Assessing aViation emission Impact on local Air quality at airports: TOwards Regulation - AVIATOR

Grant Agreement number: 814801

D7.2 and D7.3

D7.2 A synthesis of the measurement and technical evidence in a form suitable for a regulatory policy context

D7.3 Summary of outline agendas for improved regulation of aircraft emissions aligned to the needs and current understanding of air quality

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EXECUTIVE SUMMARY

Work Package 7 (WP7) has specific responsibility for identifying and offering new insights on how to facilitate closer connectivity between aircraft emission regulations and local air quality and workplace policies.

The purpose of this document is to provide a synthesis of the measurement and technical evidence (WP2, 3, 4, 5, and 6) in a form suitable for a regulatory policy context. This is the Deliverable D7.2.

Deliverable D7.3 is also included in this report and is a Summary of Outline Agendas for improved regulation of aircraft emissions aligned to the needs and current understanding of air quality. The content of these two deliverables is complementary and they are inherently linked. There is additionality in bringing them together into a single harmonised and holistic text.

D7.1 delivered at M18 provided the context and developed a framework to assess and develop a roadmap to help highlight and bridge understanding of knowledge gaps in aircraft emission regulation and between aircraft engine emissions standards and the human health-based local air quality regulation (workplace and ambient air quality). This framework helped to inform and shape activities in WP2-6 to ensure they address regulator needs and provide and enable direct routes of communication and dissemination of AVIATOR outputs to the Regulatory community.

AVIATOR has adopted a multi-level measurement, modelling and assessment approach to develop an improved description and quantification of the relevant aircraft engine emissions, and their impact on air quality under different climatic conditions. The AVIATOR measurement and modelling work packages (WP2 to WP6) are all linked but have separate and detailed reports and deliverables. This report aims to bring together the main results and findings from each of the work packages in a single document thus providing an overview of the project. The results and findings are summarised and presented in a form suitable for policy makers in the regulatory field.

Engine particulate and gaseous emissions were measured in a test-cell environment and on-wing from an IBERIA A340 aircraft to determine the immediate properties and characteristics of the pollutant plume evolution from the engine. This provided an enhanced understanding of primary emitted pollutants, specifically the nvPM and vPM (down to 5 nm in size), and the scalability between the regulatory test-cell environment and real airport environments.

AVIATOR also developed and deployed across multiple airports, a proof-of-concept low-cost sensor network for the monitoring of UFP, PM and gaseous species such as NOx and SOx, across airport environs and surrounding communities. The transport of emissions from aircraft engines were monitored and validated in this more complex environment through high-fidelity and sensor measurements.

The experimental campaigns were complemented by high-fidelity modelling of aircraft exhaust dynamics, microphysical and chemical processes within the plume. CFD models, box models, and airport air quality models were also applied, to validate the parameterizations of the relevant processes applicable to standard dispersion modelling on the local scale.

Working with the regulatory community, AVIATOR has developed improved guidance on measuring and modelling the impact of aircraft emissions with specific reference to UFP. Furthermore, and acknowledging the uncertainty surrounding health impacts of UFP, AVIATOR has also worked with the public health community to develop methodologies for the representative sampling of aircraft emissions.

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LIST OF ABBREVIATIONS

AMS	Aerosol Mass Spectrometer
APU	Auxiliary Power Unit
BC	Black carbon
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
CAEP	Committee on Aviation and Environmental Protection (ICAO)
CAEP MDG	Modelling and database group
CAEP WG3	Working Group 3 (emissions and technical)
CO	carbon monoxide
CO_2	carbon dioxide
CPC	Condensation Particle Counter
EASA	European Aviation Safety Agency
EC	European Commission
EEA	European Environment Agency
EEDB	Engine Emissions Data Bank (ICAO)
EI	emission index
EU-OSHA	European Union Occupational Safety and Health Agency
HC	hydrocarbons
H or H_2	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids (Fuel)
ICAO	International Civil Aviation Organisation
ICAO-ANC	Air Navigation Commission
ICAO-CAEP	Committee on Aviation and Environmental Protection
ISA	International Standard Atmosphere
kN	kiloNewton (of thrust)
LAQ	local air quality
LCS	Lower Cost Sensor
LTO	landing and take-off
µm	micron or micrometre (10^{-6} m)
NOx	oxides of nitrogen
nm	nanometre (10^{-9} m)
NPF	New particle formation
nvPM	non-volatile Particulate Matter (nvPM emissions from aircraft engines are predominantly composed of BC)
OEM	original equipment manufacturer
OH	Hydroxyl radical
OPC	Optical Particle Counter
O_3	ozone
PAH	PolyAromatic Hydrocarbons
PAM	Potential Aerosol Mass
PM	particulate matter

$PM_{2.5}$	particulate matter including all particles with a diameter of 2.5 microns or less
PM_{10}	particulate matter including all particles with a diameter of 10 microns or less
ppmv	parts per million by volume
SAF	Sustainable Aviation Fuel
SOA	Secondary Organic Aerosol
SARPs	standards and recommended practices
SO_2	sulphur dioxide
SMPS	Scanning Mobility Particle Sizer
STEL	short-term exposure limit
SVOC	Semi-volatile organic compounds
tPM	Total particulate matter
TWA	time-weighted average
vPM	volatile PM
UFP	ultrafine particles often defined as particles with one dimension less than 100 nanometres.
UHC	Unburnt hydrocarbons
VOC	volatile organic compounds
WHO	World Health Organisation

1. INTRODUCTION

1.1. Key Aims

A key aim of AVIATOR is to "Bridge the gap between Aircraft Engine Certification and Local Air Quality (LAQ) Regulation" with the following objectives:

- To describe the causality between the regulated gaseous and nvPM engine emission species and the subsequently evolved total PM plume concentrations.
- To build on the knowledge gaps and requirements of stakeholders to develop new outline agendas.
- To develop understanding of vPM and secondary PM precursor emissions at fleet level and within the context of regulatory standards development.

Work Package 7 (WP7) has specific responsibility for identifying and offering new insights into aircraft emission regulations and the linkages with local air quality and workplace policies.

The aim is to enhance the understanding of the importance of aircraft engine emission on air quality in and around airports.

The purpose of this document (D7.2) is to provide a synthesis of the technical work packages (measurement work packages WP2, WP3 and WP4 and the modelling work packages WP5 and WP6) in a form suitable for policy makers. It is not intended to reproduce the detailed technical inputs of the individual work packages produced for the AVIATOR project. The final chapter of this report provides a summary of outline agendas for improved regulation of aircraft emissions which is aligned to the needs and current understanding of air quality (D7.3).

1.2. AVIATOR: Regulatory and Policy Context

Aircraft main engines emit a complex mixture of particles and gases into the local environment. Once emitted, these products are subject to numerous processes including condensation, coagulation and chemical processing as the exhaust plume expands and is diluted by entrained ambient air. As the plume cools, the production of secondary aerosol from precursor gas condensation can significantly increase the overall mass and number of PM. However, the formation of these secondary materials within the evolving plume is not simply a function of plume temperature and composition, but also of the entrained local and regionally sourced pollutants, transportation times and meteorology.

Currently aircraft main engine emissions are regulated for gaseous EIs (CO, NOx, UHCs) and EI nvPM (mass and number) as measured within half a nozzle diameter of the engine exit. European OEMs perform these certification measurements within certified test-cells using the methodologies prescribed in ICAO Annex 16 Vol II. Except for the non-discriminating UHC EI concentration, neither volatile PM or gaseous precursors emitted from either the main engine core or oil breather are currently regulated. However, these pollutants will nevertheless develop into species within the plume that likely impact local air quality and health. In addition, dilution and cooling of the plume from the entrainment of ambient air significantly impacts the vapour pressure of volatile species, inducing changes of state and physicochemical properties. At present it is therefore unknown whether current regulatory measurements are sufficiently robust in predicting the downstream concentrations of the pollutants that impact local air quality.

Figure 1.1 illustrates how the individual work packages of AVIATOR broadly interact with each other and orange arrows illustrate where AVIATOR outcomes may potentially inform regulatory policy. The related H2020 health study TUBE is also shown in relation to AVIATOR.

Each of the AVIATOR technical work packages are summarised in this report **providing a synthesis of the measurement and technical evidence in a form suitable for a regulatory policy context**.

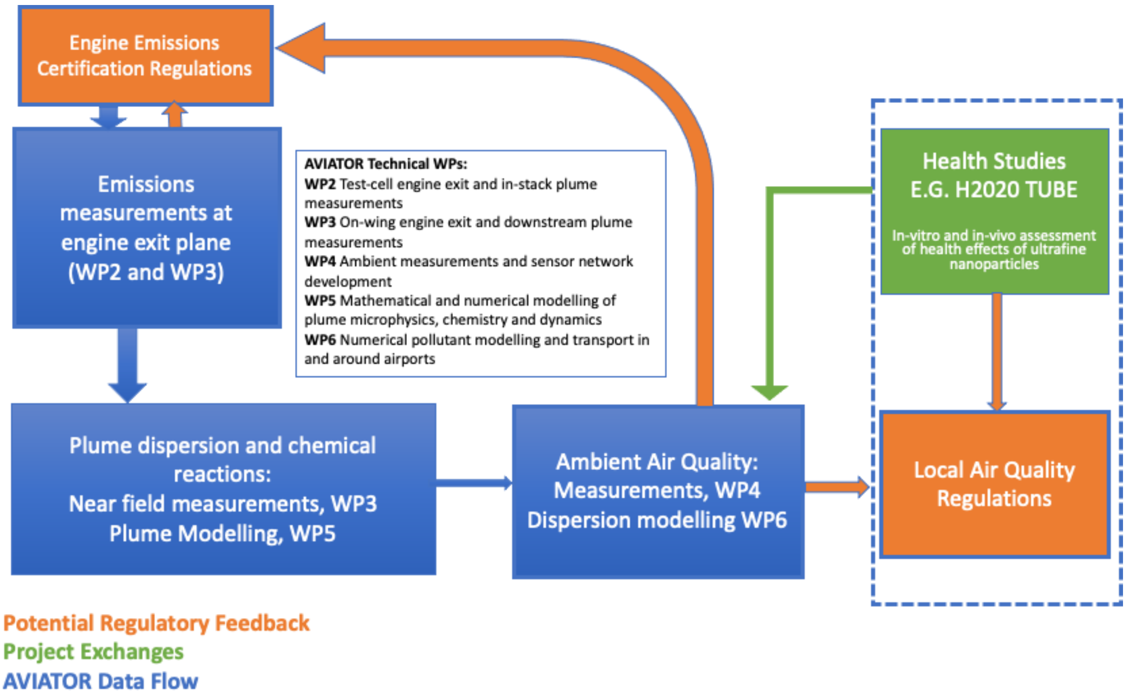

Figure 1. 1. AVIATOR technical WP links and associated health studies; showing potential regulatory feedback routes.

1.3. Emissions Regulations

ICAO-CAEP Engine Emissions Standards

ICAO Standards and Recommended Practices (SARPs) limiting the emissions of smoke, nvPM (mass and number), unburnt hydrocarbons (UHC), carbon monoxide (CO) and oxides of nitrogen (NOx) from turbojet and turbofan aircraft engines are contained in Annex 16 Volume II[1] to the Convention on International Civil Aviation.

The first SARPs for gaseous and smoke emissions became applicable in the 1980's. The smoke number regulatory level was put in place to control visible emissions and the gaseous emissions regulatory levels were put in place to address local air quality issues. The measurements and calculations of gaseous emissions are based on a reference Landing Take-Off (LTO) cycle. The engine emissions SARPs are regularly updated.

Since the original edition of Annex 16 Volume II, ICAO adopted periodically more stringent NOx regulatory levels following the technology improvement in engine emissions. The last regulatory level became applicable on 1st January 2014.

ICAO-CAEP Particulate Matter regulatory levels

[1] ICAO Annex 16 "International standards and recommended practices, Environmental protection", Volume II "Aircraft engine emissions", 4th ed. (2017) plus amendments.

Before 2016, the Smoke Number regulatory level that effectively limited the visibility of the engine emissions was the only regulatory level related to soot emissions. However, in recognition of the growing health concerns regarding ultrafine PM, ICAO adopted in March 2017 the so called "CAEP/10" nvPM maximum mass concentration certification SARPs, which also required the LTO nvPM mass and nvPM number emissions to be reported. The "CAEP/10" nvPM maximum mass concentration regulatory levels became applicable from 1st January 2020.

Using standardised data collected under the "CAEP/10" certification procedures, work continued in the CAEP through the ICAO-CAEP Emission Standards Group (Working Group 3 or WG3), to develop new emissions SARPs for nvPM mass and nvPM number and in March 2020 ICAO adopted new emissions standards for both nvPM mass and nvPM number (amendment 10 to Annex 16 Volume II). These SARPs include new regulatory levels for nvPM mass and nvPM number applying to both in-production and new engine types from 1 January 2023. These new engine emissions regulatory levels are for LTO nvPM mass and nvPM number emission indices (EIs) per kiloNewton (kN) of rated thrust. As part of this amendment the nvPM maximum mass concentration regulatory level as agreed at CAEP/10 (see above) is now considered to mitigate the exhaust plume visibility as the smoke number does. ICAO also adopted to end the Smoke Number regulatory level applicability for engines of rated thrust > 26.7 kN from 1 January 2023. Amendment 10 to Annex 16 Volume II updated to reflect these agreements is published and became applicable on 1 January 2021.

The ICAO LTO Cycle

The ICAO reference Landing and Take Off (LTO) cycle characterises the four operating modes of a flight at and around an airport: Take-off, Climb, Approach and Taxi. The ICAO reference LTO cycle defines the thrust settings to be used when making emissions and smoke measurements and the duration to be used for each operating mode. In actual operations of course, these times may vary considerably particularly for the taxi and idle mode between airports (the taxi and idle times in mode were based on values observed at Los Angeles Airport in the 1970's and do not necessarily reflect typical conditions and are more reflective of worst-case assumptions). However, the ICAO reference LTO cycle provides a standardised approach for emissions certification and also consistent means of estimating and comparing emissions. Hence individual airports may use actual times in mode to develop emission inventories.

The ICAO Landing Take-off (LTO) cycle is defined as follows.

- Take-off: 100% of rated thrust during 0.7 minutes;
- Climb: 85% of rated thrust during 2.2 minutes;
- Approach: 30% of rated thrust during 4.0 minutes;
- Taxi: 7% of rated thrust during 26 minutes.

Note that the taxi mode involves taxi and idle between the initial starting of the propulsion engine(s) and the initiation of the take-off roll and between the time of runway turn-off and final shutdown of all propulsion engine(s).

The certification process involves running the engine on a test bed at each thrust setting.

The engine emissions certification is based on:

- the fuel flows (kg/s), the EI's for NOx, HC, CO, nvPM mass (mass per kg of fuel) and nvPM number (number of particles per kg of fuel); these values allow for the calculation of emissions levels for each pollutant as follows: sum for the four LTO modes of [fuel flow x emissions indices x time in mode] and dividing with the rated thrust (total LTO mass per kN and total LTO nvPM number per kN); and
- the measured maximum smoke number and measured nvPM maximum mass concentration.

The ICAO Emissions Data Bank

The ICAO Aircraft Engine Emissions Databank (EEDB) contains information on exhaust emissions of in-production civil aircraft engines, measured according to the procedures in ICAO Annex 16, Volume II, and where noted, certified by the States of Design of the engines according to their national regulations. The databank covers engine types for which the Annex 16 Volume II SARPs are applicable. The gaseous and nvPM emissions regulatory levels apply to turbojet and turbofan engines with a rated thrust greater than 26.7 kN. The smoke number regulatory levels apply to turbojet and turbofan engines of any rated thrust till 31 December 2022 and only to turbojet and turbofan engines of a rated thrust equal or less than 26.7 kN after this date. The ICAO EEDB is hosted by the European Aviation Safety Agency (EASA) on behalf of ICAO[2] and is publicly available.

The most recent version of the ICAO EEDB includes data from the engine emissions certification data provided by the engine manufacturers for CO, HC, NOx, Smoke Number and, as engines are brought forward for certification to comply with the nvPM regulatory levels, the certified nvPM levels.

SAE E-31

SAE International develops standards in order to advance engineering for transport, including the aerospace sector, throughout the world. SAE standards include almost 10,000 documents created through consensus standards development by more than 240 SAE Technical Committees with 450+ subcommittees and task groups. These works are authorised, revised, and maintained by the volunteer efforts of more than 9,000 engineers, and other qualified professionals from around the world. Additionally, SAE has 60 US Technical Advisory Group (USTAG's) to ISO Committees. The SAE E31 committee is responsible for developing "Aircraft Engine Gas and Particulate Emissions Measurement" practices. SAE-E31 committee members include: engine manufacturers, scientists – academic/research institutes, regulators. The E31 committee produces the following products:

- Aerospace Information Report (AIR) - Information report written in the style of an ARP by a small number of committee members. Review and ballot before published.
- Aerospace Recommended Practice (ARP) - Comprehensive report written as an industry standard with input from all members. Review and ballot before published.

There are a number of members of the E31 committee who are also members of CAEP WG3 and three of these are designated as E31-WG3 liaisons. The SAE E31 committee feeds their work directly to the ICAO-CAEP Emission Standards Group (Working Group 3), through their Liaisons and using 'White Papers', to provide input on standardisation of measurement procedures and methods and provision of data on measurement repeatability and uncertainty.

1.4. Local air quality regulations

The local air quality standards for Europe are based on recommendations developed by the WHO, promulgated by the European Union and implemented into domestic regulation by individual Member States. The local air quality regulations are summarised in Table 1.1 and Table 1.2. The WHO updated its air quality guidelines in 2021 and these new AQG are provided in Table 1.2 (https://apps.who.int/iris/handle/10665/345329). The new WHO AQGs are more stringent. For $PM_{2.5}$ the annual mean is down from 10 to 5 µg/m^3 and the daily limit is down from 25 to 15 µg/m^3.

[2] https://www.easa.europa.eu/easa-and-you/environment/icao-aircraft-engine-emissions-databank

Particulate matter, nitrogen dioxide and ground-level ozone, are now generally recognised as the three pollutants that most significantly affect human health. Long-term and peak exposures to these pollutants range in severity of impact, from impairing the respiratory system to premature death (EEA website, 2020[3]). It is worth noting that there are currently no local air quality regulations specifically pertaining to ultrafine particulate matter. As yet, insufficient data are available to provide recommendations for AQG levels and interim targets for specific types of PM, notably BC, UFP and SDS[4]. However, due to health concerns related to these pollutants, the WHO proposes actions to enhance further research on their risks and approaches for mitigation are warranted. WHO good practice statements for UFP are summarised as follows:

1. Quantify ambient UFP in terms of PNC for a size range with a lower limit of ≤ 10 nm and no restriction on the upper limit.
2. Expand the common air quality monitoring strategy by integrating UFP monitoring into the existing air quality monitoring. Include size-segregated real-time PNC measurements at selected air monitoring stations in addition to and simultaneously with other airborne pollutants and characteristics of PM.
3. Distinguish between low and high PNC to guide decisions on the priorities of UFP source emission control. Low PNC can be considered < 1 000 particles/ cm3 (24-hour mean). High PNC can be considered > 10 000 particles/cm3 (24-hour mean) or 20 000 particles/cm3 (1-hour mean).
4. Utilize emerging science and technology to advance approaches to the assessment of exposure to UFP for their application in epidemiological studies and UFP management.

For BC/EC the following WHO good practice statements are as follows:

1. Make systematic measurements of black carbon and/or elemental carbon. Such measurements should not replace or reduce existing monitoring of those pollutants for which guidelines currently exist.
2. Undertake the production of emission inventories, exposure assessments and source apportionment for BC/EC.
3. Take measures to reduce BC/EC emissions from within the relevant jurisdiction and, where appropriate, develop standards (or targets) for ambient BC/EC concentrations.

The EEA (the European Environment Agency) provides independent information on the environment for those involved in developing, adopting, implementing and evaluating local air quality. The EEA is not responsible for implementing the local air quality regulations but the Agency provides much of the information to those in Europe involved in developing, adopting, implementing and evaluating local air quality policy.

The LAQ standards for particulate matter are mass concentration values for $PM_{2.5}$ and PM_{10} (as shown in Tables 1.1 and 1.2). The measure of $PM_{2.5}$ includes all particles with a diameter of 2.5 microns or less and PM_{10} includes all particles with a diameter of 10 microns or less (and therefore includes the $PM_{2.5}$ fraction). The ultrafine particulate matter often describes the fraction of particles with a diameter of 0.1 micron or less. The mass metric of $PM_{2.5}$ is therefore likely to be dominated by larger and heavier particles in the range up to 2.5 microns. Aviation nvPM particles mostly fall in the ultrafine range of less than 0.1 micron and well within $PM_{2.5}$ LAQ limit values are therefore not likely to see a significant signal from these emissions. It is worth noting that aviation PM is typically <80 nm hence contributes very little to $PM_{2.5}$ or PM_{10} given mass is volume weighted hence skewed to the larger particles.

[3] https://www.eea.europa.eu/themes/air/intro

[4] Provide qualitative statements on good practices for the management of certain types of PM (i.e. black carbon or elemental carbon (BC/EC), ultrafine particles (UFP, i.e. particles with aerodynamic diameter of of ≤ 0.1 μm), and particles originating from sand and dust storms (SDS)) for which the available information is insufficient to derive AQG levels but indicates risk.

Table 1.1. Local Air Quality Regulations[5]

EU Air Quality Directive				WHO Guidelines Updates in Table 1.2	
Pollutant	**Averaging Period**	**Objective and legal nature**	**Comments**	**Concentration**	**Comments**
$PM_{2.5}$ µg/m^3	daily			limit value, 25	99th percentile (3 days/year)
$PM_{2.5}$ µg/m^3	annual	limit value, 25		limit value, 10	
PM_{10} µg/m^3	daily	limit value, 50	not to be exceeded on more than 35 days per year	limit value, 50	99th percentile (3 days/year)
PM_{10} µg/m^3	annual	limit value, 40		limit value, 20	
O_3 µg/m^3	maximum daily 8-hour mean	target value, 120	not to be exceeded more than 25 days per year averaged over 3 years		
NO_2 µg/m^3	hourly	limit value, 200	not to be exceeded on more than 18 times per calendar year	limit value, 200	
NO_2 µg/m^3	calendar year	limit value, 40		limit value, 40	

Table 1.2. The New 2021 WHO global air quality guidelines

Pollutant	Averaging time	Interim target				AQG
		1	2	3	4	
$PM_{2.5}$ µg/m^3	annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15
PM_{10} µg/m^3	annual	70	50	30	20	15
	24-hour[a]	150	100	75	50	45
O_3 µg/m^3	peak season[b]	100	70			60
	8-hour[a]	160	120			100
NO_2 µg/m^3	annual	40	30	20		10
	24-hour[a]	120	50			25

a 99th percentile (3 to 4 days/year)
b average of daily max 8-hour mean concentration in the 6 consecutive months with the highest 6-month running average concentration

1.5. Workplace regulations

The EU keeps a list of indicative exposure limits for chemical substances including for selected pollutants found in the exhaust gases from internal combustion engines and for diesel exhaust

[5] EU Air Quality Directive (2008/50/EC), WHO, 2006, Air quality guidelines: Global update 2005.

emissions. These limit values are developed by the European Agency for Safety and Health at Work (EU-OSHA). These “community values” are minimum limit values—member states are required to establish national occupational exposure limit values for listed chemical agents “taking into account the community values”, but the national exposure limits may be lower than the EU limits. Another, mandatory list of limit values applies to exposure to chemical agents designated as carcinogens or mutagens, Directive 2004/37/EC. In January 2019, exposure limits for diesel engine exhaust emissions were added for the first time to the carcinogen listing.

Table 1.3. Indicative occupational exposure limit values for selected engine exhaust pollutants

Substance	8 hr TWA (Time Weighted Average)		STEL (short-term exposure limit)	
	mg/m^3	ppmv	mg/m^3	ppmv
CO	23	20	117	100
NO	2.5	2	-	-
NO_2	0.96	0.5	1.91	1
SO_2	1.3	0.5	2.7	1

2019 amendments to Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work introduced, for the first time, exposure limits for diesel engine exhaust emissions.

The exposure limit value for diesel engine exhaust emissions has been set at 0.05 mg/m^3, measured as elemental carbon. This limit value becomes effective in general occupational health environments from 21st February 2023. In underground mining and tunnel construction, the limit value is applicable from 21st February 2026.

The Netherlands have adopted an occupational exposure limit for diesel engine exhaust particles of 0.01 mg/m^3 (EC July 1st, 2020[6]).

[6] https://www.etui.org/news/netherlands-sets-much-lower-and-more-protective-occupational-exposure-limit-value-oel-diesel

2. Overview of the AVIATOR Measurement and Modelling Work Packages (WP2, 3, 4, 5 and 6)

The WP2, WP3 and WP4 are the AVIATOR measurement work packages designed to: a) improve the measurements of aircraft engine emissions and pollutants; and b) to provide measurements data to help with the AVIATOR modelling work packages (WP5 and WP6). WP2 takes measurements at the engine exit and in the near field whilst WP3 continues from the engine exit on-wing up to near-field distances of about 250 to 300 m from the engine exit. WP4 then continues to move in scale to the mid-field taking ambient measurements on the airport and in some cases outside the perimeter fence. A large array of complex measurement devices is used in the WP2, 3 and 4 campaigns and an important aspect of AVIATOR is to make intercomparisons between the devices. Inter-comparison data was made between the instrumentation used throughout all 3 WPs to ensure any changes can be tracked and that comparability between work packages was possible. This allows conclusions to be drawn as the scale moves from the engine exit to the ambient measurements.

Additionally, as part of WP4, a lower cost sensor (LCS) network was also developed to test whether these lower fidelity (and lower cost) devices could be utilised to measure pollutants effectively, especially particulate matter.

WP5 and WP6 are the AVIATOR modelling work packages designed to advance aircraft plume and airport modelling methodologies, respectively. WP5 seeks to improve the modelling of plume microphysics, chemistry and dynamics using the data collected in the measurement work packages to better understand and model the chemical and physical processes in the ageing plume as particles are transported and diluted, coated by volatile species and new volatile particles are created from a range of organic precursors. WP6 uses established dispersion modelling methodologies to calculate the spatial distribution of pollutant concentration in and around airports and for gaseous pollutants such as NOx dispersion calculations are routinely applied but for PM emissions (especially PM number) there are additional uncertainties as investigated in WP5 and the outputs of WP5 have been used to parameterise the dispersion modelling methodology to better capture the evolution of PM (nvPM and vPM and especially of the smaller particles, lower than 100 nm aerodynamic diameter) in the plume. WP6 output calculations are compared with the WP4 ambient measurements for two airports (Madrid and Zurich). Both measurement and modelling WPs are ultimately aimed at improving the understanding and the links between engine emissions and ambient pollutant concentrations.

3. Summary of Engine Exit and On-wing Measurements (WP2 and WP3) for Regulation and Policy Context

3.1. Introduction

The overall idea of the engine exit (WP2) and on-wing (WP3) measurement campaigns is to be able to measure the PM (and other gaseous) pollutants from the engine and their subsequent transport and evolution in the plume as they are transported and mixed with ambient air and exposed to ambient conditions. WP2 and WP3 have provided measured data to investigate the transport and evolution processes to support the ambient measurements (WP4) and inputs to the dispersion modellers (WP5), helping to provide data in the knowledge gap between the engine emissions and the ambient levels of pollutants to be found in and around the airport.

Measurements of regulated exhaust gases and particulate emissions (nvPM mass and number) together with aerosol precursor measurements and currently non-regulated particulate emissions (vPM and total PM, tPM mass and number) have been delivered to provide insights into: a) how the regulated emissions of nvPM in terms of mass and number are transported in the plume from the engine exhaust; and b) how the total PM (tPM) including vPM, evolves in the plume to contribute to tPM downwind of the exhaust.

3.2. Summary of measurement systems in WP2 and WP3

The WP2 and WP3 can be summarised as follows:

- WP2 Engine exit and in-stack plume measurements used three measurement systems: Baseline, Comprehensive and oil breather systems at three sampling locations in the test cell: at the engine exit[7]; and 50 m from the exhaust exit in the enclosed stack as shown in Figure 3.1 and from the oil breather overboard vent.
- WP3 Engine exit and downstream plume "On Wing" measurements using the Comprehensive and Baseline Systems, sampling in parallel from the near-field and far-field probes (separated by 50 m) in the ambient environment at intervals from 0 m to a maximum of 300 m from the engine exit as shown in Figure 3.2.

The Baseline and Comprehensive measurement systems were developed for AVIATOR and consisted of a complex array of instrumentation described in summary as follows (more details of the measurement devices are provided in Box 3.1 and they are fully described WP2 and WP3 reports):

- **Comprehensive system**: This system includes the European (EUR) reference system which is fully compliant for CAEP regulatory/certification measurements of nvPM, number and mass and CAEP regulatory/certification type measurements of CO, NOx and Smoke. Other measurements included PM size (>5nm); total particulate matter (tPM); Volatile Organic Compounds (VOC) composition; VOC gas composition; Secondary Organic Aerosol (SOA) gaseous precursors; CO_2; SO_2; Additionally, and not originally planned[8], measurements were also made in WP2 using an Aerosol Potential Aerosol Mass (PAM) oxidation flow reactor.
- **Baseline system**: This measurement system was specifically developed for the AVIATOR project for use across multiple work packages 2, 3 and 4. The core of the baseline system focused on nvPM and tPM number concentrations with CO_2, since

[7] within half a nozzle diameter

[8] This was via a new collaboration after AVIATOR was funded, between UoM and Prof. A. Vogel and Goethe-University, Frankfurt. They were made partners in AVIATOR and provided additional measurements and further science to the project.

these were the highest priority metrics for WP5 and 6 modellers. In addition, other PM measurements were also obtained including measurements of nvPM and tPM mass, and particle size distribution (aerodynamic and mobilty).

The PM measurements of the WP2 baseline system are designed to provide insights into the total PM picture and to be able to look at evolution of particle emissions in the plume whilst maintaining comparability with the certification measurements of engine emissions of nvPM.

WP2 aimed to establish baseline and comprehensive sampling and measurement systems for characterisation of aircraft engine exhaust within a test-cell. The baseline system was applied in the test-cell (WP2) and applied in the on-wing and plume measurements (WP3); and then further downwind in WP4 (see following section).

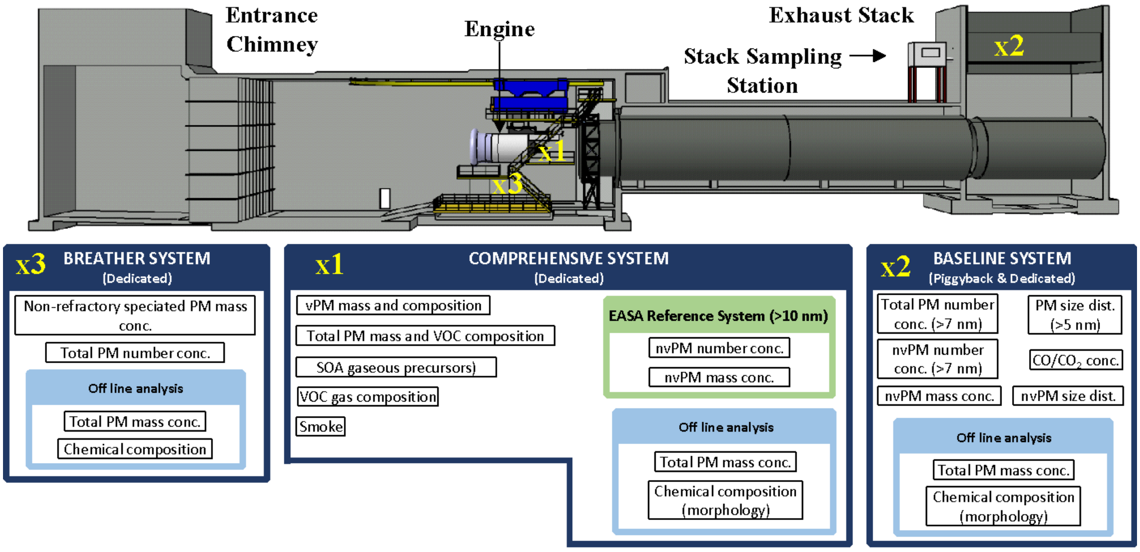

Figure 3.1. Scheme of the engine emissions measurement systems deployed at INTA's test-cell for WP2: 1. Comprehensive system, sampling emissions at engine exit plane; 2. Baseline system, sampling in the exhaust stack; 3. Breather system, sampling in the oil breath

WP3 aimed to characterise the chemical and physical properties of aerosol and gas phase compounds found within the evolving exhaust plume of main engines. WP3 applied the comprehensive and baseline systems in the measurement campaigns. The WP3 measurements were undertaken with two sampling probes each 50 m apart as shown in Figure 3.2. The aircraft moved forward at intervals of 50 m (and 5, 10, 15 & 25 m for one day) to enable samples to be taken downwind of the exhaust plume up to a distance of 300 m.

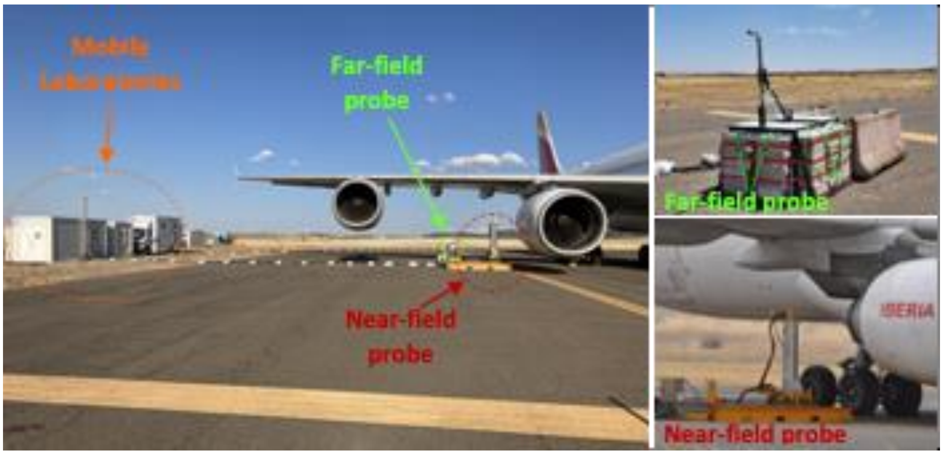

Figure 3.2. WP3 measurements, highlighting near-field and far-field probes connected to mobile test laboratories containing the Baseline System.

Comprehensive System (WP2/WP3)

FOR REGULATORY EMISSIONS MEASUREMENTS:
The European (EUR) nvPM reference system, which contains the relevant analysers to measure regulatory gases (CO_2, CO, NOx, THC), smoke and nvPM mass & number. This system is fully compliant with SAE ARP6320 and ICAO Annex16 Volume II (A16V2):
nvPM number concentrations: An aviation AVL Particle Counter (APC) was used to measure the nvPM number concentrations in accordance with A16V2. A catalytic stripper removes the volatile fraction and ensures the sample temperature and particle concentrations are within the required specifications of the TSI 3790E CPC to ensure 'single counting' with a counting efficiency >50% at 10nm and >90% at 15nm.
nvPM mass concentrations: In the EUR nvPM system two different mass instruments which meet the performance specifications as set out in ICAO A16V2 are employed, namely an Artium Laser-Induced Incandescent analyser (LII-300) and AVL Micro soot sensor (MSS). Laser-induced incandescence (LII) is a real-time technology that offers a reliable means for spatially and temporally measuring the concentration of refractory black carbon in aviation exhausts and in ambient air, offering a wide dynamic range and hence generally not requiring any pre-dilution. The AVL MSS is designed for continuous measurement of low concentrations of black carbon in a diluted exhaust gas stream and is based on the photoacoustic measurement principle. The aviation model can detect concentrations down to 1 $\mu g/m^3$.
Regulatory Gaseous Emissions (NOx, CO, total unburnt hydrocarbons) and CO_2: All gases were measured as per aviation regulatory standards in A16V2. CO_2 & CO were measured using an NDIR instrument and utilised to measure raw exhaust concentrations with the CO_2 also used to determine the primary dilution ratio of the nvPM system.
Smoke Emissions: Stained filter as per A16V2.
FOR NON-REGULATORY EMISSIONS MEASUREMENTS:
Particle Size and distribution: as electrical mobility diameter in real-time 5 nm to 1 micron (DMS 500)
SO_2 gas: measured using an NDIR instrument.
Volatile gas and particle emissions (including oil) were determined using a number of different instruments:
vGas mass and chemical composition: Proton Transfer Time of Flight Mass Spectroscopy (PTR-MS) with two modes to detect range of VOCs. And offline chemical analysis filters.
vPM mass and chemical composition: Aerosol Mass Spectrometer (AMS) measured in real time. And Offline chemical analysis filters.
vPM (oil specific) number, size and distribution: Electrical mobility diameter in real-time 5nm to 1 micron (DMS 500), and optical scattering in real time 0.25 to 32 mm (OPC).

Baseline System (WP2/3/4)

nvPM and tPM number concentrations in the range >4nm (2 x CPCs, compliant with the performance specifications for ICAO A16V2, used with and without catalytic stripper to get tPM and nvPM number concentrations. tPM-nvPM= vPM)
tPM number concentration and size distribution up to 32 µm (1 x OPC)
tPM number concentration in range 10 nm to 300 nm (this is the low fidelity 1 x Partector-2 Lower-cost particle counter **as deployed in the LCS)**
tPM particle size and distribution as aerodynamic diameter (1 x ELPI+®)
tPM particle size and distribution as electric mobility diameter (1 x SMPS)
CO_2 concentrations to determine dilution factors: 1 x NDIR LI-850
nvPM and tPM mass parameters were also measured (An Artium LII-300 used to measure nvPM mass concentration and tPM mass concentration via ELPI®+ and OPC particle size distribution integration measurements)

Box 3.1 Measurements and devices used in WP2 and WP3

Results from WP2 and 3 have provided important inputs for the mathematical and numerical modelling of plume microphysics, chemistry and dynamics (WP5) and pollutant modelling and transport in and around airports (WP6). WP3 also provides insights and data for the WP4 ambient measurement work package where the Baseline system is also deployed.

The primary role of the Baseline system setup is to measure the highest priority airport modelling parameters (as defined by the modelling experts in WP5 and WP6). This focusses on particle number concentrations of both nvPM and tPM (i.e. catalytically stripped and unstripped respectively particle concentrations) including the lowest particle sizes possible with the measurement techniques used (i.e. using a low cut-point 4 nm). These particle number measurements are made in conjunction with particle size measurements and CO_2 for dilution correction and EI calculation.

3.3. Summary of measurement campaigns WP2 and WP3

Aircraft engine testing was undertaken in both a test cell (WP2) and on-wing (WP3) to first demonstrate the performance of the Baseline system measuring in-stack when compared to the Comprehensive (regulatory) engine exit measurements and to help understand the impact of ambient conditions and fuel composition on emitted pollutants (regulated and unregulated) from large civil aviation gas turbine engines[9].

WP2 conducted measurements in the controlled environment of the test-cell, located at INTA Madrid Spain. 'Piggyback'[10] testing was performed to firstly develop sampling and measurement protocols, whilst gaining an understanding of 'near-field' plume emissions evolution using the in-stack monitoring location. Following the piggyback testing, a WP2 'dedicated' test campaign was conducted 1st- 11th June 2021, specifically looking at the impact of engine power and loading on total emissions, with specific testing to assess the impact of lubrication breather oil on plume evolution of vPM.

The two systems (Baseline and Comprehensive) were deployed at the locations shown in Figure 3.1. The Comprehensive System was deployed at the engine exit (x1) and the Baseline System was deployed in the stack (x2). A third sampling system was also added in WP2, the **Breather system** (x3); this was designed and built for the dedicated engine tests with the aim of characterising and assessing the composition of the oil released from the breather prior to mixing with the engine exhaust plume.

WP3 undertook two 'On-wing' test campaigns at Ciudad Real International Airport (CRIA), Spain. The first was performed from 19th – 30th July 2021, specifically looking at summer conditions on plume evolution with an assessment of the impact of sunlight performed by conducting specific testing in both the day and night. A second winter campaign was performed 16th - 28th Jan 2022 to first assess the impact of ambient conditions on plume evolution, then by utilising a 30% HEFA blended SAF the impact of fuel composition on emissions and plume evolution was assessed.

The Baseline system was deployed in various positions downwind of the engine exhaust from the closest location, 50 m, to up to 300 m from the engine exit as shown in Figure 3.2. the 'on-wing' test campaigns were conducted to characterise the chemical and physical properties of aerosol and gas phase compounds found within the evolving exhaust plume of the inboard main engine (Trent 500 engine), operating on an A340 aircraft under parking.

Measurement of exhaust emissions of the 'on-wing' main engine were undertaken across a number of 'nominal' ISA thrust power conditions (Ground Idle, 5%, 7%, 30% & 80%), using a

[9] large modern development Rolls Royce Trent engines

[10] 'piggyback' testing was the additional AVIATOR testing performed on engines being tested for other reasons, hence reducing the operational costs of WP2. As such measurements were limited to a Baseline system sampling within the exhaust stack.

similar sampling and measurement methodology as was demonstrated for the engine exit and in-plume sampling locations developed and successfully demonstrated during the test cell measurements (WP2). Again, measurements of exhaust gas (including VOC and SVOC), nvPM and total PM were determined using two sampling probes located 50 m apart behind a parked A340 aircraft, as shown in **¡Error! No se encuentra el origen de la referencia.**.2, which was moved axially away from the probes between test points. This test set-up allowed assessment of evolving emissions of 'real-world' exhaust at distances representative of air quality in and around airports.

The 'on-wing' measurements were conducted at Ciudad Real International Airport (CRIA), which is located approximately 230 km south of Madrid, Spain, and was chosen due to the availability of Iberia A340 aircraft, which were all permanently grounded as a direct result of the COVID pandemic. To establish a better understanding of the evolution of pollutants of an aircraft engine during the LTO cycle, inclusive of the impact of climactic conditions and potentially solar radiance, two distinct test programmes were conducted during the Summer (July 2021) and Winter (Jan 2022). In the first 'Summer' test, different aircraft axial locations (0 m, 50 m, 100 m, 150 m & 200 m) were measured at different engine power levels, which corresponded as close as possible to routine airport operations, within an Airbus prescribed 'vibration' maintenance procedure (which prohibited take-off type conditions). Additionally, the impact of solar radiation was assessed by measuring emissions at engine exit and 50 m during a night test.

To enable an assessment of the impact of ambient conditions on evolving emissions, the test aircraft was stored with sufficient volumes of the reference 'Jet A' fuel, used in the 'Summer' campaign, remaining in the onboard fuel tanks for use during the second 'Winter' test, so as the variables of fuel and engine (age & service interval) were isolated from the ambient conditions. As such nominally identical engine power conditions (in terms of emissions production), based on matched combustor inlet temperatures (T30) as tested during the Summer, were again tested at different aircraft axial locations (0 m, 5 m, 10 m, 15 m, 25 m, 50 m, 100 m, 150 m, 200 m, 250 m & 300 m). To assess the impact of fuel composition on regulated and in-plume evolving emissions the aircraft was de-fuelled and re-fuelled, at the test location, with a 30% HEFA/ Jet A blend of higher hydrogen and sulphur content, with repeat points performed at numerous test locations and engine powers.

3.4. Synthesis of results from WP2 and WP3

The WP2 test cell and engine exit measurements using the Baseline and Comprehensive systems showed sufficient repeatability and levels of accuracy within the expected levels of uncertainty for the particle mass, number and size instruments. Data corrections to the Baseline instruments across both systems were not deemed necessary because of the acceptable level of agreement (except for one particle mass measurement device in the winter on-wing test).

Intercomparison of the Comprehensive (regulatory engine exit) and Baseline (in-stack) measurement systems is fully and technically described in the WP2 Report. In summary, four emission curves against engine power, from low idle (<7% thrust) to beyond take-off (100%) thrust were performed in the test-cell with the same fuel on a modern Trent engine. Two curves with the oil breather isolated from downstream exhaust plume were also performed. Measurements were obtained close to engine exit, 50 m downstream in the stack and from the oil breather (when isolated).

The WP3 on-wing measurement campaigns were conducted during the Summer (July 2021) and Winter (Jan 2022). The WP3 on-wing data used the dilution factor derived from the CO_2 concentration measurement to establish the dilution of the exhaust plume with increasing distance downwind. However, the background correction clearly becomes more uncertain at further distances from the engine exit and a greater variance in data was observed at the further distances downwind.

The following observations can be made:

- nvPM data obtained at near engine exit compared to downstream stack data indicated that nvPM measurements obtained in-stack were similar, however it is noted that EEP nvPM is used to confirm the Dilution Factor so the measures are not mutually exclusive.
- nvPM, gaseous and smoke regulatory-style emissions measurements taken across the range of thrust levels (curves) were similar to engine certification data showing that representative data was obtained. Some variability in emissions was observed across the curves under different ambient conditions but the variance was not consistent. Up to mid-power the variance was up to ±12% for both mass and number, at higher engine powers the variance was lower (<±8%).
- As expected, at lower power conditions i.e. at ground idle with low engine loads or less than 7% thrust, the nvPM number emissions were about 30% higher than at 7% thrust. A negligible effect was observed on nvPM mass emissions.
- nvPM particle size and shape (morphology) changes were observed with engine power, as shown by differences between electrical mobility[11] and aerodynamic[12] particle size distributions.
- vPM was always present at the in-stack sampling location. tPM number was always much greater than nvPM particle number in the testbed stack (50 m downstream of the engine exit). Particle size data indicates variance in vPM formation, potentially due to ambient effects.
- The breather oil was characterised with direct particle and filter measurements, and the presence of the large (~150 nm electrical mobility in number space) oil aerosol was also detected in the stack. The oil breather aerosol mass emissions increased with engine power, but the size stayed approximately the same. When breather oil emissions mixed with the engine exhaust plume, the tPM number appeared to be influenced (reduced) when the oil was present.
- The effects of ambient conditions in the WP3 campaigns were investigated and the following observations were made: tPM/nvPM ratios observed in the plume were seen to increase with distance from the engine exit, up to 200 m. tPM/nvPM ratios in the plume were generally higher in the winter campaign.
- The impacts of fuel composition were investigated in WP3 by sampling with two different fuels (JetA1 and a 30% HEFA SAF blend) under similar ambient conditions. For nvPM emissions these are dominated by fuel H_2 content. The tPM emissions were dominated by fuel sulphur content. The SAF blend used in WP3 actually had a higher sulphur content than the Jet A used and higher tPM values with the SAF blend were observed with this fuel, as would be expected. Higher tPM ratios to nvPM were observed at higher engine power settings and a very large increase at low engine power settings at the highest air to fuel ratio.

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[11] Electrical mobility equivalent diameter, or simply mobility diameter, is the diameter of a spherical particle with the same mobility (defined as the particle velocity produced by a unit external force) as the particle in question.

[12] The aerodynamic diameter of a particle is defined as that of a sphere, whose density is 1 g cm $^{-3}$ (cf. density of water), which settles in still air at the same velocity as the particle in question. Aerodynamic diameters are larger than geometric diameters for particles finer than 100 µm.

3.5. Outcomes of WP2 and WP3

The outcomes of WP2 and WP3 can be summarised as follows:

1. The performance of the test cell Baseline system designed, manufactured and implemented in AVIATOR demonstrated that downstream stack measurements such as those implemented in AVIATOR may be possible for future nvPM regulatory measurements.
2. After suitable loss correction, the two sampling and measurement systems (Baseline and Comprehensive) were found to be comparable, allowing the data from Baseline system which was implemented in the WP3 on wing and plume measurements and the WP4 ambient measurements to be compared with the engine exit emissions (WP2).
3. A new particle loss method for nvPM and tPM was developed using measured particle size distribution (PSDs). This enabled comparison between different sampling locations and allows better prediction of real-world emissions.
4. The observed impact of the breather oil emissions on tPM when mixed with the engine exhaust plume warrants further analysis.
5. Effects of ambient conditions on engine emissions were observed and although the variance was not thoroughly consistent, the results can be used to compare with dedicated US Federal Aviation Administration funded (Honeywell) rig test data which was designed to investigate ambient effects on engine emissions in ICAO-CAEP WG3.
6. Ambient effects on plume: tPM/nvPM ratios were observed to increase up to 200 m in the plume with higher ratios generally in winter. The ratio increased with distance downwind as the plume cooled.
7. The fuel composition data on nvPM collected in WP3 was consistent with previous measurement campaigns and with the fuel H_2 content correction method in ICAO A16V2. Higher H_2 content (as found in most SAF blends) results in a decrease in nvPM emissions.
8. The fuel composition data showed a correlation between fuel sulphur content and tPM.
9. The temperature and measured emissions data at the engine exit plane and in the plume from the on-wing data were provided to the WP5 modelling team to improve the near-field parameterisation of their model.
10. The measured concentration and emission indices for total and nvPM number and nvPM mass along with the gas concentrations and dilutions ratios were provided to WP6 for the different engine powers at engine exit and downstream locations (50 m test-cell & 50, 100, 150 & 200 m On-wing). The measured concentrations and emission indices were used to improve the model parameterisation and for the dispersion model evaluation.

4. Summary of Ambient Measurements (WP4) for Regulation and Policy Context

4.1. Introduction

The ambient monitoring component of WP4 made comprehensive measurements of the particulate and gaseous pollutants at Madrid international airport, and a smaller subset of measurements at Copenhagen and Zurich airports. For Madrid, the goal was to sample from at least 10 nm to 25 µm, focusing on total PM (tPM), ultrafine particles (UFP) and providing speciated VOC and SVOC measurements, along with CO_2, CO, NO_X, O_3 and SO_2 gas phase measurements. These measurements were taken over a range of climatic conditions, with supporting meteorological data. The data from WP4 is instrumental in the high-level Aim 3 of AVIATOR, 'Bridging the gap between Aircraft Engine Certification and Local Air Quality (LAQ) Regulation'.

An important aspect of WP4 is to provide inter-comparison of ambient measurements with the Baseline system measurements used in WP2 (engine exit) and WP3 (on-wing). As part of WP4, intercomparison with measurements from the Baseline system was undertaken in each of the campaigns[13] to ensure compatibility between measurements and devices.

These WP4 high-fidelity measurement results have also been used to validate the performance of the Lower Cost Sensor (LCS) technology developed as part of WP4. A relatively low-cost sensor network was developed to provide information on the spatial distribution of air pollutants in and around the airport. The LSC nodes measure the following parameters: tPM as PM1, PM2.5 and PM10 mass concentrations; tPM number concentration and size distribution in the range 10 nm to 300 nm; CO_2 concentrations; O_3, NO, NO_2, CO and SO_2; and VOCs. Fifteen of the LCS nodes were developed, manufactured and deployed in the course of AVIATOR measurement campaigns. The LCS uses a Partector-2 to measure tPM number and size.

WP4 also provided a detailed investigation of speciated VOC and SVOC and PM specification profiles using offline samples that are likely to be important for understanding the possible health impact of aircraft emissions.

Additionally, and not originally planned[14], measurements were also made in WP4 using a Potential Aerosol Mass (PAM) oxidation flow reactor. The PAM is an ageing unit that can simulate several days of photochemical ageing under normal atmospheric condition in a few minutes. By producing ozone and exposing to UV inside the chamber, radicals are formed and react with the gases and particles in the chamber, oxidising them and changing their physical and chemical properties. An ozone monitor was used to measure the degree of ageing in the chamber and to relate it to the desired/prevailing atmospheric conditions. The PAM allowed AVIATOR to study the primary emissions and the potential ageing of those emissions and the impacts on the properties of the aerosol, allowing some information for beyond perimeter fence analysis.

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[13] During each of the WP4 deployments (Madrid, Copenhagen and Zurich airports), intercomparisons were performed. The most thorough of these was at Zurich when all instruments from WP4 and the Baseline system ran side by side for 1 week. For Copenhagen, the SMPS and CPC were intercompared. For Madrid, checks on the CPCs was performed at the start of WP4.1 and the different SMPS units were intercompared at the end of WP4.2.

[14] This was via a new collaboration after AVIATOR was funded, between UoM and Prof. A. Vogel and Goethe-University, Frankfurt. They were made partners in AVIATOR and provided additional measurements and further science to the project.

4.2. Summary of Ambient Measurement Systems (WP4)

A complex array of measurement devices from devices recording high-fidelity measurements to the lower cost sensors (LCS) were deployed in WP4. A full description of the measurement devices can be found in WP4 reports and are given in more detail in Box 4.1.

The main measurements taken as part of WP4 can be summarised as follows:

- **The Baseline system** as used in WP2/3
- **LCS nodes (15):** each including the Partector-2, the lower-cost particle counter**.**
- **WP4 Ambient Measurements:**
    - Particle number concentrations: 2 x CPCs with different size cut-offs, i.e. the D50 or the point at which the CPC has a 50% counting efficiency: 1 with a D50 of 2.5 nm; and the other at 7 nm. This allows a difference to be taken, indicating the concentrations of particle numbers below 7 nm.
    - Particle size distributions: 3 x SMPS all in the ultrafine range <100 nm down to around 5 nm, plus one SMPS in larger particle size range >250 nm.
    - Non-refractory aerosol using AMS: size distribution, mass and chemical composition of non-refractory aerosol including nitrate, sulphate and organics (excluding nvPM, sea salt and metals) down to approximately 60 nm.
    - nvPM mass
    - CO_2 concentrations
    - tPM mass concentration and speciation of PAH and metals (offline)
    - Gaseous VOCs concentration and speciation (offline)

WP4 Ambient Measurements

tPM particle number concentrations: 2 x CPCs (TSI models 3756 and 3750). The D_{50} of these CPC (the point at which the CPCs have a 50% counting efficiency) are 2.5 nm and 7 nm respectively.

1 x CPC (Model 3775 from TSI) a general-purpose particle counter that can detect airborne particles down to 4 nm in diameter.
tPM particle size distributions:2 x SMPS (TSI model 3082) fitted with 2 x TSI Differential Mobility Analysers, one (the Long DMA, model 3081) to capture particles in the range of about 10 nm to 300 nm and the other (the Nano DMA, model 3085) to capture particles in the range of about 2.5 nm to 60 nm.

The SMPS (TSI 3934 SMPS) measures the size distribution of aerosols in the size range from 5 nm to 1000 nm.

tPM particle number and size distribution: 1 x OPC (Grimm model 1.109) was used to measure the number-size distribution of particles in the size range of 0.25 µm to 25 µm.

Non-refractory Aerosol AMS i.e. components such as nitrate, sulphates and organics, but excludes sea-salt, metals and nvPM/black carbon. An Aerodyne, High Resolution Time-of-flight (HR-AMS) was used to measure the mass and chemical composition as a function of size of the sub-micron, non-refractory aerosol within the airport. The HR-AMS samples with 100% efficiency between ~ 60 nm to 600 nm, with rapidly decreasing efficiency outside this window.

nvPM mass (or black carbon mass) and composition: Thermo Multi-Angle Absorption Photometer MAAP (model 5012) and a Magee AE33 Aethalometer were used.

CO_2 concentrations: INTA LiCor LI-830

tPM mass concentration and speciation of PAHs and metals: Offline analysis of quartz filters

Gaseous VOCs and carbonyls concentration and speciation: Offline analysis of samples captured in TENAX tubes.

WP2/3/4 Baseline System

nvPM and tPM number concentrations in the range >4nm (2 x CPCs, compliant with specifications for ICAO A16V2, used with and without catalytic stripper to get tPM and nvPM number concentrations. tPM-nvPM= vPM)

tPM number concentration and size distribution up to 32 µm (1 x OPC)

tPM number concentration in range 10 nm to 300 nm (this is the 1 x **Partector-2** Lower-cost particle counter **as deployed in the LCS)**

tPM particle size and distribution as aerodynamic diameter (1 x ELPI®)

tPM particle size and distribution as electric mobility diameter (1 x SMPS)

CO_2 concentrations to determine dilution factors: 1 x NDIR LI-850

nvPM and tPM mass parameters were also measured (An Artium LII-300 used to measure nvPM mass concentration and tPM mass concentration via ELPI®+ and OPC particle size distribution integration measurements)

Box 4.1 Measurements and devices used in WP4

4.3. Madrid Airport WP4

4.3.1. Introduction

The main WP4 ambient measurement campaign was at Madrid Barajas Airport. The location of the WP4 measurement site was at the fire station in Madrid airport, which is located between the two runways, which both run parallel, north to south (36L and 36R). This is also the location of the permanent ambient measurement site (operated by AENA). The equipment summarised in 4.2 was deployed at Madrid Airport. A more detailed description of the devices used is given in Box 4.1 and a complete description in WP4 reports.

The two planned AVIATOR WP4 measurement campaigns at Madrid were run consecutively, the first (WP4.1) during October 2021 ('Autumn') and the second (WP4.2) from mid-November to mid-December 2021 ('Winter')[15]. These two periods had quite different meteorological conditions, satisfying the objective of sampling during different climatic conditions. The second period had distinctly wetter and colder conditions than the first period.

Over the two campaign periods, the average number of flights per day was relatively consistent between campaigns, but with more variation day-to-day in the second compared with the first.

The wind direction from the two campaigns is shown below in Figure 4.1. This shows the strongest winds for first campaign are from the Northeast (NE), which captures the aircraft taking off from runway 36R, but that there is a range of wind directions, allowing assessment aircraft vs airport to be performed. WP4.2 has a range of recorded wind directions with a similar frequency distribution to WP4.1, but there are higher wind speeds reported over these wind sectors.

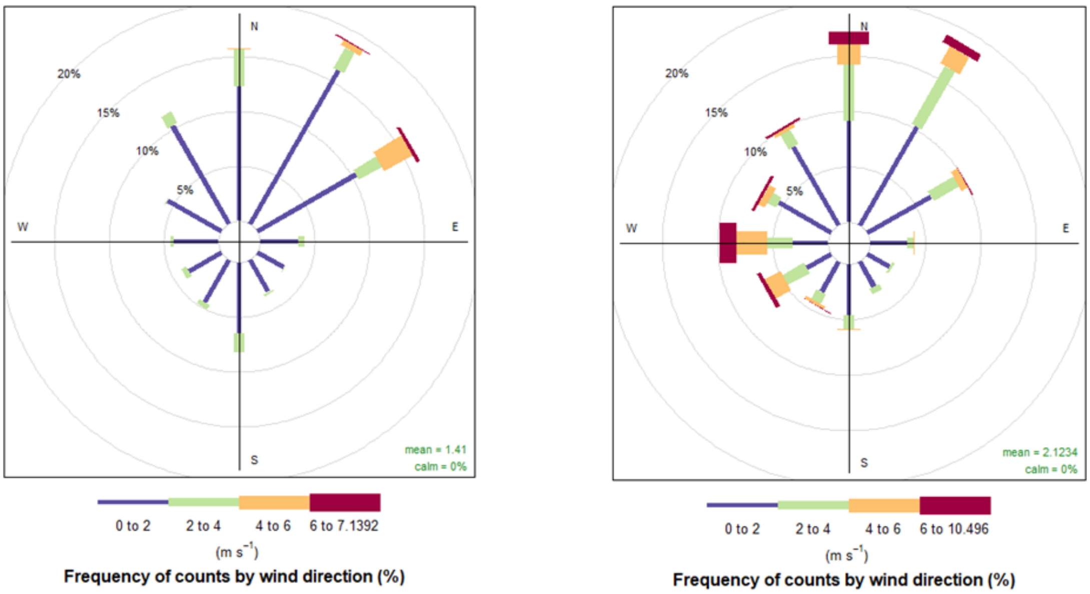

Figure 4.1. Wind rose diagrams for the WP4 campaigns at Madrid airport: WP4.1 on LHS and WP4.2 on RHS, showing wind speed as frequency of counts.

4.3.2.

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[15] Originally, the WP4 campaigns had planned to be distinct in different seasons but restrictions related to the pandemic meant that this was not possible. The official dates for WP4.1 are 8th Oct 2021 – 29th October 2021; for WP4.2 the dates are 19th November 2021 – 13th December 2021. However, a small subset of instruments was run continuously.

4.3.3. Results: Madrid Airport Main WP4 campaign

Baseline System

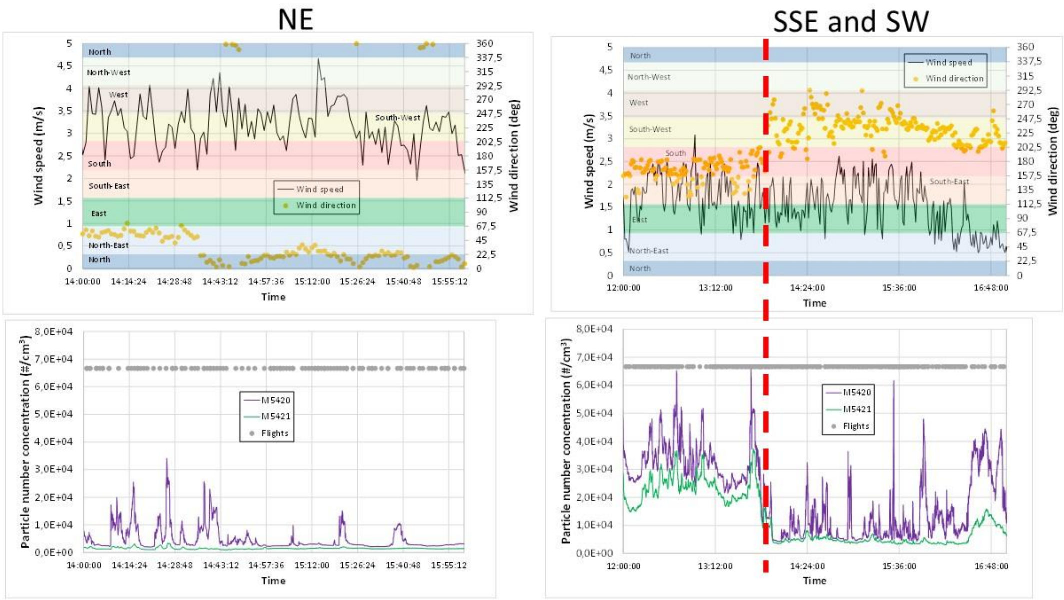

Figure 4.2. Baseline system CPC data WP4 campaigns at Madrid airport: showing the difference between the total particle number and the non-volatile fraction.

The data from the CPC (figure 4.2) shows the difference between the total particle number and the non-volatile fraction. Unlike the sampling in-stack, sampling in a mixed source environment as in WP4 makes quantifying the differences more challenging as the background is constantly changing. The analysis shows an example from three wind sectors, NE, SSE and SW. When the wind is coming more from the SSE (from 12-13:50 top right, figure 4.2), there is an increase in the baseline nvPM, and the tPM and nvPM time traces are more in sync. By contrast, when the wind is more to the SW sectors, the baseline is reduced and the tPM has more variability than the nvPM. This highlights that are difference sources of aerosol impacting the site.

The air from the NE sector is cleaner with the nvPM being lower than the air from the SW, probably due to the influence of Madrid and surrounding roads. In addition, the tPM does not follow the same trend, implying there is a large influence of nucleated particles (as condensed phase volatile will not change the total number of particles when evaporated through the catalytic stripper or CS).

Quantifying these differences is challenging because the baseline nvPM concentrations are varied. Doing a simple normalisation of the baseline (subtracting differences), shows that the tPM to nvPM ratio is higher when the wind is from the NE (predominately aircraft) compared with SW (Madrid and airport).

Particle number concentrations and size

AVIATOR WP4 used an analysis of the two different CPC results (with different size cut-offs) together with wind direction/speeds to indicate, for the first time, the direct impact of aircraft emissions on the very small end of the UFP range (sub 7 nm).

Figure 4.3 shows a wind rose plot of the total number the 3750 CPC. The radial markers are increasing windspeed, and the colours the number concentrations. The number is dominated by high concentrations from the Southerly sector, implying the impact road traffic from the surrounding roads and Madrid conurbation are dominating. However, by using the difference between the 3756 and 3750 CPCs, effectively presenting the 2.5 – 7nm size range, a different story is shown. The data shows that the plumes from the aircraft on runway 36R are detected at the measurement site during both campaigns. In both cases, there is a signal from the West, which may be from runway 36L, but there is an elevated level of UFP at higher windspeeds in WP4.2 from the South – West sector. This could be the influence of the idling aircraft from the terminal. This highlights the importance of meteorological conditions on the transport of these pollutants beyond the perimeter fence. It is worthy to note, that whilst the wind speed is affecting the detected particle concentration, the absolute values between the two sampling periods is very similar, implying the weather is having little effect on the absolute values. As this is a novel approach, the difference graphs are not presented as they are being prepared for journal publication.

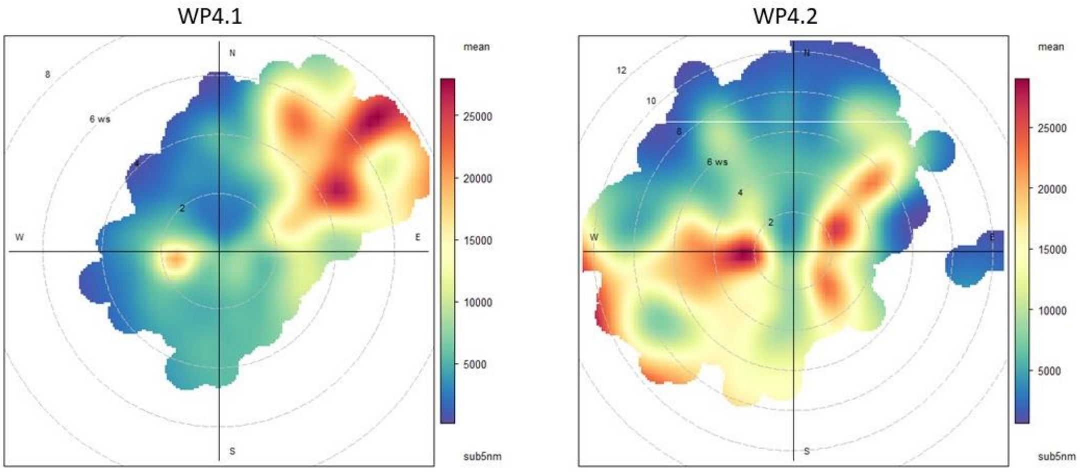

Figure 4.3. Wind roses of the 3750CPC particle concentration

Now looking at the particle concentration (upper) and size distribution measurements (lower) taken using the SMPS devices in Figure 4.4. The upper figure compares the SMPS data (triangles) with the particle concentrations captured with the two CPCs. The data shows that the SMPS is capturing some of the plumes seen by the fast particle counting devices (CPC with 1 s sample interval time).

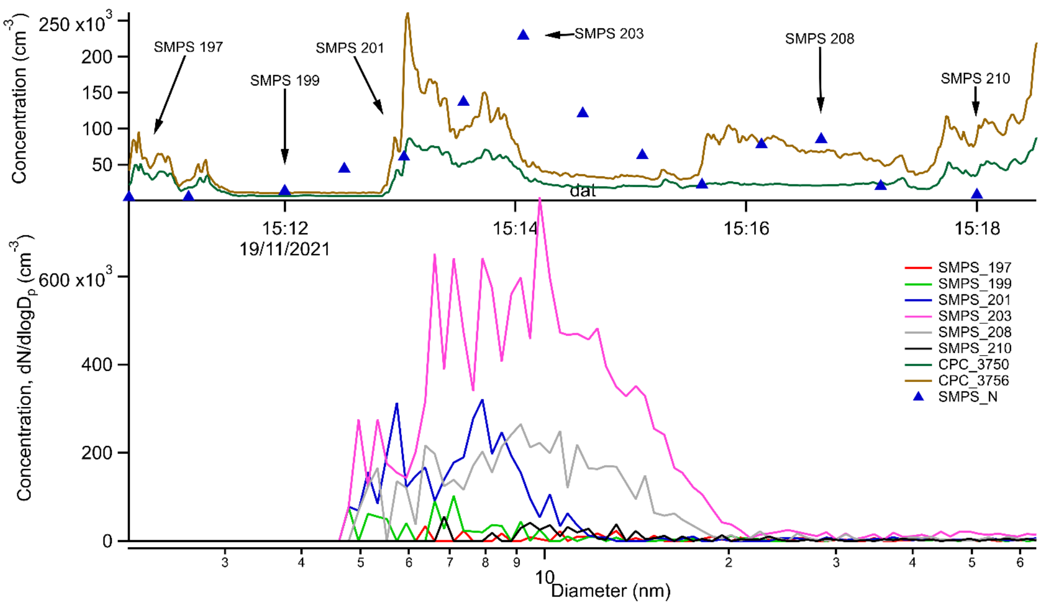

Figure 4.4. SMPS size distributions and SMPS & CPC total number

Although there is a delay between the instruments, the SMPS measurements shown in the lower plot of Figure 4.4 peak at sub-10 nm which is consistent with the wind rose data in Figure 4.3. However, the SMPS set to scan at its fastest (i.e. at 32 s intervals) misses some of the plumes seen by the CPCs (with 1 s intervals) and this finding reinforces the need to have fast measurements to correctly attribute the impact of aviation on UFPs, and to begin to assign distinct plumes to individual aircraft which are in this smallest range of UFP measured.

The SMPS measuring particles including the larger size range (up to 1000 nm) showed that under conditions of moderate wind speeds (> 3 m/s) the aerosol ambient concentration of particle sizes lower than 600 nm were generally very low, even during the hours with higher levels of flight activity. For most of time during both the campaigns, conditions were of almost calm wind (<1.5 m/s) and it was possible to detect fresh emissions on different occasions. The most significant was observed when air traffic was more significant, so despite the absence of a clear wind direction, the mode size of the aerosol < 50 nm indicates that the particles came from aircraft taking off in either of the runaways. On other occasions, an evolution of the aerosol was detected, towards larger sizes (up to 80-150 nm), throughout the day and part of the next day, when the frequency of flight decreases. This ambient aerosol ageing process that takes place at the airport area during very low wind speeds, is produced with hardly any interaction with outer air masses, that is, essentially it involves only the aerosols typically produced by the airport operations.

In contrast to the smaller particle counting devices, the data from the OPC which measures larger particles (in the range 250 nm/0.25 μm to 25,000 nm/25 μm) show little diurnal variation. The OPC data below 1 μm in WP4.1 and 4.2 are the same (consistent with the SMPS results) but above 1 μm to 10 μm the WP4.1 particle concentrations were higher than for the colder, wetter WP4.2 period. This particle size range is not indicative of aircraft sources which tend to be in the lower (<20 nm) range. This highlights the different impacts of weather on the different sources and transport of emissions. Further analysis of these data looking at the impact of local and long-range transport of different air-masses to the site to determine the differences observed between WP4.1 and WP4.2 will be published in the peer reviewed literature.

Particle Composition and Source apportionment

The non-refractory aerosol material measured using the AMS is mainly organic material rather than sulphate or nitrate.

The nvPM (black carbon) mass and composition measurements (using the MAAP and the Aethelometer) show that there was little difference in nvPM concentration between the two campaigns. The data collected with these instruments is currently being investigated and will look at the possible estimation of the contribution from biomass burning forming part of a UoM PhD thesis looking at source apportionment and Madrid airport. Analysis so far, on the effect of windspeed and direction on the main AMS components (sulphate, nitrate and organics) and the MAAP (nvPM/BC) data is provided in Figure 4.5.

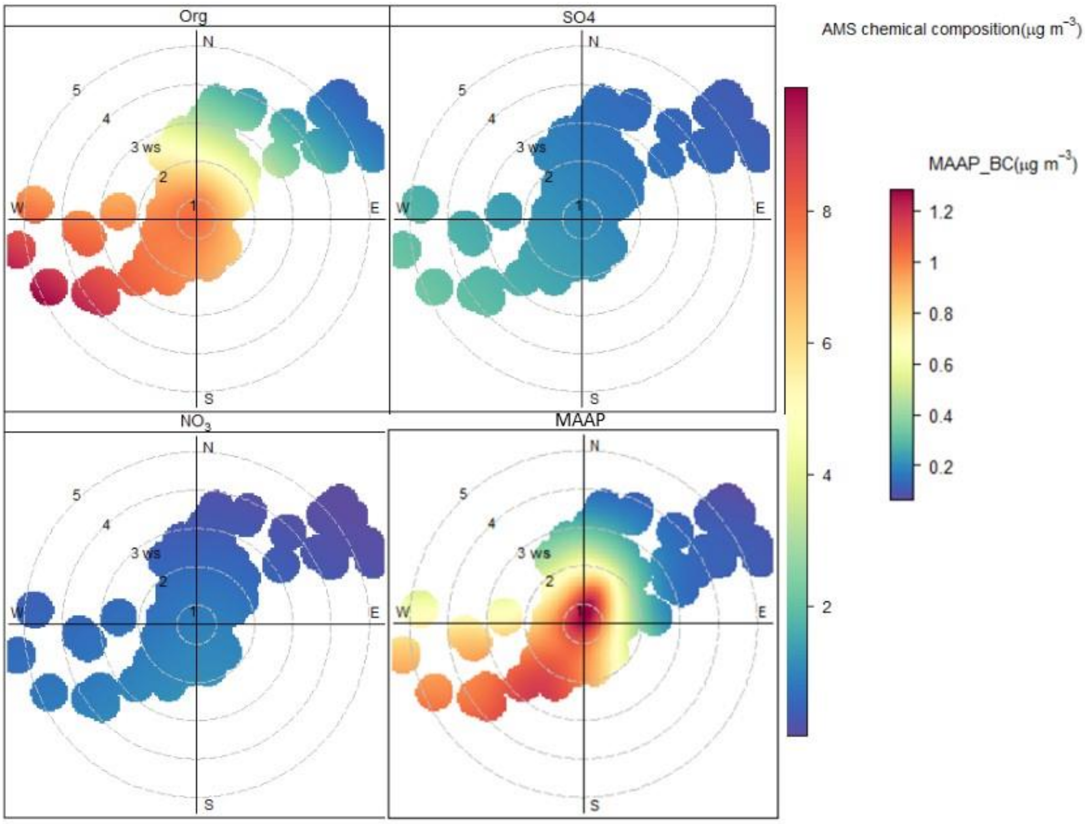

Figure 4.5. Compositional analysis of aerosol from AVIATOR. Organics, SO4 and NO3 are from the AMS, and the MAAP reporting BC/nvPM

This shows that the main sources of organics and BC/nvPM are from the SW Sector. There is little evidence of the influence of runway 36R on the concentrations, even with the relatively elevated wind speed. It is difficult to prescribe a noticeable mass from aircraft. The high concentration of BC/nvPM at low windspeeds at the measurement site is assumed to be caused by the fire station activity and the AVIATOR team's daily journeys to and from the site.

The organic fragments, as measured by the AMS, consist of a mix of aerosol and sources. They include fresh emissions, aged pollution from long range transport and the influence of aircraft, such as lubrication oils. A possible link between organics measured and the engine breather oil emissions was investigated. This involved a statistical technique (positive matrix factorisation) designed to identify markers and sources for the organic data. The method was applied to the data, but it was unable to find a link between the measured data and lubrication oil used in the engine breather system. A similar, but simpler approach looked at the ratio of two key markers in the AMS mass spectra as an indication of oil[16]. If the ratio of these markers were less than 1 means that there is little or no oil present. It was therefore difficult to apportion any significant organic (from oil or otherwise) or BC/nvPM mass from aircraft to overall levels at the sampling site.

[16] m/z 85 and 71. m/z 85 is associated with lubrication oils, whereas 71 is a fragment from a freshly emitted hydrocarbon. Ratios of 85 to 71 are calculated and a ratio below 1 means that there is little or no oil present.

PAM vs no PAM: Beyond the perimeter fence

The PAM was run at the Madrid site for WP4.1, and the sample was switched every 6 minutes between PAM – No PAM. The PAM works by generating OH and exposing the samples to this radical and UV light. This simulates the process of atmospheric ageing and yields the "potential" aerosol mass (PAM) post ageing. This ageing is of both the gas phase and aerosol phase. This effectively meant that the instruments downstream of this configuration (the AMS and the SMPS) sampled both the primary and secondary (aged) aerosol.

Analysis of the total organic from the AMS showed that the concentrations from the "No PAM" modes are higher than the PAM modes. The data showed that throughout the campaign, the oxidative state of the aerosol was higher with the PAM, compared with No PAM.

Two wind direction periods were considered in detail. South-west (SW) winds carry air from the Airport and the Madrid urban area. North-east (NE) winds carry air from the direction of the runway 36R. During a period when the wind was predominantly from the south-west, the mass-size distribution showed that the total organic loadings decreased, and the mean mode diameter of organic particles increased from 700 nm to 1040 nm with PAM. Another period with winds predominantly from the north-east, showed that organic loading was insufficient to produce a trace. Concentrations of sulphate either in mass or size were the same with PAM or no PAM for both wind direction cases.

Analysis of the SMPS data with and without PAM was also undertaken for these wind direction periods. The SMPS number and size distributions show that with PAM on both periods, there are new particles (under 20 nm) formed from nucleation mode aerosols. These nucleation mode particles are too small to be detected by the AMS.

During the south-west wind direction period higher levels of particles sub 100 nm are reported with and without PAM. The mean size of the primary aerosol (No PAM), is different between the different wind directions. From the SW, it is larger ~20 nm and from the NE ~ 14 nm. This finding agrees with other reported data, that the aircraft dominated mode (NE), is producing smaller particles. The larger SW mode is more indicative of vehicle emissions. In addition, the data is suggesting that the potential to form more new particles is higher from the SW than the NE. However, these data cannot explicitly separate out the gas phase components that are oxidising to form the particles and whether that is aircraft, airport and/or the surrounding road network and greater Madrid area.

Both wind sectors have the potential to produce new particles beyond the perimeter fence, which will impact on communities surrounding the airport. Whilst the overall mass from runway 36R is low compared with the mass of organics from the SW, the PAM data shows it is (probably) undergoing ageing. Further studies should look at these processes in more detail to determine the health impact.

Offline filter analysis

Mass distribution of PM by particle size: The concentration of PM_{10} was lower in winter (on average it was of 10.61 μg/m^3) than in autumn (20.40 μg/m^3), although the numerical distribution of UFP turned out to be similar. Probably, the resuspension of dust that occurs on the warmest and driest days increases the largest particulate matter, maintaining significant concentrations of UFP, probably related to airport operations. Also, autumn mass-size distributions showed larger coarse mode contributions.

PAH is higher in winter than autumn. PAH concentration in winter was 2.85 times higher than in autumn. It should be noted that the highest PAH concentrations in the finer particle fractions correspond to the compounds with the highest number of aromatic rings (>4).

VOC gas phase is higher in autumn than winter. The average value of the VOC concentration decreased approximately by a factor of 1.5, between autumn (8.4 µg/m^3) and winter (5.6 µg/m^3). In both periods, VOC concentrations at noon were usually higher than those in the afternoon and these were higher than those at night.

Benzene, Toluene, Ethylbenzene and Xylene (BTEX) are the dominate species of VOCs. During the autumn campaign the concentration of BTEX was observed to decrease from morning to night. However, in winter, such a clear pattern could not be observed, sometimes showing higher BTEX concentrations during the night.

The highest concentration of carbonyls was formaldehyde, followed by acetaldehyde and butanone. The mean concentration of measured total carbonyls was 40 µg/m^3 in autumn, compared with 30 µg/m^3 in winter. In the autumn, the carbonyls increased throughout the day, only decreasing at night, while in winter they increase only until evening and decrease at night.

Metals bound to the particles had the same pattern in autumn and winter. Most of the PM_{10} is probably of crustal origin, with a high concentration of aluminium, cadmium and iron. Molybdenum was also detected, probably related to emissions from rolling, braking aircraft or lubricants and wear on other aircraft components.

4.4. Copenhagen Airport WP4 campaign

4.4.1. Introduction

The WP4 Copenhagen airport (CPH) campaign was a 3-week campaign (1-23 June 2022) undertaken to sample ambient measurements at a climatically different airport taking advantage of the existing PM measurement devices located and operated at the airport. Copenhagen airport is situated in the East of Demark, close to the coast. In 2000 CPH got environmental approval to monitor the air quality (NO_x and $PM_{2.5}$) outside the fence of the airport. This resulted in the monitoring stations on the East and West side of the airport in addition to one on the airport B4.

At the airport site B4 and the West site, UFP are measured by CHP using a CPC model 3775. Black carbon mass and composition are also measured at both these sites using a Magee AE33 Aethalometer (as used in the AVIATOR campaign in Madrid). Larger particles up to 25 µm are measured using a Grimm OPC at the West and East sites.

Following this, and initiated by the report ‘Assessment of the air quality at the apron of Copenhagen Airport Kastrup in relation to the working environment’ from 2012, a new permanent monitoring station was established at stand B4 in 2012 to monitor NO_x and UFP, one of the longest running airport based UFP monitoring stations in the world. After the assessment “Airport emission particles: Exposure characterization and toxicity following intratracheal instillation in mice” from 2019, the focus has broadened to Black Carbon, which have been at station West and B4 since October 2021.There is now a total of 4 monitoring stations available around the airport, the fourth being the fire station. The location of the sites is shown in Figure 4.6.

Figure 4.6. Location of West, East, B4 and fire station at CPH

AVIATOR placed 3 x LCS at the existing CPH monitoring locations (East, West and B4) and a 4th LCS at the fire station. Although the LCS at the East site failed.

In addition to the AVIATOR 4 x LCS, the AVIATOR WP4 particle number counters (CPC 3756) were located at the West and East sites and the particle size distribution (SMPS long) at the West site.

The meteorological conditions for CPH during the period 1-23 June 2022 can be summarised as follows: The temperature ranged from about 7 to 24 C. Winds were predominantly from the west. This means that the station West will capture the inflow into the airport, the East station some of the flight activity and out flow, B4 the activity on the apron and the fire station the impacts of departing aircraft.

4.4.2. Results from Copenhagen, CPH

Particle number and size measurements:

Comparison of particle number concentration measurements at the West site between the SMPS (long) and the CPC showed good agreement as did the co-located LCS number measurements.

The airport is the major source of the UFP concentrations measured at each location. Figure 4.7 shows a wind rose of the total number concentration reported at West, East, B4 and the fire station locations, using the SMPS, 3756 CPC, and two of the LCS respectively.

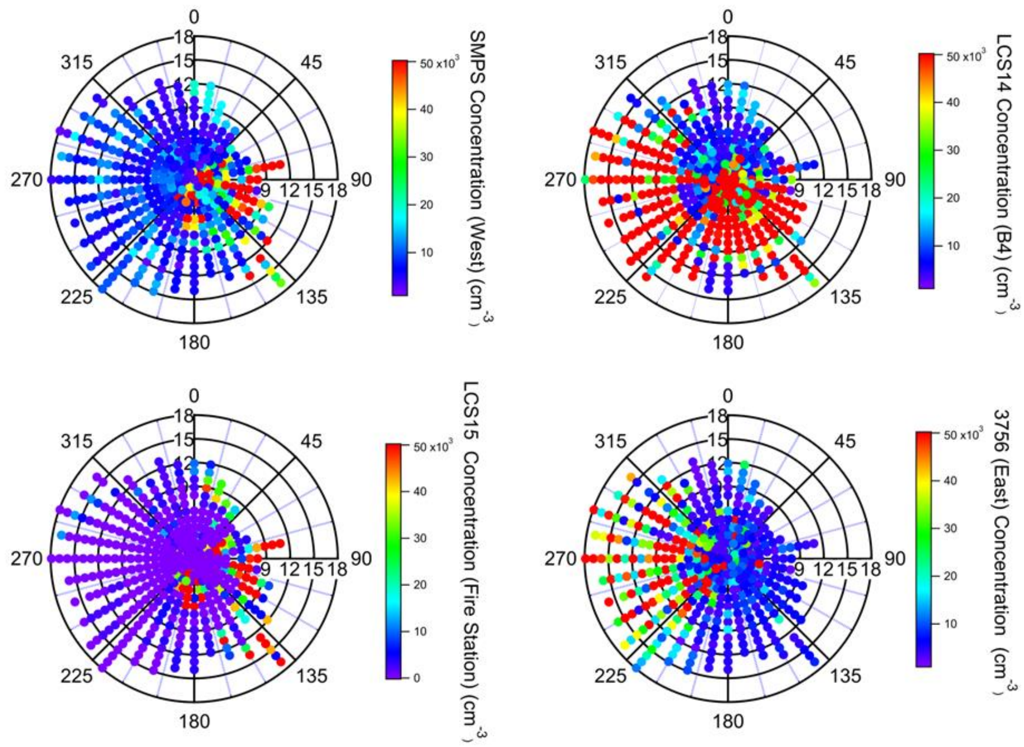

Figure 4.7. Wind rose of the 4 monitoring stations at CPH. Note the colour scale is the same for each plot

The wind rose plot (Figure 4.7) shows that there are elevated particle concentrations when the wind is transporting pollutants from the airport/aircraft to the monitoring site. The inflow from the coast (East), the city to the West and North (West and B4) and areas to the S-W of the airport is relatively low. B4 experiences high counts from all directions (except North) being sited on the airport apron.

These data, along with the meteorological data, will be used in journal publications to calculate the contribution of UFP from the airport to the regional transport across Denmark.

4.5. Zurich Airport WP4

4.5.1. Introduction

The WP4 Zurich airport (ZRH) campaign was a 5-week campaign (1 July to the 3 August 2022) undertaken to sample ambient measurements at a third (and climatically) different airport taking advantage of the existing PM measurement devices located and operated at the airport.

Zurich airport is approximately 10km north of the Zurich city centre and is the main airport in Switzerland. It consists of 3 main runways, and it is at an elevation of 432 m. Along with standard gaseous measurements, Zurich has been monitoring UFP since 2012 and has had several dedicated campaigns, including campaigns to distinguish vPM from nvPM. Zurich can deploy monitoring equipment at multiple sampling locations around the airport.

The WP4 campaign at ZRH was separated into two main work packages: Intercomparison (1-7 July) and dedicated sampling (1 July to 3 August). In addition to the equipment already running at the airport, the AVIATOR baseline system and several SMPS and CPCs were deployed, along with 4 x LCS.

The meteorological data shows that the temperature and humidity varied significantly during this period (10 – 35 C; 20 – 100% RH), with wind from the NW – NE dominating.

4.5.2. Results from Zurich, ZRH

Intercomparison

Data collected with the SMPS long (total number >10 nm) is compared with the data from the LCS (in this instance LCS06). The time series of 10-minute averages from the devices show fairly good agreement. However, there are some clear outliers where the SMPS is noticeably higher. One explanation for this may be the size, or peak, in the particle size distribution as the period of underestimation by the LCS is a period where the SMPS measures a higher concentration in the smaller mode, and it may be that the LCS (Partector-2) is possibly missing part of the smaller mode i.e. in the range of 10 nm.

One of the aims of WP4 was to develop a proof of concept low-cost and low-intervention sensor network to provide routine data on temporal and spatial variability of key pollutants including UFP, total PM, NO/NO_2, CO and CO_2. A dedicated report to the performance of the LCS and comparison with the high-fidelity air quality monitoring devices can be found in WP4 deliverable report (D4.4 Appendix I). As part of Work Package 4, field measurements were done at Zurich airport in July 2022 (1^{st}-5^{th}), at the monitoring station on the roof of passenger Pier A with a device comparison study including 4 LCS devices and several reference devices from Zurich airport. While the duration of the measurement campaign was limited to just a few days, valuable insights could be gained in the functionality of the LCS devices, also in terms of their handling and operation. The devices are simpler to operate than the reference devices, and it is also noted that set-up, installation and taking data whilst in operation are relatively easy.

The observed sensor accuracy and reliability is likely not yet at the level anticipated prior to the development of the device. Sensor devices or individual sensor heads show significant outliers. These outliers differ among pollutants, sensors and sensor heads, although not giving a clear pattern. The two main challenges in the results were: (1) the sometimes very high variability of results from the individual sensor heads within the same device; and (2) the logging of negative concentration values. However, in summary, all 4 x LCS devices tested provided acceptable agreement with high-fidelity UFP measurements; and 3 of the 4 LCS provided acceptable agreement with high-fidelity CO_2 measurements.

Baseline system

Figure 4.8 show the results from the Baseline system. This shows the volatile fraction is larger than the nvPM fraction (vPM being derived from the tPM – nvPM). It also shows the difference between the active flight times during the day and night, when the UFP dominate during the day. This is consistent with Madrid and Copenhagen results.

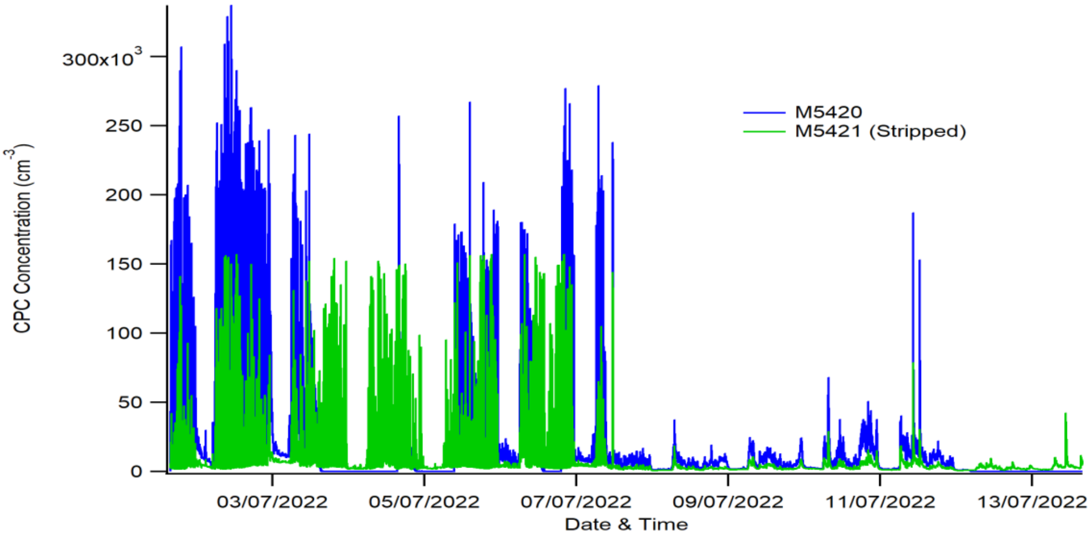

Figure 4.8. Baseline system results for Zurich Airport

Particle number and size distribution

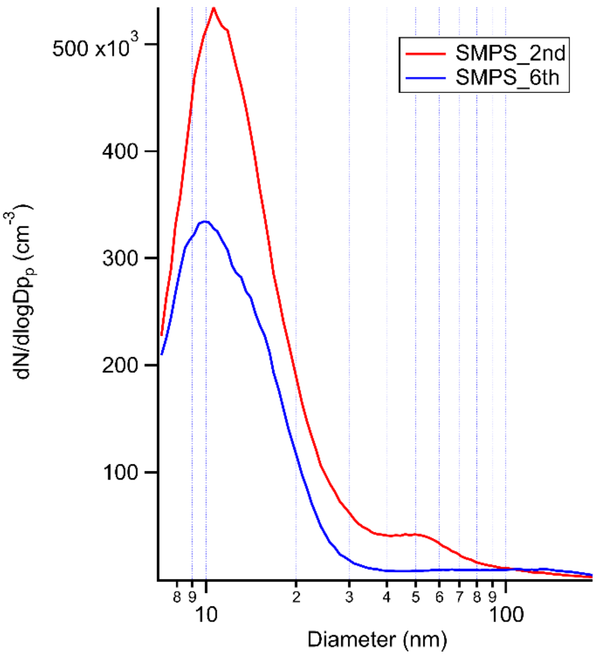

Figure 4.9. Size distributions from the SMPS from the 2nd and 6th of July 2022

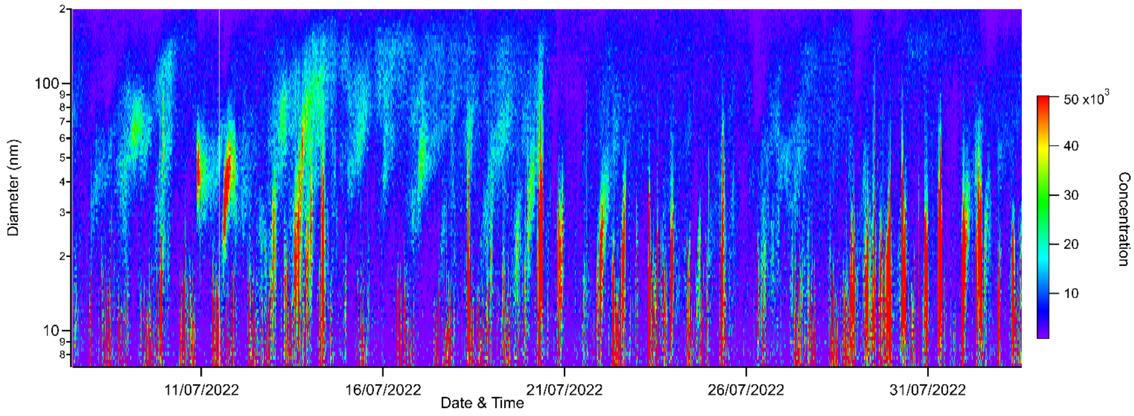

Figure 4.10. Image plot of the SMPS data from the Meteogarden, ZRH

Figure 4.9 shows that the number concentration is dominated by UFP less than 20 nm in size as is expected from aircraft, and these high concentrations of the UFP can be seen occurring throughout the sampling period in the image plot (figure 4.10). However, there are other modes visible in the plot, namely 20 – 50 nm and 50 – 100 nm. A time series of the sub 15 nm, 20 – 50 nm and 50 – 100 nm particles is shown in figure 4.11, upper. In addition, data from daytime (~7am – 8pm), was averaged over 10-degree wind directions and plotted in polar form (figure 4.11, lower). This time represented the main flight activity period of the airport, and so the polar plots are purely when flights are active, and not night-time data.

The time series shows that the sub 15 nm has the largest number concentration between the 3 modes and is mostly seen during the day. At night, the mode often drops close to zero, with no obvious baseline/background concentration. The 20 – 50 nm and 50 – 100 nm modes both always have measurable concentrations above zero, implying sources outside of the airport influence this station as they are present at night.

The average, daytime number concentration as a function of wind direction shows that for the sub 15 nm, the highest concentrations are from the North and South, when the site is directly impacted by the runways. Conversely, wind from the West yield very low UFP concentrations. For the 20 – 50 nm, there is clearly an increased source of these particles when the wind is from the Southern sector. The large mode, 50 – 100 nm, is showing similar concentrations from all wind directions, implying a more region source being transported to the airport.

Using the size segregated data, and the data from the LCS, it should be possible to calculate the contribution of the UFP from the airport to the local background, the same as with the CPH data. This will form the basis of future publications.

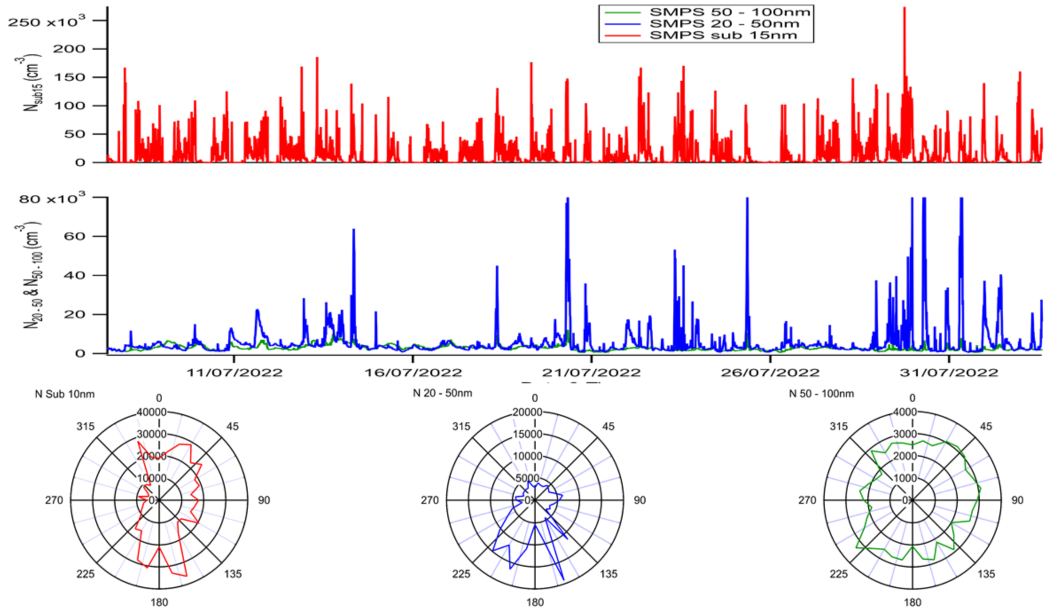

Figure 4.11. Timeseries of the number concentration in 3 different size modes (sub 15 nm, 20 – 50 nm, and 50 – 100 nm), the average number concentration of the three modes as a function of wind direction (for daytime hours only)

4.6. Outcomes of WP4

- Generally, very little difference was observed in the dynamics in autumn vs winter and the distribution of particle and gas species measured.
- The particle number concentrations signal from aircraft engines is dominated by the sub 20 nm particles.
- Combining meteorological data with SMPS data in different size ranges provides a means for a simple form of source apportionment. The particle number data together with wind direction and specific aircraft activity data was used to identify an aircraft emission signal in the lower part of the sub 10 nm range.
- Very transient peaks in the sub 20 nm were seen in the SMPS size distribution data and illustrated the need fast response instruments to observe these.
- The tPM mass and size information was used to try and detect the engine lubrication oil signal in the ambient measurements, but no signal was observed. Whereas the engine lubrication oil signal was observed in the on-wing (WP3) data, maybe owing to the 'over-board' oil breather systems used on Roll Royce Trent engines.
- The nvPM mass measurements could not distinguish airport and road traffic sources from aircraft.
- The influence of aircraft on the total particle number concentration is to enhance the concentration above the background/baseline. In the mixed source environment, it is hard to quantify the enhancement factor without careful consideration of the background.
- The particle number concentration data collected at Zurich and Copenhagen airports also show peaks in the very small range of UFP i.e., sub 20 nm range which appear to be indicative of aircraft engine emissions. The measurement data will be further investigated, and further source apportionment work will be undertaken and written up in a peer review journal article.

- Baseline CPC measurements shows there is a large volatile/nucleating fraction, and that there is less correlation between nvPM and tPM when the wind is from the cleaner wind direction sector. In addition, quantification of the difference requires careful consideration of the background/baseline nvPM concentrations.
- The offline analysis on chemical composition showed the following:
  - PM_{10} mass concentrations dominated by the larger particles were higher in autumn than the wetter winter period.
  - PAH and gaseous VOCs (dominated by BTEX) concentrations were observed to be higher in winter than autumn.
  - Metals bound to the particles had the same pattern in autumn and winter. Most of the PM_{10} is probably of crustal origin i.e., dust, with a high concentration of Al, Ca and Fe. Molybdenum was also detected, probably related to emissions from rolling, braking aircraft or lubricants and wear on other aircraft components.
- Point measurements within the airport are important to assess the impact of local sources and emissions, and exposure to workers/airport users. However, point measurements of UFP provided information only at that point. Multiple locations around the airport perimeter using for example lower cost sensors are needed to provide a means for calculating the net flux or burden of UFPs into and out of the airport.
- The AVIATOR Lower Cost Sensors provided acceptable agreement with high-fidelity UFP measurements and generally acceptable agreement with high-fidelity CO_2 measurements. Other gaseous measurements were below the level expected. Understanding the limitations of the lower cost sensors is key to explaining the observations. Critically, emissions at the lower end of the UFP scale < 10 nm, which appear to be indicative of aircraft engine vPM emissions, are not currently picked up by the LCS, leading to an under reporting of the tPM from the LCS.

5. Summary of WP5 and WP6 for Regulation and Policy Context

5.1. Introduction

The aim of these work packages is to improve the modelling of plume microphysics, chemistry, and dynamics (WP5), as well as pollutant modelling and transport in and around airports (WP6).

WP5 aims to improve the aircraft engine plume characterisation and to use the in-stack, on-wing and plume measurements taken in WP2 and WP3 to validate the plume dynamics models, including parameterizations of relevant UFP transformation processes and comparison between model results and measurements and parameterizations of physical exhaust dynamics and comparison between model results and measurements.

WP6 aims to improve the local air quality dispersion and regulatory modelling around the airport. Modelling the dispersion of aircraft engine exhaust plumes and airport emissions provides the basis for a local air quality assessment with spatially and temporally resolved concentration distributions over longer periods of time. This is an essential complement to measurements which are restricted to relatively few locations, and which do not allow the assessment of future trends. The dispersion modelling in WP6 aims to implement the WP5 plume dynamics parameterisation improvements. WP4 ambient measurements are used in the comparison of WP6 dispersion modelling with measured data.

5.2. Summary of WP5 and WP6

5.2.1. UFP characteristics from existing literature

A literature survey[17] was conducted in Phase 1 of WP5 to summarise UFP microphysical and chemical transformation processes. This was undertaken to establish the range of possible background parameter values that are required for comprehensive modelling and therefore, providing realistic dispersion results for key pollutants.

In terms of origin, the review identified two compounds that are strongly involved in the formation of atmospheric new particles: the first is sulphuric acid (example source transport emissions); and the second is ammonia (to stabilise molecular clusters formed by sulphuric acid).

The review considered aircraft-related particle measurements conducted in several studies, that provided several key findings on subjects including size distribution description, relationship between geometric mean diameter with engine thrust, formation of volatile aerosols, load dependency of secondary PM composition and how fuel sulphur content and engine thrust influence the growth factor and hygroscopic parameter. Studies conducted at different airports highlighted the significance of aircraft as a source of submicron particles, but gaps remained in the emission and dispersion characteristics. Dispersion modelling that considered both aircraft and other airport/neighbouring sources were reviewed as well, since they could have a major impact on LAQ in and around airports. The modelling of thrust-dependent emissions and exhaust dynamics of several thousands of aircraft movements of different types with various space- and time-dependent pathways is challenging, and the current guidance of modelling these is provided in ICAO Doc 9889 (Airport Air Quality Manual)[18]. However, at present, there is no ‘gold standard’ by which such complex modelling system could be evaluated. As for UFP, there is a lack of standardised, engine-specific emissions despite recent major progress on

[17] See D5.1

[18] https://www.icao.int/publications/Documents/9889_cons_en.pdf

nvPM. Emission modelling of vPM and their further transformation during transport necessitates further research.

The literature survey also focused on field campaigns in Madrid, as this is the main study area for the modelling activities in WP5/6. Previous studies found that New Particle Formation (NPF) events could extend over the full vertical extension of the mixed layer, sometimes as high as 3 km, resulting in UFPs being detected quasi-homogeneously in area spanning at least 17 km horizontally. NPF also contributed to urban UFP concentrations during photochemical pollution episodes in spring and summer (possible inter-relationships between ozone and UFP), with the most favourable ambient conditions to be high insolation, low relative humidity, available SO_2 and VOCs, and low condensation sink potential.

5.2.2. UFP transformation processes

In the second phase of WP5, parametric relationships between black carbon (BC)[19] and sulphate aerosols (SO_4) particle concentrations in engine plumes and background air at airports were derived using data from the AVIATOR WP2 and WP3 measurement campaigns. These model parameterisations enabled advection of aircraft aerosol and their microphysical transformations to be estimated during typical transport times of minutes to several hours, and a spatial scale from 50 m up to a few kilometers[20]. A series of sensitivity studies were conducted with MADE3 (Modal Aerosol Dynamics model for Europe, adapted for global applications, 3rd generation) (Figure 5.1). This box model was used to investigate the microphysical and chemical evolution of particle number concentration, size distribution and composition in the ageing plume. Different engine load conditions, background pollutant levels and meteorological conditions (relative humidity, temperature, and pressure) were investigated, and the results were compared with measurements from literature.

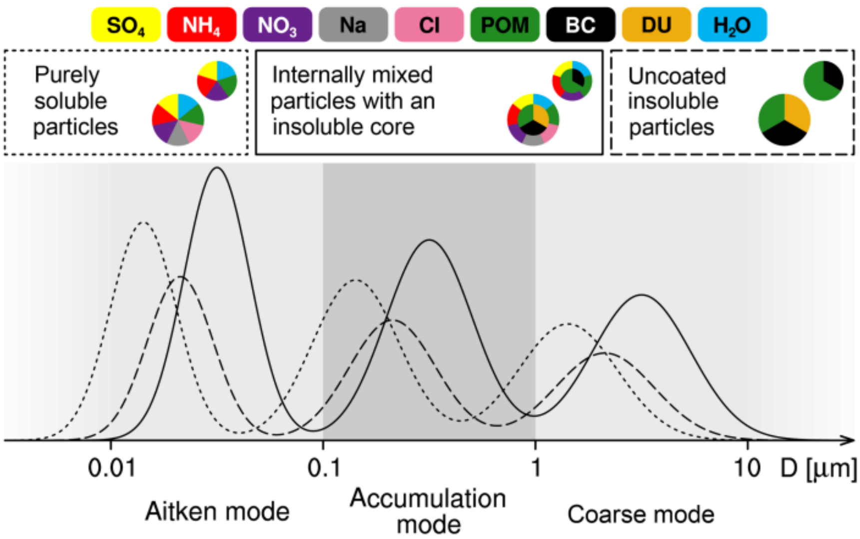

Figure 5.1. Timeseries of the number concentration in 3 different size modes (sub 15 nm, 20 – 50nm, and 50 – 100 nm), the average number concentration of the three modes as a function of wind direction (for daytime hours only)

This modelling study showed that for a typical background condition in Madrid urban area during winter:

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[19] BC is the term used by modellers and is generally interchangeable with the nvPM terms often used by measurement experts. nvPM emissions from aircraft engines are predominantly composed of BC.

[20] See D5.2

- For typical concentrations in an aircraft engine plume, the size of the resulting processed aerosol mode (Aitken and accumulation) depends on the initial BC concentration (Figure 5.2).
- In the aircraft plume, smaller SO_4 Aitken particles coagulate with BC and background particles, resulting in an increase of particle diameter as well as a decrease in number and mass concentration. This represented a combined effect of mixing with background aerosol and aerosol dynamics.

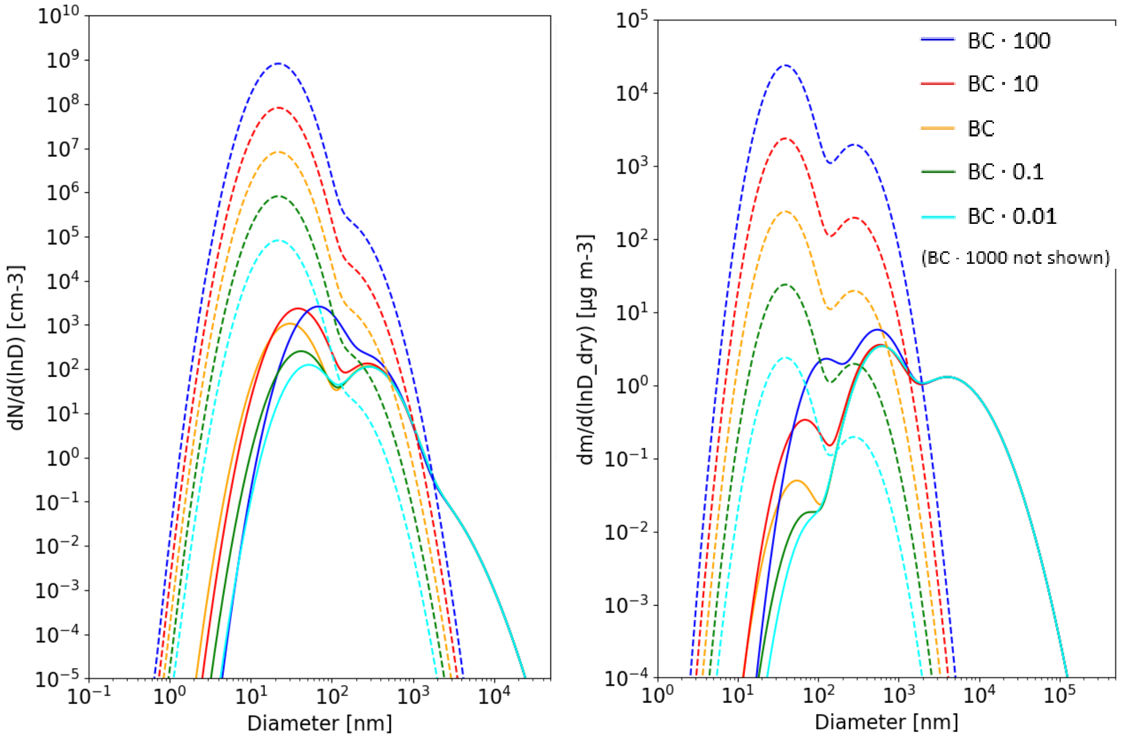


Figure 5.2. Number (left) and mass (right) size distributions for 5 different initial BC concentrations (dashed lines). Solid lines represent the respective distributions after 10 minutes of processing during mixing with background air

Results comparison between MADE3 and measured data show that it can simulate aerosol microphysical processes to represent realistic particle distributions under airport conditions. Depending on prevailing wind velocities at the airport, the modelled timespans represent distances within the airport area up to the airport fence (up to 10 minutes) and to the airport vicinity and neighbouring communities (several minutes to hours). After 10 minutes, the number and mass concentration of the Aitken mode were reduced by several orders of magnitude. Aircraft emissions (soluble, insoluble, and mixed mode particles) in the Aitken mode that were emitted into the background atmosphere are subject to loss processes comprising coagulation, resulting in an increased particle size and reduced particle number and mass concentration.

5.2.3. Parameterisations of physical exhaust dynamics

The chemistry, microphysics and dynamics of the engine exhaust plume were investigated with a CFD model, CEDRE and an airport-level air quality model, LASPORT[21]. This provided an enhanced understanding of processes to describe the impact of aircraft exhaust emissions on air quality in and around airports.

[21] See AVIATOR Deliverable D5.3

A single aircraft engine's plume dynamics was modelled using CEDRE and this was based on two configurations: a single engine with the plane at rest, using 4 different thrusts, and a full aircraft architecture during LTO phases.

The single engine simulations used boundary conditions determined by analytical models and literature. The results showed that:

- Mesh optimisation was not necessary after 3 steps for all thrust settings.
- Ratio of specific thrusts (φ) was set to 1.5 so that the total temperature for engine core corresponds to a value close to the one calculated for a similar engine in literature.
- The dilution evolution can be described in 3 steps. First, the dilution remained quasi constant for a short time corresponding to the direct engine exit. For higher thrusts, the exit velocity gets higher as the shear stress with ambient flow and the duration during which the dilution is constant is shorter as the thrust increases. Then, a fast increase of dilution is observed in all cases. Finally, a last zone is observed where the dilution increases as a power of the physical core time. The global dilution is higher as the thrust increases.
- For high thrust, the temperature and velocity at the core nozzle were higher, resulting in stronger mixing, higher plume height and shorter length.
- Exhaust species (NO_2, SO_2 and H_2SO_4) were transported further from the engine when the thrust was lower. As thrust increases, the species tend to be transported to greater heights. Their concentration fields were equivalent for all thrusts despite the difference in mass flow. H_2SO_4 was produced in the core nozzle, then transported whilst remaining constant 10 m behind the engine. Small amount of SO_3 and SO_2 were produced in the first part of the nozzle (< 3 cm) but shortly after, SO_3 was transformed to produce H_2SO_4. Temperature decreased 1 m from the engine exit, with a greater drop observed for higher thrusts. NO_3 was transformed in the nozzle to produce NO_2, HNO_2 and HNO_3. At the core exit (1 m), the NO_3 transformation was limited due to the temperature decrease. Beyond 10 m, there was a decrease of all species due to diffusion and dispersion through the mixing with ambient air.
- At idle thrust setting, ambient temperature that corresponded to summer and winter conditions were found to influence the relative humidity. Temperature remained approximately constant 7 m behind the engine but quickly dropped off beyond this. The ambient temperature impacts the core temperature, resulting in increased exhaust temperature. The dilution and radial profiles were identical for the different ambient temperature settings. Under all temperatures simulated, there was a slight impact on the velocity. The change in ambient temperature had no impact on the relative velocity and temperature profiles. The molar fractions of the exhaust species were higher for distances less than 1 m, due to a greater production as the temperature increases. The impact of ambient temperature becomes negligible beyond 10 m. It can therefore be concluded that ambient temperature showed no significant impacts on the dilution behind the engine and on the plume spread.

A comparison was made between CEDRE's and WP2's engine exit measurements despite some differences in their assumptions and setup.

- CO_2 concentration was used to compare the Dilution Factor (DF) from both modelled and measured values. In general, good trends were observed between model and experimental data, 50 m behind the engine. There was good agreement for 7% thrust for all distance. For higher thrusts, CEDRE overestimated the DF for distances greater than 50 m. Pollutant species were transported to greater distances at higher thrust in the measurement, while it was the opposite for CEDRE.
- In general, the modelled velocities were in the same order of magnitude as the measurements for distances greater than 50 m. At 25 m, CEDRE computed higher velocities for 30% and 80% thrust than the measured data.

A more realistic configuration was used to investigate plume physics behind a plane during LTO phases. The results showed that:

- The interaction between the wing and the upwind flow was more complex than the single engine configuration due to the production of a wake vortex sheet that can interact with the exhaust flow. Therefore, mesh optimisation was necessary since the simulation costs and quality of mesh refinement had to be accounted for.
- The circulation calculated with CEDRE was lower for the landing configuration and higher for the climbing configuration.
- The dilution was higher as the thrust increases, due to the strong mixing. For a constant thrust, and for the landing and climbing configurations, the dilution followed the same trend as the single engine configuration, at their equivalent thrust setting.

LASPORT 2.3 results had previously been compared with DOAS measurements of NO at Düsseldorf Airport and approach measurements of total particulate number at Zurich Airport. However, model parameters for exhaust dynamics simulation in these comparisons had constraints and limitations. In AVIATOR, an enhanced parameterisation for LASPORT was developed and a revised comparison with the new parameterisation (LASPORT 2.4) was conducted, in addition to comparison to nvPM measurements at Ciudad Real Airport (WP3 on-wing) and WP4 (ambient). The comparisons showed that:

- LASPORT 2.4 (like LASPORT 2.3) could reproduce the time course of the DOAS NO concentration reasonably well. Sometimes the concentrations were underestimated, likely because the DOAS measurement was influenced by other sources not accounted for in the modelling (Figure 5.3).
- It was not possible to reproduce the high first peak at Zurich Airport after overflight of two aircraft by standard modelling, but the subsequent other two peaks could be reproduced qualitatively with LASPORT 2.4 (Figure 5.4).
- LASPORT could only adequately resolve dynamics at 50 m beyond the engine exit.
- The higher exit velocities of LASPORT 2.4 produced better agreement for CO_2, nvPM mass and number concentrations (Figure 5.5) than LASPORT 2.3 at Ciudad Real Airport for cases with similar wind directions or lower wind speeds, between distances 50 to 250 m, for all thrust settings. It was not possible to reproduce the results for cases with strong cross wind, where more detailed local meteorological data would be required in the modelling.

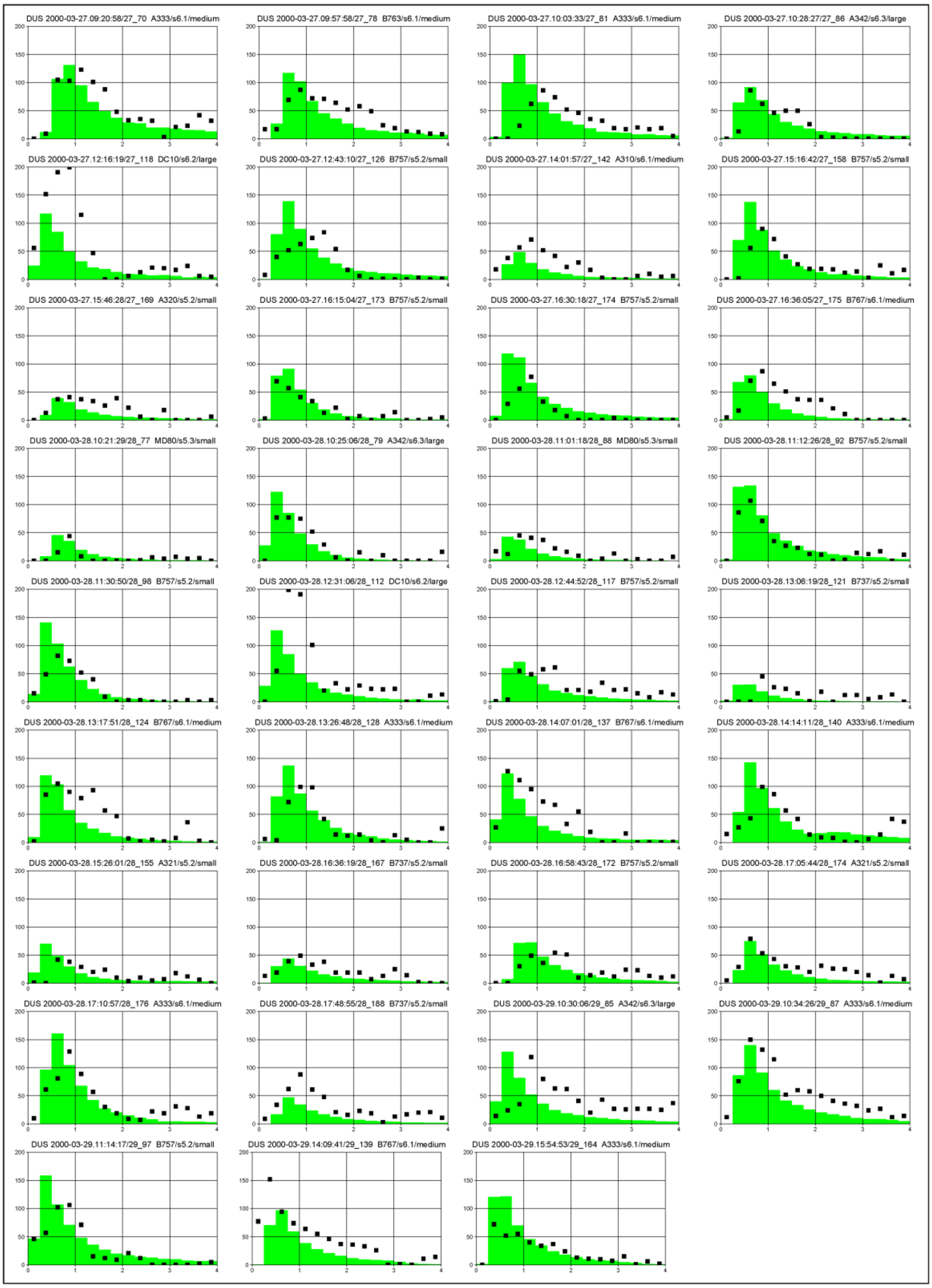


Figure 5.3. LASPORT 2.4: Time series of measured (black) and modelled (green) concentrations for all evaluated take-off events

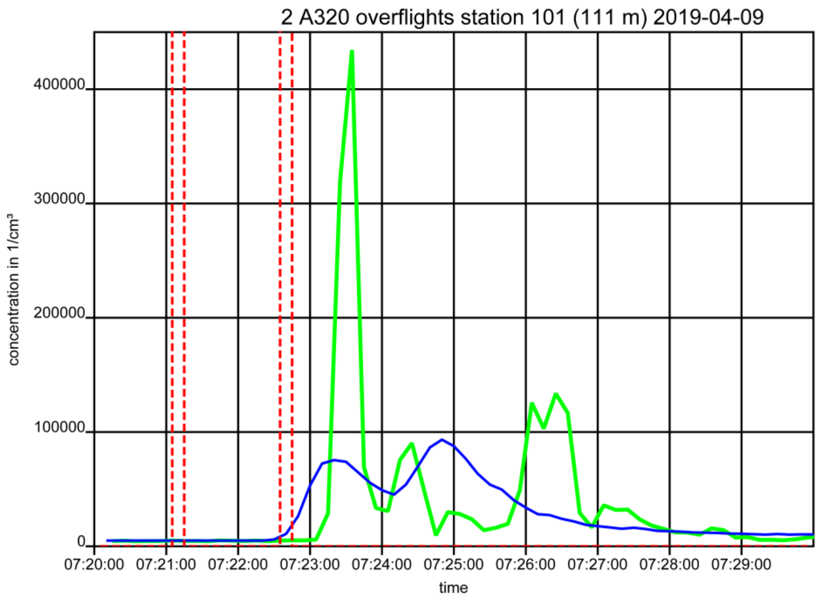


Figure 5.4. LASPORT 2.4: Measured and modelled concentrations (total particle number) at monitor station 101 at Zurich Airport. Green: measured. Blue: LASPORT 2.4 with dynamical downshift. Red: Indication of the two overflights over monitor station 101

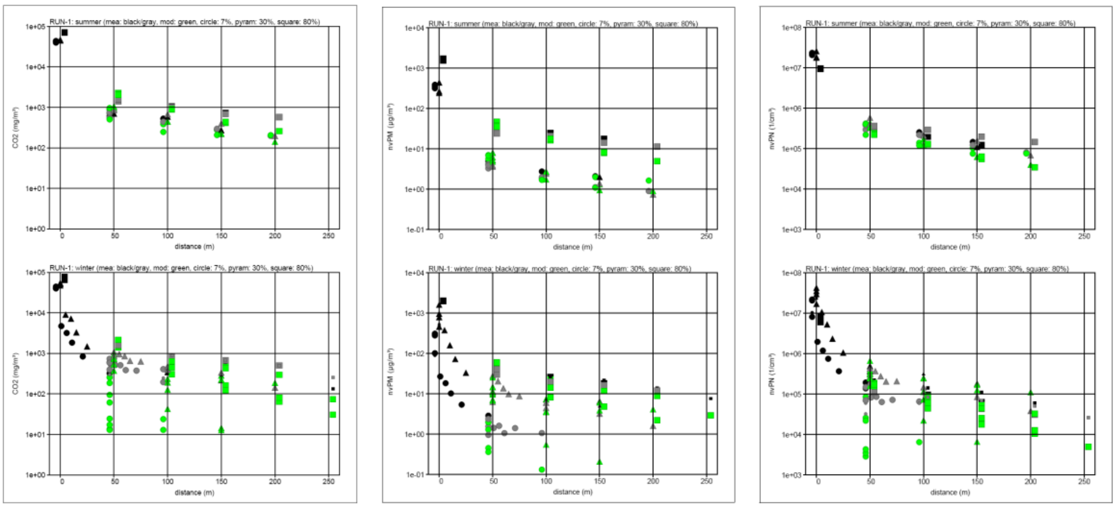


Figure 5.5. LASPORT 2.4: Measured (black/gray) and modelled (green) CO2 (left), nvPM mass (centre) and nvPM number (right) concentrations as a function of distance from engine 3 (background subtracted)

Exhaust plumes modelled by CEDRE (single engine configuration) were also compared to those from LASPORT 2.4, despite the challenges. The parameterisations in LASPORT must cover the main effects of a moving aircraft at distances of 100 m or more away from the aircraft. This is the typical regime for local air quality modelling at and around an airport, with concentrations averaged over at least an hour, with a superposition of many individual aircraft plumes. Therefore, the default values of the initial horizontal and vertical extent of the plume cross section were reduced to a typical engine diameter of 2.5 m to provide a more meaningful comparison. The vertical plume widths of LASPORT 2.4 and CEDRE were similar, and LASPORT 2.4 yields horizontally narrower plumes than CEDRE. However, using a much larger horizontal plume width in LASPORT would reduce the good agreement with measurements from WP3.

5.2.4. Emission inventories and modelled concentrations

Emissions and dispersion calculations were conducted for Madrid Barajas airport with two dispersion models[22]:

- Eulerian CFD model, CEDRE that can simulate complex flow fields, exhaust dispersion, and complex chemical reactions for a limited time, with a very high spatial resolution. The effects of aircraft main engines, APUs and airport buildings were investigated for one day (0500 to 1700 hours) in autumn 2021, with NOx, O_3 and SO_2 concentrations at 0600 and 1300 hours analysed. The influence of a new plume emission partitioning and APU running times and their contribution to total airport emissions were also conducted.
- Lagrangian regulatory model, LASPORT that can calculate airport emissions and concentrations for a complete calendar year based on ICAO and national standards, with key quantities provided in alignment with EU AQ directives. An emission inventory for the year 2021 (aircraft main engines, APU, GSE) was set up and a dispersion calculation for the last quarter of 2021 was conducted, allowing a time series of hourly mean concentrations to be produced.

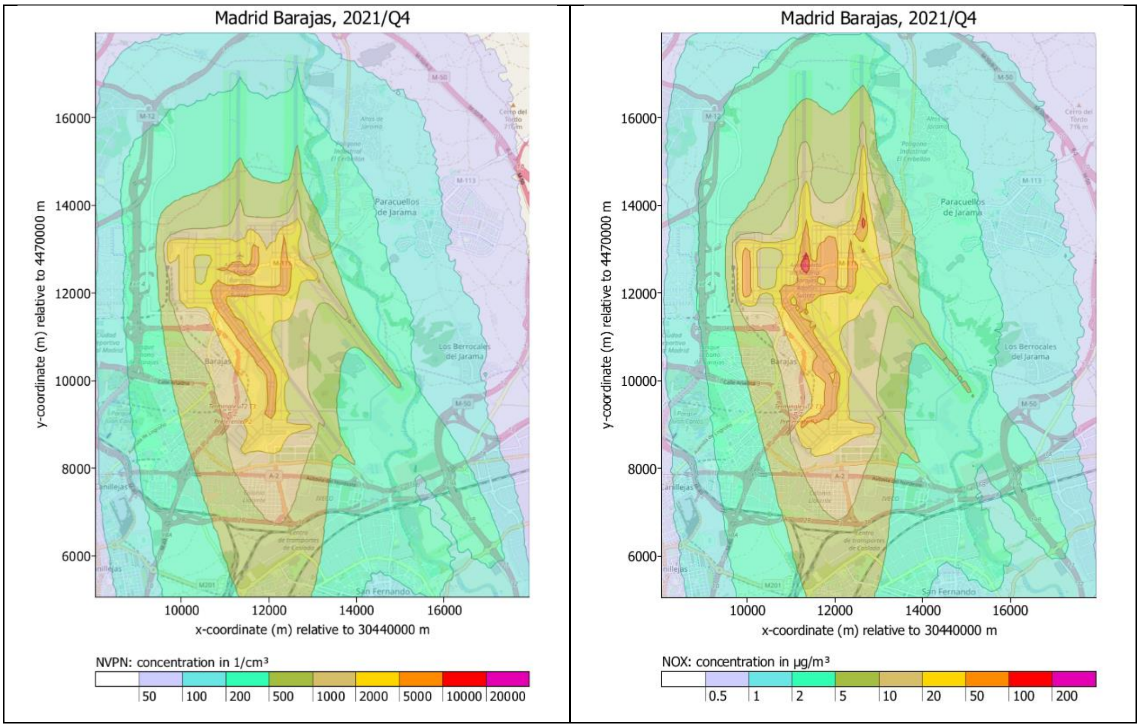
CEDRE results showed that:

- Emission partitioning had a small effect on NOx concentrations near parking stations and downstream of the buildings, with stronger effects noted when a large fleet crossed the airport area. The total emitted mass was similar, but the emitted species were more spread out when partitioning was applied, resulting in lower concentrations.
- For the species whose EI did not depend on thrust (CO_2, SO_2, and H_2O), the APU was responsible for almost half of the total airport emissions (< 2 m). For the other species, the APU is responsible for 29% of CO emissions, 32% of NOx emissions and 42% of ROC (Reactive Organic Compounds) emissions. ROC, CO and SO_2 emissions mainly occurred during the taxi phase (idle thrust) while NOx emissions mostly occurred during take-off and climb-out. A decrease of APU normal running time from 40 to 20 min yielded a strong decrease of NOx concentrations downstream of parking locations. The extent of the plumes was also reduced. However, effects of a reduction from 20 to 10 min were less pronounced. This showed the importance of APU normal running times for the prediction of concentrations around buildings and at the airport area.
- The maximum concentrations occurred at the parking locations at 0600 hours (with 18 aircraft in the CEDRE's modelling domain). The emitted NOx was transported due to local wind flow, creating large plumes that partially interacted with the buildings and recirculated. The extent of these plumes can be very large, over several hundreds of meters, which may be due to the laminar approximation of the aerodynamics in CEDRE. Away from the emission zones, the NOx concentrations remain over 100 µg/m^3, with a background close to 50 µg/m^3.
- At 1300 hours, the wind speed was lower (0.41 m/s) by a factor of 4 when compared to the wind speed at 0500 LT (1.65 m/s). Higher concentrations of NOx were observed further away from the building, due to the large number of aircraft crossing the modelling domain during this hour (63 in total). There were still many aircraft parked in the terminal areas contributing to the concentrations near buildings. The lower wind speed increased NOx transport time, so the plume concentrations away from the terminal remained high.

LASPORT 2.4 (with enhanced exhaust dynamics) results showed that:

[22] Full report AVIATOR Deliverable D6.1

- For NOx, 70% of the emissions up to 914 m (3,000 ft) were due to take-off and climb. For HC and CO, 80% of the emissions were from taxiing. For nvPM number, almost 50% from taxiing and more than 30% from approach. It was noted that integration over very different altitudes can be misleading when assessing local impacts near ground. The higher the emission release, the smaller is the contribution to the near ground concentration since the emitted pollutant is dispersed horizontally before reaching the ground due to atmospheric turbulence. For a passive release, the concentration near ground is approximately the inverse of the square of emission height. Therefore, to compare emissions from different segments of LTO with respect to LAQ, a maximum emission height of 305 m (1,000 ft) may be more suitable. For this height, nvPM contribution from taxiing and NOx contribution from take-off and climb increased to almost 70%.
- Aircraft emissions calculated from ICAO EEDB certification data may not necessarily represent conditions that are typical in real flight conditions. For example, the certification data apply 10% maximum thrust for take-off, whereas in real operations the take-off thrust is likely to be in the range of 80%. More realistic flight conditions, including effects of ambient conditions, can be accounted for in an aircraft performance model. NOx emissions (to 305 m) reduced by ~20% when the aircraft performance model ADAECAM was used, and HC and CO emissions increased by 25 – 30%. These changes are dependent on ambient temperature and therefore specific to the season and the airport. The nvPM mass and number changes were small since the performance model has not implemented effects of non-certification thrust/ambient conditions on PM emissions.
- Near ground concentrations for nvPM number, NOx, HC and SOx for the 3 months period is shown in Figure 5.6. The maxima for nvPM number and HC were located at the taxiways while NOx at the thresholds of the departure runways. For APU running times, detailed information from the airport were applied, resulting in times per LTO below 20 min at several stand positions and therefore less pronounced concentration peaks at these positions as compared to some of the CEDRE runs.



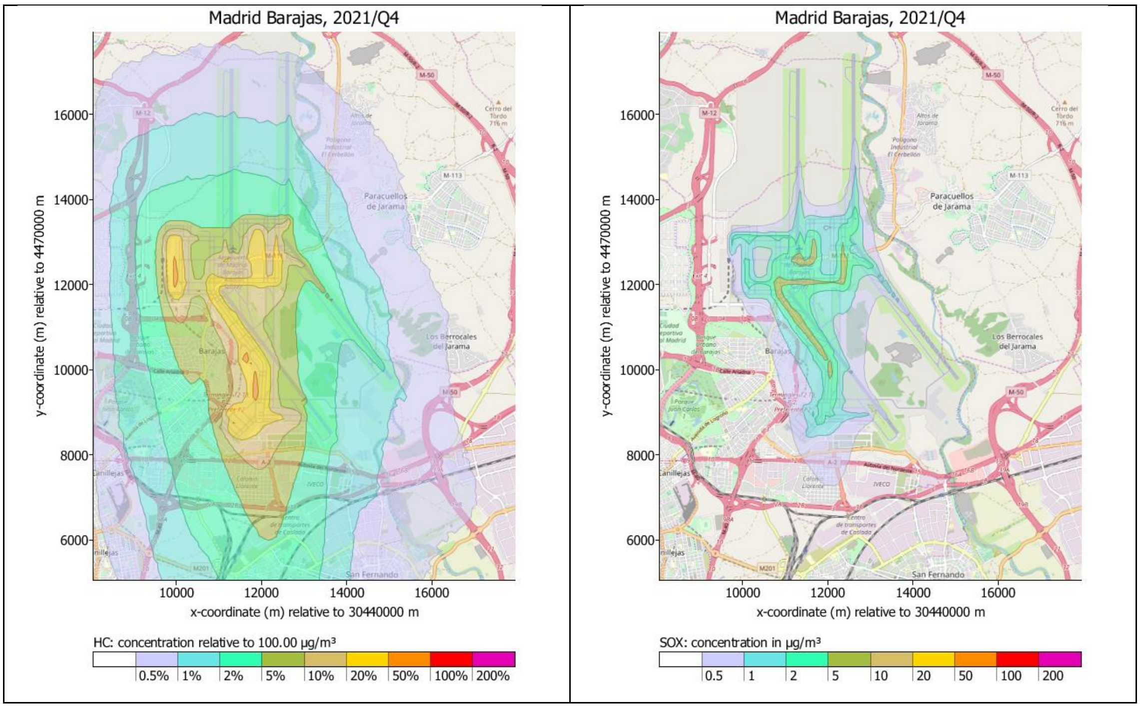


Figure 5.6. Near ground concentration (mean over the last quarter of 2021) of nvPM number (top-left), NOx (top-right), HC (bottom-left) and SOx (bottom-right) due to emissions from aircraft main engines, APU, and GSE

5.2.5. Comparison between modelled and measured concentrations

A comparison between the low cost sensors (LCS) measurements from the second AVIATOR campaign (October 2021) and simulated data using from LASPORT and CEDRE, were performed for NOx, CO, and the total number of non-volatile particles (nvPM) for Madrid Barajas international airport[23]. The comparison showed that:

- For NO, CEDRE's results consisted of a wider range of values and 100 times higher than LCS data (where available, there were technical difficulties and limited measurements). For NO_2, in general, CEDRE had higher concentrations than the LCS, even though there were good agreement with a few LCS. The maximum hourly NOx concentrations were observed from CEDRE over the parking areas due dominant APU sources. For CO, some of the values from CEDRE were in the good agreement with the LCS, even if on average CEDRE produced higher concentration.
- The LCS measured values had contribution from all sources, including nearby landside and airside road traffic and from volatile particles, while the modelled LASPORT results referred to contributions from aircraft and ground support equipment and non-volatile particles only. Therefore, a comparison of the relative concentration distribution using nvPM for LASPORT and total PM for LCS provided a reasonable qualitative description of the concentration gradients, and both LASPORT and LCS had good agreement in this aspect see Figure 5.7. Wind direction had a strong influence on the modelled concentrations at specific positions. The magnitude of high concentration peaks was similar to the LCS although sometimes the measurement showed strong peaks, while the model showed none. Reconstructing a time series of concentrations via modelling is challenging due to this variability, while on a longer time average, it would be less so. The agreement for total PM number was mostly within a factor of 2. In general, for some LCS positions, data interpretation was straightforward while for others, it was more

[23] Full report in AVIATOR Deliverable D6.2

challenging due to lack of data points and the utilisation of specific runways was not constant but varied with wind direction and was unpredictable.

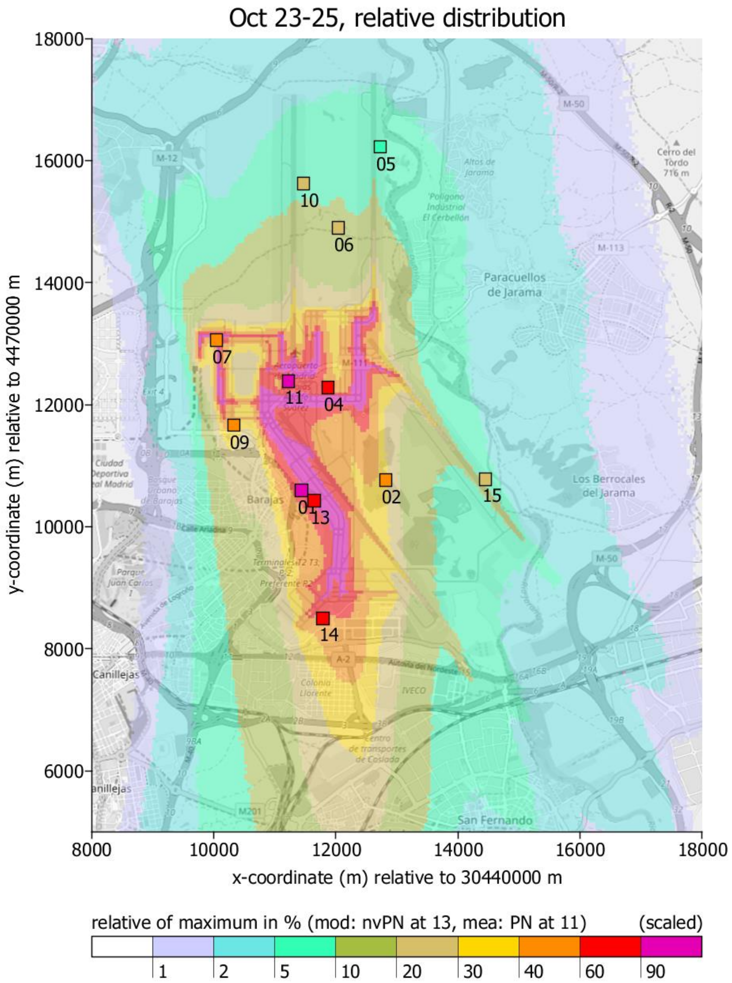


Figure 5.7. Relative concentration distribution of modelled nvPM number (background) and relative concentration distribution of measured tPM number (squares)

5.3. Synthesis of WP5 and WP6

WP5 Conclusions, LASPORT/CEDRE:

1. Successful enhancement of exhaust dynamics parametrization in LASPORT based on WP3 data; good agreement between modelled and measurement concentrations for CO_2 and non-volatile particle mass and number (mostly within a factor 2 for summer; for winter: strong cross winds hamper the comparisons).
2. Consistent key values for the down-shift of exhaust emissions due to wing-vortex interaction from ZRH measurements, CEDRE, and LASPORT.
3. WP3 summer data seem well suited as gold standard for model validation (near field, no dominant background emissions, well defined emission rates, high fidelity concentration data, moderate or small wind speeds).
4. First ideas and assumptions to account for volatile particles in standard airport dispersion modelling were developed and their development will be continued.

WP6 Conclusions, CEDRE:

1. Successful application of a CFD model to a complex airport setup (aircraft, APU, buildings).
2. Influence of plume partitioning on results is minor; assumption on APU running times has strong impact on the total concentration.
3. Laminar flow assumptions may cause an overestimate of concentrations.
4. In comparison with LCS data, concentrations of CO show better agreement than of NOx; also due to lower fidelity of LCS data (PM > CO > NOx).
5. Further research suggested for: mapping of atmospheric turbulence in CEDRE, also by improved meshing; provision of high-quality trajectory maps to improve localization of emissions in space and time.

WP6 Conclusions, LASPORT:

1. Application of the standard system LASPORT to Madrid Barajas straightforward as expected.
2. Successful application of improved parametrization from WP 5; relevant for the near field (< 500 m).
3. Good agreement (mostly within a factor of 2) between modelled and measured (LCS) total number concentration when using the applied estimate of total PM (for autumn conditions) in the model.
4. Inhomogeneous wind fields at the airport may be relevant for high-resolution comparison between modelled and measured data.
5. Further research suggested for: modelling volatile particles to obtain modelled total particle number; higher time resolution (10 minutes) for more detailed comparisons with measurements; application of 3D wind fields initialized with station data at the airport.

Conclusions, general:

1. CFD model CEDRE and regulatory model LASPORT with different focuses and virtues provided valuable information.
2. LCS data useful to provide measurement-based concentration gradients at airports in a qualitative way and for some pollutants also quantitatively, with some partly good correlation with modelled gradients.
3. Emission sources not accounted for in modelling, but relevant in measured data (e.g. roads), can be problematic for such comparisons.
4. LCS data at Madrid Barajas Airport were not well suited as gold standard for model validations (low fidelity absolute values, influence of unknown emission sources, indication of complex wind fields, annual averages more robust on airport level); WP3 near field data are better suited as a gold standard for model validations.

5.4. Outcomes of WP5 and WP6

The outcomes of WP5 and WP6 can be summarised as follows:

- Both aircraft and non-aircraft sources, and background conditions (meteorology and ambient concentration levels) in and around the airport are important for LAQ assessments.
- For an estimate of LAQ solely based on LTO emissions, a formal maximum emission height of 305 m (1,000 ft) may be more suitable than 914 m (3,000 ft) since emission released at higher altitude will have smaller contribution due to it being dispersed horizontally before reaching the ground due to atmospheric turbulence.
- For airport level assessment, aircraft performance models may result in lower NOx emissions, but higher HC and CO emissions than if the ICAO EEDB certification data are used. APU normal running times that are greater than 20 mins are important for the prediction of concentrations around buildings and the airport area.
- CFD modelling is computationally expensive but can produce very high spatial resolution data that can be parameterised and used in regulatory-level model. This can be seen from the enhanced parameterisation in LASPORT 2.4 from CEDRE data, that produced better comparison with measured data than LASPORT 2.3.
- In aircraft plume modelling with a CFD model, initial BC concentration are critical in the determination of particle size and the resulting number and mass concentration.
- It is less challenging to compare longer time averages of modelled data with LCS due to wind variability sensitivity. However, the relative concentration distribution can provide a good qualitative description of the concentration gradients.
- The summer data of WP3 could be suited as gold standard for model validation (near field, no dominant background emissions, well defined emission rates, high fidelity concentration data, moderate or small wind speeds).

6. Regulatory Outcomes

6.1. Aircraft engine emissions regulations

6.1.1. Current ICAO-CAEP nvPM standards and guidance

The ICAO-CAEP nvPM emission standards are described in Section 1.3 and technical work to improve and maintain the standards is undertaken both in the SAE E31 committee and the CAEP Working Group 3 (Emissions and Technical). The AVIATOR outcomes are relevant to a number of the work items ongoing in these groups which are part of the regulatory process. AVIATOR has provided inputs to these groups on progress during the project and will continue to provide inputs to these groups after the end of the project.

The AVIATOR outcomes with relevance to the current CAEP engine emission regulations can be summarised as follows:

- Ambient corrections – use of AVIATOR data to test ambient corrections being developed by CAEP-WG3. After the AVIATOR project end, data will be used to test the ambient corrections being developed in CAEP and the analysis will be reported to WG3.
- Fuel composition – AVIATOR findings are consistent with the H content correction developed for certification and applied in ICAO Annex 16 Volume 2. These findings have been reported to WG3. The AVIATOR findings and subsequent peer-review publications will add to the body of literature supporting the correction approach.
- Low power conditions confirmation of ICAO Doc 9889 Statement that below 7% thrust emissions of nvPM increase.
- System losses – AVIATOR found that different sampling regimes can lead to different values for system losses. SAE E31 is currently working on an improved methodology for system losses asking OEMs and researchers to apply the new method and assess differences to the ICAO loss correction methodology.
    - Outputs from AVIATOR will be used to contribute to the work in E31.
    - The AVIATOR results show that measurement of particle size distribution can be used to improve system loss calculation.
- AVIATOR datasets will be available for improving the uncertainty understanding in E31, simplification, particle size and loss method.
- Stack sampling vs. engine exit sampling. AVIATOR showed comparable results in the stack sampling as in the engine exit plane sampling, indicating that stack sampling could potentially be used in future certification measurements. These findings will be reported to SAE E31.

6.1.2. Future regulations and guidance

One of the high-level aims of AVIATOR, is ‘Bridging the gap between Aircraft Engine Certification and Local Air Quality (LAQ) Regulation’. As described in Section 1.3 the PM metrics measured as part of the engine emissions regulations (nvPM mass and nvPM number) do not read across to the ambient air quality metrics measured at and around Airports (tPM mass concentrations as PM_{10} and $PM_{2.5}$).

- To try and bridge the gap between engine emissions and ambient regulations, analysis was undertaken to detect a signal from nvPM mass and number in ambient measurements in and around the airport. The AVIATOR results showed that the nvPM mass measurements were not detectable in ambient measurements (analysis was not able to clearly to see nvPM mass different to background). However, the total PM number signal was clear. The split between nvPM and vPM number is not absolutely clear and will require further analysis of AVIATOR WP4 data and consideration of the difference with baseline.
- A further question posed by the AVIATOR results Is whether the current nvPM size limit in the current regulation is low enough.[24] Both future SAF usage and lean burn technology tend to produce lower particle number concentrations[25] than for Rich Quench Lean (RQL) combustion technology but are dominated by sub 10 nm particles. In future measurement considerations, system loss correction could be changed to go lower down (subject to technical reasons, possibly down to 7nm).
- Measurement campaigns in AVIATOR show that tPM particle number measurements of particles in the size range of approximately 10-20 nm or less are a good aviation marker. The current CAEP nvPM number engine emission standard is relevant to the tPM in this size range but, as noted above, a lower cut off than 10 nm would be more relevant where this is technically feasible and future SARPs should consider this in future updates.
- Future regulations should consider system loss improvements for tPN.
- AVIATOR WP3 detected oil particles greater 60 nm in the plume (dependent on where oil breather is based). However, WP4 didn’t see an oil signal in the online ambient measurements. Nevertheless, WP4 did see oil in the filter samples, which includes particles less than 60 nm. The potential contribution of engine lubrication oil on tPM in the plume and ambient air and the impact on suppressing the vPM nucleation mode, could be significant and thus requires further investigation.
- The vPM “signal” from aviation needs further work to:
  - Distinguish between sulphur in the fuel, engine breather oil or unburnt HC as a source of vPM.
  - Work in WP4 also indicates a need to develop and standardise use of ageing chamber in future work e.g., for very low sulphur fuels.
- There is increasing pressure for modellers to consider total PM number. For example, work in WG3 is currently ongoing to update the contribution to vPM (to add to the methods for nvPM) to be a part of the ICAO DOC9989. An approximate rule of thumb currently used is to factor nvPM by 4 to account for vPM and estimate tPM number. However, a more complex estimation is under consideration in CAEP-WG3 and data from AVIATOR can feed into checking this more complex method.
- The AVIATOR WP2, WP3 and WP4 offline analysis filter data can be used to improve understanding of speciated hydrocarbons e.g., ratios of benzene to toluene to provide approximate emission indices of benzene etc for ambient LAQ regulation. Data set will be available post-AVIATOR for analysis.

[24] The long sample lines used in existing sampling systems means that 10 nm as a lower limit was chosen.
[25] Particle size in Lean Burn engines in pilot mode not necessarily smaller.

6.1.3. AVIATOR Data beyond the project end

Work on analysis of AVIATOR data will continue beyond the end of the project and data and findings will continue to be fed into the regulatory process where relevant through the SAE E31 committee and the CAEP WG3.

To ensure continued, proper use of AVIATOR datasets:

- Protocols for the data are being developed; and
- Journal publication(s) with detailed data description are being prepared.

Several AVIATOR experts are actively involved in SAE E31 work participating as voting members and acting as the E31 vice-chair & Secretary, PM subcommittee chair and vice-chair, Uncertainty team lead and E31-WG3 Liaison.

Several AVIATOR experts are also actively involved in CAEP WG3, including the European WG3 co-rapporteur.

These linkages will continue to ensure that AVIATOR outcomes guide future improvements to existing regulations and development of future standards and corrections.

6.2. Local Air Quality Regulations and Health

Two members of the AVIATOR External Advisory Board have provided important linkages with the LAQ and Workplace regulatory community. Professor Flemming Cassee is an inhalation toxicologist at RIVM National Institute for Public Health and the Environment. In this position he is involved in research into adverse health effects from airborne particulate matter (fine dust) and gaseous components (e.g., ozone, nitrogen dioxide) in the ambient air. In addition to this, Flemming Cassee is professor of inhalation toxicology at the Institute of Risk Assessment Sciences of the Utrecht University. More recently his focus is also on the safety of nanomaterials. Ulla Vogel was also appointed to the Executive Board of AVIATOR to strengthen AVIATOR links with the workplace and health community. Ulla Vogel is professor in Nanosafety and the Chemical Working Environment at the National Research Centre for the Working Environment in Denmark and is a Registered European Toxicologist. She is also adjunct professor at Department of Health Technology at the Technical University of Denmark. She has worked with the toxicology of inhaled nano-sized particles for more than 20 years, focusing on cancer, cardiovascular disease and reproductive health.

The current ambient air quality measurements are based on large scale epidemiological studies using long term concentration measurements of PM_{10} and $PM_{2.5}$. These mass metrics tend to be dominated by the larger size particles and are not an effective marker for UFP. Furthermore, increasing amounts of toxicology evidence points to the health impacts of these smaller particles (UFP) and it may well be that particle number concentrations measured in ambient air (which are influenced more by the more numerous and smaller particles) together with the established $PM_{2.5}$ mass concentration measurements could be better indicators of the health impacts of PM emissions. AVIATOR has shown that the UFP in the very smallest range of measurable sizes (less than 20 or 10 nm) are the clearest markers from aircraft engine emissions.

Although UFP has been identified as a human health concern it is unclear whether the smaller particles e.g. less than 20 or 10 nm as emitted from aeroplane engines, are of particular concern and are more impactful than UFP particles greater than 20 nm. Questions regarding particle composition and solubility and the relative toxicity of different particle compositions still remain, requiring further research and analysis. The AVIATOR outcomes will be provided to the toxicology experts on the Executive Board and to the European agencies EUOSHA and EEA to provide the linkage between the measurement and health impacts community.

Current consideration for ICAO's Environmental Trends report and aircraft emissions standard analyses are based on LTO emissions calculated with global aircraft emissions model. CAEP MDG/FESG is currently looking into the feasibility of reporting/using pollutant concentrations in addition to emissions in future CAEP cycles. This could include an outlook of population affected by aircraft emissions (similar to CAEP noise analyses) and would provide a better impact proxy than just emissions. AVIATOR experts are actively involved in this work, with LASPORT being one of the models used for the feasibility study.

7. Summary of outline agendas for improved regulation of aircraft emissions aligned to the needs and current understanding of air quality (D7.3)

AVIATOR outcomes aim to identify knowledge gaps in relation to engine particulate emissions and air quality in and around airports.

A number of knowledge gaps were identified in the AVIATOR project which the measurement and modelling work packages aimed to fill or at least partially fill as described in Section 6. This Section seeks to identify those knowledge gaps remaining, or additional gaps identified during the course of the project and fulfils the D7.3, thus providing a summary of possible outline agendas for improved regulation of aircraft emissions aligned to the needs and current understanding of air quality in and around airports.

7.1. Engine emissions and local air quality measurements

Knowledge gaps are summarised as follows:

- Health and toxicology gaps include whether the smaller UFP particles i.e., less than 20 or even 10 nm, are the main concern and there are questions regarding the solubility of coatings and the relative toxicity of different chemical compositions.
- Further work is required using an ageing chamber to look at consistency between real world plume evolution and ageing chamber data. This would allow the use of ageing chambers to simulate potential downstream air quality impacts of e.g., fuel and oil effects on real world emissions.
- APU contribution downstream plume evolution. AVIATOR was not able to collect data on APU emissions.
- Oil breather emissions including looking at breather location into hot exhaust. Also further investigate the impacts seen in AVIATOR where the oil interacted to reduce observed tPM number. The engine lubrication oil emissions may be significant in the nucleation and condensation regimes in the plume.
- Speciation of nucleation particles at the lower particle size and possibly coatings on nvPM at sizes below 60 nm require further investigation and linkage with the health impacts and toxicology community.
- Remote monitoring of aircraft plumes 2D/3D is needed to further investigate the aerosol behaviour in the plume.
- Impact of emissions from brakes and tyres. This was not part of the AVIATOR project, but these can be significant localised sources of tPN.
- Further improvement in source apportionment of emissions and measurements around airports. Methods to assess the relative contribution of aircraft to better target air quality and workplace mitigation measures. The AVIATOR outcomes will be provided to EUOSHA and the EEA.
- Further development of lower cost sensors to provide reliable data at multiple points around global airport environments.

7.2. Modelling the dynamics and dispersion of engine emissions

Knowledge gaps are summarised as follows:

- Further work is required to improve/parameterize the ageing process and formation of particles in regulatory models. CFD and global models may not be accessible or are computationally too expensive for regulatory purposes.
- Comparison between AVIATOR measured data and results from aerosol model with microphysical processes such as MADE3. This will provide information on the limitations of plume dynamics within these models, under real airport-level conditions.
- Further work in CFD modelling should focus on the turbulent aspect of the boundary layer since laminar flow (as assumed in AVIATOR) could lead to an overestimation of concentrations. This work should include the development of alternative meshing procedure, whereby wind speed and turbulent kinetic energy can be introduced to the vertical profiles.
- Provision of high-quality sets of trajectory locations and associated emissions for aircraft movements at an airport. This would avoid unrealistic assumptions on the emissions location and magnitude during taxiing, which could lead to large uncertainties in the modelled concentrations, especially near terminals.
- Enhancing the time resolution of regulatory models, for example 10-min averages instead of hourly means. This would improve understanding of local variations or effects of exhaust dynamics. The inclusion of complex wind field models that account for wind variability, would provide more accurate concentrations for time series assessment.
- Further data analysis/comparison between the modelling systems and measurements. Many datasets and results were generated in AVIATOR. However, there is still much work needed to fully understand and apply the data, including understanding the uncertainties and applicability at different airports.
- The relationship between aircraft emissions and other emissions/background conditions in and around an airport. AVIATOR established the importance of some of these parameters, but gaps remained in terms of their contributions to ambient level concentrations.

7.3. Engine emissions and non-CO_2 climate impacts

The focus of AVIATOR is local air quality but some of the data collected are also relevant to the non-CO_2 impacts (i.e., tPM) on climate.

Knowledge gaps are summarised as follows:

- Oil breather and location of breather impacts independent of all future fuels – impacts on contrail-cirrus formation.
- Ageing chamber data could be used in conjunction with ice chamber work to consider contrail-cirrus formation.

7.4. Concluding remarks

AVIATOR will continue to develop policy briefs, information papers and working papers designed to meet the needs of regulatory bodies beyond project close (as described in AVIATOR Deliverable D8.6). This is viable since several of the AVIATOR partners are deeply embedded and highly active within the regulatory community.

The AVIATOR publication strategy will also continue to provide a rich resource in the peer review literature which will provide a scientific basis to underpin future developments in regulation and policy in this area.

The outline agenda items identified within AVIATOR and summarised above will provide a firm foundation for the exploration and debate of new concepts within the regulatory communities aligned to the needs and current understanding of air quality in and around airports.