ICAO

Doc 9889

Airport Air Quality Manual

Third Edition, 2023

Approved by and published under the authority of the Secretary General

INTERNATIONAL CIVIL AVIATION ORGANIZATION

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Amendments are announced in the supplements to the *Products and Services Catalogue;* the Catalogue and its supplements are available on the ICAO website at www.icao.int. The space below is provided to keep a record of such amendments.

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FOREWORD

This manual covers an evolving area of knowledge and represents currently available information that is sufficiently well-established to warrant inclusion in international guidance. This manual covers issues related to the assessment of airport-related air quality that are either specifically within the remit of the International Civil Aviation Organization (ICAO) (such as main engine emissions) or where there is an established understanding of other non-aircraft sources (such as boilers, ground support equipment and road traffic) that will contribute, to a greater or lesser extent, to the impact on air quality.

There are potential emissions source issues relevant to, but not covered in, this manual (for example, forward speed effects of aircraft, influence of ambient conditions on aircraft emissions, brake and tire wear) that have been identified and are the subject of further investigation by ICAO, Member States, observer organizations or other expert organizations, taking into account practical experience.

This edition of the manual includes chapters on the regulatory framework and drivers for local air quality measures; emissions inventory practices (including a detailed sophisticated aircraft emissions calculation approach); dispersion modelling; airport air quality measurements; mitigation options and trade-offs. Throughout the document, additional references are provided for those interested in exploring these topics in further detail.

This is intended to be a living document, and as more knowledge on this subject becomes available, it will be updated accordingly. Comments on this manual, particularly with respect to its application and usefulness, would be appreciated. These comments will be taken into account in the preparation of subsequent editions. Comments concerning this manual should be addressed to:

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Canada

CONTENTS

GLOSSARY

Above ground level (AGL). A height above the known runway or ground elevation.

Air climate unit (ACU). A self-driven or trailer-mounted compressor unit to provide aircraft with pre-conditioned air during ground time.

Airshed. Mass of air that behaves in a coherent way with respect to the dispersion of emissions. For the purpose of dispersion studies performed with numerical models, it can therefore be considered as a single analysis and management unit.

Auxiliary power unit (APU). A self-contained power unit on an aircraft providing electrical/pneumatic power to aircraft systems during ground operations.

Carbon dioxide (CO_2). A naturally occurring gas that is also a by-product of burning fossil fuels and biomass, land-use changes and other industrial processes. Carbon dioxide is the reference gas against which the global warming potential of other greenhouse gases is measured. Effects: Its contribution to climate change. CO eventually oxidizes to CO_2 and contributes to climate change.

Carbon monoxide (CO). A colourless, odourless gas formed during incomplete combustion of heating and motor fuels. Effects: CO acts as a respiratory poison in humans and warm-blooded animals. It plays a role in the formation of ozone in the free troposphere.

Environmental control system (ECS). APU bleed air is supplied to the aircraft air-conditioning packs, which supply conditioned air to the cabin. For emissions testing the bleed load condition is set for typical aircraft gate operation (depending on the aircraft type and size) and normally includes some shaft (electric) load.

Fixed energy system (FES). A system at aircraft stands (remote or pier) that provides centrally produced energy (electricity and sometimes PCA) to aircraft during ground time.

Ground power unit (GPU). Provides electrical power to aircraft during ground time.

Ground support equipment (GSE). The broad category of vehicles and equipment that service aircraft, including those used for towing, maintenance, loading and unloading of passengers and cargo, and for providing electric power, fuel and other services to the aircraft.

Kerosene. Fuel for jet engines (e.g. Jet-A1).

Landing and take-off (LTO) cycle. LTO consists of four phases of aircraft operations: approach, taxi, take-off and climb.

Nitrogen oxides (NO_x/NO_2). Nitrogen oxides is a generic term encompassing nitrogen dioxide (NO_2) and nitrogen monoxide (NO). Because NO rapidly oxidizes to NO_2, the emissions are expressed in terms of nitrogen dioxide (NO_2) equivalents. Nitrogen oxides are formed during combustion of heating and motor fuels, especially at high temperatures. Characteristics: NO is a colourless gas, converted in the atmosphere to NO_2; NO_2 assumes a reddish colour at higher concentrations. Effects: respiratory disorders, extensive damage to plants and sensitive ecosystems through the combined action of several pollutants (acidification) and overfertilization of ecosystems.

Particulate matter (PM). Particulate matter is the term used to describe particles with an aerodynamic diameter of 10 micrometres or less. From a physico-chemical standpoint, dust is a complex mixture consisting of both directly emitted and secondarily formed components of natural and anthropogenic origin (e.g. soot, geological material, abraded particles and biological material) and has a very diverse composition (heavy metals, sulphates, nitrates, ammonium, organic carbons, polycyclic aromatic hydrocarbons, dioxins/furans). $PM_{2.5}$ are particles with an aerodynamic diameter of 2.5 micrometres or less. They are critical in connection with health effects. PM is formed during industrial production processes, combustion processes, mechanical processes (abrasion of surface materials and generation of fugitive dust) and as a secondary formation (from SO_2, NO_x, NH_3 and VOC). Characteristics: solid and liquid particles of varying sizes and composition. Effects: fine particles and soot can cause respiratory and cardiovascular disorders, increased mortality and cancer risk; dust deposition can cause contamination of the soil, plants and also, via the food chain, human exposure to heavy metals and dioxins/furans contained in dust.

ABBREVIATIONS AND ACRONYMS

AAL	Above aerodrome level
ACARE	Advisory Council for Aeronautics Research in Europe
ACU	Air climate unit
ADAECAM	Advanced aircraft emission calculation method
ADMS	Atmospheric Dispersion Modelling System (United Kingdom)
AEDT	Aviation Environmental Design Tool (United States FAA)
AFR	Air/fuel ratio
AGL	Above ground level
ALAQS	Airport Local Air Quality Studies (EUROCONTROL)
ANSP	Air navigation service provider
APU	Auxiliary power unit
ARFF	Airport rescue firefighting
ARP	Aerodrome reference point
ASQP	Airline service quality performance
ASU	Air starter unit
ATA	Air Transport Association
ATOW	Actual take-off weight
Avgas	Aviation gasoline
BADA	Base of aircraft data
BFFM2	Boeing fuel flow method 2
bhp	Brake horsepower
BPR	Bypass ratio
BTS	Bureau of Transportation Statistics (United States)
CAEP	Committee on Aviation Environmental Protection
CDO	Continuous descent operations
CERC	Cambridge Environmental Research Consultants (United Kingdom)
CNG	Compressed natural gas (carburant)
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Double annular combustor
DfT	Department for Transport (United Kingdom)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOAS	Differential optical absorption spectroscopy
DOT	Department of Transportation (United States)
EASA	European Union Aviation Safety Agency
ECS	Environmental control system
EDMS	Emission and Dispersion Modeling System (United States FAA)
EEA	European Environment Agency
EEDB	Engine Emissions Databank (ICAO)
EI	Emission index
EMEP	European Monitoring and Evaluation Programme
EPA	Environmental Protection Agency (United States)
ETFMS	Enhanced tactical flow management system (EUROCONTROL)
ETMS	Enhanced traffic flow management system (United States)
EU	European Union
FAA	Federal Aviation Administration (United States)

FAF	Final approach fix
FBO	Fixed based operation
FDR	Flight data recorder
FES	Fixed energy system
FESG	ICAO CAEP Forecasting and Economic Analysis Support Group
FIRE	Factor Information Retrieval Data System (United States EPA)
FOA	First Order Approximation
FOCA	Federal Office for Civil Aviation (Switzerland)
FOD	Foreign object damage
FOI	Swedish Defence Research Agency
FSC	Fuel sulphur content
g	Gram
GE	General Electric
GPU	Ground power unit
GSE	Ground support equipment
h	Hour
HAP	Hazardous air pollutant
HC	Hydrocarbon
hp	Horsepower
Hz	Hertz
IAE	International Aero Engines
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industries Associations
ILS	Instrument landing system
IOAG	International Official Airline Guide
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
kg	Kilogram
km	Kilometre
kN	Kilonewton
kt	Knot
kW	Kilowatt
LASAT	Lagrangian simulation of aerosol – transport
LASPORT	LASAT for Airports (Europe)
LPG	Liquefied petroleum gases
LTO	Landing and take-off
m	Metre
min	Minute
MSDS	Material safety data sheet
NAAQS	National Ambient Air Quality Standards (United States)
NASA	National Aeronautics and Space Administration (United States)
NGGIP	National Greenhouse Gas Inventories Programme
NMHC	Non-methane hydrocarbon
NO	Nitrogen monoxide
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
NPR	Noise-preferential route
nvPM	Non-volatile Particulate Matter
nvPMmass	Non-volatile particulate matter mass
nvPMnumber	Non-volatile particulate matter number
O_3	Ozone content
OPR	Overall pressure ratio
PCA	Pre-conditioned air (for cooling/heating of parked aircraft)

PLTOW	Performance-limited take-off weight
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter (with an aerodynamic diameter of 2.5 micrometres or less)
PM_{10}	Coarse particulate matter (with an aerodynamic diameter of 10 micrometres or less)
PPM	Parts per million
P&W	Pratt & Whitney
s	Second
SAE	SAE International
SHP	Shaft horsepower
SN	Smoke number
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
TAF	Terminal area forecasts (United States)
TEOM	Tapered element oscillating microbalance
THC	Total hydrocarbon
TIM	Time-in-mode
TOW	Take-off weight
UID	Unique IDentifier (e.g. engine denomination)
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
$\mu g/m^3$	Micrograms per cubic metre
V	Volt
VMT	Vehicle-miles travelled
VOC	Volatile organic compounds
WHO	World Health Organization

REFERENCE DOCUMENTS

ICAO PUBLICATIONS

(referred to in this manual)

Annexes to the Convention on International Civil Aviation

Annex 16 – *Environmental Protection*
  Volume I – *Aircraft Noise*
  Volume II – *Aircraft Engine Emissions*

Procedures for Air Navigation Services

*OPS – Aircraft Operations (*Doc 8168)
  Volume I – *Flight Procedures*
  Volume II – *Construction of Visual and Instrument Flight Procedures*

Manuals

Airport Planning Manual (Doc 9184)
  Part 1 – *Master Planning*
  Part 2 – *Land Use and Environmental Management*
  Part 3 – *Guidelines for Consultant/Construction Services*

ICAO Engine Exhaust Emissions Data Bank (Doc 9646)[1]

Guidance on Aircraft Emissions Charges Related to Local Air Quality (Doc 9884)

Recommended Method for Computing Noise Contours Around Airports (Doc 9911)

Operational Opportunities to Reduce Fuel Burn and Emissions (Doc 10013)

Circulars

Effects of PANS-OPS Noise Abatement Departure Procedures on Noise and Gaseous Emissions (Cir 317)

Reports of Meetings

Report of the Seventh Meeting of the Committee on Aviation Environmental Protection (CAEP/7) (Doc 9886)

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[1] This document is permanently out of print. ICAO provides the emissions certification data on the worldwide web at http://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank.

Chapter 1

INTRODUCTION

1.1 PURPOSE

1.1.1 This document contains advice and practical information to assist ICAO Member States in implementing best practices with respect to airport-related air quality. Information related to State requirements, emissions from airport sources, emissions inventories and emissions allocation are addressed throughout the document.

1.1.2 This document also provides a process for States to determine the best approaches and analytical frameworks for assessing airport-related air quality and identifies best practices for different needs or scenarios. It is not intended as a basis for any regulatory action, it does not describe specific projects or actions, nor does it address research-related aspects of airport air quality.

1.1.3 As this guidance material was developed to potentially assist all ICAO Member States in implementing best practices in relation to airport-related air quality, it is necessarily broad and extensive. Accordingly, some States may already have in place some, or many, of the processes and measures addressed herein. In such cases, this manual may be used to supplement those processes and measures or used as an additional reference.

1.1.4 Since this guidance material is broad and extensive, it cannot be expected to provide the level of detail necessary to assist States in addressing every issue that might arise, given that there may be unique legal, technical or political situations associated with airports and/or air quality at particular locations. As with any guidance material of broad application, it is advised that States use it as a reference to be tailored to specific circumstances.

1.2 THE COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION

1.2.1 ICAO has been involved with airport-related emissions for many years. In particular, the ICAO Committee on Aviation Environmental Protection (CAEP) and its predecessor, the Committee on Aircraft Engine Emissions, have, since the late 1970s, continually addressed emissions standards for new engine types, their derivatives and new production engines. One of the principal results arising from their work is the ICAO provisions on engine emissions in Volume II of Annex 16 to the Convention on International Civil Aviation (the "Chicago Convention"). Among other issues, these provisions address liquid fuel venting, smoke and the following main exhaust emissions from jet engines: hydrocarbons (HC), nitrogen oxides (NO_x) carbon monoxide (CO) and particles. Specifically, they set limits on the amounts of gaseous, smoke and particle emissions in the exhaust of emission relevant civil engine types. In addition to technological innovation and certification standards, CAEP has pursued two other potential approaches for addressing aviation emissions:

a) alternative airfield operational measures; and

b) the use of market-based emissions reduction options.

1.2.2 ICAO also has produced several documents related to aircraft emissions, including the three-part *Airport Planning Manual* (Doc 9184) and the *Operational Opportunities to Reduce Fuel Burn and Emissions* (Doc 10013), the latter having replaced *Operational Opportunities to Minimize Fuel Use and Reduce Emissions* (Circular 303, now obsolete).

1.2.3 Doc 9184, Part 2 – *Land Use and Environmental Management* provides guidance on land-use planning in the vicinity of airports and includes information on available options for reducing airport-related emissions and improving fuel efficiencies of aircraft engines.

1.2.4 Doc 10013 identifies and reviews various operational opportunities and techniques for minimizing aircraft engine fuel consumption and, therefore, emissions associated with civil aviation operations. The manual builds on the information previously provided in Circular 303.

1.3 BACKGROUND

1.3.1 Interest in aircraft and airport air pollutant emissions has been on the rise ever since the substantial increase in commercial turbojet traffic in the 1970s. Aircraft emissions produce air contaminants such as NO_X, HC and fine particulate matter (PM), which in turn can involve broader environmental issues related to ground level ozone (O_3), acid rain and climate change, and present potential risks relating to public health and the environment. Unlike most transportation modes, aircraft travel great distances at a variety of altitudes, generating emissions that have the potential to have an impact on air quality in the local, regional and global environments.

1.3.2 ICAO recognizes that airport-related sources of emissions have the ability to emit pollutants that can contribute to the degradation of air quality of their nearby communities. As such, national and international air quality programmes and standards are continually requiring airport authorities and government bodies to address air quality issues in the vicinity of airports. Similarly, attention must also be paid to other possible airport-related environmental impacts associated with noise, water quality, waste management, energy consumption and local ecology in the vicinity of airports, to help ensure both the short- and the long-term welfare of airport workers, users and surrounding communities.

1.3.3 Notably, significant improvements have been made over the past three decades regarding aircraft fuel efficiency and other technical improvements to reduce emissions. However, these advancements may be offset in the future by the forecasted growth of airport operations and other aviation activities. Because aircraft are only one of several sources of emissions at an airport, it is also considered essential to effectively manage emissions from terminal, maintenance and heating facilities; airport ground service equipment (GSE); and various ground transport travelling around, to and from airports. Optimizing airport design, layout and infrastructure; modifying operating practices for greater efficiencies; retrofitting the GSE fleet to “no-” or “low-” emitting technologies; and promoting other environmentally-friendly modes of ground transport are some of the current opportunities airports and the rest of the aviation industry can adopt or apply to help meet these goals and encourage sustainable development in commercial air transportation.

1.4 AIR QUALITY ASSESSMENT

1.4.1 In most areas, air quality is regulated by a combination of national, regional and/or local regulations[1] that establish standards on emissions sources and/or ambient (i.e. outdoor) levels of various pollutants and define the procedures for achieving compliance with these standards. For example, Figure 1-1 shows the relationship of the principle requirements of an air quality assessment reflecting this legal framework.

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[1] This guidance material generally uses the term “regulations” to refer to national air quality laws and regulations (which can include national regulations adopted to incorporate ICAO emissions Standards for aircraft engines) and “Standards” when referring to ICAO engine emissions Standards. Some national air quality regulations, however, are themselves called “standards” (e.g. the National Ambient Air Quality Standards, or NAAQS, in the United States). Where national schemes refer to their own air quality provisions as “standards”, that terminology will be used in this guidance when referring to those provisions. To avoid confusion in terminology, the guidance will specifically refer to ICAO engine emissions Standards as “ICAO” Standards.

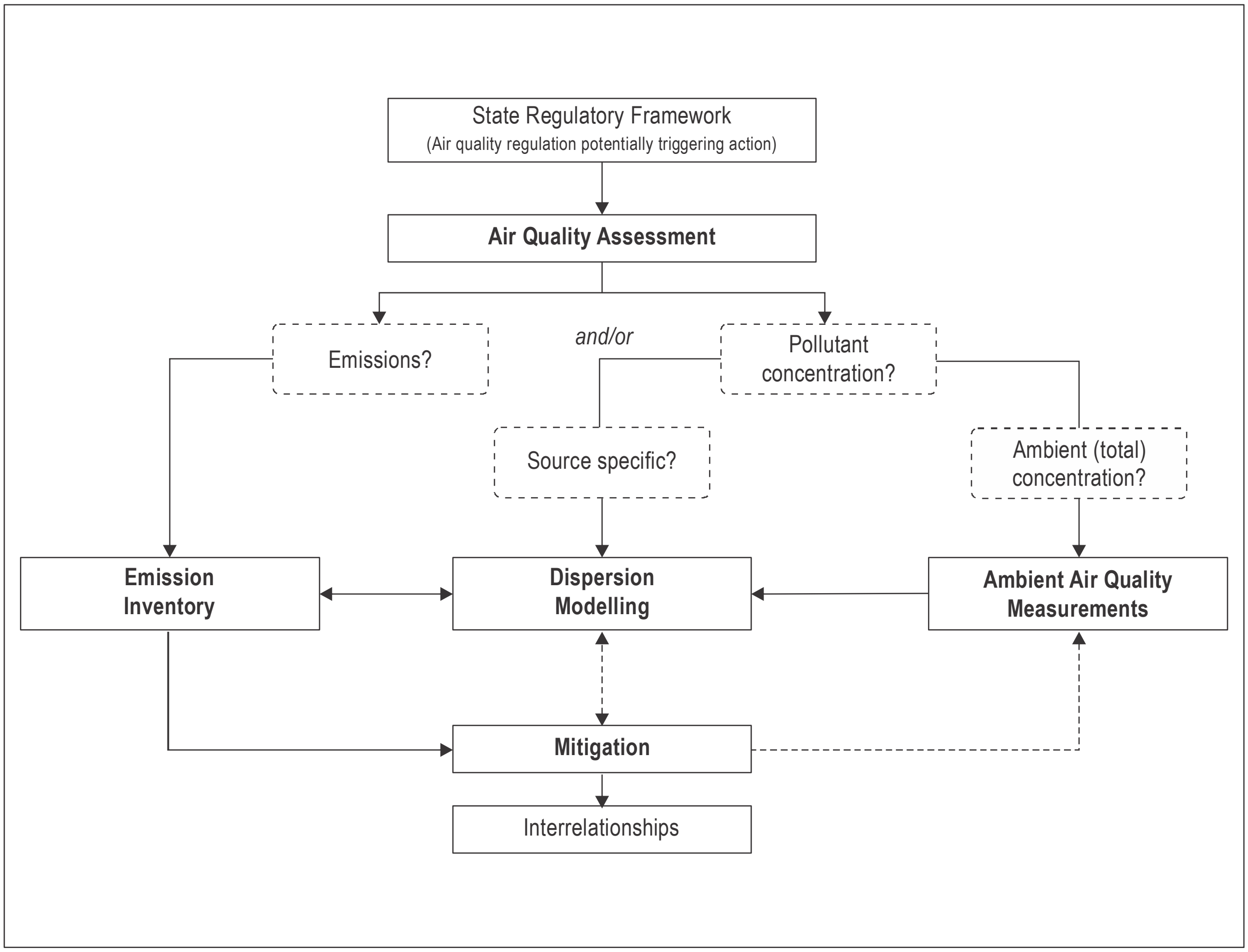

Figure 1-1. Local air quality elements and their interactions

1.4.2 As shown, the two main areas of an air quality assessment are:

a) the emissions inventories; and

b) the dispersion modelling of pollution concentrations.

An emissions inventory gives the total mass of emissions released into the environment and provides a basis for reporting, compliance and mitigation planning, and can be used as input for modelling pollution concentrations[2]. In order to link emissions to pollution concentrations, the spatial and temporal distribution of the emissions have to be assessed as well. This combined approach of using emissions inventories and dispersion modelling enables the assessment of historical, existing and/or future pollution concentrations in the vicinities of airports or from individual emissions sources.

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[2] There is one exception to the total mass of emissions, if non-volatile particle number emissions are assessed: For non-volatile particle number emissions, the total *number* of emitted particles respective to the particle *number* concentration is computed.

1.4.3 Existing pollution concentrations can also be assessed by measuring (for example, sampling and monitoring) ambient conditions, although this assessment method can include contributions from other nearby and distant sources, including those that are non-airport related. Depending on the specific task, computer modelling results and ambient measurements can be used for evaluating existing or historical conditions. In contrast, future conditions can only be simulated using computer modelling.

1.4.4 The emissions inventory, concentration modelling and ambient measurement elements of an air quality assessment can be used individually or in combination to aid the process of understanding, reporting, compliance and/or mitigation planning by providing information on overall conditions as well as specific source contributions.

1.4.5 Ambient air quality measurements normally do not provide specific source contributions, although knowledge of airport emissions contributions can be important. Exemplary inclusion of all emission sources for concentration modelling and comparison of concentration results to measurement results can instil confidence in the modelling results for airport source contributions.

1.4.6 Subsequent air quality mitigation or other implemented measures (with proper consideration of the interrelationship with, primarily, noise and other airport environmental impacts) can have beneficial results for the total emissions mass, the concentration model results and measured concentrations.

Chapter 2

REGULATORY FRAMEWORK AND DRIVERS

2.1 INTRODUCTION

2.1.1 States (and their delegates) have historically adopted local air quality regulations to protect public health and the natural environment. Local air quality may be generally described as the condition of the ambient air to which humans and nature are typically exposed. In most cases, determining the quality of the air is based on the concentration of pollutants (both from natural and anthropogenic sources, that is, human-made sources). These concentrations are compared to regulations and standards that are established to define acceptable levels of local air quality, including the necessary measures to achieve them. Many issues particular to the local air quality in and around airports are subject to these same regulations. In this context, there are assorted and varying pressures on individual States relating to air quality in the vicinity of airports, including:

a) worsening local air quality leading to reduced margins against existing regulations;

b) increased awareness of health impacts, prompting the introduction of new regulations, including the addition of new pollutant species;

c) development constraints resulting from limitations imposed by the need to meet local air quality regulations;

d) greater public expectations regarding local air quality levels; and

e) increased public concerns about the effects of aircraft.

2.1.2 These pressures also need to be considered in the wider context of other pressures on aviation – notably the impact of aviation emissions on climate, the impact of aviation noise on the community, and the economic status of the aviation industry. These additional pressures bring their own economic and regulatory measures which in most cases raise trade-off issues with each other and with local air quality in the vicinity of airports.

2.1.3 Typically, airport environments comprise a complex mix of emissions sources including aircraft, GSE, terminal buildings and ground vehicular traffic. For any given State, there is often an associated complex mix of existing regulations and standards covering many of the sources of emissions that are present at airports (for example, aircraft engines, transport vehicle engines, power-/heat-generating plants and aircraft maintenance facilities). In this regard, regulations covering non-aircraft sources are generally established nationally. By comparison, emissions Standards for aircraft engines are agreed internationally through the ICAO CAEP and subsequently adopted into domestic regulations by each ICAO Member State.

2.1.4 In most countries, national authorities establish the guiding principles and objectives for attaining and maintaining acceptable air quality conditions. Together with regional and local authorities, they also have important tasks in taking air quality measurements, implementing corrective plans and programmes and informing the general public of matters pertaining to local air quality conditions.

2.2 DRIVERS FOR ACTION

2.2.1 Legal requirements, established for the protection of public health and the environment as early as the mid-20th century and adapted periodically in response to the latest technology and health science, created a driver for action by many industries (including aviation) and the need to comply with regulations. In some cases, air quality compliance in environmental impact statements and assessments became a required consideration in airport development initiatives.

2.2.2 In parallel with the local air quality regulations, increased public awareness and expectations regarding air quality, expressed through media, government and stakeholder groups, also applied pressure on the aviation industry. These initiatives also served as drivers for the aviation industry to inform the public and, where appropriate, to attempt to meet those expectations.

2.2.3 Among the options open to the aviation industry as a response to these drivers is the control of emissions from aircraft engines. In 1971, ICAO published Annex 16, *Environmental Protection,* Volume I – *Aircraft Noise,* followed in 1981 by Volume II – *Aircraft Engine Emissions*. These Standards covered the prohibition of fuel venting and the limiting of emissions of HC, CO, NO_x and smoke, the latter in the form of a smoke number (SN). The Annex 16 Volume II was updated in 2020 to include particulate matter (nvPM mass and number). Annex 16, Volume III, published in 2017, covers the fuel efficiency (CO_2 emissions) standards for aircraft.

2.2.4 The ICAO engine emissions Standards are applied through national and multi-national certification processes to turbojet and turbofan engines greater than 26.7 kilonewtons (kN) of thrust, but not turboprops, turboshafts, piston engines or aircraft auxiliary power units (APUs). The ICAO Standards are based on uninstalled engine performance measured against an idealized landing and take-off (LTO) cycle up to 914 m (3 000 ft) above ground level (AGL). Certification procedures are carried out on a single engine in a test cell, referenced to static sea level and International Standard Atmosphere (ISA) conditions. It is widely recognized that the ICAO Standards used in certification differ from actual aircraft emissions that occur in specific locations and operational situations. Nevertheless, some States currently use the ICAO Standards as default values for some local air quality assessment purposes. Therefore, one of the key purposes of this document is to provide a methodology that produces a more precise assessment of actual aircraft engine emissions than the use of default ICAO Standards.

2.2.5 Finally, it is worth noting that aircraft engine technology has reached a stage where there are fewer developments that reduce both noise and emissions together. With the continuing drive to reduce aircraft environmental impacts, there are expanding needs to assess the trade-offs between reducing noise and emissions and the effect on greenhouse gas emissions (among these emissions is CO_2, associated with fuel burn), whenever a new aircraft is designed and operated.

2.3 LOCAL AIR QUALITY REGULATIONS AND POLLUTANT REGULATION

2.3.1 Local air quality regulations often regulate specific emissions species from combustion or fugitive processes as well as formation of the secondary pollutants that these emissions may cause by prescribing maximum allowable concentrations. As a result, regulations may vary and be tailored to the local conditions and priorities in the countries where they are applied. An example of this is the difference in emphasis that the European Union (EU) and the United States place on NO_2, NO_x and O_3, with many EU States more concerned with NO_2 concentrations and the United States and others, more concerned with NO_x emissions, which is an O_3 precursor.

2.3.2 States have also historically developed their own local air quality regulations and/or guidelines, and therefore a number of national regulatory criteria exist worldwide. Table 2-1, although not comprehensive in its coverage, is included to demonstrate the variability that exists between States for a number of air pollutants. Beyond the detail shown in the table, which might change periodically, this variability also extends to the manner in which the numerical standards are applied. For example, some regulations are treated as maximum acceptable levels, while some specify the number of acceptable exceedances. Also included in the table are the EU Air Quality Framework Directive and the World Health

Organization (WHO) guidelines for comparison. It is noteworthy that local air quality regulations are typically in the form of micrograms per cubic metre (μg/m^3) and for a specified time frame (usually hour, day or year) by pollutant.

2.3.3 The ability to conform to these national concentration guidelines and regulations is highly dependent on local variables, including meteorological conditions, background concentrations, population density, types and sizes of industry, and the types of emissions control technologies available in the area, which may be limited by affordability. The WHO guidelines recommend that the regulations cover certain time frames from one hour, eight hours, 24 hours or a year.

2.3.4 There are also parts of the world that do not have air quality regulations. In some developing countries, it is only recently that there has been rapid urbanization and industrialization resulting in the intensification of air pollution and deterioration in local air quality to levels that may warrant specific attention or corrective actions.

Table 2-1. Local air quality regulations in different countries

		Sulphur dioxide			Nitrogen dioxide			Carbon monoxide		Ozone			PM$_{2.5}$		PM$_{10}$	
		1 hour*	24 hours	Annual	1 hour	24 hours	Annual	1 hour	8 hours	1 hour	8 hours	24 hours	24 hours	Annual	24 hours	Annual
		μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	mg/m^3	μg/m^3	mg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3
WHO	WHO guidelines (updated in 2005)	–	20	–	200	–	40	30	10	–	100	–	25	10	50	20
EU	Air Quality Framework Directive	350	125	–	200	–	40	–	10	–	120	–	–	25	50	40
Australia	National Environmental Protection Measure for Ambient Air Quality	570	230	60	250	–	60	31.24	11.25	210	–	–	25	8	50	–
Brazil	Resolution 03 of CONAMA (National Council for the Environment), June 1990 – Air Quality National Standards	–	365	80	320	–	100	40	10	160	–	–	–	–	150	50
Canada	Canadian Ambient Air Quality Standards, 2020	186	–	13	115	–	33	–	–	–	124	–	27	8.8	100	60
China	Ambient Air Quality Standards GB3095 – 2012 (Class 1 – cities)	150	50	20	200	80	40	10	–	160	100	–	35	15	50	40
India	National Ambient Air Quality Standards, notified on 18 November 2009	–	80	50	–	80	40	4	2	180	100	–	60	40	100	60
Japan	Ministry of the Environment Environmental Quality Standards	260	100	–	–	100	–	12	25	120	–	–	35	15	–	–
South Africa	Air Quality Act (No. 39 of 2004) (SANS 1929:2011)	350	125	50	200	–	40	30	10	–	120	–	40	20	75	40
Switzerland	Swiss Luftreinhalteverordnung (LRV)	–	100	30	–	80	30	–	–	120	–	–	–	10	50	20
United States	NAAQS (as of May 2020)	197	–	–	188	–	100	40	10	–	140	–	35	12 Primary 15 Secondary	150	–

μg/m^3 = micrograms per cubic metre.

* Time periods given are those over which the average pollutant concentrations are measured.

2.3.5 In many countries, regional and local authorities carry out the monitoring of local air quality but they also have an important task in taking corrective measures, implementing management plans and other programmes to meet the requirements of the local air quality regulations.

2.3.6 Increased urbanization is a concern in many countries and there is a tendency for airports to attract new development areas. Some States use available land-use planning measures to manage this growth in order to prevent incompatible development in the surrounding countryside from encroaching on airport boundaries. Providing a buffer for airport-related noise and emissions is also commonly practised. Planning permits for the creation or expansion of airports requires consultation with key stakeholders and strategic decision-makers at national, regional and local levels. This often will include engaging railway, highway and planning authorities.

2.4 AIRCRAFT ENGINE AND ROAD VEHICLE EMISSIONS STANDARDS AND REGULATIONS

2.4.1 Presently, the regulations and standards affecting aircraft and other airport sources of emissions typically fall into two distinct categories:

a) ***Measures that set limits on particular sources of emissions.*** These include both ICAO aircraft engine emissions Standards (as adopted into national and multi-national regulations) and national measures establishing limits for non-aircraft sources such as stationary facilities (such as boilers, generators, incinerators) and road vehicles; and

b) ***National regulations*** (in some States called “standards”) establishing ambient pollutant concentrations for local air quality conditions (such as local air quality limit values).

2.4.2 The distinction above is important because, while all the individual emissions sources operating at or in the vicinity of a particular airport may meet limits pertaining to that type of source (including ICAO Standards for aircraft engines), the local pollutant concentration thresholds still may not be met. This may be due to a variety of factors particular to each locality, including road and air traffic volumes, topography, short-term meteorological conditions and proximity to other emissions sources and/or high background pollution levels.

2.4.3 Airport studies confirm that aircraft may be a relatively small contributor to regional pollution, although, as an example, aircraft-related NO_x contributions could increase as air traffic increases and other non-aircraft emissions sources become progressively cleaner. Therefore, although reductions in aircraft emissions (through operational and air traffic measures and/or more stringent ICAO engine Standards) can help to improve local air quality in the vicinity of airports, it is also important to consider the emissions from both regional and local road vehicles. Within this context, the emissions performance of new road vehicles is expected to improve significantly in coming years. Therefore, depending upon the circumstances in particular localities, the relative proportion of the total airport-related emissions that are attributable to aircraft emissions could increase as a consequence.

2.4.4 The international nature of commercial aviation has resulted in the development of uniform international certification Standards, developed within ICAO CAEP and adopted by the ICAO Council. New aircraft engines that are certified after the effective date of an ICAO Standard are required to meet that Standard. ICAO engine emissions Standards are contained in Annex 16, Volume II, and were originally designed to respond to concerns regarding emissions that affect local air quality in the vicinity of airports. These engine Standards establish limits of NO_x, CO, HC, nvPM and smoke for a reference LTO cycle up to 914 m (3 000 ft) in height above the runway.

2.4.5 ICAO first established aircraft engine emission standards for smoke, NOx, HC and CO in 1981, applying to turbofan and turbojet engines greater than 26.7 kN rated thrust. The smoke emission standard applied to all turbofan and turbojet engines irrespective of the rated thrust. NO_x emissions Standards have gradually been tightened since their introduction. Adopted in 1981, the ICAO Standard for NO_x was made more stringent in 1993 when ICAO reduced the permitted levels by 20 per cent for newly certificated engines, applicable 1 January 1996, with a production cut-off of

1 January 2000. In 1999,[1] ICAO tightened the NO_x Standard by about 16 per cent on average for engines newly certified from 1 January 2004. In 2005, the ICAO Council adopted the CAEP decision for a further tightening of the NO_x Standard so that the Standard, with an applicability date of 1 January 2008, was 12 per cent more stringent than the levels agreed in 1999. In 2011, ICAO tightened the NO_x Standard again, delivering a 15 per cent reduction (at an overall pressure ratio (OPR) of 30) with an applicability date of 1 January 2014. For the engines to which they apply, the combined effect of these changes has been a 50 per cent tightening on average of the original ICAO NO_x emissions Standards.

2.4.6 In 2016, ICAO introduced the first nvPM engine emission Standard applicable to all in-production turbofan and turbojet engines with rated thrust greater than 26.7 kN, from 1 January 2020. In 2019 ICAO added LTO based regulatory limits for non-volatile particulate matter (nvPM) mass and number emissions for the same engine categories, for in-production engines and new types, applicable from 1 January 2023.

2.4.7 With the introduction of the nvPM Standards, the smoke number Standard is no longer needed for the respective engine categories and its applicability for those engines ended on 1 January 2023. For the small turbofan and turbojet engines with less than or equal to 26.7 kN rated thrust, the smoke number Standard continues to be applicable. ICAO Standards also require that fuel not be vented from the main propulsion engines during normal engine shutdown.

2.4.8. At present there are no ICAO pollutant emission Standards related to turboprop engines, aircraft APU, helicopter gas turbines or aircraft piston engines.

2.4.9 National application of ICAO Standards in the certification process for aircraft engines employs a "type-testing" approach. This involves the engine manufacturer demonstrating to the certificating authority by use of a limited number of engines that the engine type pending certification meets the ICAO Standards. All of the engines of this type are then given an emissions certification on an engine-type basis. This certification is also effective for the life of the engine type (for example, there is no requirement for an emissions check after engine maintenance or overhaul procedures). However, there is typically only a small change in emissions during the service life of the engine and this is discussed elsewhere in this guidance material.

2.4.10 Non-aircraft emissions sources at and in the vicinity of airports are subject to nationally-determined emissions source limits rather than Standards set by international bodies such as ICAO. Identifying and quantifying these key non-aircraft emissions sources are important for assessing local air quality in the vicinity of airports. These sources include other airport-related activities, such as road vehicles accessing the airport and operating on nearby roadways, airside vehicles such as tugs, other GSE, fire engines, as well as other sources in the geographical area deemed relevant to the assessment under the national regulatory scheme.

2.4.11 As previously mentioned, road vehicles fitted with engines are typically regulated to some degree under national regimes but they differ in how they are regulated. For example, heavy-duty vehicles are typically regulated based on engine performance characteristics alone (such as in grams per kilowatt-hour), because of the wide variety of vehicles (from light box trucks to 38-tonne articulated vehicles and buses) in which these engines can be used. In this sense, these emissions source regulations are comparable to the ICAO Standards applicable to aircraft engines, which are also based on the engine type alone. For light-duty road vehicles (cars, vans, etc.), regulations are established for each vehicle/engine combination. Hence there are a myriad of regulations covering the different requirements for each combination of vehicle type, fuel type, engine type, power rating and emissions reduction device. Within the EU, passenger road vehicles are regulated based on their emissions per kilometre, using test drive cycles[2] designed to be representative of on-road conditions and load. The test cycles are effectively traces of vehicle speed versus time, simulating a predetermined set of on-road urban and rural and motorway driving conditions.

2.4.12 GSE and vehicles operating airside are also subject to an assortment of emissions regulations based on their heavy-duty/light-duty (or off-road/on-road) utilization characteristics. For example, many GSE fall under non-road

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[1] Details are available in Annex 16, Volume II Amendment 10

[2] The "New European Drive Cycle".

mobile machinery standards if the vehicle is never intended for road use. These vehicles are regulated based on the engine alone, typically with a test cycle representing off-road duty patterns. Vehicles used at airports that are also used in a normal road context, such as fire engines or delivery vehicles, are subject to a State's normal road emissions regulations, as previously discussed.

2.4.13 Hence, while aircraft, road vehicles and airside vehicles are regulated using specified procedures (including reflecting steady state or theoretically representative conditions either for the engine or for the total vehicle), the emissions actually produced at a particular site will likely show differences from these conditions. For example, the range of road vehicles tested is relatively small for each production vehicle/engine combination; there are wide variations in traffic conditions, driving style and weather conditions – all of which have a bearing on the actual emissions levels.

2.5 CHANGING REGULATIONS AND TECHNOLOGY TARGETS

2.5.1 Local air quality regulations are still evolving and gradually becoming more stringent as industrial activities and transportation systems expand and the impact of local air quality on human health is better understood. Given the continued expansion of most industry sectors, performance and technological improvements to airport-related emissions sources must be made if any increased stringencies are to be met.

2.5.2 In recognition of growing pressures from possible local air quality and climate effects, coupled with the predicted continued growth in air traffic, aviation stakeholders have set out their goals and vision for the future of aircraft emissions in the medium and long term. Those set by the Advisory Council for Aeronautics Research in Europe (ACARE) and the National Aeronautics and Space Administration (NASA) in the United States are two examples.

2.5.3 Looking forward, CAEP is anticipating further stringency increases in ICAO aircraft engine pollutant emissions Standards by LTO. In particular, NO_x and particulate matter are examined, although potential reductions will be assessed against trade-offs, including with noise, fuel consumption and cost. Engine and airframe technology development have to take existing trade-offs into consideration. Therefore, the evaluation of environmental effects and long-term consequences from individual measures is very important to establish the future priority improvements. A key example is the trade-off between fuel burn reduction and NO_x emissions increase. Evaluation of the trade-offs from any regulatory change and its attendant technological consequences will therefore be required for all future changes in ICAO engine Standards. To support this activity, CAEP has established a process to set medium-term (e.g. 10-year) and long-term (e.g. 20-year) NO_x technology goals. CAEP will use this process in determining the degree to which technology-based NO_x reductions are appropriate to meet local air quality needs while taking into account other environmental and economic requirements and their interdependencies. Such goals will facilitate concerted government and industry efforts on this issue and lead to better informed forecasts and scenarios in aviation-related air quality over the next 20-year timescale. This is even more important, as gas turbines (and kerosene or kerosene-like fuel combustion) will still play a major role in aircraft propulsion in the decades to come.

Chapter 3

EMISSIONS INVENTORY

3.1 INTRODUCTION

3.1.1 Airports and their associated activities are sources of an assortment of gaseous and particulate emissions. Within the context of airport air quality, the total amount (usually expressed as mass) of airport emissions meeting particular characterizations is an important value with respect to their relative impacts and regulatory compliance issues. This value is determined through the completion of an emissions inventory. Emissions inventory objectives can include, but are not necessarily limited to, the following:

a) collecting information on emissions while monitoring trends and assessing future scenarios;

b) benchmarking emissions against legal requirements (such as thresholds);

c) creating input data for dispersion models in an effort to determine pollution concentrations; and

d) establishing mitigation programme baselines.

3.1.2 A bottom-up process is typically used to calculate emissions inventories because this approach can provide a high level of accuracy. As such, the first step requires the calculation of the emissions mass by source, time period and pollutant. These variables are calculated by using information about individual emissions sources with their associated emission factors (expressed as grams per kilogram of fuel, grams per hour of operation or grams per kilowatt of power) and the respective operational parameters over a determined period of time (activity profile). These two parameters are then used to calculate the total source-related emissions at the airport. The total emissions source can then be expressed in various forms such as an individual source or group of sources, by pollutant or by period of time (hour, day, week, month or year).

3.1.3 In order to develop an emissions inventory, the following steps are required:

a) define general inventory parameters such as the purpose, spatial and functional perimeter and frequency of updates;

b) determine the emissions species to be considered;

c) determine the existing emissions sources;

d) quantify the emissions from those sources;

e) consider macroscale issues (regional emissions inventories) to the extent relevant; and

f) implement quality assurance and control measures (to characterize uncertainties and limitations of data).

3.2 EMISSIONS INVENTORY PARAMETERS

3.2.1 The following factors should be considered when developing an emissions inventory:

a) ***Inventory purpose.*** The use of and requirement for an emissions inventory largely determines its design. If the requirement is solely to calculate the total emissions mass, then the methodologies utilized will be simple and straightforward. If the inventory is to be utilized as part of a dispersion model, the methodologies could be different and more detailed because dispersion modelling requires spatial and more detailed temporal information. The design of the emissions inventory has to take this into account so as not to limit its future use.

b) ***System perimeter.*** The system perimeter defines the spatial and the functional area within which emissions will be calculated. The spatial area could be the airport perimeter fence, a designated height (for example, mixing height) and/or access roads leading to the airport. The functional area is typically defined by emissions sources that are connected functionally to airport operations, but could be located outside the airport perimeter (such as fuel farms).

c) ***Updates.*** The frequency of inventory updates influences the design of the inventory and any applied databases or data tables (for example, one annual value versus many values over the year determines the necessary temporal resolution). It is also important to evaluate the efforts needed and available to compile the inventory at a certain frequency.

d) ***Level of accuracy/complexity.*** The necessary accuracy level of data inputs is determined by the fidelity required for the analysis and the knowledge level of the analyst. This guidance is intended to be a framework for conducting analysis at various levels of complexity. Whenever possible, guidance is given for three different levels of complexity:

   1) simple approach;

   2) advanced approach; and

   3) sophisticated approach.

3.2.2 As shown in Table 3-1, an emissions inventory can be conducted at various levels of complexity, depending on the required fidelity of the results as well as the availability of the supporting knowledge, data and other resources. This guidance material is intended to be a framework for conducting studies at various levels of complexity. Whenever possible, guidance is given for three different levels of complexity (simple, advanced and sophisticated). When conducting an analysis, the approach applied should also be stated.

Table 3-1. Emissions inventory conducted at three levels of complexity

Characteristics	Simple approach	Advanced approach	Sophisticated approach
Complexity	Basic knowledge required; necessary data are easy, standardized and available; straightforward methodology.	Advanced knowledge, airport-specific and/or access to additional data sources are required.	In-depth knowledge, cooperation among various entities and/or access to proprietary data might be required.
Accuracy	Generally conservative	Good	Very high
Confidence	Low	Medium	High

3.2.3 Unless required otherwise for specific legal reasons or regulatory compliance, it is recommended to make use of the best available data for creating emissions inventories while considering the level of accuracy and confidence required. This could evolve to using advanced and/or sophisticated approaches rather than a simple approach. Approaches can also be combined by using one approach for one emissions source and a different approach for another emissions source in compiling the inventory. In addition, combinations of approaches could be used for the same emissions source where various parameters are needed to calculate the emissions mass.

3.3 EMISSIONS SPECIES

3.3.1 There are a variety of air pollutants present as gaseous and particulate emissions from aviation-related activities that can potentially have an impact on human health and the environment. However, not all of them are relevant or needed for emissions inventories. State requirements should be consulted to determine which emissions species are actually necessary to the inventory. Generally, the following common species could be considered as primary species in emissions inventories:

a) nitrogen oxides (NO_x), including nitrogen dioxide (NO_2) and nitrogen oxide (NO);

b) volatile organic compounds (VOC), including non-methane hydrocarbons (NMHC);

c) carbon monoxide (CO);

d) non-volatile particulate matter mass (nvPMmass), corresponding mainly to black carbon mass;

e) $PM_{2.5}$ and PM_{10} mass, where the sum of volatile plus non-volatile particulate matter mass is used as a proxy for $PM_{2.5}$ and PM_{10};[1]

f) non-volatile particulate matter number (nvPMnumber), corresponding mainly to black carbon particle number; and

g) sulphur oxides (SO_x).

3.3.2 Carbon dioxide (CO_2) is sometimes included in inventories (using the total fuel burn or refrigerant uses as a basis for calculation). It must be recognized that CO_2 is of a global rather than a strictly local concern, but local CO_2 inventories can feed into global inventories where required.

3.3.3 Additional emissions species of potential health and environmental concern may also need to be considered in emissions inventories, including so-called hazardous air pollutants (HAPs). Low levels of HAPs are also present in aircraft and GSE exhaust in both the gaseous and particulate forms. It should be noted that knowledge of emission factors is very limited for many of these species. Therefore, the creation of an inventory of HAPs might not be possible, or such an inventory cannot be expected to have the same level of fidelity as other, more common species. In such cases, the proper authorities would have to provide further guidance. Examples of HAPs that have been identified as being representative of airport sources of air emissions include (but are not necessarily limited to) the following:

a) 1,3-butadiene;

b) acetaldehyde;

c) acrolein;

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1. Aircraft engine exhaust particles are much smaller in geometric diameter than 2.5 micrometers. Therefore, $PM_{2.5}$ exhaust equals PM_{10} exhaust for aircraft engines.

d) benzene;

e) diesel particulate matter;

f) formaldehyde;

g) lead (this is relevant for leaded fuel, e.g. avgas, which is used only in a few small aircraft types);

h) naphthalene;

i) propionaldehyde;

j) toluene; and

k) xylene.

3.4 AIRPORT-RELATED EMISSIONS SOURCES

3.4.1 A wide assortment and number of emissions sources can be found at airports. However, depending on the specific activities at individual airports, not all types of emissions sources are actually present (for example, some are located off-airport). To better account for this variability, the emissions sources have been grouped into four categories:

a) aircraft emissions;

b) aircraft handling emissions;

c) infrastructure- or stationary-related sources; and

d) vehicle traffic sources.

3.4.2 Categories of aircraft emissions sources typically comprise the following:[2]

a) ***Aircraft main engine.*** Main engines of aircraft within a specified operating perimeter (from start-up to shutdown).

b) ***Auxiliary power unit (APU).*** A self-contained power unit on an aircraft providing electrical/pneumatic power to aircraft systems during ground operations.

c) ***Aircraft frame***. Wear of brakes and tires during ground operations.

3.4.3 Aircraft handling emissions sources typically comprise the following:

a) ***Ground support equipment (GSE).*** GSE necessary to handle the aircraft during the turnaround at the stand: ground power units, air climate units, aircraft tugs, conveyer belts, passenger stairs, forklifts, tractors, cargo loaders, etc.

b) ***Airside traffic.*** Service vehicle and machinery traffic (sweepers, trucks (catering, fuel, sewage), cars, vans, buses, etc.) within the airport perimeter fence (usually restricted area) that circulate on service roads.

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[2] There are potential emissions source issues relevant to but not covered in this guidance material that have been identified and are the subject of further investigation.

c) ***Aircraft refuelling.*** Evaporation through aircraft fuel tanks (vents) and from fuel trucks or pipeline systems during fuelling operations.

d) ***Aircraft de-icing.*** Application of de-icing and anti-icing substances to aircraft during winter operations.

3.4.4 Stationary- or infrastructure-related source categories of emissions comprise the following:

a) ***Power-/heat-generating plant.*** Facilities that produce energy for the airport's infrastructure: boiler house, heating/cooling plants, co-generators.

b) ***Emergency power generator.*** Diesel generators for emergency operations (such as for buildings or for runway lights).

c) ***Aircraft maintenance.*** All activities and facilities for the maintenance of aircraft, that is, washing, cleaning, paint shop, engine test beds.

d) ***Airport maintenance.*** All activities for the maintenance of airport facilities (cleaning agents, building maintenance, repairs, landscaping) and machinery (vehicle maintenance, paint shop).

e) ***Fuel.*** Storage, distribution and handling of fuel in fuel farms and vehicle fuel stations.

f) ***Construction activities.*** All construction activities associated with airport operation and development.

g) ***Fire training.*** Activities for fire training with different types of fuel (kerosene, butane, propane, wood).

h) ***Surface de-icing.*** Emissions of de-icing and anti-icing substances applied to aircraft moving areas and service and access roads.

3.4.5 Landside traffic emissions sources comprise the following:[3]

a) ***Vehicle traffic.*** Motor bikes, cars, vans, trucks, buses and motor coaches associated with the airport on access roads, curbsides, drive-ups, and on- or off-site parking lots (including engine turn-off, start-up and fuel tank evaporative emissions) and rail or ferry.

3.4.6 The mass of emissions from each of these source categories is considered (to the extent that it is relevant to the study), and the totals are summed to provide the emissions inventory for the entire airport.

3.5 LOCAL AND REGIONAL EMISSIONS

When creating airport emissions inventories, it is important to note that an airport is always part of a wider environment that goes beyond the perimeter fence and property line of the airfield. For certain purposes, such as modelling of O_3 formation, emissions inventories of a larger regional perimeter (for example, an airshed) may be developed. The relevant governmental bodies (including local, regional and/or national authorities) would conduct these larger inventories, typically in cooperation with the airport. In particular, the system boundaries must be defined to avoid the double counting of emissions. Depending on the chosen assumptions (for example, the considered sources and their spatial extent or area boundaries), the airport inventory itself might contribute only a relatively small percentage to the overall area emissions inventory. However, an inventory in and of itself does not necessarily give an indication of the full impact of an emissions source. In some cases, dispersion modelling is used to better define the air quality impact.

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[3] Landside sources may also include trains, which are not currently within the scope of this guidance material.

3.6 QUALITY ASSURANCE

3.6.1 Depending on the local situation, developing an emissions inventory can be a complex exercise that might lead to some simplifications or limitations. In order to generally achieve reliable results, emissions inventories should go through a quality control process during and after their development. As in the following discussion, this quality control includes, but is not limited to, the discussion of missing information, the use of assumptions, error estimations, transparency/traceability of data sources and methodologies, and validation of the results.

3.6.2 ***Missing information.*** Due to the lack of availability of certain data (that is, operational data and/or accurate emission factors), information or data might be missing. In these cases, estimations or assumptions should be made prior to omissions because inventories or methodologies can be improved once data or information become available. It is generally more difficult to justify the addition of sources that have not been considered previously.

3.6.3 ***Error estimations.*** For credibility reasons and for evaluating the accuracy of an inventory, error estimations are an important part of the development of the inventory. Available data and information usually have one of three levels of quality, as shown in the following:

a) *Measured.* Data are actually measured with or without calibrated and verified tools and methods, counted or else assessed by other means directly associated with the data source. This can also include calculation of a measured value with a relationship factor (that is, taking the actually measured fuel flow and using a CO_2 relationship factor of, for example, 3 150 grams per kg of fuel to determine CO_2 mass emissions from kerosene-burning engines).

b) *Calculated.* Data are calculated using available algorithms and data not directly associated with the data source.

c) *Estimated.* Data are estimated using reference information, experience from the past or qualified assumptions.

3.6.4 For each level of data quality, an error bar (value ± absolute deviation) or percentage (value ± per cent) can be predefined and a total error can be calculated. If applied for all sources, it can easily be determined where it is appropriate to improve data quality or where higher levels of uncertainty can be accepted without significant detriment to the overall result.

3.6.5 ***Transparency and traceability.*** In order to enable effective quality control and prevent the potential duplication of emissions inventory calculations with improved data, the applied calculation methodology needs to be outlined and properly documented. Sources of information and emission factors used in inventories must be identified and referenced. When an identified ideal data source might not be a viable option, then other (such as the next best) data sources need to be specified.

3.6.6 ***Validation.*** The final results should be validated and cross-checked by a proper quality control system. This can include comparison with reference data of similar systems or recalculation of specific emissions inventory elements with different tools.

3.7 FORECASTING

While conducting air quality analysis for past and present conditions, analysts may also wish to consider the contribution of future airport emissions sources. In preparing an airport emissions inventory representing future scenarios (for example, five, 10 or 25 years into the future), a methodology should be employed that addresses all airport elements, including aircraft operations and movements, passenger and cargo handling, airport infrastructure needs and surface vehicle traffic volumes. Forecasting methodologies can become very complex undertakings and often require many assumptions and/or advanced knowledge of the airport and its environs, market behaviours, airline equipment usage and regulatory enactments. The description of detailed forecasting methodologies is generally beyond the scope of this emissions inventory guidance.

Appendix 1 to Chapter 3

METHODOLOGIES FOR THE ESTIMATION OF AIRCRAFT ENGINE EMISSIONS

1. INTRODUCTION

1.1 Aircraft main engines may, at times, receive the most amount of attention from those parties concerned with aviation emissions because they can be the dominant airport-related source. This appendix recommends methodologies for the estimation of aircraft engine emissions. Main engines are those used to propel the aircraft forward. Other on-board engines include APUs, which provide electrical power and pneumatic bleed air when the aircraft is taxiing or parked at the gate and no alternative is available. Fuel venting from aircraft fuel tanks is not allowed and therefore is not addressed as an emissions source.

1.2 Main engines are generally classified as either gas turbine turbofan or turbojet and turboprop engines fuelled with aviation kerosene (also referred to as jet fuel) or internal combustion piston engines fuelled with aviation gasoline.

Main engine emissions in the vicinity of airports

1.3 Emissions from an individual aircraft main engine combination are primarily a function of three parameters: time-in-mode (TIM), main engine emission indices (EI) and main engine fuel flow. Aggregate emissions from a fleet serving an airport also include two additional parameters, fleet size/type and number of operations. In the calculation of aircraft emissions at a given airport, the desired accuracy of the emissions inventory will dictate the values and methodology used (simple, advanced or sophisticated approach) to determine each of these parameters. While this document tries to simplify the inventory analysis into three approaches, it is generally agreed that the user may at times use a hybrid approach, combining elements from the simple, advanced and sophisticated approaches. However, care should be taken not to use a hybrid approach where all aspects are overestimated, thereby inadvertently assigning a higher burden to aircraft emissions when assessing airport inventories. Consequently, it is recommended that the analyst fully document the analysis methodology, including how this guidance material is used. This is discussed further in Chapter 4. The following information provides basic descriptions of each of these parameters:

a) ***Time-in-mode (TIM)*** is the time period, usually measured in minutes, that the aircraft engines actually spend at an identified power setting, typically pertaining to one of the LTO operating modes of the operational flight cycle.

b) ***Emission index (EI) and fuel flow.*** An EI is defined as the mass of pollutant emitted per unit mass of fuel burned for a specified engine. The ICAO Engine Emissions Data Bank (EEDB) provides the EI for certified engines in units of grams of pollutant per kilogram of fuel (g/kg) for NO_x, CO, HC, and in units of milligrams and particle number per kilogram of fuel (mg/kg or particles/kg) for non-volatile Particulate Matter (nvPM) mass and number, respectively, as well as the mode-specific fuel flow in units of kilogram per second (kg/s), for the four power settings of the engine emissions certification scheme. Multiplying the mode-specific EI by the mode-specific fuel flow yields a mode-specific emission rate in units of grams per second. Multiplying this emission rate with the TIM (in units of seconds) yields the mode-specific emission in units of grams. For more accurate inventories, adjustments to these values are necessary to take account of different power settings, installation effects, etc. Additional information is available on nvPM measured in grams per kilogram of fuel (g/kg) for mass, and number per kilogram of fuel (particles/kg) for number.

2. AIRCRAFT ENGINE EMISSIONS CERTIFICATION

2.1 For emissions certification purposes, ICAO has defined a specific reference LTO cycle below a height of 914 m (3 000 ft) AGL,[1] in conjunction with its internationally agreed certification test, measurement procedures and limits (see Annex 16, Volume II, for additional information).

2.2 This cycle consists of four modal phases chosen to represent approach, taxi/idle, take-off and climb and is a more simplified version of the operational flight cycle (see Table 3-A1-1). An example of its simplification is that it assumes that operation at take-off power abruptly changes to climb power at the end of the take-off roll and that this is maintained unchanged up to 3 000 ft. While not capturing the detail and variations that occur in actual operations, the emissions certification LTO cycle was designed as a reference cycle for the purpose of technology comparison and repeatedly has been reaffirmed as adequate and appropriate for this purpose.

Table 3-A1-1. Reference emissions LTO cycle

Operating phase	Time-in-mode (minutes)		Thrust setting (percentage of rated thrust)
Approach	4.0		30
Taxi and ground idle	26	7.0 (in) 19.0 (out)	7
Take-off	0.7		100
Climb	2.2		85

2.3 This reference emissions LTO cycle is intended to address aircraft operations below the atmospheric mixing height or inversion layer. While the actual mixing height can vary from location to location, on average it extends to a height of approximately 914 m (3 000 ft), the height used in deriving airborne TIM. Pollutants emitted below the mixing height can potentially have an effect on local air quality concentrations, with those emitted closer to the ground having possibly greater effects on ground level concentrations.[2]

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1. In an emissions inventory study, 3 000 ft above ground level is referred to as the elevation of the chosen aerodrome reference point used in the study.

2. ICAO recognizes that different States may have different standards or thresholds for designating whether a pollutant as emitted has a local effect. In many cases, this is expressed in terms of a maximum altitude up to which a particular pollutant is emitted. Some States may specify a specific altitude for such purposes. Others may direct that modelling be undertaken to identify the altitude at which pollutants may have a local effect in a particular area. This is often referred to as the mixing height within the atmospheric boundary layer. In basic terms, the mixing height is the height of the vertical mixing of the lower troposphere. Also in basic terms, the boundary layer is that part of the troposphere that is directly influenced by the presence of the earth's surface. States that specify a mixing height be determined for purposes of local air quality assessment typically have accepted models for such analyses and/or specify a default height for the mixing height, such as 3 000 ft.

2.4 The certification LTO cycle characteristics selected were derived from surveys in the 1970s. They reflected peak traffic operations (that is, typical adverse conditions) rather than average LTO operations. The justification for using these for aircraft emissions Standards was largely based on protecting air quality in and around large metropolitan air terminals during high operational or adverse meteorological conditions.

2.5 It was recognized that even for aircraft of the same type, there were large variations in actual operating times and power settings between different international airports, and even at a single airport there could be significant variations day-to-day or throughout a single day. However, the use of a fixed LTO cycle provided a constant frame of reference from which differences in engine emissions performance could be compared.

2.6 Thus, the reference emissions LTO cycle is of necessity an artificial model that is subject to many discrepancies when compared to real world conditions at different airports. It was designed as a reference cycle for the purpose of certifying and demonstrating compliance with the emissions standards in effect.

2.7 This LTO cycle, developed for certification purposes, may also be adequate for simple emissions inventory calculations. However, in light of its generic assumptions, use of this cycle typically would not reflect actual emissions. If more precise operations data are available, these data should be used instead to achieve a more accurate inventory.

2.8 As stated elsewhere in this guidance, ICAO aircraft engine emissions Standards cover emissions of CO, HC, NO_x, nvPM and smoke. They apply only to subsonic and supersonic aircraft turbojet and turbofan engines of thrust rating greater than or equal to 26.7 kN (Annex 16, Volume II). ICAO excluded, from its Standards, small turbofan and turbojet engines (thrust rating less than 26.7 kN), turboprop, piston and turboshaft engines, APU and general aviation aircraft engines on the grounds of the very large number of models, the uneconomic cost of compliance and small fuel usage compared to commercial jet aircraft.

Emissions certification data

2.9 Emissions certification testing is carried out on uninstalled engines in an instrumented and calibrated static test facility. Engine emissions and performance measurements are made at a large number of power settings (typically greater than 10) covering the whole range from idle to full power and not just at the prescribed four ICAO LTO modes. The measured data are corrected to reference engine performance conditions and reference atmospheric conditions of ISA at sea level and humidity of 0.00634 kg of water/kg of air, using well-established procedures (see Annex 16, Volume II, for additional information).

2.10 The ICAO engine emissions certification data for CO, HC, NO_x and nvPM, together with associated fuel flow rates, are reported at a set of four reference power settings defined as “take-off”, “climb”, “approach” and “taxi/ground idle”, respectively and for prescribed times at each of these power settings (that is, “time-in-mode”). However, smoke emissions are required to be reported only as a maximum value of smoke density, reported as smoke number (SN) for each engine, irrespective of the power setting (although for the majority of certified engines, mode-specific SNs are now reported). Note that beginning 1 January 2023, engines of rated thrust greater than 26.7 kN will not be required to be certified for SN. Because of this, SN data will not be reported for these engines beginning 1 January 2023.

2.11 The emissions certification values previously described are provided in the ICAO EEDB, both as individual engine data sheets and as a spreadsheet containing the data for all certified engines for which manufacturers have made data available. This data bank is publicly available on the worldwide web at http://easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank and is periodically updated. An example of an engine emissions data sheet is presented in Attachment A to this appendix.

2.12 Issue 28 and later ICAO EEDB also contain information on the nvPM mass and number emissions, together with the associated fuel flow rates at the four specified LTO reference points, both as individual engine data sheets and as a spreadsheet containing the data for all certified engines for which manufacturers have made data available. An example of an engine emissions data sheet for nvPM mass and number is presented in Attachment A to this appendix.

3. OPERATIONAL FLIGHT CYCLE DESCRIPTION

3.1 The departure and arrival phases of an actual operational flight cycle for a commercial aircraft are more complex than the four modal phases (approach, taxi/idle, take-off and climb) used for ICAO certification purposes. Actual cycles employ various aircraft engine thrust settings, and the times at those settings are affected by factors such as aircraft type, airport and runway layout characteristics and local meteorological conditions. However, there are a number of segments that are common to virtually all operational flight cycles. These are depicted in Figure 3-A1-1 and described in the subsequent sections.

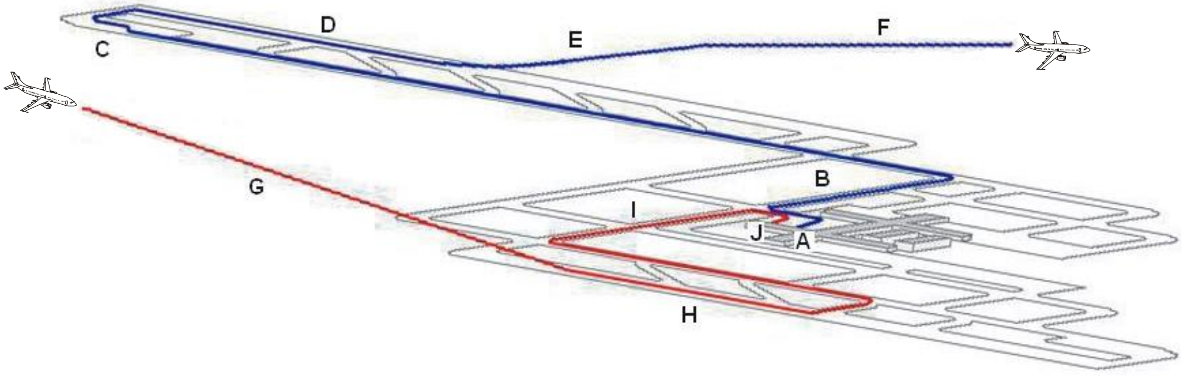

Figure 3-A1-1. Operational flight cycle

DEPARTURE

A. ***Engine start.*** It is normal to start the main engines prior to, or during, pushback from the aircraft gate/stand. Where aircraft do not require pushback, the main engines are started immediately prior to taxi.

B. ***Taxi to runway.*** Aircraft typically taxi out on all engines to the runway or holding area prior to entering the runway, though aircraft may taxi on fewer than all engines under some circumstances. Taxi-out is normally carried out at the idle/taxi power setting, apart from brief bursts of power to overcome the initial inertia at the start of taxiing or, if necessary, to negotiate sharp turns.

C. ***Holding on ground.*** Where necessary, aircraft may be required to hold in a queue while awaiting clearance to enter the runway and taxi to the take-off position. Main engines are normally set to idle thrust with brief bursts of power to move into position.

D. ***Take-off roll to lift-off.*** The aircraft is accelerated along the runway to the predetermined rotation speed at the end of the take-off run with the main engines set to take-off power. Operators rarely use full power for take-off; rather, a predetermined thrust setting is set at the beginning of the take-off roll. Operators use either derated take-off thrusts or, more often, reduced (e.g. flexible) thrust settings, which are determined by the aircraft's actual take-off weight, runway length and prevailing meteorological factors. Throttle handling during the take-off run is sometimes staged in the early part, whereby the throttles are initially set to an intermediate position, then a few seconds later are advanced to the predetermined take-off power setting.

E. ***Initial climb to power cutback.*** After leaving the ground, the undercarriage (that is, wheels) of the aircraft is raised and the aircraft climbs at constant speed with the initial take-off power setting until the aircraft reaches the power cutback height (that is, between 800 and 1 500 ft AGL) where the throttles are retarded.

F. ***Acceleration, clean-up and en route climb.*** After the throttle cutback, the aircraft continues to climb at a thrust setting less than that used for take-off, with flap/slat retraction following as the aircraft accelerates and reaches cruising altitude.

ARRIVAL

G. ***Final approach and flap extension.*** The stabilized final approach from the final approach fix (FAF) follows a relatively predictable glide slope at low engine thrusts. Thrust settings are increased to counteract the additional drag as flaps and the undercarriage are lowered, while speed decreases towards the flare.

H. ***Flare, touchdown and landing roll.*** Throttles are normally retarded to idle during the flare and landing roll. This is followed by application of wheel brakes and, where appropriate, reverse thrust to slow down the aircraft on the runway.

I. ***Taxi from runway to parking stand/gate.*** Taxi-in from the runway is a similar process to taxi-out to the runway described above; however, operators may shut down one or more engines, as appropriate, during the taxi if the opportunity arises.

J. ***Engine shutdown.*** Remaining engines are shut down after the aircraft has stopped taxiing and power is available for on-board aircraft services.

3.2 APU operation, for aircraft equipped with this equipment, is usually confined to periods when the aircraft is taxiing or stationary at the terminal. The APU is typically shut down just after main engine start-up, and after landing the APU is generally started when the aircraft is approaching the terminal area parking position. If one or more main engines are shut down during the taxi, it may also be necessary to start the APU during the taxi-in. A number of airports specify maximum APU running times, principally to limit noise in the terminal area.

3.3 As contained within the following discussion, aircraft activity at an airport is quantified in terms of either LTO cycles or operations. An operation represents either a landing or a take-off, and two operations can equal one LTO cycle (for example, taxi-out, take-off, landing and taxi-in).

4. EMISSIONS CALCULATION APPROACHES

4.1 There are various approaches, or methodologies, to quantify aircraft emissions – each with a degree of accuracy and an inverse degree of uncertainty.

4.2 This section covers three general approaches to quantifying aircraft engine emissions, with each still having several levels of complexity incorporated. Each approach may incorporate various options for certain parameters and contributing factors, depending on the availability of the data and information:

a) The simple approach is the least complicated approach, requires the minimum amount of data and provides the highest level of uncertainty, often resulting in an overestimate of aircraft emissions. It uses public information and data tables that are very easily available and requires a minimum amount of airport-specific information. This is the most basic approach for estimating aircraft engine emissions provided in this guidance. The only airport-specific data required are the number of aircraft movements (over a certain period such as a year) and each aircraft type involved in each movement (option A) or some additional basic information on the engine used for each aircraft type (option B).

   The simplified approach should be used only as a means of conducting an initial assessment of the aircraft engine emissions at an airport. For most pollutant species, the approach is generally conservative, meaning that the outcome will often overestimate the total level of aircraft engine emissions. However, for some emissions species and less common aircraft, the resultant emissions may be underestimated. As such, it is unclear how accurately the simple approach accounts for actual aircraft engine emissions at a given airport.

b) The advanced approach reflects an increased level of refinement regarding aircraft types, engine types, EI calculations and TIM. This approach requires specific airport-related information or qualified assumptions that are still publicly available but may be more difficult to obtain. It reflects local conditions in incorporating some sort of performance calculation of the aircraft. These improvements result in a more accurate reflection of main engine emissions over the simple approach, yet the total emissions are still considered conservative.

c) The sophisticated approach best reflects actual aircraft emissions. It is the most comprehensive approach, requires the maximum amount of data and provides the highest level of certainty. The sophisticated approach goes beyond LTO certification data and TIM and utilizes actual engine/aircraft operational performance data. Use of this approach requires a greater knowledge of aircraft and engine operations and in certain instances will require the use of proprietary data, or data or models that are normally not available in the public domain. In most instances, it requires the users to perform higher levels of analysis.

4.3 The alternate methodologies afford a progressively higher degree of accuracy and an inverse degree of uncertainty. The purpose and need for quantifying aircraft emissions drive the level of accuracy needed in an inventory, which in turn determines the appropriate methodology. A secondary factor is data availability. Although an analysis may warrant a high degree of accuracy, it may not be possible for certain elements of the analysis due to lack of available data. ICAO urges that if an emissions inventory involves policies that will affect aircraft operations at a particular airport, then the calculations should be based on the best data available and the simple approach should not normally be used. Where further information on the aircraft operations at an airport is available, then a more advanced approach is more appropriate.

4.4 It is also important to note that, although at its simplest level it may be possible for individuals to construct an emissions inventory, the advanced and sophisticated methods likely necessitate some form of collaboration with other aviation resources. For example, the identity of actual aircraft and engine types, realistic and accurate TIM and actual engine power settings used in the analysis, require data that are often difficult to obtain. In general, the more sophisticated the method, the greater the level of collaboration that will be required.

4.5 ICAO stresses the importance of airports and States using the best data available when assembling an aircraft engine emissions inventory. The ICAO emissions inventory methodologies increase in accuracy, moving from the simple to the advanced and eventually to the sophisticated approach. ICAO recommends selecting an approach, or portions thereof, to reflect the desired, or required, fidelity of the results. The air quality practitioner can reference these approaches as the ICAO simple approach, advanced approach or sophisticated approach. It should also be noted that the methods can be combined and that just because a simple approach is used for one part of an inventory does not preclude more precise approaches from being employed for the remaining parts of the emissions inventory.

4.6 Table 3-A1-2 provides an overview of the calculation approaches. It lists each of the four primary parameters (fleet mix, movements, TIM and EI) along with other contributing factors. Also included are explanations of how each of these parameters is determined using the three approaches (simple, advanced and sophisticated).

4.7 When choosing an approach for creating an aircraft emissions inventory, a mix of the various approaches and options can be selected. The choice is based upon the availability of data and information, as well as the required accuracy of the inventory. The various elements listed and described in Table 3-A1-2 are to some degree independent of each other; for example, not all option B elements necessarily have to go together.

4.8 For logical and consistency reasons, the “Fleet” and “Movements” elements for each approach go together. The simple approach, option A, cannot be mixed with other options or approaches either; the same holds true for the sophisticated approach. The other elements (simple approach, option B, and options A and B) can be mixed.

4.9 As a prelude to the details involved in each approach, ICAO wishes to establish the general concept within each method. In summary, the inventory starts with an individual aircraft/engine combination and generally applies the operational and emissions parameters in a two-step process, as follows:

a) ***Step one.*** Calculate emissions from a single aircraft/engine combination by summing the emissions from all the operating modes which constitute an LTO cycle, where emissions from a single mode could be expressed as:

    1) Modal emissions for an aircraft/engine combination = TIM x fuel used (at the appropriate power) x EI (at the appropriate power) x number of engines.

    2) The emissions for the single LTO operational flight cycle are then a summation of the individual parts of the cycle. In more sophisticated methods, EI and fuel flow data may not be constant throughout the TIM.

b) ***Step two.*** Calculate total emissions by summing over the entire range of aircraft/engine combinations and number of LTO cycles for the period required.

Table 3-A1-2. Overview of the calculation approaches

Key parameters	Simple approach		Advanced approach		Sophisticated approach
Fleet (aircraft/engine combinations)	Identification of aircraft group types (e.g. all B737 or all A319/320/321)		Identification of aircraft and representative engine types (e.g. all A320 with 50 per cent V52527 and 50 per cent CFM56-5B4/3)		Actual aircraft type/subtype and engine combinations (by tail number and engine (UID) or similar)
Movements	Number of aircraft movements by aircraft type (according to look-up table), as defined in “Fleet”		Number of aircraft movements by aircraft-engine combinations as defined in “Fleet”		Number of aircraft movements by aircraft tail number
Emissions calculation	Option A UNFCC look-up table (no calculation)	Option B Spreadsheet calculation	Performance-based calculation, potentially reflecting additional parameters like forward speed, altitude, ambient conditions (model-dependent)		Performance-based with actual engine data (P3/T3) and including ambient conditions
Thrust levels	Option A N/A	Option B Rated thrust	Option A Average airport and/or aircraft-group-specific reduced thrust rate	Option B Performance model calculated rated reduced thrust	Actual thrust provided by the air carrier
TIM		Option B ICAO certification LTO	Option A Modified times in mode (airport-specific average or actual for one or several modes)	Option B Performance model calculated TIM	Movement-based actual values for all modes
Fuel flow		Option B ICAO certification data bank values	Option A Derived from ICAO EEDB with thrust-to-fuel flow conversion model	Option B Derived from ICAO EEDB with performance model	Refined values using actual performance and operational data derived from the air carrier
EI	Option A Total LTO emissions mass by aircraft type	Option B ICAO certification data bank values	Option A Derived from ICAO EEDB and thrust level through BFFM2 curve-fitting method or linear interpolation using 4 or 5 points (nvPM)	Option B Derived from ICAO EEDB through BFFM2 curve-fitting method or linear interpolation using 4 or 5 points (nvPM)	Refined values using actual performance and operational data derived from the air carrier
Start-up emissions	Not considered		Consider including – see paragraphs 6.53 to 6.59		Consider including – see paragraphs 6.53 to 6.59
Engine deterioration	Do not consider – see paragraphs 6.44 to 6.52		Do not consider – see paragraphs 6.44 to 6.52		Do not consider – see paragraphs 6.44 to 6.52

5. AIRCRAFT FLEET AND MOVEMENTS

5.1 Aircraft fleet is a generic description of the various aircraft and engine combinations that serve an airport. In its simplest form, the aircraft fleet can be generally characterized according to descriptors such as, for example, heavy, large, small, turboprop and piston. For aircraft emissions inventory purposes, however, it is typically necessary to identify fleets more accurately (for example, by aircraft type).

5.2 Aircraft can be generically labelled according to manufacturer and model. For example, “A320” is an Airbus model 320 or a “B737” represents the Boeing 737, though it should be noted that a generic aircraft type may contain significant variations in engine technology and widely differing emissions characteristics between different types and their engine fits.

5.3 A more descriptive labelling for an aircraft type would also include the series number for each model, such as B747-400 (B744) for a 400 series Boeing 747 aircraft. This helps to establish the size of, and technology used in, the aircraft engine and is necessary for a more accurate emissions inventory. However, even within one class, such as B744, different airline operators may have different engine types for their own reasons.

5.4 Finally, the most accurate representation of aircraft is to identify the aircraft model and series along with the actual engines fitted on the aircraft and modifications that affect its emissions performance (for example, B777-200IGW with GE90-85B engines with DAC II combustors). Since the aircraft itself does not produce emissions, having detailed information on the engines installed on the aircraft fleet is an essential component of an accurate emissions inventory.

Simple aircraft fleet

5.5 For the simple approach, the two primary elements of the aircraft fleet (that is, aircraft and engine types) have been simplified in a list of the types of aircraft for which pre-calculated emissions data are provided. For each aircraft, the engine type has been assumed to be the most common type of engine in operation internationally for that aircraft type,[3] and emissions from that engine type are reflected in the associated emission factors. Attachment B to this appendix features Table B-1, which lists 63 aircraft and provides emissions data for each of their engine types.[4]

5.6 If the fleet servicing an airport includes aircraft that are not contained in Table B-1, then Table B-2 should be used to determine an appropriate generic aircraft. Refer to the column headed “IATA aircraft in group” to locate the aircraft type shown in the column headed “Generic aircraft type”.

5.7 If an aircraft is not contained in either Table B-1 or B-2, then it is recommended to use supplementary information such as weight, number of engines, size category and range to identify a suitable equivalent aircraft that is in Table B-1 or B-2, recognizing that this will introduce additional assumptions that may affect the accuracy of any result. In the case of an airport primarily served by regional jets, business jets and/or turboprops, it is unlikely that the range of aircraft will yield a reliable result. In these cases, a more advanced method is recommended.

Simple aircraft movements

5.8 For the simple approach, it is necessary to know (or to have an estimate of) the number of aircraft movements or operations (for example, LTO) and type of aircraft at an airport over a specified period (such as hour, day, month, or year).

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[3] As of 30 July 2004, emissions data for the B747-300 are based on proportioned emissions for the two most common engine types.

[4] CAEP initially developed these data at the request of the UNFCCC in connection with UNFCCC guidelines for national greenhouse gas inventories, which are used for global emissions issues rather than local air quality. It therefore includes data for greenhouse gas emissions that are not relevant to local air quality. These may be disregarded for purposes of inventories assembled for local air quality assessments (though some locations may wish to inventory CO_2 emissions for other purposes). Since the UNFCCC’s main focus was on greenhouse gas emissions over the entire course of flight, the data for LTO emissions are based on ICAO certification Standards and therefore will not accurately reflect actual emissions in an operating setting. In most cases, use of the refinements discussed in the advanced and sophisticated approaches will help to achieve a more accurate inventory for the relevant pollutants.

5.9 Most airports levy user charges for provision of facilities and services, typically collected as a landing fee. In these cases, airport operators have accurate records of landing movements, including the number of landings and the type of aircraft. Some airports also record the number of take-offs, although the landing records usually provide more reliable data. For this reason, at larger airports, published data on the annual aircraft movements are often available.

5.10 An LTO cycle contains one landing and one take-off, so the number of landings and take-offs at an airport should be equal. The total number of either landings or take-offs may be treated as the number of LTOs. Any difference in the number of landings and the number of take-offs will usually indicate an error in the records; if there is no explanation for this discrepancy, then the greater number should be used.

5.11 If no data are available, it will be necessary to conduct a survey of the number of aircraft movements and the types of aircraft over a short- or medium-term period (for example, one to six months), noting that there are normally seasonal differences in the number of movements at most airports.

Advanced aircraft fleet

5.12 Like the simple approach, the first step of the advanced approach is to quantify the aircraft operations or LTO by aircraft type and specific to the airport. Typically, this information can be obtained directly from airport records, thereby reflecting the most accurate form of this information. However, because no database is entirely accurate, and changes due to aircraft engine fits, temporary intermixes and other considerations over time can introduce inaccuracies, it is important to gather as much information as close to the source of the operation as is possible. If access to this information is not possible, then national traffic statistics can be accessed if available. Additional sources of data include air navigation service providers such as EUROCONTROL and the United States FAA, the Internet and the other sources described below.

5.13 The advanced approach then tries to match the various aircraft types operating at the study airport with the engines that are fitted to them. Airports typically have lists with aircraft type/engine combinations obtained from the carriers that service the airport. However, if this information is unavailable, States have access to several publicly available databases that enable the matching of aircraft types with specific engines. Attachment C to this appendix describes these important databases, which can assist practitioners in identifying the aircraft/engine combinations that characterize the fleet mix at a particular airport.

5.14 Other sources of information include the International Official Airline Guide (IOAG) database, which contains data that identify the type of aircraft, carrier and frequency of scheduled flights. In addition, the IOAG lists scheduled passenger flights by participating airlines; lists are updated on a monthly basis. IOAG provides the main components in determining the fleet mix at a specific airport such as airport, aircraft type, carrier and frequency of aircraft arrivals and departures. However, the IOAG does not include unscheduled and charter flights or general aviation flights, including business jets. The IOAG covers the flights of all United States scheduled airlines and of the majority of scheduled worldwide airlines. Specifically, Attachment C provides a description of the useful fields contained in the IOAG database. The most important IOAG airport-specific parameters are the flight number, aircraft type, carrier and schedule, when determining the number of operations at a specific airport.

5.15 Bucher & Company's "Airline Fleets Quick Reference 2020", by publisher Air-Britain, is a partial replacement of the former "JP Airline-Fleet International" (out of publication).

5.16 The Airline Service Quality Performance (ASQP) database is available from the United States Department of Transportation's (United States DOT) Bureau of Transportation Statistics (BTS). This database consists of performance and flight data for approximately 20 of the largest United States carriers. Attachment C lists the useful fields in the ASQP database. The practitioner should note that the ASQP database provides good coverage for the fleets flying in the United States and their associated markets abroad.

5.17 Depending upon the reasons for assembling an emissions inventory, a different method of assigning engines to aircraft can be used. One approach is to identify the specific engines used for the aircraft operations. This is achieved by collecting aircraft-type information, scheduled flight numbers and arrival/departure data for a specific airport (for example, using IOAG), then finding the specific engine types assigned to the identified aircraft using the available databases described above. If this degree of accuracy is not necessary, then an alternative approach can be used to estimate the engine.

5.18 This alternative is based upon the popularity of engines within the worldwide fleet. If the data available do not allow the identification of specific aircraft-engine combinations at a particular airport, these might be estimated. One way of doing this is to extrapolate the information on aircraft-engine combinations from a larger fleet database, such as a worldwide fleet database. For example, if the reference database shows that X per cent of the B777s in the worldwide fleet have Y engines, then it might be assumed for purposes of an airport inventory that X per cent of the B777s that operate into that airport have Y engines. States should be aware that a single aircraft type may be fitted with more than one type or subtype of engine, which in turn can have differing emissions characteristics in an airline's worldwide inventory.

5.19 It should be remembered that no database is entirely accurate, and changes due to aircraft engine fits, temporary intermixes, cross-referencing between databases and other considerations over time can introduce even greater levels of inaccuracy. It is therefore important to gather as much information as close to the source of the operation as is possible to minimize uncertainties.

Advanced aircraft movements

5.20 The requirements for aircraft movements needed for the advanced approach is nearly identical to that for the simple approach. It is necessary to know the number of aircraft movements or operations by type of aircraft and engine for the advanced approach. When the emissions for the single LTO are calculated for each aircraft/engine combination using the above inputs and equations, the total emissions are calculated by multiplying the single LTO emissions for each aircraft/engine by the corresponding number of movements and summing over the entire range of aircraft/engine combinations and movements for the period required.

Sophisticated aircraft fleet and movements

5.21 In the sophisticated approach it is assumed that the modeller has the actual and accurate information on aircraft type and subtype, number and correct engine name and designation for every single movement available. The match between aircraft and engine is through the aircraft registration number in connection with the ICAO, or similar, engine unique identifier (UID).

5.22 The total of the movements is derived from the actual movement information for each single aircraft serving the particular airport. Every movement (landing or take-off) is logged by the aircraft's registration number in order to provide the detailed engine information. Therefore, the number of movements for a specific aircraft type might include various numbers of this type but by varying aircraft registrations numbers.

6. AIRCRAFT MAIN ENGINE EMISSIONS CALCULATIONS

Fuel flow and emission indices

6.1 Aircraft engines with rated power greater than 26.7 kN are emissions-certified by ICAO for emissions of NO_x, CO, and HC and maximum nvPM mass and SN, based upon the standardized LTO cycle as set out in Annex 16, Volume II, and published originally in Doc 9646 (1995, now out of print) and website amendments. ICAO provides the emissions certification data on the worldwide web at http://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank. Updates to the Aircraft Engine Emissions Databank (EEDB) are made as new engines are certified. An example from the ICAO EEDB can be found in Attachment A. Additional information is provided in Attachment D, which addresses particulate matter aircraft engine emissions.

6.2 When ICAO engine data are used to calculate aircraft emissions, it is important to select the pollutant measured average value and not the pollutant characteristic level, which also is reported in the ICAO data bank. The characteristic level of a gaseous pollutant or smoke is derived for certification purposes and contains statistical coefficients corresponding to the number of engines tested.

6.3 For the vast majority of commercial aircraft engines operated at major airports, fuel flow and EI values are reported in the ICAO EEDB, at the four certification thrust settings. In addition, nvPM peak values are reported. Aircraft engine EIs are reported in grams of pollutant per kilogram of fuel consumed (g/kg), and the fuel flow rates for each mode are reported in kilograms per second (kg/s). The reported EI and fuel flow values are recommended by ICAO to be used to calculate emissions from main aircraft engines.

6.4. It has to be noted that the ICAO EEDB contains two separate data sheets of fuel flow and emission factors: one sheet for the certified gaseous emissions species and SN and one for the additional information on nvPM mass and number. The latter may contain different fuel flow information than the fuel flow reported in the gaseous emissions data sheet (See Attachment A to this Appendix). The nvPM mass and number emissions were often acquired at a later date than gaseous emissions for in-production engines and the fuel flow differences are a result of refinement to the engine cycle analysis. If consistency with prior emissions calculations is needed, an accepted simplification is to use the originally reported fuel flow information combined with the newly reported nvPM EIs. For creating new baseline emissions inventories, the later reported fuel flows may provide more accurate results.

6.5 If the ICAO EEDB contains only an input for the certified gaseous emissions and SN, but no nvPM entry, it is suggested to estimate nvPM mass and number from SN. The recommended practice is described in the scheme below Figure 3-A1-2. Two expressions are used successively. First, SCOPE11 correlation is used to get the concentration for each LTO condition. Then, it is multiplied by the volume flow rate and the system loss correction factor k_{slm} to get the EIs, with AFR being the Air-to-Fuel ratio and β being the reference Bypass Ratio of the engine. AFR at the four LTO conditions have been estimated as 106 at idle, 83 at approach, 51 at climb-out and 45 at take-off. EInum is estimated using the Geometric Mean Diameter (GMD). GMD recommended values for LTO conditions are: Idle=20nm, App=20nm, C0=40nm, TO=40 nm.

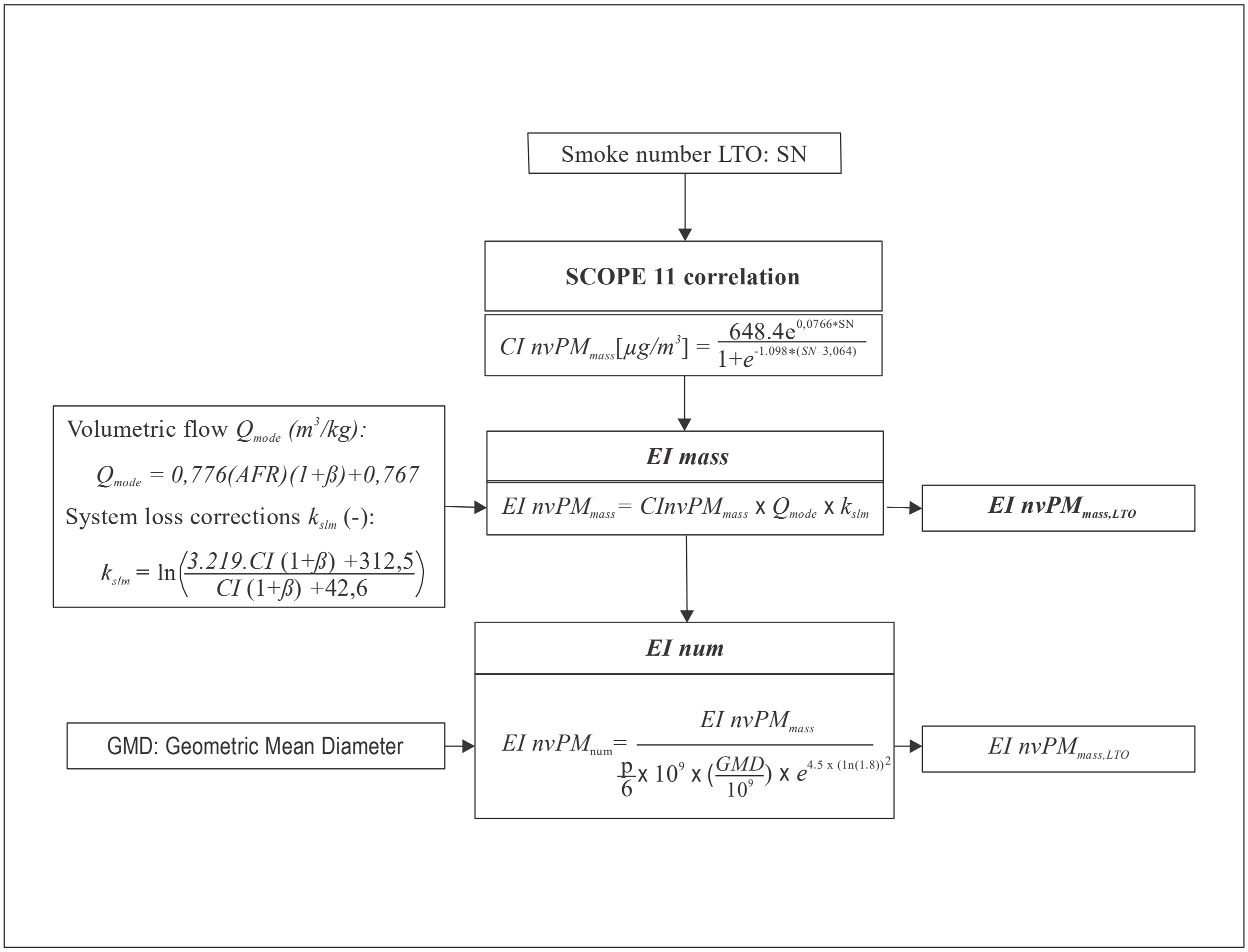

Figure 3-A1-2: Estimation of nvPM mass and number EIs from SN

6.6 There are other databases available that address EI and fuel flow information for aircraft engines that are not certified or regulated by ICAO. The following are two of the primary non-ICAO databases.

6.7 The Swedish Defence Research Agency (FOI) is the keeper of a database of EIs for turboprop engines supplied by the manufacturers for the purposes of developing emissions inventories. Although the database is publicly available only through FOI, the International Coordinating Council of Aerospace Industries Associations (ICCAIA) closely monitors who requests the use of the database to ensure the data are not misused. The FOI database is not endorsed by ICAO because the data are not certified and may have inaccuracies resulting primarily from the unregulated test methodologies. There is also the significant issue of an appropriate idle setting for turboprops. Therefore, while these data are not ICAO-certified aircraft engine emissions data, this information is included in this guidance material recognizing that the FOI turboprop database may assist airports in conducting emissions inventories. Currently, documentation on how the EIs were derived and the types of turboprop engines is unavailable. Information about turboprop engines, suggested TIM and how to obtain the data from FOI can be requested at https://www.foi.se/en/foi/research/aeronautics-and-space-issues/environmental-impact-of-aircraft.html.

6.8 Switzerland's Federal Office of Civil Aviation (FOCA) has developed a methodology and a measurement system to obtain emissions data from piston-powered aircraft and helicopters. For these engine types, there is no requirement for emissions certification; hence the FOCA data are one of the few sources of data available for conducting emissions inventories with respect to aircraft with these engines. However, the FOCA data have not been corroborated by ICAO and are not endorsed by ICAO. Therefore, while these data are not ICAO-certified aircraft engine emissions data, this information is included in this guidance material recognizing that FOCA data may assist airports in conducting emissions inventories for certain aircraft for which they otherwise might not have any data sources. The reader is referred to the FOCA website to obtain documentation on the emissions measurement system, the consistent measurement methodology and recommendations for the use of its data to conduct simple emissions inventories using suggested TIM. All material is openly available for download at www.bazl.admin.ch → Portal for Specialists → Regulations and Guidelines → Environment → Pollutant Emissions →Aircraft Engine Emissions.

Emissions calculations – simple approach (option A)

Emission indices

6.9 In the simple approach (option A), EI is replaced with an emission factor (EF),[5] and Table B-1 in Attachment B provides the emission factors for seven pollutant species for each of the listed aircraft.

6.10 The emission factor is provided in terms of kg of each emissions species per LTO cycle per aircraft (and number of particles). These have been calculated based on the representative engine type for each generic aircraft type and using ICAO TIM, thrust settings and other basic assumptions. Other assumptions are described in the notes to Table B-1 in Attachment B.

Emissions calculation

6.11 For NO_x, HC, CO, nvPMmass, nvPMnumber, SO_2 and CO_2 there is a standard method for calculating aircraft engine emissions using the simple approach (option A). For each aircraft type, multiply the number of LTO cycles of that aircraft (over the assessment period) by the emission factor in Table B-1 for each of the pollutant species and then add up the values for all the aircraft to get the amount of total emissions (in kg) for each pollutant. See the following generic equation:

$$\underset{\text{(in kg or \#)}}{\text{emission of species X}} = \sum_{\text{all aircraft}} \underset{\text{of aircraft Y}}{\text{(number of LTO cycles)}} \times \underset{\text{for species X.}}{\text{(emission factor)}} \qquad \text{Eq. 3-A1-1}$$

6.12 Notably, this equation does not account for specific engine types, operational modes or TIM because it assumes that the conditions under study are the same or similar to the default data being used.

6.13 If required for the inventory, a similar process is used for fuel consumption over the period under consideration using the fuel consumption data in Table B-1:

$$\underset{\text{(in kg)}}{\text{fuel consumption}} = \sum_{\text{all aircraft}} \underset{\text{of aircraft Y}}{\text{(number of LTO cycles)}} \times \text{(fuel consumption).} \qquad \text{Eq. 3-A1-2}$$

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[5] EI = emission index, expressed as g, mg or # of pollutant per kg of fuel; EF = emission factor, expressed as mass of pollutant per specified unit (e.g. aircraft).

Emissions calculation – simple approach (option B)

Aircraft time-in-mode (TIM)

6.14 As discussed previously, the reference TIM used as part of the ICAO engine emissions certification process (and contained in the ICAO EEDB) is appropriate only for the engine certification process and is not representative of the actual TIM aircraft spend in real world operations (see 6.21 through 6.28. Nonetheless, the ICAO default TIM can provide a conservative estimate of aircraft emissions at an airport when airport-specific taxi/ground idle TIM data or refined methods of estimating take-off, climb and approach times are not available. Sensitivity analyses conducted by CAEP determined that conducting an aircraft emissions inventory using the ICAO certification TIM (as well as the fuel flow and EI) normally yields an overestimation of total aircraft emissions across the entire LTO cycle.

6.15 While ICAO default TIM is applicable primarily to regulated engines, there may be other default TIM available for other engine types (for example, unregulated turbofan engines, turboprop engines, piston engines or helicopters). Sources of such information include national aviation or environmental authorities (such as FOI's suggested TIM for turboprops).

Emissions calculation methodology for NO_x, CO, HC, nvPMmass and nvPMnumber

6.16 Identification of the aircraft type will enable the determination of the number of engines and the appropriate engine models. In turn, the engine model will determine the proper EI to calculate aircraft emissions.

6.17 To determine the NO_x, CO, HC, nvPMmass or nvPMnumber emissions for a unique aircraft/engine combination, the following formula may be used. This method is repeated for each aircraft/engine type representing each TIM to establish a complete aircraft emissions inventory.

$$Ei_j = \sum (TIM_{jk} * 60) * (FF_{jk}) * (Ei_{ijk}) * (Ne_j) \qquad \text{Eq. 3-A1-3}$$

where:

Ei_j = total emissions of pollutant i, for example NO_x, CO, HC, nvPMmass (in grams or milligrams) or nvPMnumber (in number of particles (#)), produced by aircraft type j for one LTO cycle;

Ei_{ijk} = emission index for pollutant i, for example NO_x, CO, HC, nvPMmass (in grams or milligrams per pollutant per kilogram of fuel (g/kg of fuel)) or nvPMnumber (in number of particles per kg of fuel (#/kg of fuel)), in mode k (e.g. take-off, climb-out, idle and approach) for each engine used on aircraft type j;

FF_{jk} = fuel flow for mode k (e.g. take-off, climb-out, idle and approach), in kilograms per second (kg/s), for each engine used on aircraft type j;

TIM_{jk} = time-in-mode for mode k (e.g. idle, approach, climb-out and take-off), in minutes, for aircraft type j; and

Ne_j = number of engines used on aircraft type j.

6.18 If the actual measured TIM for one or more of the operating modes exists and is used, then the different flight phases have to be calculated separately and the total emissions for each species have to be summed to give the total emissions for each aircraft/engine type.

6.19 ICAO does not have emissions certification standards for SO_x. However, SO_x emissions are a function of the quantity of sulphur in the fuel. The United States EPA conducted a survey of sulphur content for commercial aviation jet fuel, which resulted in a United States average of 1 gram per 1 000 grams of fuel consumed (EI SO_x = 1 g/kg of fuel). This average should not be relied upon where validated data are needed, but can be used to perform an emissions inventory of SO_x emissions using the following equation:

$$E_j = \sum (TIM_k * 60) * (Er_{jk}) * (Ne_j) \qquad \text{Eq. 3-A1-4}$$

where:

E_j = total emissions of SO_x, in grams, produced by aircraft type j for one LTO cycle;

Ne_j = number of engines used on aircraft type j;

Er_{jk} = 1 * (FF_{jk});

where:

Er_{jk} = emission rate of total SO_x in units of grams of SO_x emitted per second per operational mode k for aircraft type j; and

FF_{jk} = the reported fuel flow by mode in kilograms per second (kg/s) per operational mode k for each engine used on aircraft type j.

Emissions calculation – advanced approach (options A and B)

6.20 The advanced emissions calculation methods make use of performance models that take into account or model ambient and specific aircraft-related operational information. As such, additional information is needed that can be obtained more easily by the modeller from public sources. Such information can include the following: aircraft information (take-off mass, actual engine); airport information (airfield elevation, runway-in-use length); ambient information (wind speed and direction, turbulence, pressure, temperature, humidity); and operational information (destination, stand, runway, departure route, approach route and glide slope, APU usage). The information actually needed depends on the model used and may vary. Reference may be made to Table 3-A1-2 for additional guidance on what parameters to use.

Thrust levels

6.21 While the certification LTO cycle suggests specific thrust settings for each mode, any operational LTO cycle may have different modes with more individual power settings (for example, 6.30 to 6.33). Specifically, take-off thrust is often less than the certification 100 per cent for performance and cost-efficiency reasons. More and more aircraft are operated using flexible thrust rates, sometimes in combination with derated thrust options. This could apply to the take-off phase of a flight as well as to other flight phases in the landing and take-off cycle.

6.22 As an option A, an airport average and/or aircraft-group-specific reduced thrust level may be available primarily for the take-off phase, but may also be available for other modes. Such information could stem from empirical data (for example, from one aircraft operator) and be extrapolated over the total of the operations.

6.23 In option B, a dedicated aircraft performance model should be utilized that gives an operational thrust level using additional, publicly available parameters unique to the model. The thrust level could be modelled for take-off only or for all modes in the LTO cycle.

Time-in-mode

6.24 As an option A, airports are encouraged to take measurements of the typical taxi times unique to the airport's taxiway structure for both taxi-in from the runway to the terminal, and vice versa for taxi-out times, including possible queuing times at departure runways. Using the measured taxi-time values for the study airport can better reflect emissions for the taxi/idle mode of the LTO cycle. Such data could be obtained from, for example, touchdown, on-block, off-block and take-off times for either all possible stand/runway combinations, or as an airport default.

6.25 As an option B, TIM could also be modelled for modes other than just the taxi mode. This option would most likely include an aircraft performance modelling approach, giving aircraft group or even aircraft-type individual TIM for those modes considered in the approach (for example, more than just the four ICAO certification modes).

Fuel flow

6.26 For option A, a relationship has been developed that uses the certification fuel flow and thrust data from the ICAO EEDB to determine fuel flow at any thrust level desired between 60 per cent and 100 per cent.

Note.— The thrust levels are a percentage of rated output thrust and represent the thrust selected by the pilot. They do not represent the actual thrust delivered by the engine (corrected net thrust).

6.27 This methodology allows for accurate calculation of fuel flow at reduced take-off thrust levels, which in some instances could be as low as 60 per cent of rated thrust. From this fuel flow, corresponding EIs can be calculated using the Boeing fuel flow method 2 (BFFM2) curve-fitting methodology. A twin quadratic methodology has been developed and is described below.

6.28 The twin quadratic method comprises calculation of fuel flow versus thrust for thrusts above 60 per cent maximum rated thrust. The fuel flow and thrust data required to define the two curves are available in the ICAO EEDB for certificated engines. The methodology is as follows:

a) 60 per cent to 85 per cent thrust: defined by a quadratic equation based on the 7 per cent, 30 per cent and 85 per cent thrust and associated fuel flow points;

b) 85 per cent to 100 per cent thrust: defined by a quadratic equation based on the 30 per cent, 85 per cent and 100 per cent thrust and associated fuel flow points.

These two quadratic equations are uniquely defined by their three points and meet at 85 per cent thrust. The slopes of the two curves at 85 per cent thrust may be different (the “kink” shown diagrammatically in Figure 3-A1-3).

6.29 A quadratic equation to fit through three points on the non-dimensionalized fuel flow versus thrust curve has the following parameters:

X = (thrust)/(maximum rated thrust), quadratic defined by values $X1$, $X2$, $X3$

Y = (fuel flow)/(fuel flow @ maximum rated thrust), values $Y1$, $Y2$, $Y3$;

giving:

$$Y = AX^2 + BX + C$$

with three known points:

$$Y1 = AX1^2 + BX1 + C$$
$$Y2 = AX2^2 + BX2 + C$$
$$Y3 = AX3^2 + BX3 + C,$$

allowing solution for A, B and C as:

$$A = (Y3-Y1)/((X3-X1) * (X1-X2)) - (Y3-Y2)/((X3-X2) * (X1-X2))$$
$$B = (Y3-Y1)/(X3-X1) - A * (X3+X1)$$
$$C = Y3 - A * X3^2 - B * X3.$$

A, B and C vary for different engine UIDs.

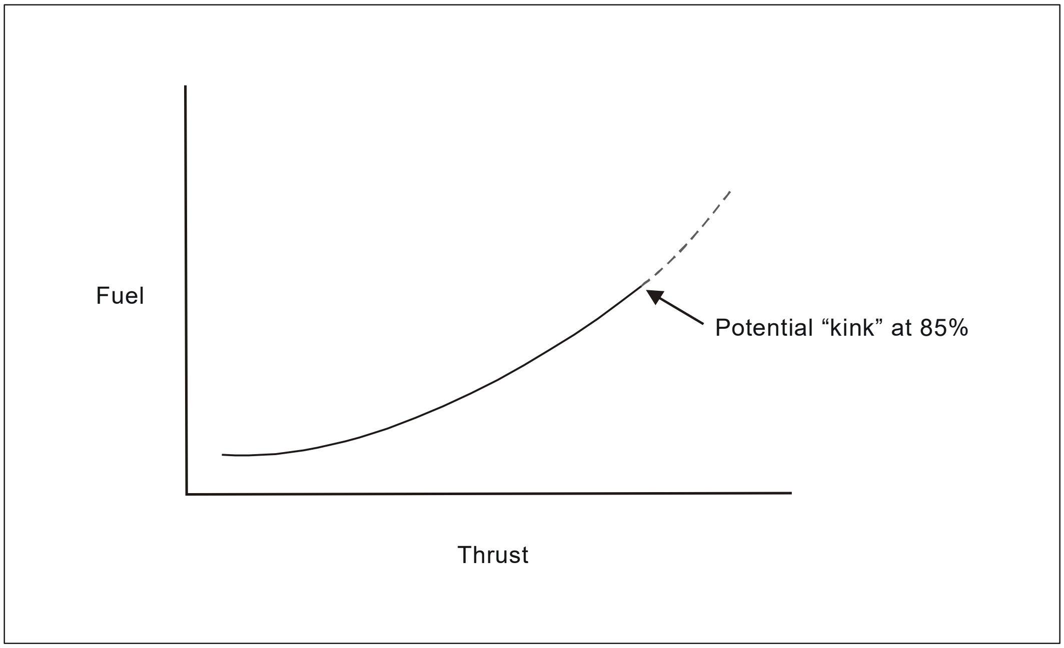

Figure 3-A1-3. Diagrammatic illustration of twin quadratic curve fit

For selected thrusts between 85 per cent and 100 per cent rated thrust

6.30 Known ICAO EEDB points for the engine UID at 30 per cent, 85 per cent and 100 per cent are used to derive A, B and C as above. These are then used in the generic quadratic equation:

$$Y = AX^2 + BX + C$$

where X is the (selected thrust)/(maximum rated thrust)

to give Y (= (desired fuel flow)/(fuel flow at maximum rated thrust)) at the selected thrust.

6.31 Fuel flow at the selected thrust is obtained by multiplying Y by the ICAO EEDB fuel flow at maximum rated thrust. The upper quadratic curve is applied between 85 per cent and 100 per cent rated thrust only.

For selected thrusts between 60 per cent and 85 per cent rated thrust

6.32 Known data bank points for the engine UID at 7 per cent, 30 per cent and 85 per cent are used to derive A, B and C as above**.** These are then used in the generic quadratic equation:

$$Y = AX^2 + BX + C$$

where X is the (selected thrust)/(maximum rated thrust)

to give Y (= (fuel flow)/(fuel flow at maximum rated thrust)) at the selected thrust.

6.33 Fuel flow at the selected thrust is obtained by multiplying Y by the ICAO EEDB fuel flow at maximum rated thrust. The lower quadratic curve is applied between 60 per cent and 85 per cent rated thrust only.

Example calculation for UID 8RR044, Rolls-Royce Trent 553-61

1) Determination of quadratic curve between 85 per cent and 100 per cent rated thrust

   X1 = 0.30
   X2 = 0.85
   X3 = 1.00

   with ICAO EEDB fuel flow data:

   Y1 = 0.2844
   Y2 = 0.8199
   Y3 = 1.0000

   → A = 0.3242
   → B = 0.6009
   → C = 0.07491
   → $Y = 0.3242\, X^2 + 0.6009\, X + 0.0749.$ (1)

2) Determination of quadratic curve between 60 per cent and 85 per cent thrust

   X1 = 0.07
   X2 = 0.30
   X3 = 0.85

   with ICAO EEDB fuel flow data:

   Y1 = 0.1090
   Y2 = 0.2844
   Y3 = 0.8199

   → A = 0.2709
   → B = 0.6622
   → C = 0.0613
   → $Y = 0.2709\, X^2 + 0.6622\, X + 0.0613$ (2)

3) Results for selected thrust (examples)

70 per cent thrust ($X = 0.7$): equation (2): $Y = 0.6576$ → multiply by ICAO EEDB maximum rated thrust fuel flow → fuel flow = 1.388 kg/s

90 per cent thrust ($X = 0.9$): equation (1): $Y = 0.8783$ → multiply by ICAO EEDB maximum rated thrust fuel flow → fuel flow = 1.853 kg/s.

6.34 For option B, a performance model would be utilized to obtain/calculate operational fuel flow data using various additional data (such as ATOW or stage length or information pertinent to fuel flow calculation) in conjunction with the ICAO EEDB. As examples, models such as BADA or PIANO or ADAECAM may be used.

Emission indices

6.35 ***Option A.*** Emission indices for option A will be calculated from the data in the ICAO EEDB using the "linear interpolation on a log-log scale" method as employed in the BFFM2 method, using the fuel flow data calculated by the methodology in 6.30. For nvPM, a linear interpolation of the EImass and number vs. per cent thrust is recommended. If applicable (and indicated in the EEDB by the engine manufacturer) the reported peak EI can be used as a 5th point (see 6.62).

6.36 ***Option B.*** The "operational" emission indices are derived from the data in the ICAO EEDB using the linear interpolation on a log-log scale method as employed in the BFFM2 method, using the operational fuel flow data from the method described in 6.34. For nvPM a linear interpolation of the EImass and number vs. per centthrust is recommended. If applicable (and indicated in the EEDB by the engine manufacturer) the reported peak EI can be used as a 5th point (see 6.62).

Application of additional parameters that may influence emissions, if appropriate

Important caveats for modellers using advanced methods

6.37 Unlike in the simple approach, different methods under the heading of advanced methods may already include some aspects of the corrections for additional parameters, such as ambient conditions. It is important to avoid double accounting in these cases. Hence, the application of the corrections may differ between different methods. It is also important to realize that ambient conditions sufficiently far from the standard may cause the aeroplane or engine to reach operational limits. For instance, many engines will not be able to provide full flat-rated thrust beyond some temperature limit (typically ISA + 15ºC, but this limit varies). The modeller must take care not to extrapolate a methodology beyond the conditions for which it is valid.

Application to advanced approach option B

6.38 If an aircraft performance model is used to calculate aeroplane and engine operating conditions (advanced option B), then it should already include the effects of forward speed on the fuel flow. It may, depending on the model, also include the effects of ambient conditions. The modeller must be aware of how the model functions. If it is necessary to correct the aeroplane performance model and/or fuel flow further to account accurately for these effects, the modeller should do so at this stage.

6.39 After the aeroplane performance and fuel flow have been correctly determined under advanced option B, then the EIs should be calculated using a fuel flow method. One documented[6] fuel flow method is the BFFM2. Depending on the needs of the modeller and the available data, other methods may be used, although the BFFM2 is recommended as a default option.

6.40 As described in SAE AIR5715, the BFFM2 accounts for the effects of ambient conditions and forward speed. It is important to recognize that if the effects of ambient conditions and forward speed are to be considered, it is not sufficient to use only the initial calculation of the EIs from the curve-fitting methods defined for the BFFM2. However, the full BFFM2 method includes corrections for both of these effects, so no further corrections to the EIs would be required if it is used.

Application to advanced approach option A

6.41 Methods that fall under advanced option A, while less sophisticated and precise, may also be more complicated to adjust for ambient conditions. First, the performance of the aeroplane (thrust, TIM, etc.) might need to be adjusted to account for ambient conditions. Then, since the fuel flow would have been calculated for the relevant thrust level at ISA static conditions (because the fuel flow is not based on an aircraft performance model in this option), corrections for both ambient conditions and forward speed would need to be implemented. The result would be a fuel flow, corrected for both sets of conditions, but without the accuracy (or temporal and spatial resolution) of an option B model.

6.42 The calculation of the EIs and their correction for ambient conditions and forward speed effects could then use the same approach as for advanced option B. However, because the fuel flow and flight conditions are not known to the same degree of resolution as with option B, the results obtained when applying a method such as the BFFM2 might not be accurate or even well-defined. The BFFM2 is defined only at fully specified[7] flight conditions and cannot be directly applied to an entire mode such as take-off or climb-out. Either a fully specified flight condition could be assumed that represents the aeroplane for the entire TIM, or else a different method would have to be used to determine the EIs. This different method might be a modification of BFFM2, or it might be unrelated. Thus, the application of corrections for forward speed and ambient conditions to an advanced option A calculation will depend on the details of the model and the requirements of the modeller.

Altitude effects

6.43 The effects of altitude on an aircraft engine are governed by local pressure, temperature and humidity. Therefore, the effects of altitude on engine emissions will be correctly treated if the approaches described above are implemented and the ambient conditions used are those local to the aeroplane in flight. As universal correction factors to nvPM emissions are not yet available, it is recommended to use the extracted EIs without any further correction applied.

Actual idle emissions

6.44 In some cases, actual idle conditions have been observed as being below the ICAO LTO reference thrust point of 7 per cent and provisions may be taken to estimate fuel flow and emissions below 7 per cent thrust. Actual idle nvPM emissions can be estimated using the 7 per cent ICAO idle LTO nvPM values, however due to uncertainties in nvPM correction methodologies for engine operating conditions, a conservative factor of 2 can be applied specifically for airport inventories.

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[6] SAE AIR5715.

[7] Fully specified: the state vector (3-D position, speed, altitude), engine parameters and airframe configuration are known.

Engine deterioration

6.45 While aircraft/engine manufacturers always design their products for peak efficiency at delivery, as aircraft enter revenue service some performance degradation may be experienced over time due to the harsh environments aircraft and engines will operate in. Erosion, seal degradation and dirt build-up on finely-tuned rotating hardware and airframes over long periods of time can lead to performance loss. If left unchecked, the deterioration can result in noticeable fuel consumption increases over time. Fuel consumption increases are an unnecessary cost increase to the carriers, and as a result they will normally perform maintenance on their products to keep the level of performance loss at acceptable levels. An analysis done by CAEP Working Group 3 (WG3) assessed the impact of aircraft/engine deterioration and provided the following guidance regarding how and when to apply deterioration in performing airport inventories.

6.46 In-service airframe and engine deterioration for the purposes of airport inventories (that is, the LTO cycle below 3 000 ft) has a small but real effect on fuel burn and NO_x emissions. There is no evidence that indicates deterioration effects on CO or HC. For smoke, there is evidence of deterioration effects for some of the tested engines. This is a matter of further investigation. At this time, no fleet-wide corrections can be indicated. For nvPM mass and number, there is a modest increase in emissions due to engine deterioration that can be considered for airport inventories. Further investigation is needed to improve confidence in these estimates.

6.47 As a cost-saving measure, airlines take precautions to keep deterioration effects to a minimum by establishing routine maintenance programmes. Based on analyses of theoretical and actual airline data, the magnitude of deterioration effects can be on a fleet-wide basis as follows:

Fuel consumption	+3%
NO_x emissions	+3%
CO emissions	no change
HC emissions	no change
Smoke number	no change
nvPMmass	+20%
nvPMnumber	+15%

6.48 For application to modelling, including emissions inventories, the appropriate use of this deterioration information in modelling activities is dependent on model/assumption and input data. Specifically, models and assumptions may already include a deterioration allowance, either explicitly (that is, actual engine operational data or calibrated/validated on actual in-service data), implicitly (that is, conservative fuel flow correction factors applied to engine certification values), or may already include conservatism which significantly outweighs the deterioration effects of fuel consumption and NO_x emissions. Care must be taken to avoid double accounting.

6.49 The simple approach is a significant overestimate of aircraft emissions and fuel consumption. The margin of conservatism of the simple approach is large enough to preclude the application of deterioration effects.

6.50 The advanced approach allows different thrust settings to be applied to fuel flow methodologies as well as some sort of aircraft performance calculations. While the results are more accurate than the simple approach, comparison with flight data recorder (FDR) data suggests that, for commonly used methods, there still is a level of conservatism on a fleet-wide basis on fuel flow calculations resulting from use of performance-estimated TIM, take-off weight (TOW) and throttle settings in the LTO cycle. The deterioration factors are considered smaller than the inherent conservatism already existing in the method, and application of deterioration factors is therefore not recommended.

6.51 Where the sophisticated approach utilizes actual engine/aircraft operational performance data (including operational fuel flow), then that would inherently include actual deterioration effects. Again, the application of deterioration factors is not recommended.

6.52 An exception to the recommendation above might occur in using a combination of advanced and sophisticated methods using actual engine/aircraft combinations, average or measured TIM, TOW and throttle settings, combined with fuel flow rates calculated from ICAO certification data. In this case, application of deterioration factors is recommended.

6.53 Fuel consumption deterioration should be applied only to modelling in the vicinity of airports (that is, the LTO cycle) and should not be used for global modelling where the deterioration factor would be different than the values reported here.

Start-up emissions calculation

6.54 During the starting sequence there are very little NO_x emissions produced compared to the LTO cycle due to the very low engine temperatures and pressures, and the only emissions that require consideration during the starting sequence are HC. Aircraft main engine starting can generally be broken down into two phases: pre-ignition and post-ignition.

Engine pre-ignition

6.55 The pre-ignition phase represents the time when the engine has been cranked using a starter motor and fuel has been permitted into the combustor to achieve ignition. Starter-motor initiation to combustor lighting can take several seconds, but there is no fuel entering the engine as the fuel system primes and the fuel valves are closed. Due to the requirement for quick start times, the combustion system is designed so that ignition occurs within the first or second spark of the igniter, typically within one second of fuel valves being opened and no later than two seconds. This has also been confirmed from rig testing by manufacturers using optical access to see fuel arrive and observe time to ignition.

6.56 Pre-ignition emissions would be purely fuel HC because combustion has not been initiated so no fuel is consumed within the combustor. This allows the HC emissions to be calculated directly from the fuel flow. During the pre-ignition period three things happen:

a) the fuel valve is opened;

b) the fuel injector system fills and fuel flow starts; and

c) the igniter begins to spark and lights the combustor.

Engine post-ignition

6.57 At this point the starting process occurs at low engine-loading conditions. At these operating points the engine emissions will primarily take the form of HC and CO emissions. The influence on nvPM emissions is currently unknown: direct measurement of starting emissions is made difficult by unburnt and partially burnt fuel contaminating gas sampling hardware. After ignition at particularly low engine loading, as would be the case during engine starting, emissions of HC dominate. For this reason, it is not unreasonable to attribute starting emissions to HC alone, resulting in a conservative estimate of HC emissions. CO emissions can be higher than HC for some engines at 7 per cent idle and below, and thus post-ignition HC emissions may be significantly lower than the estimate based on combustion efficiency. Detailed emissions measurements would be required to provide a more precise estimate of HC emissions.

6.58 Post-ignition emissions are determined from the point of ignition through the acceleration to idle. The combustor is now burning fuel; therefore, the rate of consumption must be considered to determine emissions accurately. Gas and particle sampling at sub-idle conditions is very difficult on engines because there are significant amounts of unburnt and partially burnt fuel that tend to contaminate the sampling hardware. To get around this issue, the analysis is performed using combustion efficiency correlations that have been determined by combustor rig testing at sub-idle conditions. These correlations are based on combustor inlet temperature, combustor inlet pressure, combustor air mass flow, fuel flow and fuel-air ratio. This approach to determining combustion efficiency and heat release is common among all engine manufacturers. As nvPM emission measurements started only recently, more must be understood to deal with nvPM estimations at sub-idle conditions.

6.59 The instantaneous combustor efficiency is calculated and the resulting inefficiency is allocated as a percentage of unburnt fuel representing the resulting HC emissions. Using this process throughout the acceleration to idle, the sum of the instantaneous HC emissions can be utilized to provide a conservative estimation of the total engine post-ignition HC emissions.

6.60 ICCAIA has performed a detailed analysis of engine starting data from General Electric (GE), Rolls Royce (RR), International Aero Engines (IAE) and Pratt & Whitney (P&W) engines and has developed a method to estimate total start-up emissions based on the rated sea level thrust of the engine in question. The results of this study were presented to CAEP WG3 in working paper CAEP8-WG3-CETG-WP06. In the paper, ICCAIA recommends a simple first order linear relationship between HC and the take-off engine thrust rating. The recommended equation is:

starting HC emissions (grams) = rated take-off thrust (kN)/2 + 80. Eq. 3-A1-5

Note.— This analysis is based on actual engine testing performed at moderate inlet temperature conditions. The methodology to derive the starting HC emissions is conservative because it does not account for any CO during starting. In addition, applying the methodology to all engines may be optimistic for older engines where fuel distribution controls are not as sophisticated. The methodology also considers typical times to light and typical starting times, which in practice could be quite varied and would be longer at very cold conditions. It would be reasonable to state that the uncertainty in the methodology is around ±50 per cent).

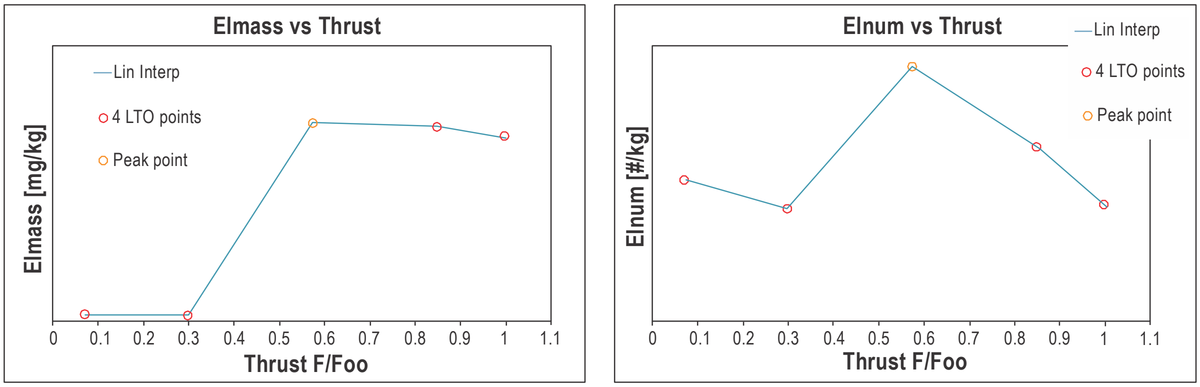

Figure 3-A1-4. Example interpolations of ground reference EIs using 5 point Method for peaks occurring between 30 per cent and 85 per cent LTO thrust points

Advanced calculation methodology for NO_x, CO, HC and nvPM

6.61 The calculation of emissions masses in the advanced approach makes use of additional data, information and existing models. As such, the emissions of an aircraft are a function (f) of the key parameters and the chosen options. This results in a performance-based calculation using various additional data and information that should yield a more accurate emissions inventory that will be unique to the specific airport and study year under consideration.

6.62 To determine the NO_x, CO or HC or emissions for a unique aircraft/engine combination, the following formula may be used. This method is repeated for each aircraft/engine type and movement.

$$E_{ij} = \sum (TIM_{jk} * 60) * f(FF_{jk}, Ei_{ijk} \text{ or } Thrust_{jk}, Cond_j, Ne_j) \qquad \text{Eq. 3-A1-6}$$

where:

E_{ij} = total emissions of pollutant i, for example NO_x, CO, HC (in grams), produced by a specific aircraft j for one LTO cycle;

Ei_{ijk} = the emission index for pollutant i, for example NO_x, CO, HC (in grams per pollutant per kilogram of fuel (g/kg of fuel), in mode k (e.g. take-off, climb-out, idle and approach) for each engine used on aircraft j;

FF_{jk} = fuel flow for mode k, in kilograms per second (kg/s), for each engine used on aircraft j;

$Thrust_{jk}$ = thrust level for mode k for aircraft type j;

TIM_{jk} = time-in-mode for mode k, in minutes, for aircraft j;

Ne_j = number of engines used on aircraft j, considering the potential use of less than all engines during taxi operation; and

$Cond_j$ = ambient conditions (forward speed, altitude, pressure, temperature and humidity) for aircraft type j movement.

6.63 To determine the nvPM mass and number emissions for a unique aircraft/engine combination, the following proposed method may be used. This method is repeated for each aircraft/engine type and movement.

$$E_{ij} = \Sigma (TIM_{jk} * 60) * f(FF_{jk}, Ei_{ijk} \text{ or } Thrust_{jk}, Ne_j) \qquad \text{Eq. 3-A1-7}$$

where:

E_{ij} = total emissions of pollutant i, e.g. nvPM mass (in miligrams) or nvPM number (in number of particles), produced by a specific aircraft j for one LTO cycle;

Ei_{ijk} = the emission index for pollutant i, e.g. nvPM mass (in miligrams per pollutant per kilogram of fuel (mg/kg of fuel)) or nvPM number (in number of particles per kilogram of fuel (particles/kg of fuel)), in mode k (e.g. take-off, climb-out, idle and approach) for each engine used on aircraft j;

FF_{jk} = fuel flow for mode k, in kilograms per second (kg/s), for each engine used on aircraft j;

$Thrust_{jk}$ = thrust level for mode k for the aircraft type j;

TIM_{jk} = time-in-mode for mode k, in minutes, for aircraft j;

Ne_j = number of engines used on aircraft j, considering the potential use of less than all engines during taxi operation;

The fuel flow for each mode obtained from the performance model can be used as formerly described for gaseous emissions. No further correction to the EI mass and number are currently available to be applied to correct for altitude or ambient conditions.

If one would like to use an EI at a thrust that differs from the four LTO modes, that is, 7, 30, 85, and 100 per cent, it is recommended to interpolate linearly. Two methods are available:

4 point Method: Linear interpolation using the four LTO points at 7, 30, 85, and 100 per cent thrust.

5 point Method: Linear interpolation using the four LTO points plus the reported peak EImass and EInum value. The additional point can be in between 30 and 85 per cent or 85 and 100 per cent thrust, that is, at 57.5 per cent or 92.5 per cent (see illustrative graph in Figure 3-A1-4).

The recommendation to use an additional 5th point would be indicated for each applicable engine by the OEM in the EEDB on a voluntary basis (in the comment column: "the maximum EImass occurs between XX per cent and YY per cent Foo" and "the maximum EInum occurs between XX per cent and YY per cent Foo").

It is recommended not to extrapolate below 7 per cent or above 100 per cent thrust ground reference, but rather use the EImass and EInum values at 7 and 100 per cent, respectively.

Emissions calculation – sophisticated approach

Parameters

6.64 Under the sophisticated approach, the actual and refined data required for the analysis are obtained from real-time measurements, reported performance information and/or complex computer modelling outputs. At a high level, these data and information characterize the actual fleet composition in terms of aircraft type and engine combinations, TIM, thrust levels, fuel flow and, possibly, combustor operating conditions for all phases of ground-based and take-off operations. In some cases, correction of engine operating conditions to reference conditions, using accepted methods, will also be required.[8] Additionally, the application of the parameters defined in 6.36 to 6.53 could be considered based on the guidance provided in Table 3-A1-2.

6.65 Listed below are the data and information typically required for computing aircraft engine emissions using the sophisticated approach:

a) TIM measurements for different aircraft/engine types under different load, route and meteorological conditions;

b) reverse thrust deployment measurements for different aircraft/engine types under different meteorological conditions;

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[8] Sources for correcting and obtaining these data will be the airlines; engine manufacturers; Annex 16, Volume II; SAE AIR1845; BADA; and ETMS, ETFMS and FDR data.

c) airport meteorological conditions, where modelling of aircraft/engine performance accounts for variation in meteorological conditions;

d) frequency and type of engine test runs;

e) frequency of operational aircraft towing; and

f) airport infrastructure and constraints (for example, runway length).

6.66 Similarly, data measured by operators may be made available, including:

a) typical or actual throttle settings used during reverse thrust operation;

b) actual aircraft/engine configuration data;

c) actual fuel flow data;

d) actual engine-type idle speeds;

e) typical or actual throttle settings for approach, take-off and climb-out (for example, reduced thrust take-off procedures);

f) approach and climb profiles; and

g) frequency of less-than-all-engines taxi operation.

These measured and actual operator data may supplement or replace elements of modelled data.

6.67 Using actual performance and operational data, engine emission factors can be calculated using programmes such as the BFFM2 (SAE AIR5715) or the DLR (Deidewig et al., 1996) method.

Sophisticated calculation methodology for NO_x, CO and HC

6.68 Once the actual fleet engine emissions factors, TIM and fuel flow are known, the LTO emissions are calculated using the same equation used in the advanced approach, however with the refined input values.

$$E_{ij} = \sum (TIM_{jk}*60) * f(FF_{jk}, Ei_{ijk} \text{ or } Thrust_{jk}, Cond_j, Ne_j) \qquad \text{Eq. 3-A1-8}$$

where:

E_{ij} = total emissions of pollutant i (e.g. NO_x, CO, HC), in grams, produced by a specific aircraft j for one LTO cycle;

Ei_{ijk} = the emission index for pollutant i (e.g. NO_x, CO, HC), in grams per pollutant per kilogram of fuel (g/kg of fuel), in mode k for each engine used on aircraft j;

FF_{jk} = fuel flow for mode k, in kilograms per second (kg/s), for each engine used on aircraft type j;

$Thrust_{jk}$ = thrust level for mode k for aircraft type j;

TIM_{jk} = time-in-mode for mode k, in minutes, for aircraft j;

N_{ej} = number of engines used on aircraft j; and

Cond_j = ambient conditions (forward speed, altitude, p, t, h) for aircraft type j movement.

Sophisticated calculation methodology for nvPM

6.69 Once the actual fleet engine emissions factors, TIM and fuel flow are known, the LTO emissions are calculated using the same equation used in the advanced approach, however with the refined input values.

$$E_{ij} = \Sigma\ (\mathrm{TIM}_{jk} * 60) * f(\mathrm{FF}_{jk}, \mathrm{Ei}_{ijk} \text{ or } \mathrm{Thrust}_{jk}, \mathrm{Ne}_j) \qquad \text{Eq. 3-A1-9}$$

where:

E_{ij} = total emissions of pollutant i, e.g. nvPM mass (in miligrams) or nvPM number (in number of particles), produced by a specific aircraft j for one LTO cycle;

Ei_{ijk} = the emission index for pollutant i, e.g. nvPM mass (in miligrams per pollutant per kilogram of fuel (mg/kg of fuel)) or nvPM number (in number of particles per kilogram of fuel (particles/kg of fuel)), in mode k (e.g. take-off, climb-out, idle and approach) for each engine used on aircraft j;

FF_{jk} = fuel flow for mode k, in kilograms per second (kg/s), for each engine used on aircraft j;

Thrust_{jk} = thrust level for mode k for the aircraft type j;

TIM_{jk} = time-in-mode for mode k, in minutes, for aircraft j;

Ne_j = number of engines used on aircraft j, considering the potential use of less than all engines during taxi operation;

The fuel flow for each mode obtained from the performance model can be used as formerly described for gaseous emissions. No further correction to the EI mass and number are currently available to be applied to correct for altitude or ambient conditions.

If one would like to use an EI at a thrust that differs from the four LTO modes, that is, 7, 30, 85, and 100 per cent, it is recommended to interpolate linearly. Two methods are available:

4 point Method: Linear interpolation using the four LTO points at 7, 30, 85, and 100 per cent thrust.

5 point Method: Linear interpolation using the four LTO points plus the reported peak EImass and EInum value. The additional point can be in between 30 and 85 per cent or 85 and 100 per cent thrust, that is, at 57.5 per cent or 92.5 per cent (see illustrative graph in Figure 3-A1-4).

The recommendation to use an additional 5th point would be indicated for each applicable engine by the OEM in the EEDB on a voluntary basis (in the comment column: “the maximum EImass occurs between XX per cent and YY per cent Foo” and “the maximum EInum occurs between XX per cent and YY per cent Foo”).

It is recommended not to extrapolate below 7 per cent or above 100 per cent thrust ground reference, but rather use the EImass and EInum values at 7 per cent and 100 per cent, respectively.

7. AUXILIARY POWER-UNIT EMISSIONS

7.1 An auxiliary power unit (APU) is a small gas-turbine engine coupled to an electrical generator and is used to provide electrical and pneumatic power to aircraft systems when required. It is normally mounted in the tail cone of the aircraft, behind the rear pressure bulkhead, and runs on kerosene fed from the main fuel tanks. Not all aircraft are fitted with an APU and, though their use on transport category jet aircraft is now almost universal, some turboprops and business jets do not have an APU fitted.

Emissions calculation methodology

7.2 Unlike aircraft main engines, APUs are not certificated for emissions, and the manufacturers generally consider information on APU emissions rates as proprietary. As a result, little data are publicly available to serve as a basis for calculating APU emissions.

7.3 Analysis performed to date on APUs has not been successful in developing advanced and sophisticated methodologies that more accurately predict APU particulate matter emissions. If more information is available to users, then they are encouraged to use this information if this would be of benefit to the study. As a result, use of the simple approach for calculating particulate matter emissions is recommended at this time.

Simple approach

7.4 If very little information is known about the aircraft types operating at the study airport, then the simple approach for APU emissions may be used. However, the results are likely to have a large order of uncertainty associated with APU use and their emissions. Generalized emissions for APUs have been made public. This information is recommended for use because the simple approach uses averaged proprietary engine-specific values obtained from APU manufacturers.

7.5 When the level of detail about the aircraft fleet does not allow this process to be used, the values in Table 3-A1-3 are considered representative of the APU emissions for each aircraft operation at the airport under study (other values may be used if deemed more appropriate).

Table 3-A1-3. Values representative of APU emissions for each aircraft operation

Aircraft group	Short-haul[9]	Long-haul
Duration of APU operation	45 min	75 min
Fuel burn	80 kg	300 kg
NO_x emissions	700 g	2400 g
HC emissions	30 g	160 g
CO emissions	310 g	210 g
Total particulate matter mass (tPMmass) emissions	40 g	50 g
nvPMnumber emissions	5.75E+17 #particles	3.75E +17 #particles

7.6 The fuel burn and emissions values given in Table 3-A1-3 are based on averaged APU-specific proprietary data from the manufacturer, but do not represent any specific APU type. The operational times noted are based on average operating times experienced by a number of operations and do not necessarily represent any specific airport operation. It should be noted that APU operating times vary considerably at different airports due to a number of factors and can be significantly different from the default values listed in Table 3-A1-3. If information on actual APU operating

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[9] Although there is no common definition of short-haul and long-haul, in the context of this document a rule of thumb is proposed that relates the term to aircraft type. The long-haul group would include aircraft capable of a maximum range of more than 8 000 km (for example, A330, A340, A380, B747, B767-200ER, B763, B764, B777, B787, IL96). Short-haul would include all other aircraft.

times is available, either from surveys or as maximum durations from local airport restrictions, then the APU fuel burn and emissions may be adjusted by factoring the values in the table by the ratio of the survey times with the default values outlined.

7.7 For example, APU NO_x emissions for a short-haul aircraft operating for 60 minutes would be calculated as follows:

NO_x (g/LTO) = (60 minutes per LTO) x (700 g/45 minutes) = 933 g/LTO.

7.8 In addition, publicly distributed manufacturer information is available showing aircraft and APU combinations including duty cycle average APU EI and fuel burn rates.[10] Air Transport Association (ATA) estimates of APU operating times are also available, based on a limited, informal survey concerning APU usage. Use of the manufacturer APU emissions data, along with the ATA estimates of APU operating times, may provide a more accurate estimate of APU emissions. The ATA estimates of APU operating times provide estimates for narrow- and wide-body[11] aircraft with and without gate power. As examples, these estimates are provided in Table 3-A1-4 (other values may be used if deemed more appropriate).

Table 3-A1-4. ATA estimates of APU operating times for narrow- and wide-body aircraft

Aircraft type	ATA operating time (hours/cycle)	
	With gate power	Without gate power
Narrow body	0.23 to 0.26	0.87
Wide body	0.23 to 0.26	1.0 to 1.5

7.9 APU and aircraft combinations can be found in the 1995 FAA technical report entitled *Technical Data to Support FAA Advisory Circular on Reducing Emissions from Commercial Aviation* (FAA, 1995). This document provides an accurate summary of which major APU family is used on different aircraft. The document also provides modal EIs and fuel flow for specific APUs, all of which would provide additional details for the APU emissions calculation.

7.10 For example, APU NO_x emissions for a wide-body aircraft utilizing a 331-200ER without gate power, where the time at load is 1.5 hours, the NO_x EI is 9.51 lb per 1 000 lb of fuel and the fuel flow is 267.92 lb per hour, would be calculated as follows:

NO_x (lb/LTO) = (1.5 hours per LTO) x (9.51 lb/1 000 lb fuel) * (267.92 lb fuel/hour) = 3.82 lb/LTO = 3 466 g/LTO.

Advanced approach

7.11 APU emissions can be estimated from knowledge of the actual aircraft/APU combination and APU running time, with EIs assigned to individual APU types. Emissions can be calculated at three suggested APU operating load conditions of:

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[10] Correspondence from Honeywell Engines & Systems to United States EPA Assessment and Standards Division, APU Emissions, 29 September 2000.

[11] Narrow body: single-aisle aircraft. Wide body: twin-aisle aircraft (for example, A300, A330, A340, A380, B747, B767, B777, B787).

a) start-up (no load);

b) normal running (maximum environmental control system (ECS)); and

c) high load (main engine start),

to represent the operating cycle of these engines.

7.12 For each of these loads, the emissions can be calculated from the following formulae:

NO_x = NO_x rate x time at load;
HC = HC rate x time at load;
CO = CO rate x time at load;
tPMmass = tPMmass rate x time at load; and
nvPMnumber = nvPMnumber rate x time at load.

7.13 Where data for actual time at load cannot be identified accurately, the times in Table 3-A1-5 are provided as examples (other values may be used if deemed more appropriate).

Table 3-A1-5. Examples of actual time at load

Activity	Mode	Two-engine aircraft	Four-engine aircraft
APU start-up and stabilization	Start-up	3 minutes	3 minutes
Aircraft preparation, crew and passenger boarding	Normal running	Total pre-departure running time – 3.6 minutes	Total pre-departure running time – 5.3 minutes
Main engine start	High load	35 seconds	140 seconds
Passenger disembarkation and aircraft shutdown	Normal running	15 minutes (default) or as measured	15 minutes (default) or as measured

7.14 To calculate APU emissions, current aircraft types have been assigned to one of six groups that characterize their emissions (see Tables 3-A1-6 to 3-A1-11). APU fuel/CO_2, NO_x, HC, CO, nvPMmass and nvPMnumber emissions can then be calculated by multiplying the time at load by the appropriate emission factor from these tables (other values may be used if deemed more appropriate).

7.15 The total APU emissions of NO_x, HC and CO for each turnaround cycle can be calculated from a summation of the emissions for each mode over the whole cycle.

Table 3-A1-6. APU fuel group

APU fuel group	Start-up No load (kg/h)	Normal running Maximum ECS (kg/h)	High load Main engine start (kg/h)
Business jets/regional jets (seats < 100)	68	101	110
Smaller (100 ≤ seats < 200), newer types	77	110	130
Smaller (100 ≤ seats < 200), older types	69	122	130
Mid-range (200 ≤ seats < 300), all types	108	164	191
Larger (300 ≤ seats), older types	106	202	214
Larger (300 ≤ seats), newer types	146	238	262

Table 3-A1-7. APU NO_x group

APU NO_x group	Start-up No load (kg/h)	Normal running Maximum ECS (kg/h)	High load Main engine start (kg/h)
Business jets/regional jets (seats < 100)	0.274	0.700	0.714
Smaller (100 ≤ seats < 200), newer types	0.384	0.702	1.128
Smaller (100 ≤ seats < 200), older types	0.329	0.733	0.826
Mid-range (200 ≤ seats < 300), all types	0.876	1.556	1.889
Larger (300 ≤ seats), older types	0.757	1.847	2.103
Larger (300 ≤ seats), newer types	1.062	2.955	3.347

Table 3-A1-8. APU HC group

APU HC group	Start-up No load (kg/h)	Normal running Maximum ECS (kg/h)	High load Main engine start (kg/h)
Business jets/regional jets (seats < 100)	1.026	0.027	0.049
Smaller (100 ≤ seats < 200), newer types	0.763	0.043	0.035
Smaller (100 ≤ seats < 200), older types	0.125	0.040	0.035
Mid-range (200 ≤ seats < 300), all types	0.108	0.018	0.020
Larger (300 ≤ seats), older types	0.113	0.048	0.042
Larger (300 ≤ seats), newer types	0.093	0.031	0.030

Table 3-A1-9. APU CO group

APU CO group	Start-up No load (kg/h)	Normal running Maximum ECS (kg/h)	High load Main engine start (kg/h)
Business jets/Regional jets (seats < 100)	3.345	0.615	0.655
Smaller (100 ≤ seats < 200), newer types	2.948	0.386	0.543
Smaller (100 ≤ seats < 200), older types	1.477	0.927	0.736
Mid-range (200 ≤ seats < 300), all types	1.446	0.230	0.170
Larger (300 ≤ seats), older types	1.476	0.331	0.257
Larger (300 ≤ seats), newer types	1.349	0.152	0.173

Table 3-A1-10. APU tPMmass group

APU tPMmass group	Start-up No load (kg/h)	Normal running Maximum ECS (kg/h)	High load Main engine start (kg/h)
Business jets/Regional jets (seats < 100)	0.063	0.035	0.036
Smaller (100 ≤ seats < 200), newer types	0.057	0.022	0.021
Smaller (100 ≤ seats < 200), older types	0.048	0.056	0.047
Mid-range (200 ≤ seats < 300), all types	0.031	0.038	0.041
Larger (300 ≤ seats), older types	0.070	0.117	0.127
Larger (300 ≤ seats), newer types	0.022	0.025	0.023

Table 3-A1-11. APU nvPMnumber group

APU nvPMnumber group	Start-up No load (#/h)	Normal running Maximum ECS (#/h)	High load Main engine start (#/h)
Business jets/Regional jets (seats < 100)	8.45E+15	2.00E+17	2.66E+17
Smaller (100 ≤ seats < 200), newer types	3.65E+16	9.48E+16	1.14E+17
Smaller (100 ≤ seats < 200), older types	1.20E+18	1.06E+18	9.53E+17
Mid-range (200 ≤ seats < 300), all types	2.86E+17	3.49E+17	3.35E+17
Larger (300 ≤ seats), older types	2.11E+17	7.34E+17	1.18E+18
Larger (300 ≤ seats), newer types	5.80E+16	2.04E+17	8.22E+16

Sophisticated approach

7.16 The sophisticated approach requires detailed knowledge of the APU type, operating modes and time in these modes, aircraft operations and fuel burn and associated emission factors. As noted, many of these may not be available publicly and the APU manufacturers would have to be approached. TIM data is another factor that would need to be carefully researched and collected. It may be that only typical values are available for specific operators/aircraft types, and in this case, it may be necessary to use the default values of the advanced approach but coupled with more accurate EIs from the manufacturers to give a more reliable result.

7.17 The APU emissions for each aircraft APU mode of operation can then be calculated from the following formula:

emissions mass = TIM x fuel flow x EI, for each mode and each emissions species. Eq. 3-A1-8

7.18 The mass of each emissions species can then be calculated for each operation by summing the emissions masses for the different power loads. Finally, by summing the emissions calculated for each aircraft APU operation, the total mass of each emissions species can be calculated for the emissions inventory.

7.19 Emission indices for APUs have been made available, by the manufacturers, to some airport and aircraft operators; however, due to the proprietary nature of the data, their widespread use has not been authorized. As a result, the sophisticated approach may be available only to a few specialist inventory builders.

ICAO ENGINE EXHAUST EMISSIONS DATA BANK
SUBSONIC ENGINES

ENGINE IDENTIFICATION:	Trent 895	BYPASS RATIO :	5.7
UNIQUE ID NUMBER:	5RR040	PRESSURE RATIO (π_{00}) :	41.52
ENGINE TYPE:	TF	RATED OUTPUT (F_{00}) (kN) :	413.05

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NOx	SMOKE NUMBER
D_P/F_{00} (g/kN) or SN	1.7	23.1	78.6	6.9
AS % OF ORIGINAL LIMIT	8.6 %	19.6%	63.9%	4 2.8%
AS % OF CAEP/2 LIMIT (NOx)			79.9%	
AS % OF CAEP/4 LIMIT (NOx)			87.3%	

DATA STATUS

- PRE-REGULATION
x CERTIFICATION
- REVISED (SEE REMARKS)

TEST ENGINE STATUS

- NEWLY MANUFACTURED ENGINES
x DEDICATED ENGINES TO PRODUCTION STANDARD
- OTHER (SEE REMARKS)

EMISSIONS STATUS

x DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)

CURRENT ENGINE STATUS

(IN PRODUCTION, IN SERVICE UNLESS OTHERWISE NOTED)
- OUT OF PRODUCTION
- OUT OF SERVICE

MEASURED DATA

MODE	POWER SETTING (%F_{00})	TIME minutes	FUEL FLOW kg/ s	EMISSIONS INDICES (g/kg) HC	CO	NOx	SMOKE NUMBER
TAKE-OFF	100	0.7	4.03	0.02	0.27	47.79	-
CLIMB OUT	85	2.2	3.19	0	0.19	34.29	-
APPROACH	30	4.0	1.05	0	0.54	11.39	-
IDLE	7	26.0	0.33	0.89	14.71	5.11	-
LTO TOTAL FUEL (kg) or EMISSIONS (g)			1357	462	7834	28029	-
NUMBER OF ENGINES				1	1	1	1
NUMBER OF TESTS				3	3	3	3
AVERAGE D_p/F_{00} (g/kN) or AVERAGE SN (MAX)				1.1	18.8	67.81	5.34
SIGMA (D_p/F_{oo} in g/kN, or SN)				-	-	-	-
RANGE (D_p/F_{00} in g/kN, or SN)				0.95 – 1.24	17.71 – 19.67	65.76 – 69.5	4.7 – 6.0

ACCESSORY LOADS

POWER EXTRACTION 0 (kw) AT - POWER SETTINGS
STAGE BLEED 0 % CORE FLOW AT - POWER SETTINGS

ATMOSPHERIC CONDITIONS

BAROMETER (kPa)	100.2
TEMPERATURE (K)	287
ABS HUMIDITY (kg/kg)	.0053 - .0089

FUEL

SPEC	AVTUR
H/C	1.95
AROM (%)	16

MANUFACTURER: Rolls-Royce plc
TEST ORGANIZATION: Rolls-Royce plc
TEST LOCATION: SINFIN, Derby
TEST DATES: FROM Sep 94 To -

Remarks

1. Data from certification report DNS59304

This document was prepared on 1 October 2004. Check website for latest version.

Gaseous Emissions Data sheet

ICAO ENGINE EXHAUST EMISSIONS DATA SHEET
SUBSONIC ENGINES

ENGINE IDENTIFICATION:	CF6-80C2B1F	BYPASS RATIO:	5.1
UNIQUE ID NUMBER:	01P02GE186	PRESSURE RATIO (π_{00}) :	30.1
COMBUSTOR:	LEC		
ENGINE TYPE:	TF	RATED OUTPUT F_{00} (kN) :	254.3

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NO_x	SMOKE NUMBER
D_P /F_{00} (g/kN) or SN	2.6	28.2	48.0	8.1
AS % OF ORIGINAL LIMIT	13.3	23.9	47.9	44.1
AS % OF CAEP/2 LIMIT (NO_x)			59.9	
AS % OF CAEP/4 LIMIT (NO_x)			71.4	
AS % OF CAEP/6 LIMIT (NO_x)			81.1	
AS % OF CAEP/8 LIMIT (NO_x)			95.3	

For non-volatile particulate matter (nvPM) emissions, please refer to the ICAO Engine nvPM Emissions Data Sheet.

DATA STATUS

- \- PRE-REGULATION
- x CERTIFICATION
- \- REVISED (SEE REMARKS)

EMISSIONS STATUS

- x DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)

TEST ENGINE STATUS

- x NEWLY MANUFACTURED ENGINES
- \- DEDICATED ENGINES TO PRODUCTION STANDARD
- \- OTHER (SEE REMARKS)

CURRENT ENGINE STATUS

(IN PRODUCTION, IN SERVICE UNLESS OTHERWISE NOTED)

- \- OUT OF PRODUCTION (DATE: -)
- \- OUT OF SERVICE (DATE: -)

MEASURED DATA

MODE	POWER Setting (% F_{00})	TIME (minutes)	FUEL FLOW (kg/ s)	EMISSIONS INDICES (g/kg) HC	CO	NO_x	SMOKE NUMBER
TAKE-OFF	100	0.7	2.422	0.05	0.04	29.94	6.9
CLIMB OUT	85	2.2	1.983	0.05	0.04	19.72	4.5
APPROACH	30	4.0	0.650	0.11	2.13	12.47	0.0
IDLE	7	26.0	0.199	1.54	19.23	4.73	0.0
LTO TOTAL FUEL (kg) or EMISSIONS (g)			830	513	6317	11113	-
NUMBER OF ENGINES				2	2	2	2
NUMBER OF TESTS				4	4	4	4
AVERAGE D_p/ F_{00} (g/kN) or AVERAGE SN (MAX)				2.0	24.8	43.7	6.9
SIGMA (D_p/F_{oo} in g/kN, or SN)				0.2	1.2	0.3	0.6
RANGE (D_p /F_{00} in g/kN, or SN)				1.87 – 2.36	23.7 – 26.5	43.3– 44	6.2 – 7.7

ACCESSORY LOADS

POWER EXTRACTION	0	(kw)	AT	- POWER SETTINGS
STAGE BLEED	0	(% CORE FLOW)	AT	- POWER SETTINGS

ATMOSPHERIC CONDITIONS

BAROMETER (kPa)	97.6 – 98.2
TEMPERATURE (K)	279-293
ABS HUMIDITY (kg/kg)	0.00457 – 0.00743

FUEL

SPEC	Jet A
H/C	1.94
AROM (%)	15.3

MANUFACTURER:	General Electric Company
TEST ORGANIZATION:	CF6 Eval Engineering
TEST LOCATION	Site IIIB, PTO Peebles
TEST DATE:	13/01/1995-17/01/1995

NO_x. REGULATION PARAGRAPH

	2.3.2 c) (CAEP/4)
	2.3.2 d) (CAEP/6)
x	2.3.2 e) (CAEP/8)

Remarks

1. Ref GE report TM95-17.
2. Engine S/N 704/233 & 704/234
3. 1862M39 combustor
4. Certification in accordance with Part III, Chapter 2, of Amendment 7 of Annex 16 Vol. II.
5. NO_x levels in accordance with Part III, Chapter 2, 2.3.2 e)

Compliance with Fuel Venting requirements: - *('x' if complies, 'PR' if pre-regulation, '- ' if information is not available)*

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Non-volatile Particulate Matter (nvPM) Emissions Data sheet

ICAO ENGINE NVPM EMISSIONS DATA SHEET
SUBSONIC ENGINES

ENGINE IDENTIFICATION:	CF6-80C2B1F	BYPASS RATIO: (-):	5.1
UNIQUE ID NUMBER:	01P02GE186	PRESSURE RATIO π_{00} (-):	30.6
COMBUSTOR:	LEC		
ENGINE TYPE:	TF	RATED OUTPUT (F_{00}) (kN) :	254.3

REGULATORY DATA

CHARACTERISTIC VALUES:	LTO_{mass}/F_{00} (mg/kN)	LTO_{mass}/F_{00} (particles/kN)	NVPM MASS CONCENTRATION (µg/m^3)
LTO /F_{00} AND MAX $nvPM_{mass}$	49.6	6.28E+14	1109
AS % OF CAEP/10 LIMIT	-	-	25.6
AS % OF CAEP/11 LIMIT (InP)	14.3	15.1	
AS % OF CAEP/11 LIMIT (NT)	23.2	22.6	

MEASURED DATA

				EMISSIONS INDICES*		
MODE	POWER SETTING (%F_{00})	TIME minutes	FUEL FLOW kg/s	EI_{mass} (mg/kg)	EI_{num} (particles/kg)	NVPM MASS CONCENTRATION PEAK $nvPM_{mass}$ (µg/m^3)
TAKE-OFF	100	0.7	2.417	34.9	2.36E+14	
CLIMB OUT	85	2.2	2.057	18.3	2.39E+14	
APPROACH	30	4.0	0.645	1.3	3.96E+13	
IDLE	7	26.0	0.195	1.2	6.54E+13	
LTO TOTAL (kg, mg, number of particles)			832	9082	1.15E+17	-
NUMBER OF ENGINES				1	1	1
NUMBER OF TESTS				3	3	3
AVERAGE LTO/F_{00} VALUES (mg/kN, particles/kN)				35.7	4.52E+14	-
MAX EI VALUES (mg/kg, particles/kg) AND MAX MASS CONC.(µ g/m$^{3)}$				34.9	2.47E+14	861

** Emissions Indices are corrected for thermophoretic loss and fuel hydrogen content*

DATA FOR EMISSIONS INVENTORIES (ESTIMATIONS FOR ENGINE EXIT PLANE VALUES)

		CORRECTED EMISSIONS INDICES	
MODE	POWER SETTING (% $F_{00)}$	EI_{mass_SL} (mg/kg)	EI_{num_SL} (particles/kg)
TAKE-OFF	100	40.7	6.00E+14
CLIMB OUT	85	23.4	9.25E+14
APPROACH	30	1.9	2.48E+14
IDLE	7	2.2	5.99E+14

AMBIENT CONDITIONS

	From	To
BAROMETER (kPa)	97.6	97.8
TEMPERATURE (K)	284.8	290.6
HUMIDITY (kg water/kg dry air)	0.0038	0.0062

FUEL

HEAT OF COMBUSTION (MJ/kg)	43.21
HYDROGEN CONTENT (%mass)	13.65
AROMATICS CONTENT (%vol)	17.5
NAPHTHALENE CONTENT(%vol)	0.22
SULPHUR CONTENT (ppm by mass)	78

MANUFACTURER:	General Electric Company
TEST ORGANIZATION:	General Electric Company
TEST LOCATION:	PTO, Ohio
TEST DATES:	11/02/2017

Remarks:

1. GE Aviation Report R2019AE437/Rev. 0
2. Engine S/N 707-368

This document was prepared on 22/01/2021

Check website for latest version

Attachment B to Appendix 1

SIMPLIFIED AIRCRAFT EMISSION INDICES

Table B-1. LTO emission factor by aircraft

Aircraft[1]		LTO emission factors/aeroplane (kg/LTO/aircraft and particles/LTO/aircraft)[2]							Fuel consumption (kg/LTO/aircraft)
		CO_2[3]	*HC*	*NO_x*	*CO*	*SO_2*[4]	*tPMmass*	*nvPMnumber*	
Large commercial aircraft[5]	A300	5 445	1.25	25.86	14.80	0.86	0.16	1.58E+18	1 723
	A310	4 761	6.30	19.46	28.30	0.75	0.17	9.99E+17	1 507
	A318	2 274	0.91	6.76	12.14	0.36	0.07	5.48E+17	719
	A319	2 390	1.20	8.70	7.86	0.38	0.14	2.54E+18	756
	A320	2 665	0.34	9.90	8.14	0.42	0.17	3.28E+18	843
	A320neo	1 981	0.10	5.95	6.95	0.31	0.04	2.35E+17	627
	A321	3 195	0.17	16.23	5.81	0.51	0.23	4.62E+18	1 011
	A321neo	2 373	0.09	10.76	6.94	0.38	0.06	2.86E+17	751
	A330-200/300	7 052	1.28	35.57	16.20	1.12	0.21	2.42E+18	2 232
	A340-200	6 111	4.05	31.08	25.75	0.97	0.18	8.18E+17	1 934
	A340-300	6 383	3.90	34.81	25.23	1.01	0.19	8.77E+17	2 020
	A340-500/600	10 659	0.14	64.45	15.31	1.69	0.19	7.95E+17	3 373
	A350-900	6 756	0.94	39.81	20.27	1.07	0.20	2.63E+18	2 138
	A350-1000	7 851	0.90	56.91	20.23	1.24	0.24	2.77E+18	2 484
	A380	11 952	3.70	69.42	39.06	1.89	0.34	3.37E + 18	3 782
	707	5 890	97.45	10.96	92.37	0.93	2.15	1.88E+19	1 864
	717	2 143	0.05	6.68	6.78	0.34	0.09	7.80E+17	678
	727-200	4 610	8.14	11.97	27.16	0.73	0.52	1.11E+19	1 459
	737-300/400/500	2 737	1.43	6.98	6.48	0.43	0.14	2.55E+18	866
	737-600	2 279	1.01	7.66	8.65	0.36	0.09	1.23E+18	721
	737-700	2 462	0.86	9.12	8.00	0.39	0.09	1.40E+18	779
	737-800/900	2 784	0.72	12.30	7.07	0.44	0.12	2.04E+18	881
	747-200	11 370	18.24	49.52	79.78	1.80	0.46	3.33E+18	3 598
	747-300	11 074	2.73	65.00	17.84	1.75	0.37	4.01E+18	3 504
	747-400	10 245	2.25	42.88	26.72	1.62	0.24	6.28E+17	3 242
	747-8	11 044	0.84	44.32	27.61	1.75	0.24	2.76E+18	3 495
	757-200	4 317	0.22	23.43	8.08	0.68	0.11	1.20E+18	1 366
	757-300	4 625	0.11	17.85	11.62	0.73	0.33	5.88E+18	1 464

Aircraft[1]		LTO emission factors/aeroplane (kg/LTO/aircraft and particles/LTO/aircraft)[2]							Fuel consumption (kg/LTO/aircraft)
		CO_2[3]	*HC*	NO_x	*CO*	SO_2[4]	*tPMmass*	*nvPMnumber*	
	767-200	4 622	3.32	23.76	14.80	0.73	0.18	1.04E+18	1 463
	767-300	5 608	1.19	28.19	14.47	0.89	0.17	1.68E+18	1 775
	767-400	5 522	0.98	24.80	12.37	0.87	0.13	3.74E+17	1 748
	777-200/300	7 197	1.35	37.47	16.60	1.14	0.18	1.14E+18	2 277
	787-8	5 468	0.24	28.75	10.34	0.87	0.12	1.15E+18	1 730
	CS 100 / A220-100	1 890	0.06	8.25	3.44	0.30	0.05	5.34E+17	598
	CS 300 / A220-300	1 890	0.06	8.25	3.44	0.30	0.05	5.34E+17	598
	EMB170	1 589	0.04	4.84	4.05	0.25	0.03	1.01E+17	503
	EMB190	2 059	1.14	6.43	12.13	0.33	0.06	1.87E+17	652
	DC-10	7 287	2.37	35.65	20.59	1.15	0.24	1.26E+18	2 306
	DC-8-50/60/70	5 357	1.51	15.62	26.31	0.85	0.14	1.46E+18	1 695
	DC-9	2 646	4.63	6.16	16.29	0.42	0.29	6.18E+18	837
Large commercial aircraft[5] Source: ICAO (2018)[6] ICCAIA (2014) ICCAIA (2018)	MD-11	7 287	2.37	35.65	20.59	1.15	0.24	1.26E+18	2 306
	MD-80	3 184	1.87	11.97	6.46	0.50	0.27	5.76E+18	1 008
	MD-90	2 759	0.06	10.76	5.53	0.44	0.26	5.93E+18	873
	TU-134	2 931	17.98	8.68	27.98	0.46	0.66	1.24E+19	928
	TU-154-M	5 959	13.17	12.00	82.88	0.94	1.11	2.96E+19	1 886
	TU-154-B	7 030	119.03	14.33	143.05	1.11	1.58	1.96E+19	2 225
Regional jets/business jets > 26.7 kN thrust	RJ-RJ85	1 906	1.35	4.34	11.21	0.30	0.09	2.09E+18	603
	BAE 146	1 801	1.41	4.07	11.18	0.29	0.07	8.26E+17	570
	CRJ-100ER	1 056	0.63	2.27	6.70	0.17	0.04	5.16E+17	334
	CRJ-900	1 517	0.04	4.40	4.12	0.24	0.03	7.34E+16	480
	ERJ-145	993	0.56	2.69	6.18	0.16	0.02	1.81E+17	314
	Fokker 100/70/28	2 387	1.43	5.75	13.84	0.38	0.34	9.19E+18	755
	Dornier 328 Jet	868	0.57	2.99	5.35	0.14	0.04	5.56E+17	275
	Gulfstream IV	2 030	0.55	4.99	8.25	0.32	0.07	5.22E+17	642
	Gulfstream V	1 857	0.60	5.70	8.90	0.29	0.13	1.00E+18	588
	Gulfstream VI	1 925	0.80	5.13	11.82	0.30	0.09	6.21E+17	609
	Gulfstream VII-500	1 619	0.01	6.34	3.20	0.26	0.03	6.04E+16	512
	RRJ95-LR	2 147	0.27	5.90	9.21	0.34	0.15	1.04E+18	679
	Yak-42M	1 919	1.68	7.11	6.81	0.30	0.09	1.62E+18	607
Low thrust jets (Fn < 26.7 kN)	Cessna 525/560	458	1.66	0.28	16.20	0.07	0.05	1.20E+18	145
Turboprops Source: FOI[7]	Beech King Air[8]	241	0.64	0.32	2.99	0.04	0.02	6.51E+17	76
	DHC8-100[9]	658	0.00	1.55	2.27	0.10	0.07	2.23E+18	208
	ATR72-500[10]	641	0.29	1.88	2.35	0.10	0.07	2.36E+18	203

Notes.—

1. Equivalent aircraft are contained in Table B-2.
2. Information regarding the uncertainties associated with the data can be found in the following references:
   - QinetiQ/FST/CR030440 “EC-NEPAir: Work Package 1 Aircraft engine emissions certification — a review of the development of Annex 16, Volume II,” by D.H. Lister and P.D. Norman.
   - Annex 16, Volume II, 4th edition (2017).
   - Attachment D to Appendix 1 of this document.
3. CO_2 for each aircraft based on 3.16 kg CO_2 produced for each kg of fuel used.
4. The sulphur content of the fuel is assumed to be 0.05 per cent (same assumption as in the 1996 IPCC NGGIP revision).
5. Engine types for each aircraft were selected on the basis of the engine(s) most representing the fleet in terms of LTO cycle number and/or average engine emission levels, as of 30 September 2018. This approach, for some engine types, may underestimate or overestimate fleet emissions.
6. ICAO (International Civil Aviation Organization) Engine Exhaust Emissions Data Bank (2004) based on average measured certification data. Emission factors apply to the certification LTO cycle only. Total emissions and fuel consumption are calculated based on ICAO standard time-in-mode and thrust levels.
7. FOI (Swedish Defence Research Agency) turboprop LTO emissions database non-certified data.
8. Representative of turboprop aircraft with shaft horsepower (SHP) of up to 1 000 SHP/engine.
9. Representative of turboprop aircraft with shaft horsepower of 1 000 to 2 000 SHP/engine.
10. Representative of turboprop aircraft with shaft horsepower of more than 2 000 SHP/engine.

Table B-2. Representative aircraft and engines

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
Airbus A300	PW4158	1PW048	A30B	AB3
			A306	AB4
				AB6
				ABF
				ABX
				ABY
Airbus A310	CF6-80C2A2	1GE016	A310	310
				312
				313
				31F
				31X
				31Y
A318	CFM56-5B9/3	8CM060	A318	318
Airbus A319	CFM56-5B5/P (60%) V2524-A5 (40%)	3CM027 3IA007	A319	319
Airbus A320	CFM56-5B4/3 (50%) V2527-A5 (50%)	8CM055, 1IA003	A320	320
				32S
Airbus A320Neo	PW1127G-JM CFM LEAP-1A26	18PW122 17CM082	A20N	320
Airbus A321	CFM56-5B3/3 (30%) V2533-A5 (70%)	8CM054, 3IA008	A321	321
Airbus A321Neo	PW1133G-JM CFM LEAP-1A35	18PW126 17CM083	A21N	321
Airbus A330-200	Trent 772B-60	3RR030	A330	330
			A332	332
Airbus A330-300	Trent 772B-60	3RR030	A330	330
			A333	333
Airbus A340-200	CFM56-5C3	1CM011	A342	342
Airbus A340-300	CFM56-5C4	2CM015	A340	340
			A343	343
Airbus A340-500	Trent 556-61	6RR041	A345	345
Airbus A340-600	Trent 556-61	6RR041	A346	346
Airbus A350-900	Trent XWB-84	14RR079	A350	350
Airbus A350-1000	Trent XWB-97	18RR080	A350	350
Airbus A380-8	GP7270 (60%)	9EA001, 18RR081	A388	380

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
	Trent 970 (40%)			
Boeing 707	JT3D-3B	1PW001	B703	703
				707
				70F
				70M
Boeing 717	BR700-715A1-30	4BR005	B712	717
Boeing 727-100	JT8D-7B	1PW004	B721	721
				72M
Boeing 727-200	JT8D-15	1PW009	B722	722
				727
				72C
				72B
				72F
				72S
Boeing 737-100	JT8D-9A	1PW007	B731	731
Boeing 737-200	JT8D-9A	1PW007	B732	732
				73M
				73X
Boeing 737-300	JT8D-9A	1PW007	B733	737
				73F
				733
				73Y
Boeing 737-400	JT8D-9A	1PW007	B734	737
				734
Boeing 737-500	JT8D-9A	1PW007	B735	737
				735
Boeing 737-600	CFM56-7B20	3CM030	B736	736
Boeing 737-700	CFM56-7B22	3CM031	B737	73G
				73W
Boeing 737-800	CFM56-7B26	3CM033	B738	738
				73H
Boeing 737-900	CFM56-7B26	3CM033	B739	739
Boeing 747-100	JT9D-7A	1PW021	B741	74T
			N74S	74L

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
			B74R	74R
			B74R	74V
Boeing 747-200	JT9D-7Q	1PW025	B742	742
				74C
				74X
Boeing 747-300	JT9D-7R4G2 (66%) RB211-524D4 (34%)	1PW029 (66%) 1RR008 (34%)	B743	743
				74D
Boeing 747-400	CF6-80C2B1F	2GE041	B744	747
				744
				74E
				74F
				74J
				74M
				74Y
Boeing 747-8	GEnx 2B67	11GE139	B748	748
Boeing 757-200	RB211-535E4	3RR028	B752	757
				75F
				75M
Boeing 757-300	RB211-535E4B	5RR039	B753	753
Boeing 767-200	CF6-80A2	1GE012	B762	762
				76X
Boeing 767-300	PW4060	1PW043	B763	767
				76F
				763
				76Y
Boeing 767-400	CF6-80C2B8F	3GE058	B764	764
Boeing 777-200	Trent 877	2RR025	B772	777
				772
Boeing 777-300	GE90-115B	7GE099	B773	777
				773
Boeing 787-8	GEnx 1B70 Trent 1000 PkgB	11GE138 12RR057	B787	787
Airbus A220-100 / Bombardier CS 100	PW 1524G	16PW111	BCS1	CS1
Airbus A220-300 / Bombardier CS 300	PW 1525G	16PW110	BCS3	CS3

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
Douglas DC-10			DC10	D10
				D11
				D1C
				D1F
Douglas DC-10	CF6-50C2	3GE074	DC10	D1M
				D1X
				D1Y
Douglas DC-8	CFM56-2C1	1CM003	DC85	D8F
			DC86	D8L
			DC87	D8M
				D8Q
				D8T
				D8X
				D8Y
Douglas DC-9	JT8D-7B	1PW004	DC9	DC9
			DC91	D91
			DC92	D92
			DC93	D93
			DC94	D94
			DC95	D95
				D9C
				D9F
				D9X
Lockheed L-1011	RB211-22B	1RR003	L101	L10
				L11
				L15
				L1F
McDonnell Douglas MD11	CF6-80C2D1F	3GE074	MD11	M11
				M1F
				M1M
McDonnell Douglas MD80	JT8D-217C	1PW018	MD80	M80
			MD81	M81
			MD82	M82
			MD83	M83

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
			MD87	M87
			MD88	MD88
McDonnell Douglas MD90	V2525-D5	1IA002	MD90	M90
Tupolev Tu134	D-30-3	1AA001	T134	TU3
Tupolev Tu154	D-30-KU-154-II NK-8-2U	1AA004 1KK001	T154	TU5
Avro RJ85	LF507-1F, -1H	1TL004	RJ85	AR8
				ARJ
BAe 146	ALF 502R-5	1TL003	B461	141
			B462	142
			B463	143
				146
				14F
				14X
				14Y
				14Z
CRJ-100ER	CF34-3A1	1GE035		CR1
CRJ-900	CF34-8C5	8GE110		CR9
Embraer ERJ145	AE3007A1	6AL007	E145	ER4
				ERJ
Embraer EMB170	CF34-8E5A1	8GE105	E170	E70
Embraer EMB190	CF34-10E5A1	11GE144	E190	E90
Fokker 100/70/28	TAY Mk650-15	1RR021	F100	100
			F70	F70
			F28	F21
				F22
				F23
				F24
				F28
BAC 111	Spey-512-14DW	1RR016	BA11	B11
				B12
				B13

Generic aircraft type	ICAO engine	Engine UID	ICAO	IATA aircraft in group
				B14
				B15
Dornier Do 328	PW306B	7PW078	D328	D38
Gulfstream IV	Tay 611-8C	11RR048		GRJ
Gulfstream V	BR700-710A1-10	6BR010		GRJ
Gulfstream VI	BR-700-725A1-12	11BR011		
Gulfstream VII-500	PW814GA	19PW127		
RRJ95-LR	SaM146-1S18	11PJ002		
Yakovlev Yak 42	D-36	1ZM001	YK42	YK2
Cessna 525/560	PW545A or similar	FAEED222		
Beech King Air	PT6A-42	PT6A-42		
DHC8-100	PW120 or similar	PW120		DH1
ATR72-500	PW127F or similar	PW127F		AT5

Note.— Table B-2 contains representative engines for the given aircraft model; they are not necessarily the most used. Therefore, there may be differences from Table B-1 when LTO emission masses are calculated.

Attachment C to Appendix 1

PUBLICLY AVAILABLE DATABASES FOR MATCHING AIRCRAFT TYPE WITH ENGINE TYPE

1. USEFUL DATA FIELDS IN THE IOAG DATABASE

LveTime = Time flight is scheduled to depart origin in local time
LveGMT = Time flight is scheduled to depart origin in Greenwich Mean Time (GMT)
ArrCode = Number representing arrival airport
Arrive = Arrival airport alphabetic code (for example, JFK)
ArrTime = Time flight is scheduled to arrive in local time
ArrGMT = Time flight is scheduled to arrive in GMT
Equip = Type of aircraft, in code (for example, B738)
FAACarr = Abbreviation for air carrier name
FltNo = Flight number
Freq = 1/0 code showing days of the week that the flight flies that time slot and city pair
ATACarr = Carrier name in Air Transport Association (ATA) Code
IOAGCARR = Air carrier company in two-letter IOAG code
CarrType = Commuter or carrier company
ATAEquip = Aircraft type in ATA code
EqType = J for jet, T for turboprop, P for propeller-driven aircraft
CarrName = Air carrier company name spelled out
LveCity = Origin city and country/state, spelled out
ArrCntry = Destination country or state if the destination is in the United States
LveCntry = Origin country or state if the origin is in the United States
YYMM = Year and month of the current schedule
Eday = 0/1 code indicating whether this flight flies on each day of the month given by the schedule
FPM = Number of times (days) this fight is flown between this city pair at this time slot in a month

2. USEFUL DATA FIELDS IN THE ASQP DATABASE

IATA carrier code
Flight number
Depart airport
Arrival airport
Date of operation
Day of week
IOAG depart time
Actual depart time
IOAG arrival time
CRS arrival time
Actual arrival time
Wheels-off time
Wheels-on time
Aircraft tail number
Taxi-out time
Taxi-in time

Attachment D to Appendix 1

FIRST ORDER APPROXIMATION V4.0 METHOD FOR ESTIMATING PARTICULATE MATTER MASS AND NUMBER EMISSIONS FROM AIRCRAFT ENGINES

1. NOMENCLATURE

AFR	Air-to-fuel ratio (mass basis)
BPR	Bypass ratio
C_k	Estimated non-volatile particulate matter mass concentration for an engine operating in mode k, which is an estimation of the non-volatile particle mass at an instrument location in the ICAO standardized measurement system per standard volume of flow (μg/m^3)
C_r	Unit scale factor for nvPMmass concentration
D_r	Unit scale factor for geometric mean diameter (GMD) estimation
EI	Emission index. A pollutant emission rate based on one kilogram of fuel burned. The units of an EI are normally given as g/kg of fuel. However, for convenience the unit mg/kg of fuel is used in this document unless explicitly stated otherwise.
EI_{HC}	Emission index for total hydrocarbons as listed in the ICAO EEDB (g/kg of fuel)
$EI_{HCCFM56}$	Emission index for total hydrocarbons for the CFM56-2-C5 engine as listed in the ICAO EEDB (g/kg of fuel)
$EI_{vPMmass-orgCFM56}$	Emission index for organic volatile particulate matter mass for the CFM56-2-C1 engine as derived in the APEX1 measurements (mg/kg of fuel)
$EI_{HCEngine}$	Emission index for total hydrocarbons from the ICAO EEDB for the subject engine (g/kg of fuel)
$EI_{nvPMmass}$	Emission index for non-volatile particulate matter mass (g/kg of fuel or mg/kg of fuel) at instrument level
$EI_{nvPMmass,e}$	Emission index for non-volatile particulate matter mass (g/kg of fuel or mg/kg of fuel) at engine exit
$EI_{nvPMnumber,e}$	Emission index for non-volatile particulate matter number (particles/kg of fuel) at engine exit
$EI_{tPMmass}$	Total particulate matter mass emission index. The sum of volatile and non-volatile particle mass components (mg/kg of fuel).
$EI_{vPMmass-FSC}$	Emission index for volatile sulphate particulate matter mass due to fuel sulphur (mg/kg of fuel)

$EI_{vPMmass-FuelOrganics}$	Emission index for organic volatile particulate matter mass primarily due to incomplete combustion of fuel (mg/kg of fuel)
HC	Total hydrocarbons
ICAO	International Civil Aviation Organization
F_k	Static sea level engine thrust at operating mode k
F_{oo}	Rated engine thrust from the EEDB
FOA	First Order Approximation. FOA4.0 is the latest version of the methodology to provide emission indices for particulate matter emitted from aircraft listed in the ICAO EEDB.
FSC	Fuel sulphur content (mass fraction)
GMD_k	Geometric mean diameter of non-volatile particles in mode k
k	An LTO operating mode
$k_{slm,k}$	System loss correction factor for nvPMmass at operating mode k
LTO	ICAO landing and take-off cycle
nvPM	Non-volatile particulate matter. Emitted particles that exist at the gas turbine engine exhaust nozzle exit plane that do not volatilize when heated to a temperature of 350°C. nvPM consists mainly of black carbon.
OPR	Overall pressure ratio
MTF	Mixed turbofan
MW_{out}	Molecular weight of SO_4^{-2} ($S^{VI} = 96$)
$MW_{Sulphur}$	Molecular weight of elemental sulphur ($S^{IV} = 32$)
N_r	Unit scale factor for nvPMnumber
PM	Particulate matter
Q_k	Specific exhaust volume for an engine operating in mode k, exhaust volume related to fuel burn (m^3/kg fuel)
Q_r	Unit scale factor for specific exhaust volume
ϱ	Assumed nvPM effective density
σ	Assumed geometric standard deviation of nvPM particle distributions
SF	Scaling factor

SN	Smoke number. The methodology in this document is based on smoke numbers as defined in Appendix 2 of Annex 16.
SN_k	Smoke number for an engine operating in mode k. For the ICAO standard LTO, the defined modes are take-off, climb-out, approach and idle.
SN_{max}	Maximum smoke number
STP	Standard temperature and pressure. The STP used in this document is 0° C and 1 atmosphere of absolute pressure.
TF	Unmixed turbofan
vPMmass	Volatile particulate matter mass. vPMmass consists of particles that volatilize when heated to a temperature of 350°C.
tPMmass	Total particulate matter mass. The sum of nvPMmass and vPMmass.
ε	Fuel sulphur conversion efficiency (mass fraction)
δ_k	Ratio of $\mathrm{EI}_{\mathrm{PMvol-FuelOrganics}} = \frac{\mathrm{EI}_{\mathrm{PMvol-orgCFM56}}}{\mathrm{EI}_{\mathrm{HCCFM56}}}$ as derived for use in Eq. D-12 (mg/kg).

2. INTRODUCTION

2.1 The ICAO EEDB contains a data sheet with information on engine nvPM mass and number emissions. Information contained therein should primarily be used to calculate emission inventories at airport level. However, in certain cases (such as out of production engines) this information may not be available. In addition, volatile particulate matter emissions for all engines are estimated using prescribed methods. This section provides a calculation procedure for estimating engine exhaust nvPM emissions from smoke number and volatile particulate matter emissions.

2.2 FOA4.0 is a method for estimating the engine exhaust particulate emissions. For non-volatile and volatile particle mass, the results for each mode of engine operation are given in the form of emission indices (EIs), as mass emitted per kilogram of fuel. For non-volatile particle number emissions, the EIs for each mode of engine operation are given as number of emitted particles per kilogram of fuel. Currently, there is no estimation of volatile particulate number available.

Non-volatile particulate matter (nvPM) ($\mathrm{EI}_{\mathrm{nvPMmass}}$ and $\mathrm{EI}_{\mathrm{nvPMnumber}}$)

2.3 The estimation of non-volatile particulate matter mass (nvPMmass) is based on the engine's smoke number (SN), air fuel ratio (AFR) and, if applicable, its bypass ratio (BPR). The essence of the technique is to convert the SN via an experimental correlation into a non-volatile mass concentration (C), which is the mass of non-volatile PM per unit volume of exhaust. Using the engine AFR and BPR, the volume of the exhaust (Q) per kilogram of fuel is calculated, then the product C and Q gives the EI with the unit of mass per kilogram of fuel burn.

2.4 The FOA4.0 correlation used to convert the SN into a non-volatile mass concentration has been developed based on certification-like measurements and corresponds to an estimation of mass concentration at the instrument level, not at the engine exit plane. As particulate matter (PM) measurements are affected by physical loss mechanisms during the sampling process, estimated values at the instrument level are lower than at the engine exit plane. For emission inventories, loss correction is needed, and the FOA4.0 provides an empirical correction.

2.5 The estimation of $EI_{nvPMnumber,e}$ (emission index of non-volatile PM number (nvPMnumber) at the engine exit plane) is based on system loss-corrected $EI_{nvPMmass,e}$ (emission index of nvPMmass at the engine exit plane), an estimation of the particle geometric mean diameter (GMD), an assumed particle effective density and lognormal particle size distribution.

2.6 For nvPM mass and number emissions, the methods of FOA4.0 are based on the SCOPE11 method for estimating aircraft black carbon emissions (see Agarwal et al. (2019) in list of references).

2.7 $EI_{nvPMmass,e}$ and $EI_{nvPMnumber,e}$ need to be computed for the various thrust settings used in the vicinity of airports.

Volatile sulphate PM $EI_{vPMmass–FSC}$

2.8 Volatile sulphate PM is formed from the fuel sulphur via oxidation of SO_2 (S^{IV}) to SO_3 (S^{VI}) and subsequent hydration, in the exhaust plume, of SO_3 to H_2SO_4. The EI is calculated from the fuel sulphur content and the conversion rate of S^{IV} to S^{VI} (ε). Assuming a constant ε (see 3.8), the EI does not vary by power setting.

Volatile organic PM $EI_{vPMmass–FuelOrganics}$

2.9 Measurements of condensable organics in the engine exhaust are very limited. Based on the assumption that condensable organics are directly related to unburned hydrocarbons, an estimate is made by scaling the engine's reported ICAO hydrocarbon (HC) EI to those of other engines in the database. Making a second assumption that modern engines behave in a similar manner, the HC ratio can be multiplied by the volatile organic PM mass EI for the CFM56-2-C1 engine which was measured during NASA's Aircraft Particle Emissions Experiment 1 (APEX1).[1] The result is an EI that is both engine and power-setting specific for the volatile organic PM.

PM from engine lubricant

2.10 Data are not available to allow prediction of this EI for PM. It is currently assumed, based upon measurement results from APEX1, that the present EI volatile organic PM includes a contribution due to lubrication oil.

3. DATA SOURCES

ICAO Engine Emissions Data Bank (EEDB)

3.1 Values of SN, EI_{HC} and BPR for engines can be found in the ICAO EEDB for the four power settings of the landing and take-off (LTO) cycle. Unfortunately, there are gaps in the data bank for SN and BPR values. This problem has been addressed by ICAO's CAEP as follows:

a) the addition of new engine data;

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[1] NASA. Aircraft Particle Emissions Experiment (APEX), C.C. Wey, U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio, ARL–TR–3903, 2006-214382, September 2006.

b) clarification for mixed turbofans as to whether the measurements were made on the engine core or over both the core and bypass flows by indicating "TF" if the reported SN corresponds to the engine core and indicating "MTF" if the reported SN is diluted by the fan bypass air; and

c) addition of missing SN data.

3.2 Since the SN data in the ICAO EEDB are fragmentary for many engines, some only showing the maximum SN, general guidelines have been developed to help fill in the data gaps. These guidelines apply when, instead of a listed value, the symbol "–" or "NA" appears, denoting that either the SN was not derived at that particular thrust setting or it was not reported since only the maximum is required. These guidelines were developed by Calvert[2] and are based on analysing modal trends within groups of engines to derive scaling factors that can be used to predict the missing data. A scaling factor is a ratio of a modal SN to the maximum SN for an engine:

$$SF = \frac{SN_k}{SN_{max}} \qquad \text{Eq. D-1}$$

where:

SF = scaling factor;

SN_k = SN for one of the modes k (take-off, climb-out, approach or idle); and

SN_{max} = maximum SN.

3.3 In order to reduce the uncertainties in developing the SF values, SNs with values less than 6 were excluded from the analysis. The resulting SF values are presented in Table D-1. The majority of engines are covered by the category non-DAC (double annular combustor) engines; however, Aviadgatel, General Electric CF34, Textron Lycoming and DAC engines have significantly different SF values from the norm.

Table D-1. Suggested SF values to predict missing SN in the ICAO EEDB

Engine category	Take-off	Climb-out	Approach	Idle
Most non-DAC engines	1.0	0.9	0.3	0.3
Aviadgatel engines	1.0	1.0	0.8	0.3
GE CF34 engines	1.0	0.4	0.3	0.3
Textron Lycoming engines	1.0	1.0	0.6	0.3
CFM DAC engines	0.3	0.3	0.3	1.0

3.4 Using these SF values and Eq. D-1, missing SN data can be filled in if at least one of the modal SN values for an engine is known.

3.5 It is also important to note that in addition to some missing SN in the ICAO EEDB, other concerns for the estimation of nvPM also exist. If an SN is listed as zero, the FOA4.0 estimates for $EI_{nvPMmass}$ and $EI_{nvPMnumber}$ will be above zero, which is realistic, but the values will be highly unreliable. The SCOPE11 correlation was developed based on the

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[2] J.W. Calvert, "Revisions to Smoke Number Data in Emissions Databank," *Gas Turbine Technologies*, QinetiQ, 23 February 2006.

correlation between measured Smoke Number and nvPM mass concentration. At Smoke Numbers higher than 3, the correlation is better defined with a smaller scatter of the data points. When SN is less than 3, the scatter increases, thus increasing the uncertainty in the correlation. These uncertainties have been quantified in Agarwal et al. (2019). The data also indicates that even when the reported SN is zero, there is still a non-zero mass concentration measured on the average given that the SN measurement uncertainty is ±2. Because of this, the SCOPE11 estimated mass and number EIs for a zero SN will have non-zero values. The reader is referred to Agarwal et al. (2019) for more details.

Air-fuel ratio (AFR)

3.6 AFR is not included in the ICAO EEDB. This problem has been overcome by the use of average fleet AFRs. These generic values were agreed with representatives of the three main engine manufacturers and are shown in Table D-2.

Table D-2. Representative AFR_k listed by ICAO power settings (mode k)

Thrust setting	AFR
7% (k = idle)	106
30% (k = approach)	83
85% (k = climb-out)	51
100% (k = take-off)	45

Volatile sulphate PM ($EI_{vPMmass–FSC}$)

3.7 Fuel sulphur contents (FSC) can vary widely between different batches of aviation fuel and are not included in the ICAO EEDB. For application to airport emission inventories, this input has been left as a variable to allow the most applicable value, such as the national and/or international mean sulphur contents, to be used. As a guide, typical FSC values range from 0.005 to 0.068 weight per cent[3] with a global average of 0.03 weight per cent.[4] Using a conservative value of 0.068 weight per cent is currently recommended in the absence of more specific FSC data.

3.8 There is uncertainty about the S^{IV} to S^{VI} conversion process, the non-linear production of S^{VI} that varies with changing FSC and engine operating conditions. The variable for fuel sulphur conversion efficiency (ε) may be inputted directly by the practitioner if detailed information is known. However, the value is often unknown and a default value is recommended in these situations. Based on the most recent measurements from APEX and Partemis,[5] the sulphur conversion efficiency can range from 0.5 to over 3.5 weight per cent. A median value of 2.4 weight per cent, based on the APEX measurements, is recommended as the default value. The value of the fuel sulphur conversion efficiency is still a topic of ongoing research, and future refinements are expected.

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[3] Coordinating Research Council, Inc., *Handbook of Aviation Fuel Properties*, Third Edition, CRC Report No. 635, Alpharetta, GA, U.S.A, 2004.

[4] IPCC, *Aviation and the Global Atmosphere*, Intergovernmental Panel on Climate Change, Cambridge University Press, 1999, ISBN 0 521 66404 7.

[5] E. Katragkoue et al., “First gaseous Sulphur (VI) measurements in the simulated internal flow of an aircraft gas turbine engine during project PartEmis,” *Geophysical Research Letters*, November 2003, ISSN 0094-8276.

Volatile organic aerosol ($_{\text{vPMmass–FuelOrganics}}$)

3.9 Organic volatile PM is calculated from the engine ratio of EI_{HC} reported in the ICAO EEDB with the denominator being the EI_{HC} for the CFM56-2-C5 engine, which is the closest value to the engine measured during APEX1. This ratio is multiplied by the measured volatile organic PM EI from APEX1 for the CFM56-2-C1 engine. The measured values are shown in Table D-3.

Table D-3. Measured volatile EI (from reference 1) used to calculate organic volatile PM

LTO mode k	$EI_{vPMmass–orgCFM56,k}$(mg/kg fuel)
Take-off	4.6
Climb-out	3.8
Approach	4.5
Idle	11.3

4. PM EI CALCULATION

nvPM mass and number

4.1 This section describes the estimation procedure for nvPMmass and nvPMnumber EIs at engine exit plane $EI_{nvPMmass,e,k}$ and $EI_{nvPMnumber,e,k}$ for a single mode k of engine operation.

4.2 Steps 1 to 3 provide $EI_{nvPMmass,e,k}$ (based on engine mode-specific smoke number, SN_k), and Step 4 provides $EI_{nvPMnumber,e,k}$ (based on $EI_{nvPMmass,e,k}$).

Estimation of $EI_{nvPMmass,e,k}$ $\left(\frac{\text{g}}{\text{kg fuel}}\right)$

4.3 The following information is needed from the EEDB: smoke numbers for each engine in operation mode k (SN_k); information on whether the SNs are from the engine core (EEDB engine designator “TF” = unmixed SN_k) or diluted with bypass air (EEDB engine designator “MTF” = mixed SN_k); and the BPR in the case of mixed SN_k.

4.4 **Step 1:** From the SN at engine operation mode k, the estimated nvPM mass concentration at the instrument (C_k) of the ICAO standardized measurement system can be found using the correlation in Eq. D-2:

$$C_k\left(\frac{\mu g}{m^3}\right) = \frac{648.4\ e^{0.0766 \cdot SN_k}}{1+e^{-1.098 \cdot (SN_k - 3.064)}} \times C_r \qquad \text{Eq. D-2}$$

with $C_r = 1\ \frac{\mu g}{m^3}$

4.5 **Step 2:** The nvPMmass EI at the instrument ($EI_{nvPMmass,k}$) is found by multiplying C_k with the specific exhaust volume (Q_k) (see Eq. D-3), whereas Q_k is found using Eq. D-4 with the value of β depending on the engine exhaust configuration (unmixed or mixed SN_k). Engines with mixed nozzles ("MTF" in the EEDB) require a correction for the BPR, and therefore β = BPR. For all other engines (e.g. "TF" in the EEDB), set β = 0.

$$EI_{nvPMmass,k}\left(\frac{g}{kg\ fuel}\right) = C_k\left(\frac{\mu g}{m^3}\right) \times 10^{-6} \times Q_k\left(\frac{m^3}{kg\ fuel}\right) \qquad \text{Eq. D-3}$$

$$Q_k = (0.777 \times AFR_k \times (1 + \beta) + 0.767) \times Q_r \qquad \text{Eq. D-4}$$

with $Q_r = 1\ \frac{m^3}{kg\ fuel}$

Average values for AFR_k are provided in Table D-2.

4.6 **Step 3:** The nvPMmass concentration at the instrument (C_k) determined by Eq. D-2 is always lower than at the engine exit plane due to particle losses in the sampling and measurement system. For gaseous emission measurements, a sampling system without chemical reactions of gaseous species will preserve the sample to the instrument location, but for particle measurements, a portion of particles will always be lost – for example, to walls in the sampling system. For emission inventories, the nvPMmass EIs for each engine mode at the engine exit plane ($EI_{nvPMmass,e,k}$) are needed, and require an estimated and engine mode-dependent correction for particle losses. The particle loss characteristic of the ICAO standardized particle sampling system has been transferred to Eq. D-5.

a) Use the estimated C_k to calculate the mode-dependent system loss correction factor for nvPMmass ($k_{slm,k}$) from Eq. D-5:

$$k_{slm,k} = \ln\left(\frac{3.219 \times C_k \times (1+\beta) + 312.5}{C_k \times (1+\beta) + 42.6}\right). \qquad \text{Eq. D-5}$$

b) $EI_{nvPMmass,e,k}$ is finally calculated by multiplying $EI_{nvPMmass,k}$ with $k_{slm,k}$:

$$EI_{nvPMmass,e,k}\left(\frac{g}{kg\ fuel}\right) = k_{slm,k} \times EI_{nvPMmass,k}\left(\frac{g}{kg\ fuel}\right). \qquad \text{Eq. D-6}$$

Estimation of $EI_{nvPMnumber,e,k}\left(\frac{particles}{kg\ fuel}\right)$

4.7 The estimation of $EI_{nvPMnumber,e,k}$ requires $EI_{nvPMmass,e,k}$ from Eq. D-6 and engine mode-dependent geometric mean diameters (GMD_k) of the nvPM particles from Table D-4.

Table D-4. Standard values for GMD_k listed by ICAO thrust settings (mode k)

LTO mode k	GMD_k (nm)
Take-off	40
Climb-out	40
Approach	20
Idle	20

4.8 **Step 4:** The nvPMnumber EI at engine exit plane for a single mode of engine operation k ($\mathrm{EI}_{\mathrm{nvPMnumber,e,k}}$) is then found using Eq. D-7:

$$\mathrm{EI}_{\mathrm{nvPMnumber,e,k}}\left(\frac{\mathbf{particles}}{\mathrm{kg\ fuel}}\right)=\frac{6\times\mathrm{EI}_{\mathrm{nvPMmass,e,k}}\left(\frac{\mathrm{g}}{\mathrm{kg\ fuel}}\right)\times\mathrm{N_r}}{\pi\times\rho\left(\frac{\mathrm{kg}}{\mathrm{m^3}}\right)\times\mathrm{GMD_k}^3(\mathrm{nm^3})\times e^{4.5(\ln(\sigma))^2}} \qquad \text{Eq. D-7}$$

where σ = 1.8 is the assumed geometric standard deviation of the nvPM particle size distribution. ρ = 1000 kg/m^3 is the assumed average nvPM particle effective density and $\mathrm{N_r} = 10^{24}\ \frac{\mathrm{kg \cdot nm^3}}{\mathrm{g \cdot m^3}}$ is the unit scale factor.

Volatile sulphate PM

4.9 The EI for sulphate PM is calculated from:

$$\mathrm{EI}_{\mathrm{vPMmass-FSC}}\left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)=(10)^6\left[\frac{(\mathrm{FSC})(\varepsilon)(\mathrm{MW_{out}})}{\mathrm{MW_{Sulphur}}}\right]\times S_\mathrm{r} \qquad \text{Eq. D-8}$$

where:

$\mathrm{MW_{out}}$ = 96 ($\mathrm{SO_4}^{-2}$) and $\mathrm{MW_{Sulphur}}$ = 32. The values of FSC and *ε* are user-defined with default values as previously defined, and $\mathrm{S_r} = 1\frac{\mathrm{mg}}{\mathrm{kg}}$ is the unit scale factor.

Volatile organic PM

4.10 The EI of the volatile organic PM is calculated from:

$$\mathrm{EI}_{\mathrm{PMvolvPMmass-FuelOrganics,k}}=\frac{\mathrm{EI}_{\mathrm{vPM-orgCFM56,k}}}{\mathrm{EI}_{\mathrm{HCCFM56,k}}}\left(\mathrm{EI}_{\mathrm{HCEngine,k}}\right)\ \mathrm{mg/kg} \qquad \text{Eq. D-9}$$

where $\mathrm{EI}_{\mathrm{HCCFM56}}$ is the ICAO total hydrocarbon EI for the CFM56-2-C1 engine. $\mathrm{EI}_{\mathrm{vPM-orgCFM56}}$ is the APEX1 measured volatile organics EI from Table D-3, and $\mathrm{EI}_{\mathrm{HCEngine,k}}$ is the $\mathrm{EI}_{\mathrm{HC}}$ from the ICAO EEDB for the subject engine (the engine where the EI is being determined) for mode k. Of note are:

a) the units of $\mathrm{EI}_{\mathrm{HCEngine}}$ and $\mathrm{EI}_{\mathrm{HCCFM56}}$ are g/kg of fuel as listed in the ICAO EEDB and cancel; and

b) the ratio of $\mathrm{EI}_{\mathrm{vPM-orgCFM56,k}}$ and $\mathrm{EI}_{\mathrm{HCCFM56,k}}$ is a constant for each mode. Since only the modal value of the $\mathrm{EI}_{\mathrm{HC}}$ for the subject engine changes, a simplification can be made to Eq. D-10, which is easier to calculate. This results in:

$$\mathrm{EI}_{\mathrm{vPM-FuelOrganics,k}} = (\delta_k)\ (\mathrm{EI}_{\mathrm{HCEngine,k}})\ \mathrm{mg/kg} \qquad \text{Eq. D-10}$$

where δ_k is a constant ratio by mode k. Values of this constant are given in Table D-5 for each mode.

Table D-5. Modal values for the ratio of $EI_{vPM-orgCFM56}$ and $EI_{HCCFM56}$ in Eq. D-10

LTO mode k	δ_k (mg/g)
Take-off	115
Climb-out	76
Approach	56.25
Idle	6.17

5. EXAMPLE CALCULATIONS

5.1 This example is based on calculating PM EIs for the JT8D-217 series engines with an ICAO UID of 1PW018. Derived values are presented for all modes, while complete calculations are shown only for the idle mode since the process is simply repeated for the other modes using appropriate variables. Of course, the PM for sulphur does not change by power setting and is the same for all modes. EI_{HC} and SN data for the idle mode from the ICAO EEDB for this engine are shown in Table D-6.

Table D-6. ICAO data for the JT8D-217 series engine, idle mode

LTO mode	EI_{HC} (g/kg)	SN
Take-off	0.28	13.2
Climb	0.43	Missing
Approach	1.6	Missing
Idle	3.33	Missing
Maximum value	NA	13.3

5.2 To fill in the missing SN value for the idle mode, a scaling factor of 0.3 from Table D-1 corresponding to "most non-DAC engines" and the k = idle mode is used:

$$SN_{idle} = (0.3) \times (13.3) = 3.99.$$

5.3 Assuming a fuel sulphur content of 0.068 weight per cent (fraction 0.00068) and an S^{IV} to S^{VI} conversion rate of 2.4 weight per cent (fraction 0.024), the modal independent $EI_{PMvol-FSC}$ is calculated as follows:

$$\mathrm{EI}_{\mathrm{vPMmass-FSC,idle}} = (10^6)\left[\frac{(0.00068) \times (0.024) \times (96)}{32}\right] = 49.0\ \mathrm{mg/kg\ or\ 0.049\ g/kg}.$$

5.4 The $EI_{vPM\text{–}FuelOrganics}$ may be calculated using the values in Table D-3, Table D-5 and the EI_{HC} for the specific engine as listed in the ICAO EEDB corresponding to the idle mode:

$$EI_{vPMmass-FuelOrganics,idle} = \frac{11.3}{1.83} \times (3.33) = 20.6 \text{ mg/kg or } 0.021 \text{ g/kg.}$$

5.5 Alternatively, the values in Table D-5 may be multiplied by the EI_{HC} for the specific engine as listed in the ICAO EEDB as:

$$EI_{vPMmass-FuelOrganics,idle} = (6.17) \times (3.33) = 20.5 \text{ mg/kg.}$$

5.6 The engine JT8D-217 is a mixed flow engine (“MTF”) with a BPR of 1.73, which has to be taken into account for estimation of the nvPM mass and number EIs. In summary, the example calculation results of applying the FOA4.0 nvPM mass and number method to the idle mode for the JT8D-217 series engine are:

$EI_{nvPMmass,e,idle}$ = 0.181 g/kg = 181 mg/kg,

$EI_{nvPMnumber,e,idle}$ = 9.2×10^{15} particles/kg.

5.7 The total EI for all components of PM mass emissions is then:

$EI_{tPMmass,idle}$ = 181 + 49 + 21 = 251 mg/kg of fuel or 0.251 g/kg of fuel burn.

5.8 While the EI for sulphur does not change by power setting, the other EIs must be calculated for each mode k. Table D-7 shows the results for all modes. Of note is that the maximum SN was used for the nvPM EI estimates.

Table D-7. Values of EI_{PM} for the JT8D-217 series engine (mg/kg of fuel and particles/kg of fuel)

ICAO defined power setting (mode)	$EI_{nvPMmass,e,k}$	$EI_{vPMmass\text{–}FSC,k}$	$EI_{vPMmass\text{–}FuelOrganics,k}$	Total EI_{PMmass} by mode k	$EI_{nvPMnumber.e.k}$
Idle	181	49.0	21	251	$9.2 \cdot 10^{15}$
Approach	142	49.0	90	281	$7.2 \cdot 10^{15}$
Climb-out	212	49.0	33	294	$1.3 \cdot 10^{15}$
Take-off	207	49.0	32	288	$1.3 \cdot 10^{15}$

6. UNCERTAINTIES

6.1 As its title suggests, FOA4.0 is an approximation. The PM ad hoc group of CAEP WG3 has endeavoured to make the methodology as accurate as possible. However, the user should be aware that not all physical concepts are well understood and data for many of the parameters are sparse. This leads to uncertainties in the estimation methodology including:

a) lack of data in the ICAO EEDB, particularly:

   1) SN_k;

b) reliance on average values of the specific engine’s:

    1) AFR;
    2) fuel sulphur content;
    3) S^{IV} to S^{VI} conversion factor; and
    4) combustor technology and individual engine behaviour for particle formation;

c) extremely limited data on volatile organics and lack of measurement conventions;

d) no information on the effect of engine lubricants;

e) inaccuracies and measurement differences in reported data:

    1) Annex 16, Volume II states that measured SNs can vary by ±3; and
    2) low SNs as input into the estimation formulae can lead to very inaccurate predictions of nvPMmass and, in turn, of nvPMnumber;

f) higher uncertainties must be expected in the particle loss correction, meaning in the conversion from estimated values at the measurement instrument to the estimated values at the engine exit plane. Quantifying so-called system particle loss correction is extremely difficult and can only be derived by physical models; and

g) assumptions for the nvPM GMDs, particle effective densities and particle size distributions.

6.2 Implementation of the certification nvPM sampling and measurement system requires a long sample line of up to 35 m and includes several sampling and measurement system components, which can result in significant particle loss, typically on the order of 20 to 50 per cent for nvPM mass and 50 to 90 per cent for nvPM number. The particle losses are size dependent and hence are dependent on engine operating condition, combustor technology and possibly other factors. The system loss corrected EIs for nvPM mass and number are estimated using the standardized methodology described in Annex 16, Volume II, Appendix 8 and SAE International Aerospace Recommended Practice 6481 (SAE ARP 6481) using the ratio of measured nvPM mass to number concentrations and other system specific input parameters. The system loss correction estimation methodology is generally robust except when nvPM measurements are very low. Full system loss factor uncertainties are difficult to determine. However, the random uncertainties in the estimated system loss corrections are known to be greater than 10 per cent for nvPM mass EIs and 40 per cent for nvPM number EIs for 20 nm emitted particles (Ref: ARP 6481). There are higher uncertainties and system loss factors that will also be underestimated when estimated geometric mean diameters of emitted particles are smaller than 20 nm. In general, the larger the correction factor estimated by the ratio $EI_{corrected}/EI_{uncorrected}$, the bigger the uncertainty will be. The uncertainties should be noted when the system loss corrected EIs are used in the generation of airport level emissions inventories.

6.3 The limitations of the EEDB are being addressed by the engine manufacturers through CAEP WG3. Values of engine AFR and other combustion-related parameters for individual engine types are unlikely to be available because they are commercially sensitive. More confidence in the S^{IV} to S^{VI} conversion factor, volatile organics and the effect of engine lubricants will come with more experimental measurements and improved measurement techniques.

6.4 Estimated nvPM (mass and number) may differ in the order of 50 per cent to 125 per cent for most engines and perhaps significantly more (orders of magnitude) from measured values. When available, engine nvPM certification data should always be used for inventories due to estimation methodology inaccuracies. The methods are offered for fleet-wide estimations of PM emissions at airports. Based on paragraph 6.1 above, the methods are not appropriate to assess PM emissions from individual engines, for engine comparisons or individual engine modes.

6.5 Since the inception of the FOA process and its development into FOA3.0 and FOA4.0, the methodology has continued to evolve and the estimate accuracy for non-volatile PM has improved. The FOA process is not static and will continue to evolve, while certification measurement data for nvPM are publicly available. For some out-of-production engines prior to 2020 and for volatile PM emission calculations, estimation methods will still be needed. In the interim, CAEP will continue to review available information to improve the methodology and the input parameters to the degree possible.

Attachment E to Appendix 1

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EXAMPLES OF MODELLING SYSTEMS

The following list contains examples of modelling systems for airport local air quality studies. This list is neither complete nor prescriptive.

Name and version	Availability	Website
ADMS	Application, publicly available	www.cerc.co.uk
Open ALAQS	Application, available through EUROCONTROL	www.eurocontrol.int
AEDT and EDMS 5.1	Application, publicly available	www.faa.gov
LASPORT 2.3	Application, publicly available	www.janicke.de

Appendix 2 to Chapter 3

AIRCRAFT HANDLING EMISSIONS

1. INTRODUCTION

1.1 Ground handling of aircraft during operational turnaround or for maintenance is an important airport-related emissions source. The type and number of vehicles and equipment used for ground handling depends on several factors, including aircraft size and type, aircraft stand properties and layout, and the technological and operational characteristics of the ground handling equipment. There are two general types of emissions comprising four distinct sources in this category: a) ground support equipment (GSE) and airside vehicle emissions (emissions of engine exhaust) and b) aircraft refuelling and aircraft de-icing (evaporative emissions of volatile organic compounds (VOC)):

a) ***Exhaust emissions***

   1) *Ground support equipment (GSE).* Emissions from vehicles and machinery used to service the aircraft on the ground at the aircraft stand or maintenance area; and

   2) *Airside vehicles.* Service vehicles and machinery operating on service roads within the airport property (other than GSE).

b) ***Evaporative emissions***

   1) *Aircraft refuelling.* VOC evaporation emissions during fuelling of aircraft; and

   2) *Aircraft de-icing.* VOC evaporation emissions during de-icing of aircraft (where applicable).

1.2 Vehicle refuelling, fuel farms and surface de-icing emissions are described in Appendix 3 to Chapter 3.

2. GROUND SUPPORT EQUIPMENT EMISSIONS

Operations

2.1 The operation of GSE is a function of several parameters that can vary considerably from airport to airport (see Figure 3-A2-1). However, in terms of spatial and temporal resolution, GSE emissions can be related to the aircraft operations.

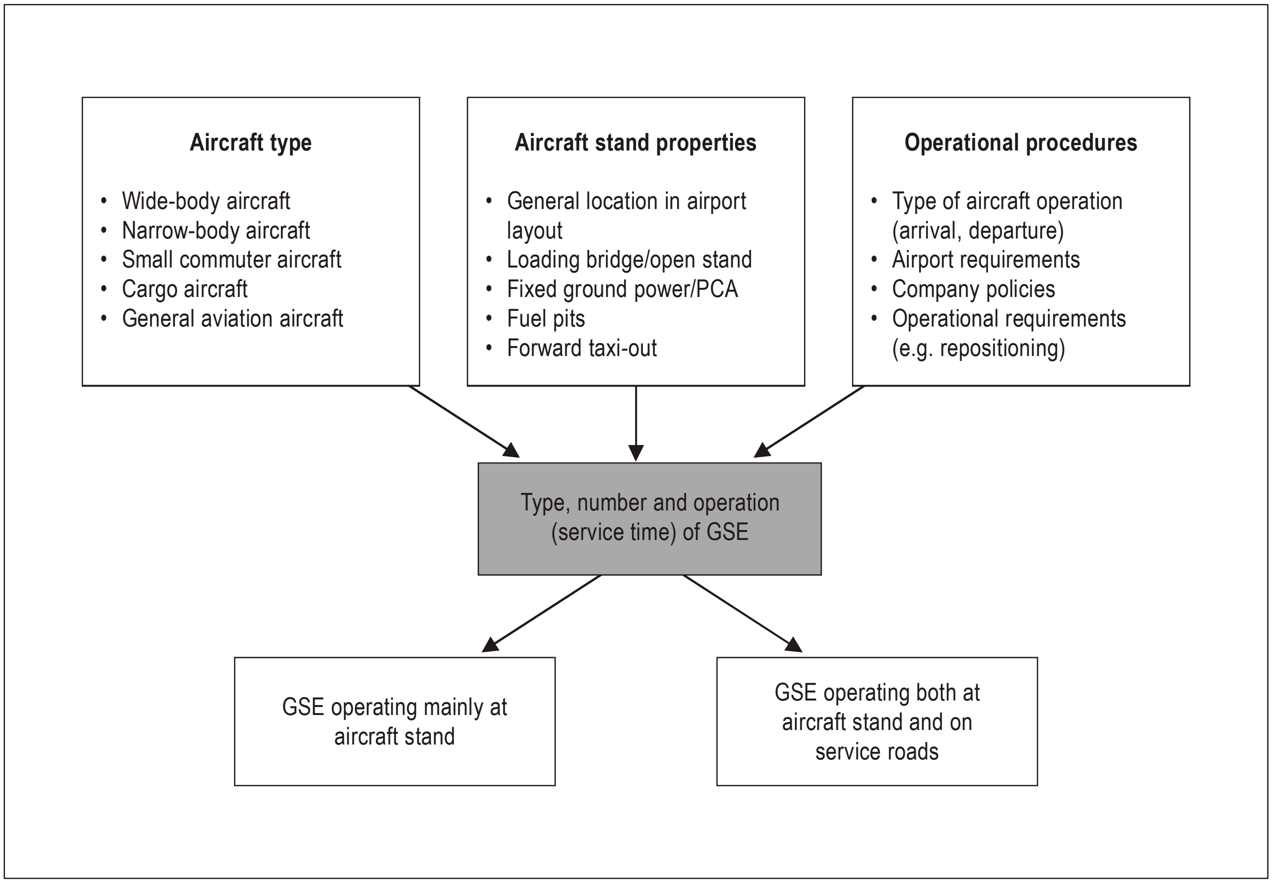

Figure 3-A2-1. Characterization of GSE operations

2.2 GSE often consists of non-road vehicles that have been specially designed to provide services required for aircraft (including cargo loaders, baggage belts, aircraft tugs). They are geared for low-speed, high-torque duties and are built to manoeuvre in tight locations around parked aircraft. They may move across the airport, but generally service a limited number of specific locations. They are generally powered by internal combustion engines of various kinds, but other technologies are sometimes used. Some GSE units (such as catering trucks, lavatory trucks, and baggage tugs) operate on an aircraft stand for some time and then use service roads to return to specific facilities). They may also be equipped with on-road certified engines. Table 3-A2-1 lists the GSE most frequently used to provide ground support services to aircraft with suggested default values for engines and service times.

Table 3-A2-1. Typical ground support equipment

Ground support equipment	Function	Engine type/equipment	Service time per turn	Comments
Ground power unit (GPU)	Provides electrical power to aircraft	100–150 kW diesel or gasoline; 15%–50% load	Depends on schedule	Electric system may be integrated into gate/bridge
Air conditioning/heater unit	Provides preconditioned air and/or heat to aircraft	150 kW diesel or gasoline; 50% load	Depends on schedule and weather conditions	Electric PCA may be integrated into gate/bridge
Air starter unit	Provides high pressure air flow for starting main engines	150 kW diesel; 90% load	3–5 minutes	Generally not used if aircraft is equipped with an on-board APU
Narrow-body push-out tractor	Pushback and maintenance towing	95 kW diesel; 25% load	5–10 minutes	Electric-powered units available
Wide-body push-out tractor	Pushback and maintenance towing	400 kW diesel; 25% load	5–10 minutes	Electric-powered units available
Passenger stairs	Provides easy ramp access	30–65 kW diesel or gasoline; 25% load	2–10 minutes	Non-powered and electric units available
Belt loader	Transfers bags between carts and aircraft	33 kW diesel, gasoline or CNG; 25% load	10–50 minutes	Electric units available
Baggage tug	Tows loaded carts to exchange baggage	30 kW diesel, CNG or gasoline; 50% load	10–50 minutes	Electric units available
Cargo and container loader	Lifts heavy cargo and containers to assist transfer	60 kW diesel or gasoline with lift devices; 25% load	10–50 minutes	Different types
Cargo delivery	Transfers cargo from dollies to loader	30 kW diesel or gasoline; 25% load	10–50 minutes	Different types
Bobtail truck	Miscellaneous towing and heavy services	90 kW diesel truck; 25% load	Variable	Highly variable
Catering and service truck	Cleans and restocks food and supplies	85–130 kW diesel with scissors lift; 10–25% load	10–30 minutes	May use on-road certified engines
Lavatory, potable water truck	Empties aircraft toilet storage, refills aircraft water storage	120 kW diesel with tank and pumps; 25% load	5–20 minutes	May use on-road certified engines
Fuel hydrant truck	Delivers fuel from pits to aircraft	70–110 kW diesel with pumps; 10–50% load	10–40 minutes	May use on-road certified engines
Fuel tanker truck	Pumps fuel from truck to aircraft	200 kW diesel with pumps; 10–50% load	10–40 minutes	May use on-road certified engines
De-icing truck	Sprays de-icing fluid on aircraft prior to departure	180 kW diesel with tank, pumps, sprayers; 10–60% load	5–15 minutes	May use on-road certified engines
Maintenance lift	Provides access to outside of aircraft	70–120 kW diesel, CNG or gasoline; 25% load	Variable, little used	May use on-road certified engines
Passenger buses	Transports passengers to and from aircraft	100 kW diesel, CNG or gasoline; 25% load	Variable (distance rather than time)	May use on-road certified engines
Forklift	Lifts and carries heavy objects	30–100 kW diesel; 25% load	Highly variable	Electric units available; mostly cargo-related use
Miscellaneous vehicles (cars, vans, trucks)	Miscellaneous services	50–150 kW diesel, electric, CNG or gasoline; 10–25% load	Highly variable (distance rather than time)	Usually on-road certified engines

2.3 As shown in Table 3-A2-2, the size of the aircraft sometimes influences the stand allocation and often the handling procedures (for example, number, types and operating time) involving GSE.

Table 3-A2-2. Aircraft group characterization

Aircraft group	Characterization
Wide-body aircraft	Passenger baggage pre-loaded in containers Large cargo volume Passenger stairs with buses or boarding bridge required Turnaround time could include moving aircraft (day-parking)
Narrow-body aircraft	Passenger baggage is free-loaded (for example, not in a container) Small cargo volume Passenger stairs with buses or boarding bridge required Short turnaround times
Small commuter aircraft	Passenger baggage open Carry some cargo (very small volume) Short turnaround times Built-in passenger stairs
Cargo aircraft	No “comfort” needs (buses, baggage, air-conditioning) Specialized cargo-handling equipment and vehicles
General aviation aircraft	No baggage, cargo, stairs Limited handling activities

2.4 At most airports, the two following types of aircraft stands can be found:

a) pier stands, where a passenger boarding bridge connects the aircraft to the building; and

b) remote/open stands, where an aircraft is parked free of direct building connections (for passenger and/or cargo operations).

2.5 The stands themselves can exhibit considerable differences in terms of location and technical equipment available, which influence the number and operations of GSE and thus emissions from this source (see Table 3-A2-3). Stands may also differ for reasons of dedicated usage (for example, whether a stand is used for cargo aircraft or for passenger aircraft).

Table 3-A2-3. Properties of aircraft stands

Stand properties	GSE and operational consequences	Notes
Stand equipped with passenger boarding bridge	Aircraft does not require passenger stairs	May require pre-conditioned air (PCA), heating and/or GPU
Stand equipped with fixed 400 Hz	Aircraft does not require GPU and might need air climate unit (ACU)	
Additionally equipped with PCA (stationary) or through aircraft climate unit (ACU)	Aircraft does not require GPU or ACU	Stationary only together with 400 Hz
Stand equipped with kerosene pipeline	Aircraft does not require refuelling tanker truck	Aircraft requires hydrant fuel truck
Proper layout for self-powered breakaway	Aircraft does not require pushback tractor	Not possible on stands with bridge

2.6 Operational procedures also determine the types and amounts of GSE services required, described as follows:

a) The type of GSE used varies widely across applications. For example, different GSE types are required for servicing aircraft after landing than are used prior to departure and for servicing passenger and cargo operations.

b) Government regulations (including safety, operational requirements) and airport operator requirements (such as airport-specific procedures or restrictions) may limit or preclude the use of certain GSE.

c) The airline operator, in cooperation with the handling agent, might follow specific procedures that influence GSE emissions.

d) Airport infrastructure can affect the feasibility of alternative fuel types or other factors that can affect emissions.

e) Airport stand layout and flexibility in operations may also be a factor (relocating GSE from stand-to-stand or to remote stands during operations).

2.7 Operational data can be obtained in different ways (for example, bottom-up, by assessing individual pieces of GSE, or top-down, by using global operating times or fuel consumption over the total GSE population). Each alternative provides advantages and the choice among them will depend on factors such as the purpose and design of the emissions inventory, the availability of data and their accuracy. Operational data could include:

a) total fuel burn by all GSE (by different fuel types);

b) total hours of operation for each GSE type and number of units per type (again, with distinction by fuel type); and

c) operating time for each GSE unit for specific or individual aircraft operations (for example, LTO in general or arrival and departure separately). Spatial and temporal information might be also included. The accuracy of GSE service time in this case is very important because even small deviations can yield large errors.

For example, if a tug is used eight minutes per cycle (instead of six minutes) and the handling cycles are 25 000, the error would be 843 operating hours.

Emission factors

2.8 Emission factors for GSE are not uniform for all regions of the world. Depending on regional or national standards or local operational requirements, the same type of equipment might be equipped with different engines (for example, size and technology). Emission factors are also often reported as off-road vehicle or non-road mobile machinery emission factors. They are dependent on fuel type, engine size, load factor, technology, age (or deterioration factor) and additional emissions reduction devices. It is recommended that analysts obtain industry-specific data first or check with the proper authorities for other available emission factors if they are not otherwise available.

Emissions calculation

2.9 The calculation of GSE emissions can be done by following either of the two following simple approaches, as well as the advanced and sophisticated approaches.

Primary simple approach

2.10 In a very simple method using the aircraft-based approach, emissions can be calculated using the number of aircraft arrivals, departures, or both, and default emission factors. With this approach, no analysis of the GSE fleet and GSE operation is necessary. Examples of emission factors representative of Switzerland's Zurich Airport that could be used for this approach are provided in Table 3-A2-4. Because aircraft handling equipment varies by State, airport and aircraft operator, an analysis should be performed using emission factors appropriate for the GSE fleet being assessed.

Table 3-A2-4. Example default emission factors representative of Zurich Airport for aircraft handling[1]

		GSE technology 1995–2010		GSE technology 2005–2020	
Pollutant	Unit	Narrow-body aircraft (single-aisle fixed-wing jet)	Wide-body aircraft (double-aisle fixed-wing jet)	Narrow-body aircraft (single-aisle fixed-wing jet)	Wide-body aircraft (double-aisle fixed-wing jet)
NO_x	kg/cycle	0.270	0.440	0.150	0.400
HC	kg/cycle	0.022	0.035	0.015	0.040
CO	kg/cycle	0.900	0.160	0.100	0.240
PM_{10}	kg/cycle	0.015	0.030	0.010	0.025
nvPM	#/cycle	n/a	n/a	1.5E+16	4.4E+16
CO_2	kg/cycle	15.2	36.5	17.2	41.5

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[1] Flughafen Zürich AG, 2006 and 2014, updated 2020 (includes a fuel mix of gasoline, diesel, CNG and electric)

2.11 For this application, emissions are calculated by multiplying the number of movements (by aircraft category or the total if no differentiation is available) by the respective emission factor (or the average of both factors if no aircraft differentiation is available).

2.12 For example, at an airport with 23 450 narrow-body aircraft movements and 9 600 wide-body aircraft movements and assumed NO_x emission factors of 0.4 kg/cycle and 0.9 kg/cycle, the total amount of NO_x is:

0.4 kg/cycle * (23 450 movements) [narrow-body] + 0.9 kg/cycle * (9 600 movements) [wide-body] = 9 010 kg NO_x.

Secondary simple approach

2.13 An alternate, more simplified, method involves the fuel use by GSE. In this approach, emissions are calculated by obtaining actual fuel-use data for GSE (or estimating such data) and then combining these data with average emission factors, independent of equipment number, size or technology. Examples of emission factors representative of Europe that could be used for this approach are provided in Table 3-A2-5. Because aircraft handling equipment varies by State, airport and aircraft operator, an analysis should be performed using emission factors appropriate for the GSE fleet being assessed.

$$\text{Emission}_{\text{Pollutant}}\ [\text{g}] = \Sigma_{\text{fuel types}}\ (\text{total fuel type used [kg]} \times \text{average emission factor [g/kg fuel type]}) \qquad \text{Eq. 3-A2-1}$$

Table 3-A2-5. Example European emission factors for aircraft handling[2]

Pollutant	Diesel (g/kg)	Gasoline (g/kg)
NO_x	32.8	7.1
HC	3.4	17.6
CO	10.7	770.4
PM	2.1	0.1
CO_2	3 160	3 197

2.14 For example, if the total amount of diesel fuel used for GSE is 128 500 kg, and an average emission factor of 48.2 g NO_x/kg fuel is assumed, the total amount of NO_x emissions is 6 194 kg.

Advanced approach

2.15 Following this approach, emissions are calculated for the entire GSE population as a whole or individually according to aircraft-specific GSE requirements. In both cases, the actual operating time or fuel usage during a defined period of time (such as one year) for each type of GSE is used. To apply this calculation method, it is necessary to obtain or estimate the population for fleet of GSE by category and associated activity (hours/year, fuel usage/year) for each piece of GSE. There are two alternatives using the total fuel usage or the total operating hours over the population of a specific GSE model. When using the total operating hours, emissions can be calculated using the specific fuel flow or the size and load factor of the GSE model. If available, a deterioration factor can be considered as well.

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[2] Diesel and gasoline: *EMEP/EEA air pollutant emission inventory guidebook 2013*, 1.A.4.a.ii (other values may be used if deemed more appropriate).

$$\text{Emission}_{\text{Pollutant}}\ [\text{g/GSE}] = \text{fuel flow}\ [\text{kg/h}] \times \text{emission factor}_{\text{Pollutant}}\ [\text{g/kg fuel}] \times \text{time}\ [\text{h}]\ (\times\ \text{DF}) \qquad \text{Eq. 3-A2-2}$$

or

$$\text{Emission}_{\text{Pollutant}}\ [\text{g/GSE}] = \text{power}\ [\text{kW}] \times \text{load}\ [\%] \times \text{emission factor}_{\text{Pollutant}}\ [\text{g/kW}] \times \text{time}\ [\text{h}]\ (\times\ \text{DF}) \qquad \text{Eq. 3-A2-3}$$

or

$$\text{Emission}_{\text{Pollutant}}\ [\text{g/GSE}] = \text{fuel flow}\ [\text{kg}] \times \text{emission factor}_{\text{Pollutant}}\ [\text{g/kg fuel}]\ (\times\ \text{DF}) \qquad \text{Eq. 3-A2-4}$$

where:

power = size of engine (kW, sometimes bhp);

emission factor = based on engine type, fuel type, age, and reflecting design and emissions control technology of GSE;

time [h] = total annual operating time; and

DF = deterioration factor.

2.16 For this application, GSE emissions are then summed for all individual pieces of a specific equipment type and over the whole GSE population.

2.17 For example, if all passenger stairs at the airport, with diesel engines of 95 kW, an EI of 6.0 g NO_x/kWh and a load factor of 25 per cent, total 3 500 operating hours, and a deterioration factor of 3 per cent is assumed, the total amount of NO_x emissions is:

95 kW × 0.25 load factor × 6.00 g/kW-h × 3 500 hours × 1.03 deterioration factor = 513 712.5 g (514 kg NO_x).

Sophisticated approach

2.18 Under this approach, all GSE emissions are calculated for each individual aircraft operation (e.g.for example, arrival, departure and maintenance). This operational distinction is relevant when linking the aircraft handling activities to flight tables where an arriving and departing flight does not have the same flight number, or arrival and departure are not in a timely sequence (such as for night stops).

$$\text{Emission}_{\text{Pollutant}}\ [\text{g}] = \text{power}\ [\text{kW}] \times \text{load factor}\ [\%] \times \text{emission factor}_{\text{Pollutant}}\ [\text{g/kWh}] \times \text{time}_{\text{A/C–Ops}}\ [\text{h}] \times \text{DF} \qquad \text{Eq. 3-A2-5}$$

where:

$\text{time}_{\text{A/C–Ops}}$ [h] = average time for GSE unit operation, dependent on type of operation (arrival, departure or maintenance), stand property and aircraft size; and

DF = deterioration factor (reflecting age and maintenance of GSE).

2.19 GSE emissions are again tallied up for all individual pieces of a specific equipment type and all individual aircraft handling (including maintenance) operations.

2.20 For example, a passenger stairway is operated for 10 minutes for a B-737-size aircraft at an open (for example, remote) stand upon arrival. The stairway has a 45-kW engine, operated at 25 per cent load, with NO_x EI of 6.0 g/kWh and a deterioration factor of 3 per cent. The total NO_x of this GSE operation is:

45 kW × 0.25 load factor × 6.0 g/kWh × 1.03 deterioration factor × 10 minutes × 1-hour/60 minutes = 11.61 g NO_x.

3. AIRSIDE VEHICLE TRAFFIC

3.1 Airside vehicle traffic is considered to be all machinery and vehicles that operate on airside service roads within the airport perimeter as opposed to on aircraft stands only. As such, emissions are considered to be generated while travelling over distances rather than during periods of time. Airside vehicles do not include GSE as defined previously. Also, passenger and employee traffic operating on the landside are described separately in Appendix 4 to this chapter.

3.2 Most airside vehicles are on-road-equivalent vehicles and calculation of their emissions can be done the same way as for landside road vehicles. The guidance to do so is given in Appendix 4.

4. AIRCRAFT REFUELLING

4.1 At most airports, aircraft are either refuelled through an underground pipeline system with fuel hydrant trucks or from individual fuel tanker trucks. In both cases, fuel vapour (remaining from flight fuel mixed with air) is emitted from aircraft fuel tanks during the fuelling process. Vapours are also emitted when the tanker truck is being filled with fuel at the fuel farm or equivalent storage facility. Any emissions caused by the handling of fuel during delivery to the fuel farm or storage facility are not considered to be part of this procedure but are described separately in Appendix 3 to this chapter.

4.2 The operational data that are required for computing aircraft refuelling emissions include:

a) amount of fuel, by fuel type (for example, kerosene or aviation gasoline), delivered to aircraft by fuel hydrant truck (kg); and/or

b) amount of fuel delivered to aircraft by fuel tanker truck (kg).

4.3 The average emission factors (also called emission indices (EIs)) that are needed include:

a) emissions in g VOC/kg fuel for refuelling with kerosene; and

b) emissions in g VOC/kg fuel for refuelling with aviation gasoline.

4.4 Typical emission factors for Zurich, Switzerland, are provided in Table 3-A2-6. An analysis should be performed using emission factor values appropriate for the State and/or airport being assessed.[3]

Table 3-A2-6. Typical emission factors for Zurich, Switzerland

Aircraft refuelling*	Unit	Value
Refuelling with kerosene	g VOC/kg fuel	0.01
Refuelling with aviation gasoline	g VOC/kg fuel	1.27

* KIGA (Cantonal Office for Trade and Industry), Zurich, Switzerland, 1994 (other values may be used if deemed more appropriate).

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[3] For example, from the *EMEP/EEA air pollutant emission inventory guidebook 2013*, 1.B.2.a.v.

4.5 From this information, the emissions calculation is conducted using the following general equation:

emissions [g VOC] = $\Sigma_{\text{fuel types}}$ ((fuel$_{\text{hydrant delivered}}$ [kg] + 2 × fuel$_{\text{tanker delivered}}$ [kg]) × emission factor [g/kg]). Eq. 3-A2-6

4.6 For example, if a total of 1 500 000 kg of Jet-A1 (EI of 0.01 g VOC/kg) is delivered by truck, of which 85 per cent is by a hydrant system and 500 kg of avgas (EI of 1.27 g VOC/kg), the total amount from aircraft refuelling is:

(1 500 000 kg Jet-A1 x 0.85 x 0.01 g VOC/kg Jet-A1) + (1 500 000 kg Jet-A1 x 0.15 x 2 connections x 0.01 g VOC/kg Jet-A1) + (500 kg avgas x 2 connections x 1.27 g VOC/kg avgas) = 18 520 kg VOC.

5. AIRCRAFT DE-ICING

5.1 De-icing operations for aircraft and airfield facilities can be a source of VOC and other compounds. Comprised of propylene glycol and/or ethylene glycol and water, the mechanical application of de-icing and anti-icing agents to aircraft results in some loss to the atmosphere due to evaporation and overspray. However, because of growing concerns over the effects of de-icing chemicals on water quality, conservation and recovery processes are now commonly used which also reduce the potential air quality impacts.

5.2 VOC emissions from de-icing/anti-icing activities[4] are generally based on the amount of de-icing fluid used, the percentage of the de-icing chemical (for example, ethylene glycol) in the mixture and an emission factor. A United States source of VOC emission rate data for de-icing/anti-icing activities for aircraft and for runways, taxiways, etc., is provided in Table 3-A2-7. An analysis should be performed using emission factor values appropriate for the State and/or airport being assessed.

Table 3-A2-7. United States source of emissions data – de-icing/anti-icing activities

Substance	Source
Propylene glycol/ethylene glycol	FAA *Aviation Emissions and Air Quality Handbook*, 2014

5.3 For demonstration purposes, the following formula for calculating VOC emissions from de-icing/anti-icing activities is provided:

$$E_{VOC} = DF \times DS \times W_{DS} \times EF \qquad \text{Eq. 3-A2-7}$$

where:

E_{VOC} = emissions of VOC (for example, kilograms);

DF = amount of de-icing fluid (for example, litres);

DS = amount of de-icing substance in de-icing fluid (percentage);

W_{DS} = weight of de-icing substance (e.g. kilograms/litre); and

EF = emission factor (e.g. kilograms/kilograms of de-icing chemical).

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[4] At airports, there are two types of de-icing activities, which are disconnected: aircraft de-icing, as part of the handling activities of an aircraft, and surface de-icing as part of the maintenance of the airport (irrespective of traffic volume or size of aircraft).

5.4 Using this formula, the following example is given for de-icing operations at an airport. Assume an airport uses 5 kilolitres of a de-icing mixture to de-ice aircraft and 65 per cent of the de-icing mixture is ethylene glycol. The weight (or density) of the ethylene glycol is approximately 2 kilograms/kilolitre and the emission factor is 0.11 kilograms of VOC per kilogram of ethylene glycol used. Therefore, the amount of VOC emissions produced would be:

5 kilolitres × 0.65 × 2 kilograms/kilolitre × 0.11 kilograms VOC/kilogram of de-icing agent = 0.65 kilograms of VOC.

5.5 Future emissions levels can be based on a projected increase in aircraft operations and/or on the total area of runways, taxiways and roadways, if applicable.

Appendix 3 to Chapter 3

INFRASTRUCTURE-RELATED AND STATIONARY SOURCES OF EMISSIONS

1. INTRODUCTION

1.1 Airports are typically viewed as an assemblage of moving or mobile sources of emissions (such as from aircraft, GSE and motor vehicles). However, most airports also include stationary sources of emissions (boilers, emergency generators, incinerators, etc.) as part of their infrastructure and support facilities. In contrast to mobile sources, stationary sources are non-mobile and remain fixed or motionless, discharging the emissions through an assortment of conveyances such as smokestacks, chimneys, flues and/or vents.

1.2 Other airport infrastructure-related sources of air emissions are classified as area sources. In concept, these sources discharge emissions directly into the atmosphere and can be either mobile or stationary in nature. Typically, area sources at airports include fuel storage and transfer facilities, live-fire training facilities, de-icing operations and construction activities. Also categorized as off-road or non-road sources of emissions, the construction activities comprise a wide variety of trucks, earth movers, excavators, pavers and other heavy equipment. Construction activities involving the storage and transportation of raw materials, the disposal of construction debris and the production of asphalt or concrete are also considered to be area sources.

1.3 This appendix provides guidance on preparing emissions estimates for stationary and area sources at airports and for pollutants of CO, THC, NMHC, NO_x, SO_x and PM_{10}.

1.4 There are a wide range of databases for emission factors which can be used to calculate the types and amounts of emissions releases from stationary sources at airports. The two which are most commonly cited in Europe and North America are those produced by the United States EPA and the European Environment Agency:

a) United States Environmental Protection Agency, Office of Air Quality Planning and Standards, *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources (AP-42)*, Fifth Edition and Supplements: https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors#5thed (as of February 2020); and

b) *EMEP/EEA emission inventory guidebook* (2019 or later versions): https://www.eea.europa.eu/publications/emep-eea-guidebook-2019 (as of February 2020).

1.5 The methodological approaches set out in the documents cited, however, are broadly similar to those used in other countries and regions, and it is beyond the scope of this guidance manual to list all national sources of information. In this appendix, a number of worked examples are put forward using data from the United States EPA, but the authors could have chosen others. It is the responsibility of the airport officials who are tasked with developing emissions inventories to use the most appropriate emission factors.

2. POWER/HEATING PLANTS, BOILERS AND GENERATORS

2.1 Emissions from power/heating plants (that is, boilers and space heaters) and emergency generators are largely contained in the exhaust of burning hydrocarbon-based fuels. These include emissions of CO, NO_x, HC, SO_x, PM_{10}

and number of particles. A variety of fuels are used in power-/heating-generating plants including coal, fuel oil, diesel fuel, gasoline, natural gas as well as liquid petroleum gases (LPG), and each one has its own emissions characteristics.

2.2 For existing stationary sources that have operating permits, the types and amounts of air pollutant emissions can usually be obtained from the appropriate regulatory agency files and/or the operating permit itself. In the absence of such a permit or supporting information, emissions are typically based on the time period (that is, horsepower-hours) of actual or estimated equipment usage (that is, activity rates), the fuel type and any applicable emissions control or reduction technologies. For new or expanded boilers/space heaters, future activity rates can be based on the increase in airport terminal area in cases where gross estimates are sufficient for the analysis.

2.3 Commonly used sources of available emission rate data for boilers/space heaters (by fuel type and pollutant) are provided in Table 3-A3-1, and emissions data for emergency generators are provided in Table 3-A3-2.

Table 3-A3-1. Sources of emission rate data – boilers/space heaters

Fuel	Source
Coal, including anthracite, bituminous, bituminous/subbituminous, and subbituminous coal	EPA, AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Ch. 1 *EMEP/EEA emission inventory guidebook* (2019 or later versions), groups 1.A.1 and 1.A.4
Fuel oil	EPA, AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Ch. 1 *EMEP/EEA emission inventory guidebook* (2019 or later versions), groups 1.A.1 and 1.A.4
LPG	EPA, AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Ch. 1 *EMEP/EEA emission inventory guidebook* (2019 or later versions), groups 1.A.1 and 1.A.4
Natural gas	EPA, AP 42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Ch. 1 *EMEP/EEA emission inventory guidebook* (2019 or later versions), groups 1.A.1 and 1.A.4

Table 3-A3-2. Sources of emission rate data – emergency generators

Fuel	Methodology	Source
Diesel fuel	USAF (distillate oil)	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
Gasoline	USAF	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
Kerosene/naphtha (jet fuel)	USAF	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
LPG (propane or butane)	USAF	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
Natural gas	USAF	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
Residual/crude oil	USAF	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 3
Various fuels	EEA	*EMEP/EEA air pollutant emission inventory guidebook* (2019 or later versions), group 1.A.4

2.4 For demonstration purposes, estimates of emissions from power/heating plants, boilers and generators are calculated using the following general equation:

$$E = A \times EF \times (1 - ER/100) \qquad \text{Eq. 3-A3-1}$$

where:

E = emissions (e.g. kilograms/day);

A = activity rate (e.g. horsepower-hour or litres/day);

EF = emission factor (e.g. kilograms/litre specific to fuel type and pollutant); and

ER = control equipment emissions reduction efficiency (%).

2.5 In cases where fuel sulphur content is important, an alternative formula may be more appropriate. Using this formula, the following example is given for an airport emergency generator. Assume an airport has a 335-horsepower diesel engine emergency generator with an emissions reduction efficiency of 75 per cent. If the emission factor for NO_x is 14.0 grams/horsepower-hour and the airport operates the generator 1 000 hours annually, total NO_x emissions would be:

$$1\,000 \text{ hours} \times 14.0 \text{ grams/horsepower-hour} \times 335 \text{ horsepower} \times (1-75/100) = 1\,172\,500 \text{ grams of } NO_x.$$

3. INCINERATORS

3.1 When located at airports, incinerators are typically used to destroy or sterilize refuse and other regulated waste products produced and transported on international aircraft. An airport may also have food preparation facilities that use incinerators to dispose of solid wastes (that is, paper, wood, plastics and other rubbish).

3.2 Combustible waste incinerators have a variety of furnace types and configurations (in-line, retort, etc.), include single or multiple combustion chambers and are typically fuelled by natural gas, oil or LPG. Control equipment and technologies are used in both the burning process and at the stack to help reduce excess emissions.

3.3 For existing incinerators that have operating permits, estimates of air pollutant emissions can be obtained from the appropriate regulatory agency files and/or the operating permit itself. In the absence of a permit, emissions estimates are often based on the fuel type, the content and amount of refuse incinerated and appropriate emission factors for the fuel, refuse and combustion chamber design. For new and expanding facilities, the forecasted amounts of incinerated refuse can be based on the projected increase in international flights and/or increase in food service providers, if applicable.

3.4 Commonly used sources of emission rate data for combustible waste incinerators are provided in Table 3-A3-3.

Table 3-A3-3. Sources of emission rate data – combustible waste incinerators

Number of chambers	Source
Single and multiple	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 2 *EMEP/EEA emission inventory guidebook* (2019 or later versions), group 5.

3.5 For demonstration purposes, estimates of emissions from a combustible waste incinerator are calculated using the following general equation:

$$E = A \times EF \times (1 - ER/100) \qquad \text{Eq. 3-A3-2}$$

where:

E = emissions (e.g. kilograms/year, grams/day);

A = amount of refuse incinerated (e.g. metric tonnes or kilograms/day);

EF = emission factor (e.g. kilograms or grams/metric tonne); and

ER = control equipment emissions reduction efficiency (%).

3.6 Using this formula, the following example is given for an incinerator. Assume an airport has a single chamber incinerator with an emissions reduction efficiency of 80 per cent. If the emission factor for CO is 1.0 kilograms/metric tonne of waste and the airport incinerates 2 500 metric tonnes of waste, the total CO emissions would be:

1.0 kilograms × 2 500 metric tonnes × (1–80/100) = 500 kilograms of CO (that is, 0.5 metric tonnes).

4. AIRCRAFT/AIRPORT MAINTENANCE FACILITIES

4.1 At most large airports, aircraft maintenance facilities are typically operated by commercial airlines or other service providers and perform scheduled aircraft inspections and repairs on the aircraft fuselage, engines and other apparatuses. A variety of surface treatment, coating and painting operations may also occur. At smaller airports, these maintenance services are typically offered by privately owned fixed-based operators.

4.2 Airports also often involve a variety of support facilities for the building and airfield maintenance staff, supplies and activities. Actions and operations that generate emissions associated with these types of facilities include building painting, runway/taxiway/apron striping, asphalt/concrete repair and cleaning. Because these activities often involve liquid coatings, petroleum-based solvents and other evaporative substances, the primary pollutants of concern are VOC.

4.3 In most cases, the emissions from these sources generally result from evaporation and/or overspray of the used materials. In only a few cases are the amounts of emissions considered to be significant.

4.4 Material safety data sheets (MSDS) for most products and substances can be used to obtain the volatile content of the VOC (typically expressed in pounds (or grams) of VOC per gallon (or litre) of the substance used). Alternative sources of emission rate data for surface coating and other solvents are provided in Table 3-A3-4.

Table 3-A3-4. Sources of emission rate data – aircraft/airport maintenance facilities

Activity	Substance	Source
Surface coating	Paint (solvent and water-based), enamel, lacquer, primer, varnish/shellac, thinner and adhesive	• FAA *Aviation Emissions and Air Quality Handbook*, 2014 • *EMEP/EEA emission inventory guidebook* (2019 or later versions), group 2.D
Solvent degreasers	Acetone, alcohol (ethyl and methyl), carbon tetrachloride, chloroform, ether, isopropyl alcohol, methylene chloride, perchloro-ethylene, stoddard solvent, 1,1,1-trichloroethane, trichloro-ethylene and turpentine	• FAA *Aviation Emissions and Air Quality Handbook*, 2014 • Occupational Safety and Health Administration (OSHA) https://www.osha.gov/ • *EMEP/EEA emission inventory guidebook* (2019 or later versions), group 2.D

4.5 For demonstration purposes, estimates of VOC emissions from surface coating can be obtained using the following general equation, which considers the quantity of the coating used, the VOC content of the substance and, if applicable, an emissions reduction efficiency factor for the application process:

$$E_{VOC} = Q \times VOCC \times ER \qquad \text{Eq. 3-A3-3}$$

where:

E_{VOC} = emissions of VOC (e.g. kilograms);

Q = quantity of coating substance (e.g. litres);

VOCC = VOC content of the coating substance (e.g. grams/litre); and

ER = control equipment emissions reduction efficiency (per cent).

4.6 Using this formula, the following example is given for the use of a metal cleaning solvent. If an aircraft maintenance facility uses 2 500 litres of primer in a spray booth that has an emissions reduction efficiency of 65 per cent, and the VOC content of the primer is 3.2 kilograms per litre, the amount of VOC emitted would be:

2 500 litres × 3.2 kilograms/litre × (1–65/100) = 2 800 kilograms of VOC (ithat is, 2.8 metric tonnes).

4.7 Another example involves the evaporation of a solvent directly into the atmosphere. In this case, it is assumed that not all of the solvent is disposed of. Therefore, as shown in the following equation, the difference between the amount of the solvent used and the amount of the solvent disposed of is multiplied by the density of the substance to derive the amount emitted into the atmosphere:

$$E_{VOC} = (QC - QD) \times D \qquad \text{Eq. 3-A3-4}$$

where:

E_{VOC} = emissions of VOC;

QC = quantity of solvent consumed (e.g. litres);

QD = quantity of solvent disposed of as liquid waste (e.g. litres); and

D = solvent density (e.g. kilograms/litre).

4.8 Using this formula, the following example is given for an airport emergency generator. Assume an airport maintenance facility uses 950 litres of turpentine, disposes of 750 litres thereof as liquid waste, and the density of turpentine is 0.87 kilograms per litre. The amount of VOC would be:

950 litres consumed – 750 litres disposed of = 200 litres

200 litres x 0.87 kilograms/litre = 174 kilograms of VOC (that is, 0.174 metric tonnes).

5. FUEL FARMS, HYDRANT SYSTEMS AND VEHICLE REFUELLING STATIONS

5.1 Airport fuel storage and transfer facilities can contain a variety of fuels, with jet fuel (Jet-A, jet kerosene, JP-4), aviation gasoline (avgas) and motor vehicle fuels (gasoline and diesel) being the predominant types. These facilities and transfer operations are a potential source of evaporative hydrocarbons (for example, VOC).

5.2 Fuel storage tanks can emit VOC from both “standing” (that is, storage) and “working” (that is, withdrawal and/or refilling) activities. Important variables that have an effect on the amounts of emissions released include the vapour pressure of the fuel; the storage and throughput volumes; the types of tanks (above-ground, floating roof, etc.); and climatic conditions (that is, temperature and humidity). Importantly, the vapour pressures of jet fuel and diesel are so low that most environmental agencies do not require any controls on these emissions.

5.3 A commonly used source of emission rate data for fuel storage tanks is provided in Table 3-A3-5.

Table 3-A3-5. Sources of emission rate data – fuel storage tanks

Tank type	Fuel	Source
Horizontal, vertical fixed roof, internal floating roof, external floating roof, domed external floating roof	Jet naphtha (JP-4), jet kerosene, gasoline, distillate fuel oil no. 2, residual fuel oil no. 6	EPA, AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Vol. 1, Chapter 7: Liquid Storage Tanks; *EMEP/EEA emission inventory guidebook* (2019 or later versions), group 1.B.2

5.4 For demonstration purposes, estimates of VOC emissions from fuel storage tanks can be obtained using the following general equation, which considers both the standing and working losses.

$$E_{VOC} = SL + WL = (QS \times EF) + (QT+EF) \qquad \text{Eq. 3-A3-5}$$

where:

E_{VOC} = emissions of VOC (e.g. kilograms);

SL = standing loss;

WL = working loss;

QS = quantity of fuel stored (e.g. kilolitres);

QT = quantity of fuel throughput (e.g. kilolitres); and

EF = emission factor for fuel type (e.g. kilograms/kilolitre).

5.5 Using this formula, the following example is given for the storage and transfer of jet fuel in an above-ground tank. If a fuel facility stores 1 500 kilolitres of jet fuel (with a standing loss of 200 grams of VOC/kilolitre a day) and dispenses 90 kilolitres of fuel daily (with a working loss of 100 grams of VOC/kilolitre a day), the estimated amount of VOC emitted would be:

$$(1\,500 \text{ kilolitres} \times 200 \text{ grams/kilolitre}) + (90 \text{ kilolitres} \times 100 \text{ grams/kilolitre})$$
$$= 309 \text{ kilograms of VOC (that is, 0.31 metric tonnes).}$$

6. FIRE TRAINING

6.1 At some airports, airport rescue and firefighting (ARFF) personnel conduct emergency response training using live-fire simulators. Fuelled with either jet fuel or diesel, these facilities can be a source of dense black smoke, PM and VOC when used. New, low-smoke fuels are also available and are considered to be more environmentally acceptable, as are the propane-fuelled facilities.

6.2 The quantity of fuel used for ARFF live-fire training varies by the frequency of use, the types of fires created and the fuel type.

6.3 While the FAA *Aviation Emissions and Air Quality Handbook* is the most authoritative source of information for fire training activities, it is not included within EMEP/EEA publications. Available sources of emission rate data for the most common fuels used in fire training activities are provided in Table 3-A3-6.

Table 3-A3-6. Sources of emission rate data – fire training

Fuel type	Source
JP-4, JP-8, propane	FAA *Aviation Emissions and Air Quality Handbook*, 2014
JP-5, tekflame	FAA *Aviation Emissions and Air Quality Handbook*, 2014

6.4 Estimates of air pollutant emissions from live-fire training exercises are based on the fuel type, quantity of fuel burned and emission rates by pollutant. These emissions can be calculated using the following equation:

$$E_{VOC} = QF \times EF \qquad \text{Eq. 3-A3-6}$$

where:

E_{VOC} = emissions of VOC;

QF = quantity of fuel (e.g. in kilolitres); and

EF = emission factor (e.g. grams/kilolitre of fuel).

6.5 Using this formula, the following example is given for an ARFF live-fire training facility. Assume an airport conducts live-fire training once every month, and 3 kilolitres of propane are used each time (that is, 36 kilolitres per year). Assuming a PM emission factor for propane of 18 kilograms/kilolitre of fuel, the amount of PM emitted would be:

36 kilolitres x 18 kilograms/kilolitre = 648 kilograms of PM (that is, 0.65 metric tonnes).

7. DE-ICING/ANTI-ICING ACTIVITIES

7.1 De-icing operations for airfield surfaces can be a source of VOC and other compounds. Comprising either propylene glycol or ethylene glycol and water, the mechanical application of de-icing and anti-icing agents results in some loss to the atmosphere due to evaporation and overspray. On runways, taxiways and aprons, potassium acetate or solutions of ethylene glycol, urea and water are used. However, because of growing concerns over the effects of de-icing chemicals on water quality, conservation and recovery processes are now commonly used and reduce the potential air quality impacts.

7.2 VOC emissions from de-icing/anti-icing activities are generally based on the amount of de-icing fluid used, the percentage of the de-icing chemical (that is, ethylene glycol) in the mixture and an emission factor. The sources of VOC emission rate data for de-icing/anti-icing activities for aircraft and for runways, taxiways, etc., are provided in Table 3-A3-7. An example calculation for aircraft de-icing can be found in Appendix 2 to this chapter, section 5, and the calculation for airfield surfaces is conducted in the same manner.

Table 3-A3-7. Sources of emission rate data – de-icing/anti-icing activities

Substance	Source
Propylene glycol/ethylene glycol	FAA *Aviation Emissions and Air Quality Handbook*, 2014

8. CONSTRUCTION ACTIVITIES

8.1 Construction activities that generate air pollutant emissions include land clearing and demolition (dust emissions), the use of construction equipment and vehicles (exhaust emissions), storage of raw materials (wind erosion emissions) and paving (evaporative emissions). Construction-related vehicles include vehicles that remain on the construction site (such as off-road or non-road vehicles) and vehicles that travel off-site (such as haul and dump trucks). Pollutant emissions also result from construction-related employee commute trips to and from a construction site.

8.2 Common United States sources of emission rate data for construction activities are provided in Table 3-A3-8.

Table 3-A3-8. Source of emission rate data – construction activities

Activity/vehicle type	Source
Land clearing/demolition	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 13: Miscellaneous Sources
Construction equipment/vehicles (off-road)	EPA NONROAD model
Construction vehicles (on-road)	EPA MOBILE model
Material storage piles (standing and working)	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 13: Miscellaneous Sources
Asphalt paving	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 4: Evaporation Loss Sources
Batch mix plants	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 11: Mineral Products Industry
Concrete batching	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 11: Mineral Products Industry
Open burning	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 2: Solid Waste Disposal
Vehicle travel on unpaved roads	EPA AP-42, Fifth Edition Compilation of Air Pollutant Emissions Factors, Volume 1, Chapter 13: Miscellaneous Sources

8.3 For Europe, emission factors for these activities can be found in the *EMEP/EEA emission inventory guidebook* (2019 or later versions), groups 1.A.3, 1.A.4, 2.D, 5.A, 5.C.

8.4 For demonstration purposes, estimates of PM emissions from the working of a storage pile can be obtained using the following general equation, which considers the throughput of the operation (that is, the quantity of material used over a given time and the number of drops the material undergoes (once during loading and once during unloading)). Notably, the emission factors for various materials vary depending on the type, particle size, silt content and moisture content of the material.

$$E_{PM} = 2 \times TH \times EF \qquad \text{Eq. 3-A3-7}$$

where:

E_{PM} = emissions of PM (e.g. kilograms);

2 = number of drops material undergoes;

TH = total throughput; and

EF = emission factor (e.g. grams).

8.5 Using this formula, the following example is given for construction operations at an airport. Assume a construction operation involves the movement of 100 metric tonnes of limestone. Given a moisture content of approximately 0.2 per cent, an aerodynamic particle size of 0.45 micrometres and an average wind speed of 20 kilometres per hour, the amount of PM generated would be as follows based on an emission factor of 54 grams/metric tonne:

2 x 100 metric tonnes x 54 grams/metric tonne = 10 800 grams (that is, 0.01 metric tonnes).

8.6 Another common example of construction emissions involves the use of an off-road vehicle. The equation used to obtain pollutant estimates from this type of construction activity considers the type of equipment (for example, bulldozer, articulated truck), the size of the equipment (that is, horsepower), the load factor placed on the equipment (i.e. the ratio of the load over a designated period of time to the peak load) and the period (that is, hours) of operation.

8.7 For demonstration purposes, estimates of exhaust emissions from construction vehicles and equipment can be derived from the following formula:

$$E = H \times EF \times LF \times T \qquad \text{Eq. 3-A3-8}$$

where:

E = emissions (e.g. grams/day);

H = horsepower of the equipment;

EF = emission factor (e.g. grams/horsepower-hour);

LF = load factor (per cent); and

T = total period of operation (hours).

8.8 Using this formula, the following example is given for the use of a bulldozer. Assume an airport contractor uses a 400-horsepower bulldozer for 3 hours each day, 15 days a month, for a period of one year, and the average load factor for the equipment is 59 per cent. If the emission factor for the bulldozer is 9.6 grams per horsepower-hour, the amount of NO_x would be:

400 hp x 9.6 grams/hp-h x 0.59 x 540 hours = 1 223 424 grams (that is, 1.2 metric tonnes).

Appendix 4 to Chapter 3

VEHICLE TRAFFIC EMISSIONS

1. INTRODUCTION

1.1 Emissions from airport-related surface transportation can constitute a significant portion of the total emissions associated with airport activities. The guidance provided in this appendix focuses on approaches and methods for preparing an inventory of emissions from both landside and airside on-road motor vehicles. The data and other supporting information required to prepare these estimates are also discussed. Airports may need to include in the inventory other surface transportation systems whose emissions may be attributed to airport operations (such as diesel trains on an airport rail link).

1.2 On-road landside vehicles include taxis, vans, buses and privately owned cars; light- and heavy-duty vehicles; and motorbikes and scooters travelling on the airport's internal roadway network and within the airport's parking facilities. On-road airside vehicles are the vehicles that travel primarily within an airport's secured area (that is, the area where aircraft arrive and depart). These vehicles can include airline crew and passenger buses, aircraft/airport service vehicles, and other vehicles for which emissions estimates are calculated in the same way as for landside vehicles (that is, the vehicles are designed around chassis that are used on public roads and they are driven airside in a manner similar to public road driving). Approaches for estimating emissions from GSE are discussed in Appendix 2 to this chapter.

1.3 In the following sections, three approaches for calculating motor vehicle emissions are discussed – a simple approach, an advanced approach and a sophisticated approach – each requiring increasingly comprehensive levels of input data and calculation complexity.

1.4 All three approaches are based on the vehicle average speed method, which is commonly used for road traffic emissions calculations for meso-scale (that is, district) and macro-scale (that is, city or region) inventories, to which the airports emissions must be integrated and compared. It is recognized that average speed models may have limitations at low vehicle speeds due to varying transient speeds. Output from these models is also influenced by the availability of supporting data from outside sources.

2. PARAMETERS

2.1 Depending on the approach (that is, simple, advanced or sophisticated), some or all of the parameters in the following discussion are necessary in different levels of detail to prepare an estimate of vehicle traffic emissions.

2.2 Although the purpose of this guidance is to prepare an emissions inventory, the reader should note that, ultimately, an air quality study using dispersion modelling may also be required. In this context air quality models often incorporate road traffic models, which contain only a few of the input parameters needed, and so analysts are required to estimate the missing parameters by other means.

2.3 Clearly, certain parameters will have more effect on the results than others. To this end, the notion of parameter ranking may be used to identify the relative importance of each parameter. The ranking system may be used to prioritize the input data collection for the inventory.

2.4 The following is an example of a ranking system based on experiences at London Heathrow Airport.[1] The list shows, in order of importance, the parameters that are judged to influence inventory results. The basic ranking is summarized in the list in order of importance.

a) Rank 1 – road network extent;

b) Rank 2 – traffic flow (periods modelled – profiles);

c) Rank 3 – fleet and composition;

d) Rank 4 – road traffic speeds;

e) Rank 5 – road traffic queues;

f) Rank 6 – trip end; and

g) Rank 7 – other traffic parameters.

Some of the issues for each rank are also discussed in the following sections.

Geographical scope – road network extent

2.5 The geographical scope defines the road network and road types that are included in a vehicle traffic emissions inventory. The geographical scope is also used in conjunction with the chosen approach to identify the type of input data required for the inventory.

2.6 The geographical scope can be limited to the roadways and parking lots inside an airport's property boundary (both airside and landside) or, in some cases, be expanded to include public roads and parking lots that feed an airport and have a significant amount of airport-related traffic. The choice of the geographical scope for a project depends on the purpose of the study, the type of available input data and the chosen approach, discussed as follows:

a) The simple approach aggregates all roads together to provide an overall inventory based on total distance travelled (or vehicle-miles travelled (VMT)) with broad assumptions on vehicle fleet mix, age and speed. The simple approach may be limited to the airport perimeter with no link to regional vehicle emissions.

b) The advanced approach disaggregates the results into individual roads according to the level of detail of the input data. Each road segment will require average traffic volumes or VMT and typical vehicle speed.

c) The sophisticated approach captures as much detail as possible about the road network in the study, with sufficient detail to give an inventory that is highly sensitive to changes in infrastructure and use. For example, the road network should be divided to give portions of constant gradient to allow for compensation of uphill and downhill emissions.

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1. Department for Transport (United Kingdom), *Project for the Sustainable Development of Heathrow: Report of the Air Quality Technical Panels,* 19 July 2006, http://webarchive.nationalarchives.gov.uk/+/http:/www.dft.gov.uk/pgr/aviation/environmentalissues/heathrowsustain/ (accessed June 2020).

2.7 The advanced and sophisticated approaches may include off-airport traffic that are related directly to airport activities but are located off-site. Whichever approach is used, to avoid double counting vehicle emissions, the analysis must not include vehicles in the vicinity of the airport that are inventoried by other parties (such as vehicles from non-airport-related transit traffic on nearby roads). These non-airport vehicle emissions may also be relevant to assessing the air quality in the vicinity of the airport, depending on the purpose of the study and/or regulatory requirements of the State, regional or local agencies.

Time scope – traffic flow

2.8 The time (that is, temporal) scope defines the averaging period over which a vehicle traffic emissions inventory is to be calculated (for example, an hour, a day, a season, a year). Conventionally, periods of one calendar year are chosen and, among other reasons, this simplifies alignment with EI data and national vehicle databases.

a) For the simple approach, it is sufficient to calculate the total annual amounts of the emissions of each pollutant, based upon annual traffic volumes, travel distances, average operating speeds and representative fleet mix.

b) For the advanced approach, the temporal resolution should allow for estimates or measurements of the daily and/or hourly variations in traffic conditions (such as morning and evening peak periods) and fleet mix (see vehicle fleet and composition).

c) For the sophisticated approach, the temporal resolution should use time-dependent profiles to provide hourly fleet mix on all the roads in the study that are judged to make significant contributions to the inventory.

Vehicle fleet and composition

2.9 As previously stated, the motor-vehicle categories typically included in an airport-related emissions inventory include passenger cars and vans, light- and heavy-duty trucks, buses, taxis and other motorized vehicles. Separate inventories may be prepared for the landside and airside vehicles. Landside vehicle emissions can also be further categorized so that emissions are segregated by type of road or facility (access roads, car parks, passenger terminals, curbsides, etc.). Generally, each type of vehicle can be defined by one of the following four categories:

a) passenger cars;

b) other light-duty vehicles (for example, taxies, vans, limousines);

c) heavy-duty vehicles (including urban buses and coaches); and

d) two-wheel vehicles (scooters and motorcycles).

2.10 Within these categories, there is a wide diversity of types and age of vehicles, fuel types and operational characteristics. For this reason, the categories cited previously are often subclassified by vehicle size and type, level of emissions control, fuel type, engine type and operational purpose.

2.11 Similarly, urban buses and coaches may be put in a separate category if suitable emissions and operational load factors are available. As discussed previously, airside vehicles will need careful attention to avoid double counting traffic associated with landside vehicles and some GSE.

2.12 The alternatives for obtaining data for the vehicle fleet mix are summarized as follows:

a) The simple approach derives vehicle data from available national average vehicle fleet mix/age databases. The advanced approach may also derive vehicle data from national records, but the fleet mix/age is typically reflective of that operating at the airport. Notably, under the advanced approach, the vehicle fleet mix may also be defined using time-dependent profiles for different road segments (for example, to allow for morning and evening increases in the number of private cars and buses when airport staff arrive and depart).

b) The sophisticated approach may employ techniques to measure the actual type and age of vehicles – either as source data for the study or to validate national data. Using measured data in the airport context may be attractive since national data may not represent the typical age of vehicles using the roads in the study. An example of this technique uses video recordings of vehicle licence plates and correlation with licence records to provide exact vehicle/engine type, fuel type and age. Classification of vehicle traffic should be made according to passengers, airport personnel, maintenance, construction and freight.

Average speed and queues

2.13 As discussed previously, the alternative approaches to calculating vehicle emissions provided in this guidance rely on average speed as an input to the analysis. Vehicle queues are a special case characterized by very low average speeds and may include evaporative emissions during idling. Both conditions are addressed as follows:

a) The simple approach may use an overall average speed. Queue emissions may be factored in as a coefficient of the total traffic.

b) The advanced approach requires an estimate of the average speed for each road segment coupled with queuing time profiles for major segments that exhibit delays.

c) The sophisticated approach may augment the data used for the advanced approach with measured data. However, road segments should be further defined to give segment-specific average speed. For each segment, the average speed of each vehicle category may be defined. Traffic queue times should be assigned to separate segments.

Trip end and other traffic parameters

2.14 Trip-end emissions are the emissions associated with the cold start that occurs at the start of a trip, the similar hot soak emissions which occur at the end of a trip once the vehicle engine has been switched off, and the evaporative emissions (mostly VOC) from the fuel system during use and while the vehicle is stationary. These vehicle emissions are accounted for as additional emissions and mainly apply to parking lots and curbsides outside the airport terminals.

Other vehicle emissions

2.15 Other vehicle emissions include non-engine emissions of particulate matter (such as PM_{10}) from road vehicles that occur as a result of the application of braking systems and tire wear, from road surface wear and from the re-suspension of previously deposited particles. The spatial distribution of these fugitive sources of emissions will be relatively constant and consistent with the layout of the road network. However, there will be increases where there is routinely the most intensive stop-and-go traffic, such as either side of stop lines at road junctions and on corners. Temporal variations will occur on a diurnal and seasonal basis because road and driving characteristics vary according to traffic density and road conditions.

2.16 The simple approach does not make any allowance for fugitive emissions.

2.17 The advanced approach may include values for dense traffic zones, major junctions and construction sites. The road network should be divided to allocate a default value to each segment.

2.18 The sophisticated approach includes trip-end and non-engine emissions on a road segment basis and disaggregates the data to show separate inventories for staff vehicles and passengers.

3. VEHICLE EMISSION FACTORS

3.1 For road vehicles, emission factors represent the unit quantities of a pollutant emitted when a vehicle traverses a length of roadway (typically expressed as grams or milligrams per kilometre) and/or when a vehicle is idle with the engine running a certain length of time (typically expressed as grams or milligrams per minute).

3.2 Traffic emission factors are obtained from computer models and other databases specifically designed to generate such factors. These resources provide local vehicle emission factors that vary as functions of ambient temperature, travel speed, vehicle operating mode (for example, idle, cruise, deceleration, acceleration, cold start, hot start and stabilized), fuel type/volatility, vehicle technology, age, inspection and maintenance condition and mileage accrual rate (km/year).

3.3 Typically for the average speed models, emission factors are used to calculate an aggregate emission factor for a segment of road (g/km) for each class of vehicle using the road and for an average speed. In the case of parking lots, emission factors expressed as g/event, such as with engine start, are also used. In a sophisticated approach, emission factors may vary with the time of day/week based on local climatological factors.

3.4 For airport-related vehicles, emission factors are available from the following sources:

a) United States EPA MOVES;

b) California's EMFAC2011;

c) CITEPA[2] method based on COPERT 4;

d) EUROCONTROL ALAQS method based on COPERT 4; and

e) LASPORT method based on the Handbook Emission Factors for Road Transport (HBEFA).

3.5 The vehicle emissions models cited in 3.4 are provided as sources of current and future road vehicle emission factors but were originally designed for the purpose of monitoring the effect of national and/or local air quality legislation. These models estimate a number of exhaust pollutants including CO, HC, NO_x, PM (in some cases also number of particles), SO_x, select HAP and CO_2. Evaporative emissions from fuel and PM emissions from brake and tire wear are also provided in many cases.

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[2] Interprofessional Technical Centre for Studies on Air Pollution (CITEPA), France

4. CALCULATIONS

4.1 This section discusses the three approaches (simple, advanced and sophisticated) and presents formulae that can be used to obtain total emissions estimates from vehicles operating on airport-related roads, parking lots and curbsides.

4.2 While many different vehicle emissions calculation methods exist, the three approaches in this guidance are based on the vehicle average speed method because it is most appropriate to the airport context. However, the eventual choice of calculation method will depend on the scope of the inventory and the available input data.

4.3 The selection of a calculation approach depends on the purpose of the analysis and the complexity of the input data available for the study.

a) ***Simple.*** Suitable for what can be termed a top-down approach. The simple approach aggregates the total emissions from the total number of vehicle-kilometres travelled over the total length of all roads within a defined study area using a published national fleet mix, reference year and annual average mileage per vehicle class.

b) ***Advanced.*** Using the advanced approach, road segments are defined individually by length, average speed and fleet mix. Activity profiles may be used to describe the diurnal flow (such as time variation) of traffic on each road segment.

c) ***Sophisticated.*** The sophisticated approach requires the most data (a bottom-up approach). Emissions are aggregated by road segment by hour and are independently calculated for the actual (for example, measured) number of vehicles of each vehicle type travelling on the road segment, together with its age and engine details. Full details of the road network including gradients and road surface may be included. The emissions from the traffic on each road segment can then be aggregated for the period of interest (such as one hour, one week and one year).

Simple approach

4.4 For demonstration purposes, emissions estimates using the simple approach can be calculated using the following general equation:

$$E = RL \times NV \times EF \qquad \text{Eq. 3-A4-1}$$

where:

E = emissions (e.g. grams);

RL = road length (e.g. kilometres);

NV = number of vehicles on the road by class, age and speed; and

EF = emission factor considering vehicle class, age and speed (e.g. grams/vehicle-kilometre travelled).

4.5 Using this formula, the following example calculates the level of emissions using the simple approach. Assume a roadway is 5 kilometres in length. Over a 24-hour period, 100 000 vehicles traverse the roadway at an average travel speed of 35 kilometres per hour. The vehicle fleet mix consists of 80 per cent passenger cars, 10 per cent light-duty vehicles, 5 per cent heavy-duty vehicles and 5 per cent two-wheeled vehicles. Further, for the period of interest, (for example, 24 hours) the average temperature is 21 degrees Celsius. Assuming the CO emission factor is 30 grams per kilometre, total CO emissions from the roadway are calculated as follows:

5 kilometres x 100 000 vehicles x 30 grams per kilometre = 15 000 000 grams of CO (that is, 15 metric tonnes).

Advanced approach

4.6 For demonstration purposes, urban driving emissions estimates using the advanced approach can be calculated using the following equation:

$$E_{total} = (RL_1 \times NV_1 \times EF_1) + (RL_2 \times NV_2 \times EF_2) + (RL_n \times NV_n \times EF_n) \qquad \text{Eq. 3-A4-2}$$

where:

E_{total} = total emissions for all roadway segments (e.g. grams);

$RL_{1..n}$ = road length (e.g. kilometres);

$NV_{1..n}$ = number of vehicles on the road by class, age and speed; and

$F_{1..n}$ = emission factor considering vehicle class, age and speed (e.g. grams/vehicle-kilometre travelled).

4.7 Using this formula, the following example calculates the level of emissions using the advanced approach. Assume there are two roadways within a defined study area. One roadway is 2.4 kilometres in length and the other roadway is 2.6 kilometres in length. Over a 24-hour period, 60 000 vehicles traverse the shorter roadway and 40 000 vehicles traverse the longer roadway. The average travel speed on either roadway is 35 kilometres per hour.

4.8 On the shorter roadway, the vehicle fleet mix consists of 80 per cent passenger cars, 10 per cent light-duty vehicles, 5 per cent heavy-duty vehicles and 5 per cent two-wheeled vehicles. On the longer roadway, the vehicle fleet consists of 75 per cent passenger cars, 15 per cent light-duty vehicles and 10 per cent heavy-duty vehicles.

4.9 Assuming the CO emission factor for the shorter roadway is 30 grams per kilometre and the CO emission factor for the longer roadway is 35 grams per kilometre, the total CO emissions from the roadway segments are calculated as follows:

(2.4 kilometres × 60 000 vehicles × 30 grams per kilometre) + (2.6 kilometres × 40 000 vehicles × 35 grams per kilometre) = 7 960 000 grams of CO (that is, 7.96 metric tonnes).

Sophisticated approach

4.10 The formula for the advanced approach would also be used for the sophisticated approach as demonstrated in the following example (the only difference being the amount and scope of required data).

4.11 Assume that during the morning peak hour of a day, 5 000 vehicles traverse a road that is 1.5 kilometres in length. During the evening peak hour, 7 000 vehicles traverse the same roadway. For each of the remaining hours of the day, 25 per cent of the morning peak hour traffic (1 250 vehicles) traverses the road.

4.12 The average travel speed on the road during the morning peak hour is 45 kilometres per hour and the average travel speed on the road during the evening peak hour is 30 kilometres per hour. While the volume and speed fluctuate, the vehicle fleet mix remains constant during weekdays at 80 per cent passenger cars, 10 per cent light-duty vehicles, 5 per cent heavy duty vehicles and 5 per cent two-wheeled vehicles. On weekends the ratios change to 80 per cent passenger cars, 10 per cent light-duty vehicles, 8 per cent heavy-duty vehicles and 2 per cent two-wheeled vehicles. Of the 80 per cent of cars during weekdays, 40 per cent are personnel arriving at work and 60 per cent are passengers.

4.13 Assuming the weighted CO emission factor (accounting for fleet mix and vehicle type, age and fuel) during the morning peak hour is 30 grams per kilometre, the factor during the evening peak hour is 20 grams per kilometre, and the emission factor every other hour of the day is 25 grams per kilometre, the total CO emissions from the roadway segments are calculated as follows:

(1.5 kilometres × 5 000 vehicles × 30 grams per kilometre) + (1.5 kilometres × 7 000 vehicles
× 20 grams per kilometre) + (22 hours × (1.5 kilometres × 1 250 vehicles × 25 grams per kilometre)
= 1 466 250 grams of CO (that is, 1.47 metric tonnes).

4.14 The example shown here considers one road segment. This calculation would have to be repeated for all road segments taking into consideration the fleet mix, speeds, etc. Finally, in the example, the emission factor is assumed constant for each road segment. Use of the sophisticated approach assumes diurnal and seasonal variations are constant.

Curbside and parking lot

4.15 With one exception, the formulae and approaches discussed previously for roads can also be used to estimate emissions from vehicles idling at airport curbsides and travelling/idling in airport-related parking facilities (including garages and surface lots). In place of distance-based emission factors, these are time- or event-based and account for hot and cold starts, hot soak (curbside engine running) and evaporative emissions.

4.16 For demonstration purposes, emissions estimates for vehicles idling at curbsides and travelling/idling in parking lots can be calculated using the following general equation:

$$E_{total} = (TD_m \times NV_m \times EF_m) + (T \times NV_1 \times EF_1) \qquad \text{Eq. 3-A4-3}$$

where:

E_{total} = total emissions for all moving and idling vehicles (e.g. grams);

TD_m = travel distance (e.g. kilometres);

NV_m = number of vehicles on the road by class, age and speed;

EF_m = emission factor for mobile (moving) vehicles considering vehicle class, age and speed (e.g. grams/vehicle-kilometre travelled);

T = dwell time (e.g. minutes) that the vehicle is stationary;

NV_I = number of idling vehicles by class, age and speed; and

EF_I = idle emission factor considering vehicle class, age and speed (e.g. grams/minute).

4.17 Using this formula, the following example calculates the level of emissions for a curbside using the simple approach. Assume a curbside is 0.2 kilometres in length. Over a 24-hour period, 2 000 vehicles traverse the roadway next to the curbside at an average travel speed of 25 kilometres per hour. The vehicle fleet mix consists of 95 per cent passenger cars and 5 per cent light-duty vehicles. While drivers are loading/unloading passenger luggage, each vehicle idles two minutes. Assuming a moving CO emission factor of 30 grams per kilometre (the corresponding emission factor for the vehicle speed of 25 kilometres per hour) and an idling CO emission factor of 4 grams per minute, total CO emissions from the curbside are calculated as follows:

(0.2 kilometres x 2 000 vehicles x 30 grams per kilometre) + (2 minutes x 2 000 vehicles x 3 grams per minute) = 28 000 grams of CO (i.e. 0.028 metric tonnes).

Attachment to Appendix 4

VEHICLE MODEL REFERENCES

The EPA's Office of Transportation and Air Quality (OTAQ) has developed the MOtor Vehicle Emission Simulator (MOVES). This new emission modelling system estimates emissions for mobile sources covering a broad range of pollutants and enables a multiple scale analysis. MOVES currently estimates emissions from cars, trucks and motorcycles. It is available at http://www.epa.gov/otaq/models/moves/index.htm (accessed June 2020).

EMFAC is the mobile source emissions inventory tool used by the California Air Resources Board (ARB) for assessing the population, activity and emissions of mobile sources. The CARB released EMFAC2011, which is ARB's official model for estimating emissions from on-road cars, trucks and buses in California. The tool can be found at https://arb.ca.gov/emfac/2011/ (accessed June 2020).

COPERT 4 is a Microsoft Windows programme used to calculate air pollutant emissions from road transport. The COPERT 4 methodology is fully consistent with the section on road transport in the *EMEP/EEA air pollutant emission inventory guidebook 2019*. The use of a software tool to calculate road transport emissions enables a transparent and standardized, and therefore consistent and comparable, data-collecting and emissions-reporting procedure that meets the requirements of international conventions and protocols and EU legislation. Information is available at https://copert-4.software.informer.com (accessed November 2021).

The Handbook Emission Factors for Road Transport (HBEFA) provides emission factors for all current vehicle categories (passenger cars (PCs), light-duty vehicles, heavy goods vehicles, urban buses, coaches and motorcycles). Each vehicle category is divided into subcategories for a wide variety of traffic situations. Emission factors for all regulated and the most important non-regulated pollutants, as well as fuel consumption and CO_2, are included. The tool is available at www.hbefa.net (accessed June 2020).

Chapter 4

SPATIAL AND TEMPORAL DISTRIBUTION OF EMISSIONS

4.1 INTRODUCTION

4.1.1 Chapter 3 describes the setup of an emission inventory for a given airport perimeter (for example, airport plus nearer surrounding and altitudes up to 3 000 feet above ground) and a given period (for example, day, month, year). A further spatial and temporal allocation becomes relevant for more detailed airport air quality assessments, in particular

a) the identification of pollutant hot spots; or

b) the setup of a pollutant dispersion calculation.

4.1.2 The spatial and temporal allocation of emissions provides information on locations and times with high emissions and the relevance of different emission groups. As the pollutant concentration is (neglecting other parameters) proportional to the emission, such an allocation provides a first estimate of pollutant hot spots and source apportionment with respect to pollutant concentration. It is only a first estimate because transport effects due to exhaust dynamics, wind flow, atmospheric diffusion, deposition and physical or chemical conversion processes are not considered.

4.1.3 These effects can be accounted for in a dispersion calculation which requires a detailed spatial and temporal allocation of the emissions from the various emission sources at and around the airport. Based on the calculation of emissions described in Chapter 3 and their spatial and temporal allocation outlined in this Chapter 4, a dispersion calculation can be set up as described in Chapter 5.

4.2 SPATIAL ALLOCATION

4.2.1 The spatial allocation of emissions requires knowledge about the specific emission sources at and around an airport. In the context of an emission or dispersion calculation, the emission locations applied in the model may also depend on the way how emissions are resolved in the model, for example by means of an emission grid with a given cell width or a system of point or line sources with a certain spatial accuracy or resolution.

4.2.2 In the context of a dispersion calculation, the required spatial accuracy depends, among other factors, on the locations at which a local air quality assessment takes place. The further these locations are away from the emission location, the less relevant is the explicit spatial representation of the emission. For assessments inside the airport, the accuracy or resolution should be at least 100 meters, for assessments outside the airport, less stringent conditions apply.

4.2.3 For assessments outside the airport, individual stand positions may be bundled and allocated in the form of area sources, likewise alternative taxiways which are not too far away from each other may be approximated by a representative taxiway. On the other hand, for assessments close to an emission source like a runway, taxiway or motor road, an accurate allocation with a spatial resolution down to 10 meters or less may be required.

4.2.4 The more elevated from ground level a pollutant emission takes place, the smaller is its contribution to the near-ground concentration. This is in strong contrast to noise emissions. Whereas aircraft noise is propagated through the air with the speed of sound, aircraft pollutant emission is transported vertically with the air, mainly by turbulent diffusion. This takes place on a much larger time scale than the propagation of sound, concomitant with a strong dilution by ambient air during that time.

4.2.5 Therefore, in the context of a dispersion calculation, details of arrival and departure paths above some 100 meters above ground are in general of little relevance to the near-ground concentration if compared to near-ground emissions. For instance, while the locations of aircraft routes (horizontal course of the aircraft after initial climb) are key parameters for noise impacts around an airport, they are of little relevance for the local air quality.

4.2.6 The allocation of emissions from aircraft main engines is determined by the location of stand positions, taxiways, runways and the three-dimensional arrival and departure paths. The stand positions, taxiways and runways are static objects that are occupied by different aircraft. In contrast, the arrival and departure paths are more dynamic and depend, for example, on the type of aircraft and its weight. The static objects are defined by the airport layout and the taxiing policies, and the arrival and departure paths are defined by the vertical flight profiles and the horizontal routes of the aircraft.

4.2.7 The simple approach for calculating aircraft emissions (Chapter 3, Appendix 1) does not allow spatial allocation of emissions and, therefore, it is not suited as a basis for dispersion calculations. In contrast, emission calculations based on profile assumptions or performance models (advanced and sophisticated approaches in Chapter 3, Appendix 1) can provide consistent information on both the emissions and their locations and should preferably be applied.

4.2.8 Emissions from aircraft are often mapped onto systems of sources at fixed positions. For example, taxiing emissions at an airport during a one-hour period can be allocated on a system of line sources that reflect the locations of the applied taxiways. In other cases, it may be more appropriate to apply non-stationary source representations, for example when tracking individual aircraft with a time resolution of some seconds by means of moving point sources.

4.2.9 Emissions from engine starts, APU, GPU and GSE can in general be allocated at the stand positions in the form of area sources. Emissions from motor traffic can be allocated in the form of sequences of line sources. Emissions from other sources can be allocated in the form of point, line, area or volume sources.

4.2.10 As an alternative to individual emission sources, the emissions from the various source groups can be mapped onto a three-dimensional grid with an appropriate spatial resolution. Such emission grids are useful, for example, to identify emission hot spots and to make a first assessment of the local air quality solely based on emission figures.

4.2.11 When applying individual emission sources or three-dimensional emission grids in a subsequent dispersion calculation, care must be taken that effects of exhaust dynamics (due to excess temperature, momentum and turbulence with respect to the ambient air) are accounted for. This applies in particular to emissions from aircraft main engines, APU and guided emissions from stacks. For individual emission sources, this is usually achieved by assigning specific dynamical properties to the sources in the dispersion calculation. For an emission grid, the influence of exhaust dynamics can be accounted for in an approximate way by smoothing and shifting the emissions before mapping them onto the grid (smooth & shift approach). In this approach, for example, plume rise is accounted for by a vertically shifted effective emission height, and the initial spread of the plume due to exhaust turbulence by a horizontally and vertically extended emission volume.

4.3 TEMPORAL ALLOCATION

4.3.1 For emission inventories, a temporal allocation of emissions within the studied time period is not required. The allocation becomes relevant for the identification of temporal hots spots and for subsequent dispersion calculations.

For the temporal allocation, the studied time period is divided into smaller (usually equal) intervals. In the context of a dispersion calculation, a constant emission rate is then assumed within every interval (emission within the interval divided by the length of the interval).

4.3.2 The temporal allocation of emissions is required for a dispersion calculation because the meteorological conditions that dominate the transport and dispersion process, in particular wind speed and wind direction, change with time. The smaller the averaging interval for the concentration, the more important an accurate allocation becomes. For example, for the calculation of annual mean concentrations, a specific day course of emissions is less relevant than for the calculation of the maximum hourly mean concentration. The basic averaging interval applied in an airport-related dispersion calculation is usually one hour and should not exceed three hours. The required averaging interval may be imposed by given air quality standards.

4.3.3 Air traffic often shows a correlation with atmospheric stability; for example, strong traffic during daytime with neutral/unstable stratification and little traffic during night-time with neutral/stable stratification. Such a correlation is automatically accounted for if time series of both emission and meteorology are applied.

4.3.4 The temporal allocation of aircraft emissions is generally straightforward because at airports detailed time information on individual aircraft movements is available. This allows, for example, to extract hourly numbers of arrivals and departures of specific aircraft types at specific runways and stand positions. The time course of emissions from engine starts, APU, GPU and GSE is triggered by the air traffic and usually the same time course as for the according air traffic can be applied.

4.3.5 The time courses of emissions from motor traffic and other sources at an airport are often more difficult to obtain and thus simplified assumptions may be required. If the emission has a systematic change over the day (for example, strong emission during daytime and little emission during night-time), this should be accounted for because it may correlate with the meteorological conditions. For motor traffic (in particular landside), specialized high fidelity models are sometimes available and can be used.

4.3.6 For dispersion calculations over a calendar year, care must be taken that changes in the zone time due to daylight saving time switches are properly accounted for in the temporal allocation of emissions. For example, night flying restrictions apply to local time, while in the dispersion calculation usually a fixed zone time (for example GMT-5 or GMT+1) is applied throughout the studied time period.

Chapter 5

DISPERSION MODELLING

5.1. INTRODUCTION

5.1.1 A quantity of a pollutant emitted into the atmosphere is transported by the mean wind field (advection) and dispersed by atmospheric turbulence (diffusion). Further processes can influence the atmospheric transport, such as sedimentation of heavy aerosols, deposition and physical or chemical conversion processes. The result of these processes is a time-dependent, three-dimensional concentration distribution of the pollutant, where the concentration is the quantity of the pollutant per unit volume. In the presence of deposition, there is a time-dependent deposition to the ground, where the deposition (flux density) is the quantity of the pollutant deposited per unit time and unit area. In the following, while reference is usually made only to the concentration, the same lines of argument apply also to deposition.

5.1.2 Atmospheric dispersion models calculate these transport processes based on simplified assumptions and provide estimates of the concentration distribution. As the physical equations on which the models are based do not depend on the dimension or magnitude of the emitted pollutant quantity, a model that calculates mass concentration from given mass emission can also (at least in principle) calculate number concentration from given number emission. Likewise, the relative accuracy or reliability of the model results does not depend on the amount that is emitted (for example kg or µg).

5.1.3 Atmospheric dispersion models are an important complement to pollutant measurements. They provide comprehensive three-dimensional concentration distributions, insight into relevant transport mechanisms and a clear source apportionment. In addition, they allow study of future or other scenarios for which measurements are not available or not possible.

5.1.4 For further information about general concepts of dispersion modelling and technical terms mentioned in the following, such as Obukhov (Monin-Obukhov) length or surface roughness length, see Seinfeld & Pandis (2016). [Atmospheric Chemistry and Physics, John H. Seinfeld, Spyros N. Pandis, Wiley, 2016] as an example.

5.2. CONCEPTS AND DEMANDS

5.2.1 Atmospheric dispersion models like Gaussian puff or plume models and Lagrangian particle models account for the meteorological wind and turbulence fields in form of mean quantities (ensemble means). The resulting concentration distribution, at a given moment of time or averaged over a time interval, is therefore also a mean quantity, concentration fluctuations about the mean due to the random nature of atmospheric turbulence are not calculated. This would require, for example, Large Eddy or CFD simulations.

5.2.2 The atmospheric transport from the point of emission to a point of interest is a time-dependent process and requires a time-dependent model description. If the concentration is calculated as an average over a given time interval, and if the emission rate and the meteorological conditions are constant within this interval, and if the transport time between the point of emission and the point of interest is much smaller than this interval, then the resulting concentration distribution corresponds to a quasi-stationary distribution. These assumptions are usually fulfilled in airport calculations based on time series of hourly or half-hourly means and for distances that are not too large, therefore both quasi-stationary model types (Gaussian plume) and non-stationary ones (Gaussian puff and Lagrangian particle) are applicable and well established. In the following no further distinction is made between these different model types.

5.2.3 In the context of airport dispersion modelling, it is important to note that there is not a single model but a chain of several, mostly independent, models:

a) Emission model (see Chapters 3 and 4);

b) Exhaust dynamics model (plume rise, initial turbulence);

c) Airport setup model (setup of runways, taxiways, etc.);

d) Meteorological model (boundary layer profiles);

e) Wind field model (in case of a terrain profile and/or buildings);

f) Deposition model (sedimentation, dry and wet deposition);

g) Physical and chemical conversions model (for example $NO/NO_2/O_3$, PM);

h) Core dispersion model (for example Gaussian, Lagrangian, Eulerian); and

i) Result evaluation model (for example percentiles, isolines).

The actual dispersion model (part h in the model chain) is only one piece within a complex model system. The result of a dispersion calculation is affected by all parts of the model chain. This must be considered when interpreting the validity and robustness of the result or when comparing it with measurements. Some components of the model chain can be adjusted or replaced (for example deposition velocities or the plume rise model), others cannot.

5.2.4 For some sources, the pollutants are not emitted passively into the environment but in an exhaust that is characterized by a strong excess temperature, momentum or turbulence with respect to the ambient air. This is particularly the case for the exhaust from aircraft main engines and APU. The dynamics of the exhaust can have a strong influence on the concentration distribution in the near field (up to distances of a few kilometres). It is required that an airport dispersion model accounts for this effect (part b in the model chain).

5.2.5 Airport emission sources constitute an extended source system; outside the airport the resulting hourly mean concentration distributions are therefore rather smooth and extended. In this case, the influence of building structures on the concentration distribution outside the airport is usually small and an explicit modelling of building influences by means of a complex wind field model is not required. Likewise, the terrain at an airport is usually flat and the influence of a terrain profile is small. On the other hand, dispersion calculations focusing at the airport site may require, depending on the location of interest, explicit account of the effects of airport buildings by means of a complex wind field model. This can be the case, for example, when studying pollutant concentrations at the terminal aprons.

5.2.6 The concentration calculated by a dispersion model is the partial concentration due to the emissions that have been accounted for. There may be other emission sources and an overall background which contribute to the total concentration. For pollutant concentrations which are not subject to nonlinear reactions, concentrations from different source contributions can be simply added to provide the total concentration. This superposition principle allows, for example, to add the concentration calculated by an airport dispersion model at a specific point in time with the according concentration calculated by a regional model that accounts for the non-airport sources, and with a measured or modelled background concentration, resulting in an estimate of the total concentration.

5.2.7 Such a simple superposition of independently calculated concentrations is not adequate for NO and NO_2 because the chemical conversion between these species depends, among others, on the O_3 concentration which in turn depends on the total concentration of NO and NO_2. There are different solutions to estimate the NO_2 concentration, like the use of reaction schemes that account for local background gas concentrations, or the estimate of total NO_2 concentration from the modelled total NO_x concentration based on empirical relationships between the two.

5.3. CONTEXT OF A DISPERSION CALCULATION

5.3.1 The setup and requirements of the various parts of the dispersion model chain depend on the context and purpose of the calculation. This applies also to the result and its interpretation. The following lists some examples.

5.3.2 A standardized calculation may be required to comply with certain national or international standards in view of specific model setups or parameter values. This can be the case, for example, in the context of formal assessment procedures or to facilitate comparisons with other calculations.

5.3.3 A scientific approach may use the best available models and parameters, independent of their complexity. This can result in a large effort to carry out the calculations, the application of complex input data and very comprehensive results which, on the other hand, are hard to reproduce by others.

5.3.4 A simplified approach, for example with respect to the airport setup or the derivation of emissions, can be useful for screening applications. This approach can provide “quick and dirty” results which are useful if only the order of magnitude matters.

5.3.5 A conservative approach can be used (because of a lack of data or to simplify the calculations) with simplifying assumptions such that the concentrations are deliberately over-estimated rather than unexpectedly under-estimated. This can be a useful approach, for example, for a simple proof that the concentrations are below a given limit value.

5.3.6 A fully transparent approach can require the usage of only public data and models. This can be required, for example, in formal assessment procedures.

5.3.7 All these different approaches have their characteristic virtues and drawbacks. It is therefore important to carefully consider the context and the chosen approach. For example, for a validation with measured concentrations, a scientific approach is better suited than a conservative approach.

5.4. MODEL INPUT

5.4.1 The input data required to carry out an airport dispersion calculation can be grouped as follows.

Airport setup

5.4.2 The location of runways, taxiways and apron areas must be set up as required by the applied model. If an airport map is applied, it must be considered that map North and geographic North may differ due to Meridian convergence.

5.4.3 Departure and arrival routes (horizontal courses) can be regarded as part of the airport setup because they do not depend on the specific aircraft. The departure routes are usually defined relative to the runway reference point, while the departure profiles (vertical courses) are defined relative to the actual start point of the aircraft.

Air traffic

5.4.4 Air traffic can be defined based on a flight journal with a list of individual aircraft movements or based on more general information. The specific requirements and level of detail for the definition of air traffic and its spatial and temporal allocation depends on the context and the applied model. At minimum, information on aircraft types, the distribution over runways, apron areas and departure routes, the time of arrival or departure and some taxiing times is required. See Chapters 3 and 4 for further information.

5.4.5 If a chemical reaction scheme is applied to estimate the NO_2 concentration, then the engine emissions, which are usually provided only in form of NO_x, must be split into NO and NO_2. The initial fraction of NO_2 (primary NO_2) depends on the thrust of the engine and other parameters. Some models apply initial fractions that depend on the LTO mode. If no detailed information is available, an overall average initial fraction of 15 per cent NO_2 in NO_x can be used as a first approximation. The same applies to APU.

5.4.6 When splitting the mass emission of NO_x into emissions of NO and NO_2, the different molar masses of NO (30 g) and NO_2 (46 g) must be considered. If 15 per cent of 100 g NO_x is emitted as NO_2, then the emission of NO_2 is 15 g and the emission of NO is 85 g times 30/46, so 55 g.

Aircraft-related emission sources

5.4.7 For the calculation and allocation of emissions from APU, GPU and GSE, see Chapters 3 and 4.

5.4.8 Operation times of APU (normal running) depend on the equipment at the stand position and are correlated, for example, with GPU operation times. Beside aircraft main engines, APU emissions can make a significant contribution to the overall emission at an airport and thus realistic estimates for the APU running times should be applied. Interdependencies between APU usage and taxiing policies like single engine taxiing should be considered.

Other emission sources

5.4.9 Other emission sources are, for example, motor vehicles (airside and landside) and power plants. The extent and level of detail at which these sources are included and defined depends on the context of the dispersion calculation and the specific model. For further details see Chapters 3 and 4.

5.4.10 If a chemical reaction scheme is applied to estimate the NO_2 concentration, emissions of both NO and NO_2 must be specified.

Meteorology and Land Use

5.4.11 The dispersion calculation is based on a time series of meteorological parameters. The applied parameter values must be representative for the site of interest and the calculation area. Care must be taken that the applied values have not been distorted by local effects, like wind measurements in the lee of a building complex.

5.4.12 Simple input data include ground-based measurements or vertical profiling of wind speed and wind direction and a measure of the atmospheric stability (stability classes or continuous parameters such as the Obukhov length). If a performance model is applied for aircraft emission calculations, time series of temperature, pressure and humidity may be required. Some models allow to process more complex meteorological fields from numerical weather prediction (NWP) models.

5.4.13 If the stability is characterized by the Obukhov length, for example, based on data of a three-dimensional supersonic anemometer, its value should be a temporal mean not below 10 minutes in order to be representative for a larger area.

5.4.14 The terrain surface is usually characterized by a surface roughness length and a displacement height (vertical shift of the boundary layer profiles). The values can be derived from land-use data. If no information is available, a typical average roughness length over an airport and its close surroundings is between 0.2 and 0.5 meters. If a displacement height is applied and no other information is available, it can be estimated as six times the roughness length.

5.4.15 Land use data may also be required to define appropriate deposition velocities in case dry deposition is calculated.

Calculation area

5.4.16 The calculation area (more correctly, the calculation volume) must cover at least all emission sources that are accounted for in the dispersion calculation and all receptor points of interest. Its extent depends on the specific requirements of the dispersion calculation. It may cover only a part of the airport or the airport and its close or wider surroundings. For some models it may be required to apply a calculation area larger than the actual area of interest to allow re-entering of pollutants due to varying wind directions.

5.4.17 For very large areas, the representativity of the applied meteorological data must be checked. It may be required to apply horizontally inhomogeneous input data from several measurement locations or from a regional or global meteorology model.

5.4.18 The vertical extent of the calculation area should typically be at least 3 000 feet (914 meters), although for local calculations covering only part of the airport, a smaller extent can be used.

5.4.19 The receptor points or cells of the calculation grid for which the concentrations are calculated must reflect a spatial resolution that is enough to resolve the relevant concentration gradients. See 4.2.

Background concentration data

5.4.20 Information on background concentrations (concentrations due to emissions not accounted for in the dispersion calculation) may be required as input for the physical and chemical conversion modelling. It may also be required for an estimate of the total concentration. Background concentrations can be obtained, for example, from suitable measurements or from regional transport models.

5.5. MODEL OUTPUT

5.5.1 Once the spatial and temporal allocation of the emissions are fixed, the total emission inside the calculation area as accounted for in the dispersion calculation can be determined and should be reported for cross-checking. For pollutants that are subject to conversions during the atmospheric transport, only the primary (initial) emission can be reported.

5.5.2 The results of a dispersion calculation are concentrations (and possibly deposition fluxes) at given receptor points or grid cells or in two- or three-dimensional form. They can refer to specific time intervals (for example, hour, day, year) or statistical quantities (for example, percentiles based on the hourly means). For deposition, usually only the long-time mean (for example, annual mean) is reported.

5.5.3 The modelled concentrations and depositions can refer to the sum of all emission sources or they can be listed for different source groups separately (source apportionment).

5.5.4 Care must be taken that the correct conversion factors are applied when converting the model output to other units of concentration or deposition. The following table lists some frequently applied conversions:

Table 5-1. Frequently applied conversions of units

Quantity	Model output in	Conversion to	Conversion factor
Concentration (mass)	g/m³	µg/m³	1.E+6
Concentration (number)	1/m³	1/cm³	1.E-6
Deposition flux density	g/(m²*s)	kg/(ha*a)	3.1536E+8
Deposition flux density	g/(m²*s)	g/(m²*d)	8.64E+4

5.6. INTERPRETATION OF MODEL RESULTS

5.6.1 The quality and robustness of the model results and their interpretation depend on

- the context in which the dispersion calculation has been set up,
- the considered emission sources and
- the quality of the applied input data, models and parameter settings.

Consistency checks and rules of thumb

5.6.2 It is useful to make some consistency checks prior to a detailed result interpretation. These checks can start with the applied overall emissions, and here usually emissions from aircraft main engines make the major contribution at an airport.

5.6.3 For certification values of fuel flow, emission indices and time-in-mode, the LTO emission per aircraft (emissions from the aircraft main engines) averaged over all annual movements at a civil airport has an order of magnitude as listed in the following table.

Table 5-2. Annually averaged LTO emissions magnitude per aircraft

Pollutant	LTO emission (kg) per average aircraft (main engines)
NO_x	10
HC	1
CO	10
CO_2	2000
SO_2	1
PM10 (FOA based)	0.1

5.6.4 “Order of magnitude” means that the LTO emission of an individual aircraft can be very different (see Table B-1), but the average should be around this value within a factor of 3 or so (1/3 or 3 times the value). If the emission calculation yields an average LTO emission (total emission up to 3 000 feet divided by the number of LTOs) that differs from the value listed above by more than a factor of 4, this is an indication that there might be an error in the calculation.

5.6.5 Example: For an airport with an annual LTO number of 200 000, the rule of thumb for the annual NO_x emission of aircraft main engines up to 3 000 feet gives 200 000 times 10 kg which is 2 000 metric tons (Mg). If the emission calculation, in contrast, yields 400 Mg or 10 000 Mg, then there is likely something wrong in the calculation.

5.6.6 An order of magnitude estimate of near-ground concentrations is more difficult because the concentration depends in addition on the specific meteorology, the airport setup and the averaging interval. Annual mean concentrations of NO_x near ground due to emission sources inside the airport fence have a magnitude outside the airport fence that is typically less than 20 µg/m³, and at distances of about one kilometre or more away from the fence, less than 10 µg/m³. If calculated annual mean concentrations of NO_x outside the airport fence are much higher, this is an indication that there might be something wrong in the calculation.

5.6.7 The ratio between dry deposition flux and near-ground concentration (for the same averaging interval) must be of the order of the deposition velocity. Typical values of the deposition velocity for gaseous pollutants are around 0.01 m/s or smaller and for aerosols, depending on their diameter, between 0.01 m/s and 0.1 m/s.

5.6.8 Emission, concentration and deposition of PM2.5 must, by definition, be smaller than or equal to the one of PM10.

5.6.9 The ratio of number to mass for particles depends on the particle sizes. Assuming for non-volatile PM from aircraft engines a log-normal distribution with geometric standard deviation 1.8 and effective density 1 g/cm³, the ratio is 5.E+16 per gram for a geometric mean diameter of 20 nm and 6.E+15 per gram for a geometric mean diameter of 40 nm. Measurements of non-volatile PM from aircraft engines (as listed, for example, in the ICAO EEDB Version 28 and higher) show a wider range of number over mass ratios, roughly 1.E+14 to 1.E+17 per gram. This ratio applies to emission indices, emission rates and total emissions of non-volatile PM from aircraft engines. It also applies to the according concentrations, which are proportional to the emissions if the modelling does not include conversion processes which change mass or number of the particles.

5.6.10 Example: Reporting an annual emission of non-volatile PM from aircraft main engines of 10 Mg (mass) and 2.E+23 (number) yields a ratio of 2.E+16 per gram which is within the expected range.

Robustness and sensitivities

5.6.11 The robustness (validity and dependence on specific assumptions) of a dispersion calculation depends on the robustness of the applied input data and models. It also depends on the expertise and carefulness of the analyst that carries out the calculation.

5.6.12 Uncertainties in emissions transform linearly into uncertainties of concentration. For example, if the applied emission is wrong by a factor of 2, so is the concentration.

5.6.13 Modelled long-time means (for example, annual means) are usually more robust than modelled short-time means (for example, hourly means) because uncertainties in meteorological parameters or in the setup of emission time series tend to level out when averaged over larger time periods.

5.6.14 Modelled concentrations of those pollutants that are not subject to physical or chemical conversion processes are more robust because they do not depend on specific input and assumptions of these processes. For example, modelled NO_x concentrations tend to be more robust than modelled NO or NO_2 concentrations.

5.6.15 If based on theoretical estimates like FOA4.0, the modelled non-volatile PM mass concentration is more robust than the modelled non-volatile PM number concentration because the latter requires additional assumptions on the effective density and diameter distribution.

5.6.16 The further away from the airport, the less the modelled concentration is affected by specific assumptions on the exact source locations and the source dynamics. On the other hand, the further away from the airport, the more the modelled concentration is affected by assumptions that effectively integrate over transport time, like the assumed deposition velocities or conversion rates.

Regional context

5.6.17 When interpreting modelled concentrations due to airport-related emission sources, it must be considered that the airport contributes only a part to the total concentration at a given receptor point.

5.6.18 Motor roads around airports can contribute a significant part to the total concentration outside the airport, for example, in view of NOx and NO_2. The relative contribution depends on the substance and the specific conditions. In addition, other regional sources like industrial sites or domestic areas and an overall background concentration from long-range transport can provide significant contributions.

5.6.19 Results from airport dispersion models can be combined with suitable background measurements or modelled concentrations based on regional and meso-scale models to obtain an estimate of the total concentration. In such combinations, care must be taken that airport emissions are not double-counted. In addition, substances subject to chemical transformations of higher order may require special care, as seen in the end of 5.2.

5.7. MODEL VERIFICATION AND VALIDATION

5.7.1 An airport dispersion model, like any other model, requires verification and validation.

5.7.2 Verification means a check on whether the actual computer program implements the underlying models and algorithms correctly. This usually requires independent checks of every part of the model chain (see 5.2).

5.7.3 Validation means a comparison of the model results with measured data. This can include checks of individual parts of the model chain, but in the first instance requires a check of the complete model chain as it is applied in practise. The model validation may be affected by the context in which the model has been set up, as seen in 5.3.

5.7.4 For simple emission problems, like a single passive point source at well-defined meteorological conditions, there exist standard validation data sets. This is not the case for the complex source system of an airport. Various data sets exist; for example, concentration measurements behind individual aircraft at different thrust settings and concentrations at monitor points at and around specific airports. But so far none of the data sets serve as an international “gold standard”, partly because either the measured concentrations cannot be attributed to specific sources or some data is missing that would be required for a detailed modelling of the measured situation. Therefore, up to now, every airport dispersion model applies its own data sets and has its own history of validation.

5.7.5 A model validation requires a set of measured concentrations for which all required model input data is available. Comparisons of long-time averages may be more robust (see above) but are more demanding with respect to the required input data and the measured concentrations (for example, in view of contributions from non-airport sources). A point-to-point comparison of measured and modelled concentration time series at a specific receptor point can provide a very meaningful validation but it is demanding and restricted to the specific point of comparison. Alternatives are statistical evaluations of modelled and measured time series at various points at and around an airport.

5.7.6 For the purpose of usage within CAEP, several airport dispersion models have undergone an evaluation procedure and were approved as suitable for applications within CAEP. The models are listed in the Appendix to this Chapter.

Appendix to Chapter 5

CAEP APPROVED AIRPORT DISPERSION MODELS

1. It is not the purpose of this appendix to recommend any particular dispersion model or to provide detailed information on any model. The analyst is expected to choose the most appropriate model based on legislative requirements, data available and intent of use.

2. Table 5-A1-1 shows computerized dispersion modelling packages that have commonly been used at airports and that have undergone an extensive evaluation within CAEP. Of note is that there are many more models that are used in practice.

Table 5-A1-1. CAEP approved airport dispersion models (see the ICAO website for possible updates)

Airport air quality model	Type of dispersion model	Version	Model information
ADMS-Airport	Bi-Gaussian	5.0	Sponsoring organization: United Kingdom Model developer: CERC
AEDT	Bi-Gaussian		Sponsoring organization: United States Model developer: FAA
LASPORT	Lagrangian Particle	2.3	Sponsoring organizations: Germany and Switzerland Model developer: Janicke Consulting
Open-ALAQS	Bi-Gaussian/ Lagrangian Particle		Sponsoring organization: France Model developer: EUROCONTROL
POLEMICA	Gaussian/Eulerian	5.1	Sponsoring organizations: CAA Ukraine Model developer: NAU Kiev

3. Common to all modelling packages is that no one modelling approach totally meets all current modelling needs, especially if cost, practicality and complexity are considered. This results in either multiple models being used and selected on a case-by-case basis or adaptations/simplifications of the selected model inputs. In addition, models are subject to continuous development.

4. The analyst should carefully review any legislative requirements, sources to be modelled, inputs needed for any specific model and limitations of any model when selecting the appropriate dispersion model.

Chapter 6

AMBIENT AIR QUALITY MEASUREMENTS FOR AIRPORTS

6.1 INTRODUCTION

Airports are an important part of the economic infrastructure of the cities they serve; passenger and cargo activity at an airport support local air transportation needs. However, as part of that infrastructure, airports are a magnet for many types of activities that contribute to air pollution in the local area: aircraft, automobiles, ground support equipment, stationary sources, etc. Often responding to various objectives and requirements, airports and/or local authorities seek to obtain an understanding of the effect of airport-related pollutant sources on local air quality. While modelling tools are available, some airports undertake to quantify the local air quality situation through the conduct of actual air measurements. It is important that measurements conducted for airports comply with the appropriate measurement protocols. This chapter describes the various elements for ambient air quality measurements for airports with the framework illustrated in Figure 6-1.

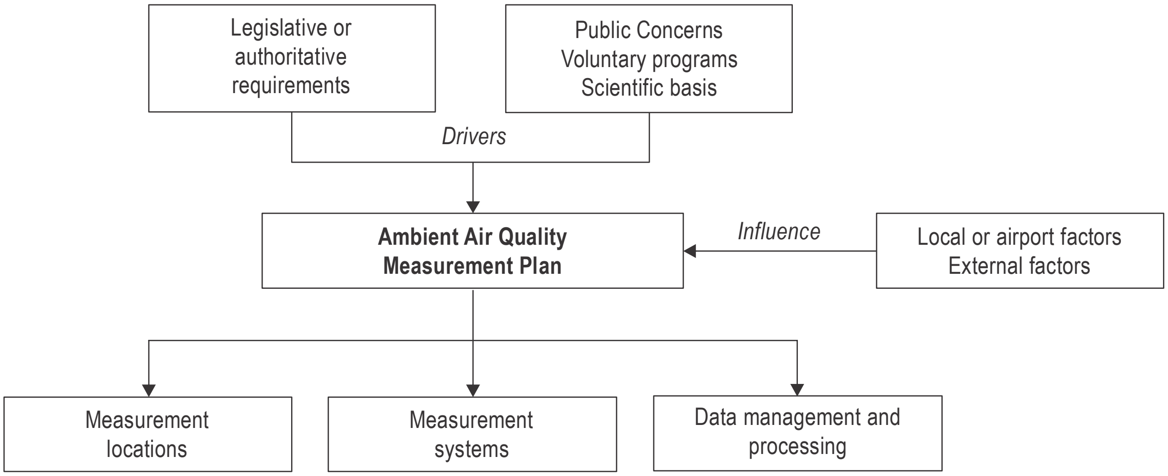

Figure 6-1. Measurement plan framework

6.2 REQUIREMENTS AND DRIVERS FOR AIR QUALITY MEASUREMENTS

6.2.1 Specific to ambient air quality measurements, numerous requirements and drivers influence the need for airport ambient air quality measurements to be conducted. Measurements are often conducted in order to meet legal obligations, as part of voluntary programmes or for model verification.

6.2.2 ***Legal compliance.*** To comply with applicable ambient air quality regulations and accompanying standards or targets for particular pollutants, airports, and in some places, local authorities, may be required to conduct ambient measurements. An airport or local authority may also be under the obligation to conduct measurements on a regular or irregular basis (such as for baseline assessment, continuous monitoring or in the context of expansion projects).

6.2.3 ***Voluntary programmes.*** Public and community concerns often trigger the need for measurements to obtain actual information about air quality in the vicinity. Alternatively, an airport may voluntarily conduct measurements and report as part of their corporate social responsibility and management activities.

6.2.4 ***Scientific issues.*** In addition to public and community concerns, new scientific evidence or hypotheses may emerge that suggest initiating measurement campaigns at or around airports to seek clarifications or obtain further information.

6.2.5 ***Model verification.*** Sometimes model results are calibrated with measured results to determine the ability of a model to characterize current conditions with some degree of confidence. Once a particular model is verified for baseline conditions, it can be used with greater confidence to predict future scenarios accurately. This is particularly important when an airport is considering potential action (for example, infrastructure development) and needs to analyse the potential impact of the action and any potential mitigation measures.

6.2.6 The major caveat associated with model verification is the fact that the model usually predicts concentrations from one or several emissions sources but not necessarily from all contributing sources. In this case, it might be difficult to compare modelled concentrations to measured values, and complex procedures have to be applied for the purpose of actually performing model verifications.

6.3 MEASUREMENT PLAN

Design process of a measurement plan

6.3.1 The measurement plan for local or regional air quality measurements is determined by external and/or internal requirements and the necessary resources available. The following main elements of a measurement plan should be addressed (see also Figure 6-1):

a) objectives and requirements for measurements (as described in 6.2);

b) airport, local and external factors;

c) measurement locations (with respect to the airport premises);

d) measurement methods; and

e) management planning.

Airport, local and external factors

6.3.2 The key external factors to be considered in ambient air quality measurements are potentially existing measurement standards, recommendations and guidelines. If applicable, practicable or available, local or national framework documentation for ambient air quality measurements should be used. This can range from general issues like measurement principles or quality assurance to prescribed measurement systems that have to be put in place.

6.3.3 In terms of external requirements, airports may have single or multiple objectives for the measurements, including the desire to obtain factual information on the actual ambient air quality concentrations at specific receptor locations for communication purposes, or to establish long-term trend analysis to observe the development of air quality at the measurement sites in response to emissions developments.

6.3.4 In some cases, airports will have to bear the responsibility for and cost of air quality measurements. To this end, the available resources, technical skills and budget may be factors that determine the possible scope of air quality measurements.

6.3.5 An air quality monitoring network operated by local authorities or other entities may already be in place. In this case, it would be advisable to coordinate or harmonize potential measurement plans to avoid duplication of similar or identical measurements, or to avoid inconsistencies or possible contradictions.

Measurement locations

6.3.6 The objectives and requirements as described in 6.2 will help determine the location of monitoring stations. A generic, yet typical, site selection plan is illustrated in Figure 6-2 with each location described and justified in Table 6-1. This site selection plan may vary from airport to airport depending on the actual regional land uses, infrastructure and development.

6.3.7 Air measurements should preferably be conducted upwind and downwind from the airport/airport sources while at the same time striving to achieve a source distribution discrimination. To achieve source distribution discrimination, locations should be defined that are most likely dominated by a specific emissions source, while other sources may contribute only marginally to the overall concentrations.

6.3.8 The following questions are associated with the choice of the measurement locations:

a) What are the current (past) pollution concentrations of relevant species near the airport?

b) Can airport-induced impacts be, at least to some degree, singled out?

c) What is the trend of the pollution concentrations?

6.3.9 In choosing the locations at and around the airport with regard to the most likely dominant pollution contributors, it may be possible to estimate qualitatively the relevance of air traffic and airport-induced impacts.

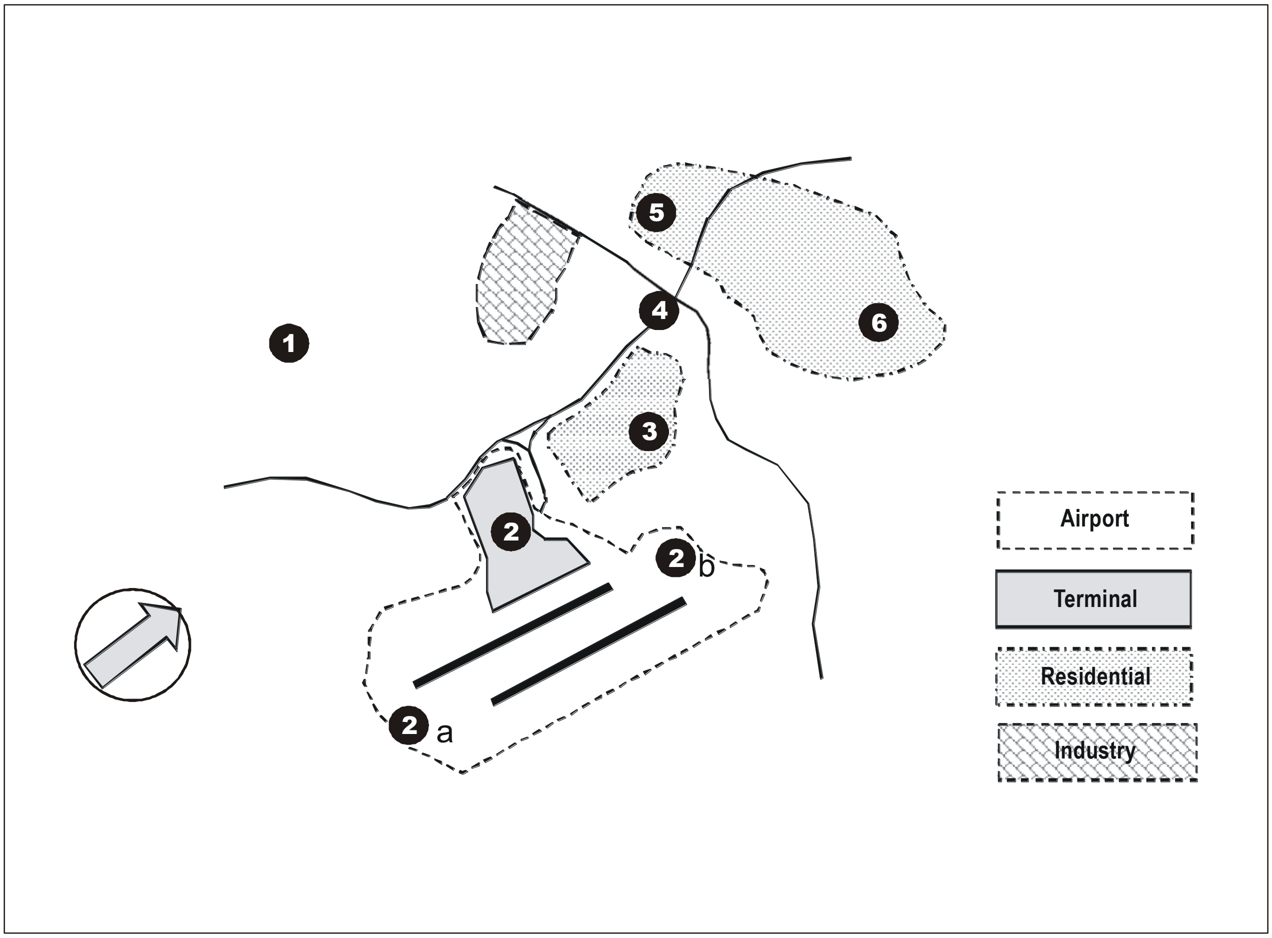

Figure 6-2. Generic measurement site selection plan (circled arrow: prevailing wind direction)

Table 6-1. Description of generic measurement sites

Number (from Figure 6-2)	Description of site	Justification
1	Background concentration site, undisturbed by any polluting activities.	This station provides the background and baseline data for the region where the airport is located.
2	All stations (including 2a and 2b) are located within the airport area with intense airport activities. Optionally, stations are located directly upwind and downwind (and sideline) of the runways, often at the airport boundary.	It can be expected that these stations will most likely best reflect the airport activities (aircraft and/or handling and infrastructure). Those activities will dominate the pollution concentrations, and significant concentration changes will likely be caused by these sources.
3	This station is located in a residential area that is located downwind of the airport, but without a dominant emissions source in its proximity.	This station will give the average situation of a residential area with permanent housing closest to the airport and downwind from it. A source attribution might not be possible, but is not necessary.
4	This station is located next to a major traffic road, but still in the proximity of the airport.	Road traffic is an important emissions source in general. This station reflects road traffic impacts on local air quality in the vicinity of the airport. There is no discrimination for airport-related traffic versus any other traffic.
5	This station is located in another residential area, but downwind of an industrial area with emissions.	Residential areas could still be subject to increased concentrations. In this case, it is important to discriminate emissions sources that are not airport-related but can have an impact on areas close to the airport.
6	This station is located further away from the airport, but again in a residential area downwind of the airport.	It can be expected that further downwind from the airport, concentrations will decrease, provided no other significant emissions sources are present.

Measurement methods

6.3.10 Various measurement methods are available that can range from simple (in terms of location site and handling) to sophisticated. The choice of each instrument must be made according to the expected measurement exigency, the definition of which rests on the analysis of customer or authority demand when it is not compulsory by law. In any case, the risk of providing a wrong result when comparing to a threshold must be discussed and accepted by all parties.

6.3.11 The main difference between measurement systems is whether they are active (the system collects air samples and analyses continuously) or passive (ambient air reacts with the system and results are obtained remotely). Table 6-2 discusses both systematic approaches in terms of various parameters that need to be considered when evaluating measurement systems.

6.3.12 When considering potential sites in combination with measurement systems, it can be concluded that sites at the airport can be equipped with active and/or passive systems, often dependent on available infrastructure and utilities, while air quality measurements in the airport region should be performed with passive systems.

Table 6-2. Active and passive measurement systems

Parameter	Active system	Passive system[1]
Possible systems	Optical path: • DOAS (differential optical absorption spectroscopy) Continuous point: • TEOM (tapered element oscillating microbalance) • Beta-attenuation mass monitor • High-volume samplers • Chemiluminescence	Bags/canisters Passive diffusion tubes Filter papers
Pollution species to be measured	Usually, multiple species can be measured in one station (for example, NO_2, O_3, PM_{10}) by using several analysers in one location.	Usually only one pollutant can be measured. Some pollutants cannot be measured at all (due to reactivity).
Analysis	Air samples are usually analysed directly in the station and when sampled.	Samples are usually analysed remotely in a laboratory and after collection.
Measurement intervals	Depending on the equipment, the measurement intervals can be short; for example, samples can be analysed every few seconds or minutes.	Intervals are usually long (for example, two-week intervals) or one-time measurements only.
Data accuracy	The accuracy of the data obtained is usually fairly high, provided there is proper installation and maintenance of the systems.	The accuracy of the measured data is fair. However, for trend or comparison analysis with a larger number of sites, the accuracy may be sufficient.
Site requirements	The measurement site requires an unobstructed location (with regard to air flow), a sheltered room for the equipment and analysers and access to electrical power. Depending on the system, communication lines for remote operations are also needed. Some access restrictions should apply. Such a system can also be mobile for measurement campaigns.	The measurement site requires an unobstructed location (with regard to air flow). Only limited infrastructure is required to install the measurement system (no shelter, no power).
Maintenance	An increased level of maintenance on electrical/electronic and precision parts is required to obtain and maintain a reliable level of operability. This may include regular calibration or exchange of critical parts.	Maintenance efforts are usually low because no, or only limited, electrical/electronic or high-precision parts are involved.
Cost	Medium to high (investments) and medium (maintenance).	Low (investments and maintenance).

1. Bioindicators/bioaccumulators: This category is more a hybrid of an active system and long-term exposition. A limited description is given in Appendix 1 to this chapter.

Management planning

6.3.13 An important element of ambient air quality measurement is ensuring that implementation and actual execution is properly accounted for. To this end, several elements have to be addressed, defined and documented in the management planning. These include the following:

a) project responsibility;

b) maintenance;

c) data management;

d) communication; and

e) quality assurance and quality control.

6.3.14 Project responsibility includes, but is not limited to, drafting the measurement concept; acquiring the necessary budget for acquisition, installation, operation and maintenance of the measurement equipment; organizing the data management (evaluation, verification, storage); and managing potential third-party contracts. It defines the roles and responsibilities of all involved parties.

6.3.15 Maintenance involves all of the elements of regular and preventative maintenance of the measurement equipment, as well as repairs, and potential contingency planning by having spare equipment available. It also deals with calibration of the equipment following manufacturer instructions or general guidelines and recommendations.

6.3.16 Data management comprises data acquisition (automatically or manually), data storage and data transfer (for example, from remotely controlled stations). Once the raw data are obtained, they are subject to a quality check that needs to be predefined, where inappropriate data are identified and either marked or removed from the data series. Depending on the data acquisition system and required evaluation and reporting interval, the data may have to be aggregated into a different interval (such as an hourly value).

6.3.17 Once the data are available for proper interpretation, there may be requirements for communication and/or publication. Public or restricted measurement reports may be produced and distributed, and communication to authorities or local stakeholders may be predefined.

6.3.18 In order to ensure long-term quality of measured data, a quality assurance process is recommended where all elements influencing the quality of the data are addressed. Such a quality control system is developed and implemented to ensure that the required level of confidence in the system and its results are achieved.

6.4 ANALYSIS OF DATA

Introduction

6.4.1 Ambient air measurement data can be used in a variety of ways, such as:

a) describing existing conditions in an area or a site and demonstrating whether or not ambient air quality standards are being met;

b) determining hourly, daily, monthly and seasonal variations;

c) determining special and temporal trends; and

d) identifying major sources that contribute to measured concentrations.

6.4.2 How the data can be used is dependent on the:

a) specific pollutants or constituents that were measured;

b) duration (days, weeks, months or years) of the measurements;

c) time resolution (seconds, minutes, hours or longer) of the measurements;

d) number and location of the monitoring sites used to collect the measurements; and

e) meteorological data (including wind speed and direction, pressure, humidity and temperature).

Describing existing conditions versus meeting ambient air quality standards

6.4.3 Ambient air quality monitoring is the traditional method for demonstrating that an area (or an airshed) currently meets the applicable air quality standards. Often, monitoring must be conducted for one to three years prior to a formal designation and determination that an area attains or does not attain a standard. Regulatory agencies have defined how the data may be used in comparing the monitored results with the air quality standards.

6.4.4 Monitoring at one or more sites near an airport provides information regarding local air quality in the vicinity of the airport. These data may be used for defining existing or baseline conditions in an environmental disclosure document for a proposed future project. Since air quality standards include the averaging period, and the averaging periods for certain standards can be up to one year, monitoring must be conducted for the period appropriate to the standard to which the data will be compared. Longer monitoring may be required if the standard is based on a limited number of measurements that can be exceeded over a number of years.

Determining periodic variations

6.4.5 Periodic variations may give some clues as to which sources may be contributing to the measured concentrations. Each source at an airport has associated peak characteristics. For example, regional surface traffic often follows a morning or evening work-related peak period. Aircraft operations often have distinct peaks. Ground vehicle access to an airport may peak 60 to 90 minutes before and after peak aircraft operations. If hourly-monitored data are available, and these data show pollutant concentration peaks corresponding in time with the rush-hour periods, then traffic is likely a major contributor to the measured values. Note that this assumes one is looking at a relatively inert pollutant (such as CO, PM_{10} or total NO_x).

6.4.6 The variation may also be by day of the week, month of the year, or seasonal. These variations may also help point to the sources or source types that may be substantial contributors to the measured concentrations. However, one should note that the periodic variations may also be associated with meteorological effects, such as temperature, mixing height or relative humidity that actually change the pollutant emissions from sources. For example, combustion sources produce more NO_x and less CO when the ambient air temperature is higher, producing both diurnal hourly fluctuations and seasonal variations. As such any monitoring periods must be sufficiently long to accommodate for short-term atmospheric variations.

6.4.7 A typical example of a source-dependent variation is the pollution concentration of aircraft. There may be airports with a distinct seasonal traffic (winter sports destination) or even weekend-based traffic. A typical example of a variation that corresponds with meteorological conditions is that of an airport power plant that operates at fairly regular load conditions throughout the year.

Trend analyses

6.4.8 Spatial gradient analysis uses ambient air measurements of a single pollutant made at multiple locations to identify and locate emissions sources that contribute to the measurements.

6.4.9 Time series analysis uses ambient air measurements of a single pollutant made at multiple locations to identify patterns of pollutant concentrations over time.

6.4.10 Long-term (multiple years) data collection at one location can provide information on the general trends in pollution emissions. In many areas where ongoing pollution control programmes have been in place, the long-term trend shows steady reductions in measured pollutant concentrations over time.

Source apportionment

6.4.11 Measurements at a point do not allow one to distinguish between different contributing sources unless a tracer substance can be isolated that is emitted from a specific source only. Therefore, it is important to conduct modelling in conjunction with measurements in order to estimate the contribution from individual sources or groups of sources (for example, an airport).

Handling of missing data

6.4.12 Local or national guidelines usually set forth the required conditions under which measured time series are valid. For longer-term measurements (such as annual), a maximum number of days without data is allowed when no specific action has to be taken. Gaps beyond this tolerance will lead to invalid measurement series or averaging periods. The obtained data can be used for information purposes but may not be used for legal reporting or justification for mitigation programmes. Where such guidelines allow, missing data can be inserted by ways of interpolation. In all cases, data gaps should be clearly documented.

6.4.13 Interpolation of one or several missing data points can be done by consulting a valid measurement period from a nearby station with comparable meteorological conditions and using the variation in the measurement points in a corresponding manner. In any case, any interpolated data have to be marked as such.

6.5 MEASUREMENT QUALITY ASSURANCE/QUALITY CONTROL

Quality management guidelines

6.5.1 One of the main targets in quality management is to provide confidence that the measurements are accurate to avoid criticism when communicating the results. The quality management process will help to minimize uncertainty by optimizing equipment performance as well as the technician’s capabilities. Furthermore, the monitoring results must be readily available; they must be traceable, well-identified, documented and unique in time and location.

6.5.2 There are a number of guidelines available, including, but not limited to, manufacturer specifications, local or national guidelines or international guidelines (International Standards Organization (ISO)). ISO 9001, the reference for quality management, deals with the processes for organizing the measurement information that allows for customer satisfaction. ISO 17025, based on the same quality management organization and goal as the ISO 9001 standard, and specially created for measurement activities, adds the technical capability evaluation and is much more constraining than ISO 9001.

Technical competence

6.5.3 An important factor in assuring the quality of measurements is the skill and expertise of staff performing the measurements. As such, adequate technical skills need to be acquired for all elements of air quality monitoring (equipment installation, operation, maintenance and repairs) and data handling (obtaining, storing, validating and interpreting). The minimum educational level should be defined in advance and documented.

6.5.4 In order to ensure the required level of expertise, a training schedule can be developed that includes internal and external training – for example, by the equipment manufacturer or environmental authorities. This is particularly true for complex analysis instruments with frequently changing technologies. It is recommended to document all training programmes (for example, according to ISO 9001). Training programmes have to be on a repetitive basis.

Equipment accuracy

6.5.5 The necessary (preventative) maintenance procedures including their periodicity have to be prescribed by the equipment manufacturer. Preventive maintenance must be programmed regularly for the equipment to ensure optimum performance during operation, particularly during continuous monitoring and communication of the data. Preventative maintenance could include, for example, cleaning, change of specific equipment parts, and software updates. All maintenance activities must be scheduled and documented. As well, the findings after each performed maintenance should be documented.

6.5.6 Calibration of the equipment is an important, necessary step and is done to ensure that the measurements are accurate and within the given range of the equipment. Calibration is done after regular, predefined intervals after each preventative maintenance and repair. When additional calibration equipment or substances (for example, reference gases) are used, they must be quality assured or certified (for example, expiration date on reference gases). Controlled temperature and humidity may be necessary for specific calibrations and they have to be respected. All information pertaining to the calibration of the equipment must be logged.

6.5.7 Despite all maintenance and calibrations, some uncertainty might remain. It is important to understand the magnitude of such uncertainty and the level of impact it could have on the overall measured values in order to determine the degree of fidelity of the final data. An uncertainty study could help determine the various factors and their relevance for ambient measurements and could also suggest ways to minimize the uncertainty of the data.

Data handling

6.5.8 Depending on the way of monitoring, a large volume of raw data may be compiled over time that requires specific data management. It has to be decided whether both raw and validated/processed data need to be kept, and over what period of time. A suggested way forward would be to keep the raw data for a period of at least ten years, while the processed data (validated, aggregated, etc.) could be kept for more than ten years.

6.5.9 Data storage will require a maintenance process, such as regularly recopying the data from one medium to another and at the same time cross-checking for data faults (missing, falsified). This data management process has to be documented as well.

Accreditation and certification

6.5.10 Periodical checks must be done to be sure that the management procedures are conveniently applied. Internal auditors could be recruited among the employees and trained for this activity.

6.5.11 Even if external companies have an established and maintained quality system, the customer (for example, the airport) would have to have confidence in such a system. To this end, the current minimum standard is an ISO 9001 certification label. In addition, the ISO 17025 standard is specifically adapted to the measurement activity and, as it combines quality management based on ISO 9001 guidelines with a clear focus on the technician’s capability, it is the best way to ensure customer confidence.

Appendix 1 to Chapter 6

DESCRIPTION OF SELECTED MEASUREMENT METHODS

1. ACTIVE SYSTEMS

Differential optical absorption spectroscopy (DOAS)

1.1 With the DOAS system, it is possible to obtain automatic measurements along a path with high resolution. The principle is based on the wavelength-dependent absorption of light caused by gases. The DOAS equipment includes an emitter and a receiver unit. A light beam with a wavelength between 200 nm and 700 nm is projected from the emitter to the receiver and passes to an analyser through a fibre-optic cable. In the path, specific gases will absorb light from known parts of the spectrum. This allows the analyser's computer to measure gases through a spectrometer. Within the spectrometer, a grating set splits the light stepwise into the different spectra. The resulting spectrum is now compared with a reference spectrum and the difference calculated with a polynomial fit. With additional calculations, the differential absorption spectrum and, finally, the concentration of the particular gas are determined. These single measurements are summarized to thirty-minute values. This system can be used for a range of pollutants including nitrogen dioxide, ozone and sulphur dioxide.

Tapered element oscillating microbalance (TEOM)

1.2 TEOM allows one to determine the PM_{10}-fraction of dust. The TEOM method is based on the principle that the frequency of an oscillating filter changes with increasing mass. The TEOM takes air samples of known volume, which pass through a filter on the top of the sampling unit. Here all particulate matter with a particle size larger than 10 μm are separated. The air sampling then passes through a second filter on which the particles smaller than 10 μm drop behind. The concentration of PM_{10} is calculated from the changes of the frequency of the filter-oscillation. The single measurements are summarized to thirty-minute values.

Beta-attenuation mass monitor (BAM)

1.3 BAM is a more rugged and less expensive continuous monitor for PM_{10} and $PM_{2.5}$ than TEOM. It has United States EPA certification (EFQM-0798-122) as an equivalent method to the standard method for monitoring ambient air PM_{10} and $PM_{2.5}$. The BAM method uses a stable radioactive carbon source (^{14}C, 60 uCi), and it measures attenuation of beta radiation by particulate matter deposited on a filter medium and relates the attenuation to the mass deposited on the filter. PM_{10} or $PM_{2.5}$ levels are measured separately, depending on the particle size discriminator placed before the filter collection device.

NO_X analyser

1.4 The NO_X analyser is used to measure the NO_2 concentration. The analyser takes two air samples. The first stream does not undergo any chemical reaction, while the second stream passes through a convertor that reduces NO_2 to NO. Both samples are analysed for NO in a single reaction cell, where the chemiluminescence produced by the reaction between NO and O_3 is measured. The instrument alternately measures the total NO_x and NO. The difference between the two readings results in a computed NO_2 value in the ambient air.

Condensation Particle Counter (CPC)

1.5 A condensation particle counter or CPC is a particle counter that detects and counts volatile and non-volatile particles by first enlarging them by using the particles as nucleation centres to create droplets in a supersaturated gas. The lower particle size detection limit is affected by both the CPC manufacturer design and the inlet sampling system. The upper particle size limit is determined by the inlet sampling system. Typical lower size detection limits are 4 nm to 20 nm. Typically, particle sizes of up to 3 µm are measured.

Scanning Mobility Particle Sizer (SMPS)

1.6 A scanning mobility particle sizer (SMPS) is an analytical instrument that measures the electrical mobility size and number concentration of volatile and non-volatile particles. Separate scanning hardware detect different particle size ranges. With multiple instruments, particle diameters can be measured from 2.5 nm to 1 000 nm. They employ a continuous scanning technique to provide a high resolution particle size distribution over a few minutes. The particles that are investigated can be of biological or chemical nature. The instrument can be used for air quality measurement indoors, vehicle exhaust (with appropriate sample conditioning), bioaerosols research, atmospheric studies, and toxicology testing.

O_3 analyser

1.7 In the O_3 analyser, two air samples are collected. The first one passes through a catalyst that converts O_3 to O_2. The second sample goes directly into an absorption cell (reference measurement). A detector measures the amount of ultraviolet (UV) radiation transmitted. The O_3 concentration is calculated from the two reference values. The interval of measurement is 30 minutes.

Conclusions

1.8 Automated analysers allow for the continuous, automated, online and time-resolved measurement of air pollutants, producing high-resolution measurements of hourly pollutant concentrations, or better, at a single point. The major drawback of a continuous point/optical path method, such as the DOAS method, is the high cost associated with the purchase and maintenance of the analysers. Consequently, low network density and low spatial resolution of the measurements may result. Mobile laboratories equipped with automated analysers constitute a useful application of this technique as a tool for measurement programmes covering several locations of interest.

2. PASSIVE SYSTEMS

Diffusion tubes

2.1 Diffusion tubes are the simplest and cheapest way to evaluate local air quality in terms of gaseous pollutants and can be used to give a general indication of average pollution concentrations over longer time periods ranging from a week or more. They are most commonly used for nitrogen dioxide and benzene (often with toluene, ethyl-benzene, m+p-xylene and o-xylene as BTEX), but are also useful for measuring a number of other pollutants such as 1,3-butadiene, ozone and sulphur dioxide.

2.2 Diffusion tubes generally consist of a small tube (test-tube size) normally made of stainless steel, glass or inert plastic; one end contains a pad of absorbent material and the other end is opened for a set exposure time. After exposure, the tubes are sealed and then sent to a laboratory where they are analysed using a variety of techniques including chemical, spectrographic and chromatographic processes.

2.3 It should be noted that the use of diffusion tubes is an indicative monitoring technique that does not offer the same accuracy as the more sophisticated automatic analysers. Also, since the exposure periods can be several weeks, the results cannot be compared with air quality standards and objectives based on shorter averaging periods such as hourly standards. It is not possible to detect peak events using diffusion tubes for the same reason. As a result, although diffusion tubes can be used for shorter period assessments, it is recommended that NO_2 diffusion tube monitoring, in particular, be carried out over a full year because assessments against objectives for annual mean concentrations can then be made.

2.4 Diffusion tubes can be affected by a number of parameters that may cause them to over-read, or under-read, relative to a reference measurement, and for this reason, best practice is to use three or more tubes at each monitoring point and collocating one set with an existing reference continuous monitor. This way any bias can be corrected by referring the results back to the continuous monitor (for example, chemiluminescant monitor for NO_2), and comparison between the tubes will identify any anomaly.

2.5 It is important to choose sites for diffusion tube monitoring correctly, and the area around the tube location should allow for the free circulation of air around the tubes, while avoiding areas of higher-than-usual turbulence, such as corners of buildings. Care should also be taken to avoid surfaces that may act as local absorbers for the pollutant being measured, and for this reason diffusion tubes should not be fixed directly on walls or other flat surfaces. Other localized sources or sinks such as heater flues, air-conditioning outlets and extractor vents, as well as trees and other areas of heavy vegetation, should also be avoided.

2.6 The relatively low cost of diffusion tubes means that sampling is feasible at a significant number of points over a large area, and this can be useful for identifying relative trends and also regions of high concentrations where more detailed studies can then be carried out. Under these circumstances, the cost and difficulty of using more accurate continuous monitoring to carry out the same study would almost certainly prove prohibitive.

Bags/canisters

2.7 For this measurement technique, a “whole air” sample is collected at selected measurement sites by drawing an ambient air sample into some sort of container. Most commonly, this could be a bag, glass bulb, steel “bomb” or a stainless-steel canister. Stainless-steel canisters and bags are the most common collection systems. The collection of an air sample may be enhanced with a small electric pump that actively fills the canister with the ambient air sample.

2.8 Once the gas is collected in the canister, it is analysed off-site by several different methods (including using solution chemistry). Measured ambient air components are often various hydrocarbon species.

2.9 Data quality issues usually revolve around the recovery of contaminants from the collection vessel. Recovery is a function of several parameters including the chemical nature of the contaminant, the surface properties of the vessel, the vapour pressure of the contaminant, the influence of various other compounds contained in the matrix, and the ability to start with a vessel free of contamination.

Conclusions

2.10 Passive sampling methods are simple and cost-effective methods which provide a reliable air quality analysis giving a good indication of average pollution concentrations over a period of weeks or months. Other methods include the use of bubblers for gaseous pollutants and the analysis of heavy metals contained in the suspended particulate matter filtrate.

3. OTHER METHODS

Biological indicators

3.1 Biological indicators, or bioindicators, are plant or animal species which provide information on ecological changes in site-specific conditions based on their sensitive reactions to environmental effects. Bioindicators can provide signs of impending environmental problems such as air and water pollution, soil contamination, climate change or habitat fragmentation. They can also provide information on the integrated effect of a variety of environmental stresses and their accumulative effects on the health of an organism, population, community and/or ecosystem. Lichen species are a commonly used bioindicator for air quality.

3.2 Various methods of investigating indicator species exist, and at the individual organism level the effects of bioaccumulation can be studied. At the population level, studies of morpho-physiological changes, changes in life cycles, relative health of populations, and population and community structures can all be conducted. Marking and recapturing; establishing sex and age ratios; and point, line, plot or plotless surveys of vegetation cover and plant frequencies are examples of the ecological field methods that are used.

3.3 The data obtained from traditional measurement methods make it possible to control compliance with current air quality standards and limit values. Data on ambient pollutant concentrations, however, do not allow direct conclusions to be drawn about potential impacts on humans and the environment. Evidence of harmful effects can more accurately be provided through the use of bioindicators. Bioindicators also integrate the effects of all environmental factors, including interactions with other pollutants, or climatic conditions. This makes it possible to assess the risk of complex pollutant mixtures and chronic effects that can even occur below threshold values.

3.4 The use of bioindicator plants to assess air pollution effects is not very well established. Insufficient standardization of the techniques and, consequently, the low comparability of the results is one of the major reasons for the poor acceptance of this air quality-monitoring methodology.

Appendix 2 to Chapter 6

EXAMPLES OF MEASUREMENT METHODS

Table 6-A2-1. Examples of measurement methods (from Europe and the United States)

Pollutant	Reference method	Other methods
Sulphur dioxide	Ultraviolet fluorescence	DOAS
Nitrogen dioxide and oxides of nitrogen	Chemiluminescence	DOAS
PM_{10}	Gravimetric	TEOM (advanced), beta attenuation, sticky tape (simple)
$PM_{2.5}$	Gravimetric	
Particle number (and diameter)	CPC	SMPS (incl. size)
Lead	Gravimetric	
Carbon monoxide	Gas filter correlation, non-dispersive infrared spectroscopy (EU)	
Ozone	Ultraviolet photometry	DOAS

Appendix 3 to Chapter 6

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Chapter 7

MITIGATION OPTIONS

7.1 INTRODUCTION

7.1.1 The need to set up mitigation plans with specific measures can be triggered by existing regulatory requirements for ambient air quality, particularly when standards are exceeded, or by regulations or conditions set forth in permits for airport operation and/or expansion.

7.1.2 Measures to reduce emissions from airport sources should be based upon information provided from emissions inventories and/or concentration information. As such, it is a requirement to have such information available prior to planning measures.

7.1.3 This chapter does not discuss specific contents of measures or their appropriateness. Rather, the local circumstances have to be considered when designing a mitigation plan.

7.2 MITIGATION PLANNING METHODOLOGY

Framework for emissions reduction measures

7.2.1 Emissions reduction measures typically fall into four different strategic categories: regulatory, technical, operational and economic, as described more fully in 7.3. Examples of each type of strategy are provided in Table 7-1. It is important to note that the value of these measures when applied to a specific problem has to be evaluated on a case-by-case basis, and a combination of measures may prove to be the best way forward. All measures aim at reducing, directly or indirectly, the emissions at source.

7.2.2 Regulatory measures refer to mandatory requirements stated in the laws and regulations of the relevant jurisdiction setting emissions standards and/or operation of emissions sources.

7.2.3 Technical measures refer to changes in the technology associated with the emissions characteristics of certain sources. These can be measures related to the reduction of emissions at the direct source of emissions (for example, vehicle) or it can also include infrastructure measures (for example, insulation, road layout).

7.2.4 Operational measures refer to measures that are implemented by the operator of the equipment in question, whether that be the airline, the airport authority, tenants, or any other entity.

7.2.5 Economic (market-based) measures[1] can include a number of different instruments to incorporate the environmental external costs of activity. A basic differentiation must be made under ICAO policy between taxes, which raise revenues for general governmental use, and charges, which are designed and applied to recover the costs of providing facilities and services for civil aviation.[2] Economic measures can also take the form of subsidies or allowances.

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[1] The economic measures category does not include fines assessed to violators of traditional regulatory requirements.

[2] *ICAO's Policies on Charges for Airports and Air Navigation Services* (Doc 9082); Assembly Resolution A37-18, Appendix H.

Table 7-1. Overview of emissions reduction measures (examples)

Source group	Measures			
	Regulatory	Technical (Infrastructure)	Operational[1]	Economic
Aircraft	• ICAO engine emissions standards, as adopted into States' national law • APU operating restrictions	• General airport layout • High-speed runway turn-offs • Parallel taxiways • Flow management • 400Hz/PCA at aircraft gates/stands • Sustainable aviation fuels	• Engine start-up • Scheduling improvement • Single/reduced engine taxiing • Reduced engine idling time • Aircraft towing • Reduced APU use • De-rated/reduced thrust • Engine washing • Use of alternative jet fuel • Airport-specific ATM measures, including RNAV, RNP and continuous descent operations (CDOs)	• See *Guidance on Aircraft Emissions Charges Related to Local Air Quality* (Doc 9884)[2]
Aircraft handling and support	• Motor-vehicle emissions standards for GSE (as applicable)	• Alternative-fuel GSE (CNG/LNG, LPG, electric) • Alternative-fuel fleet vehicles (CNG/LNG, LPG, electric) • Emissions reduction devices (PM filter traps, etc.) • Fuel fumes capturing systems	• Reduction of vehicle operational characteristics • Use of generators, GPUs, airstarts	• Emissions-related licensing fees • Subsidies or grants for low emission vehicles/GSE
Infrastructure and stationary sources	• Emissions standards for facilities (e.g. power plants, emergency generators)	• Low emissions energy plant, incinerator (perhaps filters) • Energy conservation measures in new construction and building maintenance • Change of fuel use • Change in stack heights and location	• Low emissions procedures for maintenance operations (painting, engine testing, cleaning) • Reduced intensity of hot fire practices	• Emission allowances
Landside access traffic	• Motor-vehicle emissions standards • Idling restrictions	• Enhanced public transit and intermodal connections • Road structure layout • Alternative fuels • Dedicated public traffic lanes	• Off-airport check-in • Preferential parking for alternative-fuel vehicles • Preferential queues for "green" taxis	• Employee rideshare/ carpooling incentives • Parking pricing and subsidies • Public transit incentives

1. Certain operational measures set forth in this table may be done on either a voluntary or regulatory basis. The laws of various States differ regarding the right of authorities at the regional and local level to require or regulate operational practices. In circumstances where an authority has legal jurisdiction, it may require an operational practice by regulation (e.g. APU operating restrictions, vehicle idling restrictions). When regulation is not permitted, emissions management efforts may consist of informal consultations, voluntary agreements, etc., encouraging the use of such practices and ascertaining the extent and environmental effect of their use. When the airport authority is the owner or operator of the emissions source of interest, it is empowered, within its legal mandates, to select and implement viable options.

2. This chapter does not address market-based measures, such as charges and taxes, related to aircraft engine emissions affecting local air quality. Such measures are addressed in Doc 9884.

7.2.6 The examples given in Table 7-1 do not indicate the effectiveness of the measures because the effectiveness will change from airport to airport, but the table does illustrate where they may be placed in the overall structure. It should be noted that the listed measures may not be desired or even applicable in every case and there are many other possible options. It should further be noted that not all measures are under the airport's control and cooperation with other entities is required.

Mitigation option requirements

7.2.7 When reviewing the applicability of various mitigation measures, an evaluation of the potential positive and negative results of implementation of those measures is recommended. The evaluation should include the following:

a) technical feasibility;

b) economic reasonableness;

c) environmental benefits; and

d) potential Interdependencies.

7.2.8 ***Technical feasibility.*** The anticipated technology should be reasonably available and robust to be used for the measure. Thus, the technology is developed and may have been already applied somewhere. It is anticipated that no, or only limited, technology research and development is needed.

7.2.9 ***Economic reasonableness.*** Decisions on measures, or combinations of them, should take into consideration an assessment of the relative cost-effectiveness of available options. The costs arising from implementing the measures chosen should be assessed and budgeted and should be reasonable for the anticipated benefits. If, on the other hand, the measures present any potential for cost-saving or even additional revenues, this should also be assessed.

7.2.10 ***Environmental benefits.*** The benefits of reduced emissions should be quantified or at least reasonably estimated for the different species and options. They should be set in relation to the overall airport emissions and their contribution to emissions in the geographical area relevant under local law or regulation. If the aim of the measures is to reduce or prevent exceedances of air quality regulatory standards, the benefits must be assessed in terms of those standards. Air quality modelling, particularly dispersion modelling of concentrations of primary (directly emitted) and secondary pollutants, may be necessary to assess the reduction in exceedances expected from different packages of measures and allow comparison to ambient air quality standards. Also, in order to assess which of the emissions sources are the most significant contributors to any particular exceedance, it may be necessary to perform source apportionment calculations with temporal and spatial allocation using an appropriate dispersion model.

7.2.11 ***Potential interdependencies.*** The measures should be evaluated for potential conflicts with other environmental priorities, such as noise reduction, as well as for any positive interrelationships that may occur.

Planning approach

7.2.12 It is recommended that a management approach (plan-do-check-act) as outlined in the following paragraphs be adopted.

7.2.13 ***Identify the problem.*** What are the emissions that need to be reduced and where are these emissions coming from? By referring to the emissions inventory with the various sources and then analysing the resulting concentration predictions from a dispersion model, a plan can be developed to address the proper emissions sources.

7.2.14 ***Define the objectives.*** What emissions-reduction targets should be achieved? An understanding of the regulatory requirements that are needed for local air quality compliance and/or project implementation must be developed.

7.2.15 ***Develop solutions.*** What are the available options for reducing emissions based on the identified problems and determined objectives? Thorough evaluation of possible mitigation strategies, based on previous mitigation option requirements, is required to determine the most appropriate way forward towards meeting the objectives.

7.2.16 ***Assess the cost-effectiveness of options.*** What is the relative cost-effectiveness of the measure, or combinations of measures, under consideration? How can the desired emissions reductions be achieved in the most cost-effective manner?

7.2.17 ***Stakeholder review.*** Is this plan acceptable to all interested parties? Developing a stakeholder review team and sponsoring public review forums is integral to a successful mitigation programme.

7.2.18 ***Implement measures.*** What happens after the plan has been accepted? Within the plan, there should be a clear outline of how and when the mitigation options will be implemented, including what is expected of all stakeholders, a series of goals to help achieve all objectives and a timeline.

7.2.19 ***Monitor/review the programme.*** Is the programme meeting expectations? It is crucial for the success of a mitigation plan to set up control procedures, including a performance metric to monitor the progress towards the desired outcome, verify success and benefits, monitor cost performance and also identify unexpected shortfalls. The results of this review could then be used to analyse the programme and provide feedback into the plan.

7.2.20 The design and development of measures are processes that include several stakeholders and not just one single party. Various measures should be evaluated and compared before any decision is taken and action triggered. To properly prepare the documentation, examples have shown the usefulness of a structured description of measures (see Table 7-2). Within a mitigation plan, measures can then be ranked by ecological benefits, costs or implementation time frames. This facilitates setting priorities for the actual implementation.

Table 7-2. Structured description of measures

Element	Content
Situation	States the baseline or the problem to be addressed (problem statement).
Goals	Describes the measure and the anticipated goals.
Responsibilities	Identifies who is responsible for the implementation (regulator, airport operator, airline, tenant).
Interfaces/partners	Describes which other partners are involved or need to be addressed.
Legal compliance	Describes the legal basis on which the measure is based (if needed) or suggests required changes to be initiated in order to achieve compliance.
Environmental benefits	Qualifies and quantifies the emissions or concentration reductions implementing this measure.
Economic costs	Quantifies the costs associated with the implementation of the measure or combination of measures (investments and operating costs) under consideration and the relative cost-effectiveness of available options, noting that there could also be cost savings associated with the measure. A TCO (total cost of ownership) approach is recommended.
Interdependencies	Describes potential trade-offs or interdependencies (emissions species – emissions species and emissions – noise) and provides options to mitigate them.
Implementation	Gives some limited guidelines on how to implement the measure.
Time frame	Sets time frames or even deadlines for implementation.
Evaluation	Gives an evaluation of the measure and a recommendation for implementation.

Appendix to Chapter 7

REFERENCES

ICAO, 2018, *Airport Planning Manual* (Doc 9184), Part II – *Land Use and Environmental Management*). Chapter 3 of Doc 9184, Part II, outlines emissions control measures that airport operators themselves, or in cooperation with aircraft operators, can employ for aircraft, ground support vehicles and airport facilities.

ICAO, 2014, *Operational Opportunities to Reduce Fuel Burn and Emissions* (Doc 10013). Doc 10013 documents practices that all aviation stakeholders can consider in order to reduce fuel consumption and the resultant emissions. The document outlines principles of fuel savings by identifying operational opportunities and techniques for reducing fuel use that in turn decrease the amount of emissions from aviation.

Chapter 8

INTERRELATIONSHIPS ASSOCIATED WITH METHODS FOR MITIGATING ENVIRONMENTAL IMPACTS

8.1 INTRODUCTION

8.1.1 When analysing methods for mitigating the environmental impacts of aviation, and aircraft operations in particular, it is important to note that there can be many interrelationships between environmental impacts and other factors, such as the effects on airspace and runway capacity, the use of airspace and the way that it is managed at different airports. As a result, such mitigation methods require careful evaluation to assess the results of changes to operating practices before operational or regulatory decisions are made.

8.1.2 Although Chapter 7 discusses mitigation options for a number of different source categories, and interrelationships do exist for non-aircraft sources affecting, for example, noise, carbon dioxide/greenhouse gases, NO_x, particulate and other emissions, these interdependencies are not discussed further in this chapter, which concentrates solely on aircraft operations. Furthermore, because this document deals with guidance related to local air quality at and around airports, this chapter does not address interrelationships resulting from en route phases of flight but instead concentrates on those affecting aircraft operations at lower levels (typically below 3 000 ft (914 m)) in the operational LTO flight cycle detailed in Chapter 2.

8.1.3 Some operational techniques have the potential to offer improvements in noise, fuel burn/CO_2, NO_x, particulate matter and other emissions with no significant trade-offs. An example of this is enabling continuous descent operations (CDO) where noise, local emissions (with the possible exception of CO and HC emissions) and fuel burn/CO_2 emissions are all reduced to a greater or lesser extent, although this may have an impact on capacity at busy airports depending on the way that airspace, separation and other factors are managed. However, most operational mitigation techniques exhibit interrelationships and require trade-offs to be made against one or more factors.

8.2 RECOMMENDATIONS FOR EVALUATING INTERDEPENDENCIES

8.2.1 The identification and calculation of environmental impacts and interrelationships often requires complicated modelling of effects that can be done only in conjunction with inputs provided by the sophisticated models available to aircraft and engine manufacturers and other expert groups in this field. In order to correctly define the environmental impacts, where interdependencies are involved, fuel burn calculations in particular need to be carried out to a common point along the flight profile. This is important; otherwise, differences may be derived that are not a true reflection of the overall case.

8.2.2 It is important to involve all relevant stakeholders: aircraft and airport operators, aircraft and engine manufacturers, airports, air navigation service providers (ANSPs), policymakers and regulators, in the assessment process as early as possible.

8.2.3 The following sections identify a number of examples of interrelationships that exist in the ground operations, departure and arrival phases, respectively. However, they are not meant to be either definitive or comprehensive, nor should they be seen as advocating any particular mitigation option. These examples are, however, meant to provide a practical guide to the types of interrelationships that exist for certain practices and should be seen as a subset of all those that exist in real day-to-day operations.

8.3 OPERATIONAL INTERRELATIONSHIPS FOR GROUND OPERATIONS

8.3.1 A number of different practices are available for use during ground operations, though there can be some complex interrelationships and unexpected effects on other parts of the flight cycle by following some of the practices described. Though the safety risks of utilizing different techniques are lower on the ground than in the air, for safety reasons, loss of systems or the implications of foreign object damage (FOD) or jet blast can restrict what is possible. The non-environmental operational impacts on short turnaround times and capacity at some airports for some types of operations can be more affected by different techniques than from differences in airborne procedures.

8.3.2 Some examples of the effects of different techniques/procedures for ground operations and their environmental impact on noise, fuel/CO_2 and NO_x (LAQ) are given in Table 8-1. Other emissions species, such as particulate matter, CO and HC, may be added at a later date when more information becomes available.

Table 8-1. Environmental interrelationships for ground operations

	Environmental impact on:			
Technique	Noise	Fuel/CO_2	NO_x (LAQ)	Comments
Use of fixed sources of power and pre-conditioned air, over APUs	Ramp noise reduced, ground noise reduced	Reduced	Reduced	Potential adverse impact on short turnaround times, especially when PCA is employed.
Taxi-in with less than all-engines operating	Potentially reduced, though may be masked by increased power from remaining operating engines	Reduced, though will be affected by any increased power requirement for operating engines	Reduced, though will be affected by any increased power requirement for operating engines	A number of safety concerns have to be addressed before this can be carried out. Operational requirements may mean the APU has to be operating, which will reduce the benefits, and there may be other operational considerations.
Taxi-out with less than all-engines operating	Potentially reduced, though may be masked by increased power from remaining operating engines	Reduced, though will be affected by any increased power requirement for operating engines	Reduced, though will be affected by any increased power requirement for operating engines	A larger number of safety concerns have to be addressed before this can be carried out. Operational requirements may mean the APU has to be operating, which will reduce the benefits, and there may be other operational considerations. There are also greater safety and operational constraints for this practice than there are for taxi-in.
Towing aircraft	Reduced	Reduced	Potentially reduced, but depends upon technology standard of the aircraft tug	Taxiway congestion may be a big issue at some airports. Also nose-wheel leg strength requirements may not be met for some aircraft. FOD instances will be reduced. Fire cover at start-up areas may be an issue, and for some aircraft, specialist tugs will need to be available.
Ground holding	Increased (Note)	Increased (Note)	Increased (Note)	Sometimes required to ensure the efficient use of the runway where this provides the limiting factor on capacity, so reduced ground holding may have an impact on capacity.

Note.— Although noise, fuel/CO_2 and NO_x emissions will be increased relative to no holding, they will be lower than the alternative of holding in the air – see 8.5.6.

The use of auxiliary power units

8.3.3 It is normally beneficial to restrict the use of aircraft-based APUs if alternative supply sources are available at the gate/stand. However, for safety reasons, some of the alternatives listed in Table 8-1 require the APU to power, or provide the required redundancy back-up to, certain systems to allow the technique described to be performed. If this technique is followed then it will inevitably have an impact (increase) on the use of the APU at the gate, and therefore the environmental impacts of some of these interrelationships are themselves connected. In this case, the pros and cons for the whole operational cycle need to be carefully analysed to identify what is best practice for reducing the environmental impacts of the total cycle. Note that this may result in different practices for different aircraft types at different aerodromes.

8.4 OPERATIONAL INTERRELATIONSHIPS FOR DEPARTURES

8.4.1 The take-off phase can be complex, with a number of segments, involving changes to speed, aircraft configuration and engine power setting. There are also a number of parameters that can be changed to alter the impacts of noise, fuel burn and emissions and, as well, have an impact on maintenance costs and airspace use, which all further add to the complexity of this phase.

8.4.2 Some examples of the effects of take-off and climb techniques/procedures and their environmental impact on noise, fuel/CO_2 and NO_x (LAQ) are given in Table 8-2.

The importance of performance-limited take-off weight (PLTOW)

8.4.3 The performance limited take-off weight (PLTOW) for any particular operation is the maximum weight that can be used for the conditions prevailing at the time, limited only by runway declared lengths and climb requirement considerations – that is, ignoring any limiting constraints from the certificated structural weights, including maximum take-off weight (MTOW) and maximum landing weight (MLW).

8.4.4 Most operational techniques that affect the take-off configuration of the aircraft have an impact on the PLTOW for any particular runway and meteorological condition. Changes to any of the runway length characteristics used, for example by selecting an intermediate start point for take-off or reductions to declared distances due to work in progress, can also have an impact on the PLTOW.

8.4.5 The PLTOW is an important parameter for the evaluation of the impact of NO_x emissions because the difference between the aircraft's actual take-off weight and the PLTOW very much determines the maximum amount of thrust reduction that is available for use during the take-off. This is largely due to the relationship between NO_x emissions and the actual take-off power used, affecting the amount of NO_x emitted (increases in power can result in significantly more NO_x production). It should be noted, however, that the same is not necessarily true for CO and HC emissions where lower powers can have a slightly negative impact.

8.4.6 On the other hand, increases in power will generally increase the noise levels for the ground roll and close to the airport. Once airborne, the effects of increased distance above the runway due to the higher gradient of climb will normally offset any increases in source noise, and noise levels under the flight path are generally reduced.

8.4.7 The effects on fuel burn and carbon dioxide emissions will be slight and may be either positive or negative depending on the individual circumstances and the aircraft type under consideration. As a result, they will have to be assessed for each individual circumstance.

Table 8-2. Environmental impacts of different departure techniques

	Environmental impact on:			
Technique	Noise	Fuel/CO_2	NO_x (LAQ)	Comments
Increase take-off power	Noise under flight path reduced, but footprint area can be increased	Slightly reduced or increased (Note 1)	NO_x increases with power setting	Adverse impact on engine maintenance costs (Note 2).
Reduce take-off flap setting	Reduced noise if lift-to-drag ratio improved – dependent on aircraft and runway characteristics	May be slightly reduced	May increase or decrease (Note 3)	Potential implication for tail-strike for some types under certain conditions (Note 4).
Reduce acceleration altitude	Noise increased after point of acceleration altitude, but may be reduced further out	Reduced	Little or no difference (Note 5)	Actual differences depend upon the difference in selected acceleration altitude versus standard airline practice (Note 4).
Delay flap retraction altitude in the climb	Noise reduced closer to airport, but increased further out	Increased	Little or no difference (Note 5)	(Note 4)
Increase cut-back altitude	Noise increased at some distances close to airport, but reduced further out	Slight increase or reduction depending on flap retraction schedule	Little or no difference (Note 5)	(Note 4)
Acceleration climb segment sequence (reduce power, retract flaps then accelerate)	Reduced noise under flight path after normal acceleration point	Increased	Little or no difference (Note 5)	Aircraft operating in a high-drag configuration with low power setting may concern safety regulators (Note 4).
Increase V speeds (VR, V2 and climb speeds)	Noise slightly increased close to airport, but reduced further out	Little difference – slightly increased	May increase or decrease (Note 3)	Not applicable to some aircraft types and some operators depending on standard take-off techniques. Also depends on take-off performance limitations (Note 4).
Increase climb power settings	Noise increased after cut-back closer to the airport, but reduced further out	Little difference – slightly reduced	Little or no difference (Note 5)	Adverse impact on engine maintenance costs (Note 4).
Novel power management systems (e.g. FMS "managed noise")	Reduced at specific points identified as noise sensitive	Dependent on procedure, aircraft, noise receptor and airport characteristics	Little or no difference (Note 5)	Currently feasible only with new-generation FMS in new aircraft types, e.g. A380, B787, A350.
Noise-preferential routes (NPR)	Reduced impact on populations close to airport	Normally increased due to additional track-miles flown and low-level turn requirements	Small increase depending on NPR design (Note 5)	NPRs are designed to avoid areas of high population density, so noise-impacted populations should be smaller; however, total noise emitted may be greater.
Noise-preferential runway use	Reduced impact on populations close to airport	Increase or decrease depending on individual airport design and local circumstances	Increase or decrease depending on individual airport design and local circumstances	Noise-preferential runway use is designed to avoid areas of high population density, so noise-impacted populations should be smaller. However, total noise emitted may be greater.

Notes.—

1. Although fuel flow is greater at the higher power setting, the time at that setting will be reduced, which results in slight differences that can be either positive or negative and will not be the same for all emissions.
2. Current legal constraints preclude noise abatement departure procedures (NADPs) to be applied below 800 ft AAL (ICAO 2006).
3. PLTOW (see 8.4.3 to 8.4.7) will be affected, which will in turn influence the take-off thrust setting and NO_x emissions produced.
4. Will have an impact on flight path and speeds flown, so ATC will need to be aware of the implications of these procedures to ensure safe and efficient flow management. May also have an impact on adherence to NPRs with low-level turn requirements.
5. Differences to emissions above 1 000 ft AGL will have little impact on changes in ground-level concentrations.

8.5 OPERATIONAL INTERRELATIONSHIPS FOR ARRIVALS

8.5.1 Unlike departures, most arrival techniques involve few or no trade-offs to be made between different environmental impacts. However, there may well be impacts on other non-environmentally related parameters, especially when considering the way that airspace is managed. Additionally, these may require the installation of specific equipment or navigation aids to facilitate the descent and approach flight path and may also be subject to specific regulatory policy which may slow down their adoption.

8.5.2 Some examples of the effects of different arrival techniques/procedures and their environmental impact on noise, fuel/CO_2 and NO_x (LAQ) are given in Table 8-3.

Table 8-3. Environmental impacts of different approach techniques

	Environmental impact on:			
Technique	Noise	Fuel/CO_2	NO_x (LAQ)	Comments
Continuous descent operations (CDO)[1]	Reductions prior to joining the ILS glideslope	Reduced	Little or no difference (Note 1)	Procedures need to be agreed and established first. The greatest benefit will occur when initiated at higher altitudes with more advanced navigation equipment. May impact capacity (Note 2).
Tailored arrivals[2]	Reductions prior to joining the ILS glideslope	Reduced	Little or no difference (Note 1)	Similar to CDO but tailored to a specific flight through integration of all known aircraft performance, air traffic, airspace, meteorological, obstacle clearance and environmental constraints expected to be encountered during the arrival.
Low power/low drag (LP/LD)	Reductions closer to the runway threshold	Reduced (Note 3)	Slight reduction (Note 3)	ICAO stabilized approach criteria may act as a constraint for some types at some aerodromes. May impact flow rates with different aircraft speed requirements (Note 2, Note 4).
Curved approach	Reduced impact on populations close to the airport; however, total noise emitted may be greater	Can be increased dependent on difference in track miles	Little or no difference (Note 1)	Procedures need to be agreed and established first. More advanced navigation equipment may be required to assist with flight path control (Note 4).
Displaced touchdown point	Reduced – greater reductions closer to the airport boundary	No difference (Note 3)	Reductions for impacted areas outside the airport (Note 3)	Applications may also be limited by local runway impact load bearing characteristics (Note 2, Note 4).

Notes.—

1. Differences to emissions above 1 000 ft AGL will have little impact to changes in ground level concentrations.
2. Safety considerations may preclude reductions to flap settings if the runway is short, wet or contaminated.
3. Increased application of reverse thrust as a result of this technique may compromise any improvements resulting from this technique.
4. May require specially modified aircraft and changes to, or additional, ground equipment.

Reverse thrust considerations

8.5.3 Reverse thrust is not generally required for normal operations onto a dry runway, although its availability is a prudent safety precaution. As a result, on landing, reverse idle is almost universally selected when performance or other

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[1] EUROCONTROL, *Continuous Descent Approach – Implementation Guidance Information*, EUROCONTROL, May 2008.

[2] R. Mead, *Tailored Arrivals Overview*, Boeing, 2007 .

considerations (for example, runway surface state) do not dictate that higher reverse power settings are required. A number of arrival techniques can result in an increased operational requirement for reverse thrust, including increasing runway capacity by reducing runway occupancy time.

8.5.4 It is normally possible to use increased wheel braking instead of reverse thrust, which will result in reduced noise and emissions from the engines (although PM emissions may increase) and reduced costs of fuel burn. However, the costs of increased brake and tire wear associated with this technique have to be taken into consideration.[3] In addition, although not the focus of this document, brake and tire wear can create significant local concentrations of particulates when compared to aircraft engines, and these should be taken into account when analysing the local air quality impacts of aircraft operations when increased use of wheel braking is proposed.

A note about holding

8.5.5 Holding may be required at an airport for a number of reasons, for example, to ensure the efficient use of the runway where this provides the limiting factor on capacity. In this case, holding in the air is required to provide a "reservoir" of aircraft to feed the arrivals stream, and holding on the ground ensures that the departure flow rates off the runway are always maximized.

8.5.6 For single runways, or mixed-mode operations, there can be a conflict between aircraft waiting to take off and those in the air waiting to land, especially at busy times of the day or when the airport is operating at, or close to, capacity. In this case, although it is always beneficial to reduce holding times as much as possible, when holding is inevitable, then there are clear trade-offs to be made:

a) Ground-level holding minimizes holding noise and fuel/CO_2 emissions and, for this reason, it is always far better to hold the departures on the ground and clear the arrival holds. However, the impacts on local air quality will be maximized as a result.

b) Airborne holding is not really relevant to ground-level air quality because it is carried out at levels well above 1 000 ft, where the impacts on local air quality will be minimal, if they exist at all, but the impacts on holding noise and fuel/CO_2 emissions will be greatly increased.

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[3] ICAO, *Operational Opportunities to Reduce Fuel Burn and Emissions* (Doc 10013), International Civil Aviation Organization, 2014.

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