July 2012)
19. Hudda et al. 2016. N. Hudda, M. C. Simon, W. Zamore, D. Brugge, and J. L. Durant: "Aviation Emissions Impact Ambient Ultrafine Particle Concentrations in the Greater Boston Area". Environ. Sci. Technol. 2016
20. Hudda, N. et. al. Aviation Emissions Impact Ambient Ultrafine Particle Concentrations in the Greater Boston Area. Environ. Sci. Technol. July 2016.
21. ICAO Doc 9889: Airport Air Quality Manual, 2nd unedited edition, 2016.
22. ICAO: Environmental Report. 2016.
23. International Standards Organization, ISO: Workplace atmospheres – ultrafine, nanoparticle and nano-structured aerosols – inhalation exposure characterization and assessment. ISO Technical Report 27628:2007.

24. J. Peters, P. Berghmans, J. Van Laer, E. Frijns: UFP- en BC-metingen rondom de luchthaven van Zaventem, VITO NV, Mai 2016
25. Jacobi 2013. Stefan Jacobi: „Erhebung der Luftqualität im Einzugsbereich der neuen NW-Landebahn des Flughafen Frankfurt Station „Frankfurt-Lerchesberg", Auswertung Mai 2012 – Mai 2013, HLNUG http://www.hlnug.de/fileadmin/dokumente/luft/luftmessnetz/lerchesberg/LQ_Lerchesberg_bis%20Ende_Mai_2013.pdf: Accessed 2017-03-27 17:18
26. Jacobi 2014. Stefan Jacobi: „Untersuchungen im Einzugsbereich der neuen NW-Landebahn des Flughafen Frankfurt" http://www.hlnug.de/fileadmin/dokumente/luft/sonstige_berichte/Praesentation_Umwelthaus_160714.pdf; Accessed 2017-03-27 17:37
27. Jacobi 2017. Personal communication 28/03/2017
28. Jacobi et al. 2016. Stefan Jacobi a: Holger Gerwig b, Wilma Travnicek a, Klaus Wirtz b: „Messung ultrafeiner Partikel im Umfeld des Frankfurter Flughafens". FLK-Presentation, a HLNUG, Wiesbaden, b Umweltbundesamt, Langen. 2016-09-28 http://www.flk-frankfurt.de/eigene_dateien/sitzungen/237._sitzung_am_28.9.2016/top_5_-_praes._hlnug__messungen_ultrafeiner_partikel_im_umfeld_des_frankfurter_flughafens.pdf; Accessed 2017-03-24 12:15
29. Johansson, Ch. et al: Spatial and temporal variations of PM10 and particle number concentration in urban air. Environ Monit Assess (2007 127:477-487
30. Keuken MP, Moerman M, Zandveld P, Henzing JS, Hoek G. Total and size-resolved particle number and black carbon concentrations in urban areas near Schiphol airport (the Netherlands) (2015) Atmospheric Environment, 104, pp. 132-142.
31. Kittelson David (University of Minnesota): Particle number measurements: How small should we go? 2016, Cambridge Particle Meeting.
32. Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., Harrison, R.M., Norford, L., Britter, R., 2014. Ultrafine particles in cities. Environment International 66, 1-10. http://dx.doi.org/10.1016/j.envint.2014.01.013
33. P. Kumar, P. Fennell, A. Hayhurst, R.E. Britter: Street versus rooftop level concentrations of fine particles in a Cambridge street canyon. Bound-Layer Meteorol, 131 (2009), pp. 3-18
34. Lauenborg Moller, Karina; Thygesen, Lau Caspar (Statens Institut for Folkesundhed, Syddansk Universitet), Mikkelsen, Sigurd; Brauer, Charlotte (Arbejds- og Miljømedicinsk Afdeling, Bispebjerg Hospital) Helbredsskader og partikelforurening i Københavns Lufthavn, Kastrup. October 2016.
35. Lobo, P., Durdina, L., Smallwood, G.J., Rindlisbacher, T., Siegerist, F., Black, E.A., Yu, Z., Mensah, A.A., Hagen, D.E., Miake-Lye, R.C., Thomson, K.A., Brem, B.T., Corbin, J.C., Abegglen, M., Sierau, B., Whitefield, P.D., Wang, J. (2015): Measurement of aircraft engine non-volatile PM emissions: results of the aviation-particle regulatory instrumentation demonstration experiment (A-PRIDE) 4 campaign. Aerosol Science and Technology, 49, 472-484.
36. M. Fierz, P. Steigmeier, C. Houle and H. Burtscher: Design, Calibration and Field Performance of a Miniature Diffusion Size Classifier. Aerosol Science and Technology 45, 1-10 (2011).Schlatter., J., Arens, F., Böhler, P., Brunner, J., Eugster, R., Hüglin, C., Känzig, R. & Weingartner, E. (2010). Cercl'Air Empfehlung Nr. 28 - Messung der Partikelanzahlkonzentration und –grössenverteilung. Fribourg: Schweizerische Gesellschaft der Lufthygiene-Fachleute (Cercl'Air), Fachgruppe Partikelzählung.
37. Online Ethics Center for Engineering 7/1/2010 OEC "The Problem". Accessed: Friday, March 3, 2017 <www.onlineethics.org/Resources/TeachingTools/Exercises/DualUse/28697.aspx
38. P. Paasonen, A. Visshedjik, K. Kupiainen, Z. Klimont, H.D. van der Gon, M. Kulmala, et al. Aerosol particle number emissions and size distributions: implementation in the GAINS model and initial results, IIASA interim report (2013)
39. Rijksinstituut voor Volksgezondheid en Milieu (RIVM): Verkenning gezondheidsrisico's ultrafijnstof luchtvaart rond Schiphol en voorstel vervolgonderzoek. Report 2016-0050. 2016.

40. Spatial Measurements of Ultrafine Particles Using an Engine Exhaust Particle Sizer (TM) within a Local Community Downwind of a Major International Trade Bridge in Buffalo, New York. Available from: https://www.researchgate.net/publication/233834729_Spatial_Measurements_of_Ultrafine_Particles_Using_an_Engine_Exhaust_Particle_Sizer_TM_within_a_Local_Community_Downwind_of_a_Major_International_Trade_Bridge_in_Buffalo_New_York [accessed Dec 18 2017].
41. SUVA (Swiss Accident Insurance Agency). Measurement Campaign on the Apron of Zurich Airport. 2012 (non published presentations and personal communication).
42. SUVA, Abteilung Arbeitsmedizin (Marcel Jost, Claudia Pletscher): Nanopartiel und ultrafeine Partikel am Arbeitsplatz. Factssheet, Version January 2011
43. Swiss society of air protection officers: Measurement of particle concentration and size distribution. Cercl'Air recommendation No. 28. 2010.
44. Technical Rules for Hazardous Substances (TRGS): Identification and Assessment of the Risks from Activities involving Hazardous Substances: Inhalation Exposure. TRGS 402 (GMBl 2010 No. 12 pp. 231-253, corr. GMBl 2011 p. 175. January 2010
45. TSI Incorporated: P-Trak™ Ultrafine Particle Counter, P/N 2980128, 1999
46. US EPA: Characterization of Emissions from Commercial Aircraft Engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3. EPA-600/R-09/130. October 2009
47. VCS/Vereinigung "Aerztinnen und Aerzte für Umweltschutz": Test parcours for the measurement of particle concentrations in 8 Swiss cities. 2012 (German only).
48. Verein Deutscher Ingenieure (Association of German Engineers): Measurement of particles in ambient air – Determination of the particle number concentration and number size distribution of aerosols – Electrical mobility spectrometer. VDI 3867, Sheet 3 (Draft). June 2009
49. Winer, Arthur M.: Aircraft Emission Impacts in a Neighborhood Adjacent to a General Aviation Airport in Southern California. Environmental Science and Technology, 43: 8039-8045 (2009)
50. Woodruff, T.J., Wells, E.M., Holt, E.W., Burgin, D.E., Axelrad, D.A., 2007: Estimating Risk from Ambient Concentrations of Acrolein across the United States. Environ Health Perspectives 115(3), 410–415.
51. Zhu, Y., et al., Aircraft emissions and local air quality impacts from take-off activities at a large International Airport, Atmospheric Environment (2011), doi:10.1016/j.atmosenv.2011.08.062

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