Doc 9889

Airport Air Quality Manual

Approved by the Secretary General
and published under his authority

First Edition — 2011

International Civil Aviation Organization

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FOREWORD

1. 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.

2. There are potential emissions source issues relevant to but not covered in this manual (e.g. forward speed effects of aircraft, influence of ambient conditions on aircraft emissions, aircraft start-up emissions, aircraft 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.

3. This first edition of the manual includes chapters on the regulatory framework and drivers for local air quality measures; emissions inventory practices and emissions temporal and spatial distribution; completed emissions inventory (including a detailed sophisticated aircraft emissions calculation approach); dispersion modelling; airport measurements; mitigation options; and interrelationships associated with methods for mitigating environmental impacts. Throughout the document, additional references are provided for those interested in exploring these topics in further detail.

4. 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:

The Secretary General
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Canada

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.

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 cycle (LTO). LTO consists 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.

ACRONYMS AND ABBREVIATIONS

AAL	Above aerodrome level
ACARE	Advisory Council for Aeronautics Research in Europe
ACU	Air climate unit
ADAECAM	Advanced aircraft emission calculation method
AFR	Air-fuel ratio
AGL	Above ground level
AMSL	Above mean sea level
ANSP	Air navigation service provider
APMA	Air pollution in the megacities of Asia
APU	Auxiliary power unit
ARFF	Airport rescue and fire fighting
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 (U.S.)
CAEP	Committee on Aviation Environmental Protection
CDO	Continuous descent operations
CERC	Cambridge Environmental Research Consultants (U.K.)
CH_4	Methane
CI	Carbon index
CNG	Compressed natural gas (carburant)
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Double annular combustor
DEFRA	Department for Environment, Food and Rural Affairs (U.K.)
DfT	Department for Transport (U.K.)
DOAS	Differential optical absorption spectroscopy
DOT	Department of Transportation (U.S.)
ECS	Environmental control system
EDMS	Emission and Dispersion Modelling System (U.S. FAA)
EEDB	Engine Emissions Data Bank (ICAO)
EGT	Exhaust gas temperature
EI	Emission index
EPA	Environmental Protection Agency (U.S.)
ETFMS	Enhanced tactical flow management system (Eurocontrol)
ETMS	Enhanced traffic management system (U.S.)
EU	European Union
FAA	Federal Aviation Administration (U.S.)
FAF	Final approach fix

FBO	Fixed-based operator
FDR	Flight data recorder
FES	Fixed energy system
FESG	ICAO CAEP Forecasting and Economics Sub-group
FIRE	Factor Information Retrieval Data System (U.S. EPA)
FOA	First Order Approximation
FOCA	Federal Office for Civil Aviation (Switzerland)
FOD	Foreign object damage
FOI	Swedish Defence Research Agency
FSC	Fuel sulphur contents
g	Gram
GE	General Electric
GIS	Geographical information system
GPU	Ground power unit
GSE	Ground support equipment
GUI	Graphical user interface
h	Hour
HAP	Hazardous air pollutant
HC	Hydrocarbon
HDV	Heavy-duty vehicle (e.g. truck, bus)
hp	Horsepower
Hz	Hertz
IAE	International Aero Engines
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industry Associations
IOAG	International Official Airline Guide
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
kg	Kilogram
km	Kilometre
kN	Kilonewton
kt	Knot
KVA	Kilovolt ampere
kW	Kilowatt
LASAT	Lagrangian simulation of aerosol — transport
LASPORT	LASAT for Airports (Europe)
LDV	Light-duty vehicle (e.g. delivery vans)
LPG	Liquefied petroleum gas
LTO	Landing and take-off
m	Metre
MCLT	Maximum climb-limited thrust
MES	Main engine start
min	Minute
MSDS	Material safety data sheet
NAAQS	National Ambient Air Quality Standards (U.S.)
NASA	National Aeronautics and Space Administration (U.S.)
NGGIP	National Greenhouse Gas Inventories Programme
NMHC	Non-methane hydrocarbons
NMVOC	Non-methane volatile organic compounds
NO	Nitrogen monoxide
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
NPR	Noise-preferential route

O_3	Ozone
OPR	Overall pressure ratio
Pb	Lead
PBL	Planetary boundary layer
PCA	Pre-conditioned air (for cooling/heating of parked aircraft)
PLTOW	Performance-limited take-off weight
PM	Particulate matter
$PM_{2.5}$	Particulate matter with an aerodynamic diameter of 2.5 micrometres or less
PM_{10}	Particulate matter with an aerodynamic diameter of 10 micrometres or less
POV	Privately owned vehicle
PPM	Parts per million
P&W	Pratt & Whitney
RR	Rolls Royce
s	Second
SAE	Society of Automotive Engineers
SAEFL	Swiss Agency for Environment, Forests and Landscape
SHP	Shaft horsepower
SN	Smoke number
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
TAF	Terminal area forecasts (U.S.)
TEOM	Tapered Element Oscillating Microbalance
TIM	Time-in-mode
TOW	Take-off weight
UID	Unique identifier
U.K.	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention for Climate Change
U.S.	United States
$\mu g/m^3$	Micrograms per cubic metre
V	Volt
VMT	Vehicle-miles travelled
VOC	Volatile organic compounds
WHO	World Health Organization

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 Control*
  Part 3 — *Guidelines for Consultant/Construction Services*

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

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

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

Circulars

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

Operational Opportunities to Minimize Fuel Use and Reduce Emissions (Cir 303)

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 www.caa.co.uk/.

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 Because 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 some, or many, of the processes and measures in place that are addressed in this guidance material. In such cases, this guidance material 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 gaseous exhaust emissions from jet engines: hydrocarbons (HC), nitrogen oxides (NO_x) and carbon monoxide (CO). Specifically, they set limits on the amounts of smoke and gaseous emissions of these three pollutants in the exhaust of most civil engine types. In addition to technological innovation and certification standards, CAEP also has pursued two other potential approaches for addressing aviation emissions:

a) alternative airfield operational measures; and

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

1.2.2 ICAO also has produced several documents related to aircraft emissions including Doc 9184 and Cir 303.

1.2.3 Doc 9184, Part 2 — *Land Use and Environmental Control* 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 Circular 303 identifies and reviews various operational opportunities and techniques for minimizing aircraft engine fuel consumption and, therefore, emissions associated with civil aviation operations. The information contained in Circular 303 is currently being updated and it will eventually be issued as an ICAO manual.

1.2.5 In the context described previously, CAEP established that there was a complementary need to develop guidance material to help States implement best practices related to assessing airport-related air quality, which is the purpose of this manual.

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. For example, 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 two 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 U.S.). 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.

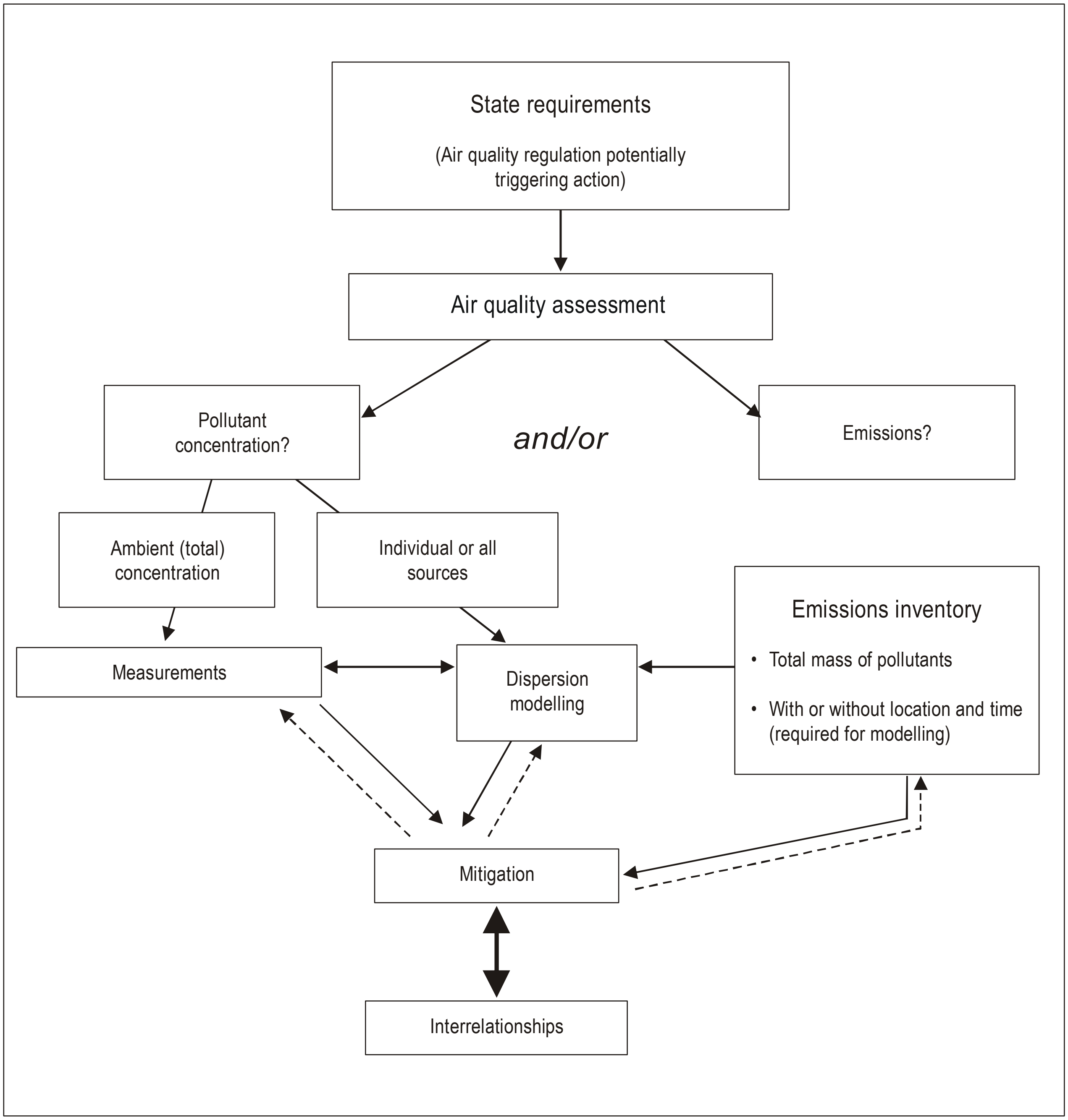

Figure 1-1. Local air quality elements and their interactions

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, mitigation planning, and can be used as input for modelling pollution concentrations. 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.

1.4.3 Existing pollution concentrations can also be assessed by measuring (e.g. 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 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, i.e. man-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 potential 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 (e.g. 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 Local air quality regulations have, since their very inception, been based around the need to protect public health and the natural environment. Early examples of local air quality regulations include the 1881 local air quality controls in Chicago and Cincinnati. These initial regulations focused on the most visible of fuel and waste combustion products, namely smoke and particulates. By the mid-20th century, regulation of emissions to reduce smoke moved from the local to the national level with the introduction of national air quality laws in the USSR (1949), the U.S. (1955) and the U.K. (1956).

2.2.2 In the case of the U.K.'s 1956 regulations, the Great Smog of 1952 was the driver for legislative action along with a significant rise in the death rate of people suffering from respiratory and cardiovascular diseases associated with this event. The resultant 1956 Clean Air Act focused its attention on reducing smoke pollution associated with industrial sources.

2.2.3 In the U.S., the 1955 Air Pollution Control Act was just the beginning of a series of measures taken to improve local air quality, affecting a broad range of industries. Major revisions in 1963 evolved into the "Clean Air Act", with additional regulations covering long-range transport, power generation and a variety of industrial activities. At the same time, the federal government established the U.S. Environmental Protection Agency (U.S. EPA), and in 1971 the National Ambient Air Quality Standards (NAAQS) were introduced. The NAAQS established air quality regulations on a national level covering six pollutants[1] and stipulating that the standards had to be met by 1975. In 1990, extensive amendments to the Clean Air Act significantly tightened these requirements.

2.2.4 These legal requirements, established for the protection of public health and the environment, created a driver for action by many industries (including aviation) and the need to comply with the regulations. In some cases, air quality compliance in environmental impact statements and assessments became a required consideration in development initiatives.

2.2.5 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 and, where appropriate, to attempt to meet those expectations.

2.2.6 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).

2.2.7 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 915 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 vary 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.

2.2.8 Finally, it is worth noting that aircraft engine technology has reached a stage where there are fewer developments which reduce both noise and emissions together. With the continuing drive to reduce aircraft environmental

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[1] Carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), particulate matter, ozone and sulphur dioxide (SO_2). Particulate matter is subdivided into particulates less than or equal to 10 microns (PM_{10}) and PM less than or equal to 2.5 microns ($PM_{2.5}$).

impacts, there are expanding needs to assess the trade-offs between reducing noise and emissions and the effect on greenhouse gas emissions (amongst these emissions is carbon dioxide (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 as well as the secondary pollutants that these emissions may form. 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 U.S. place on NO_2, NO_x and O_3, with many EU States more concerned with NO_2 concentrations and the U.S. 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, 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 ($\mu g/m^3$) and for a specified time frame (usually hour, day or year) by pollutant.

2.3.3 Importantly, Table 2-1 is a snapshot of States' air quality regulations in 2005, and it should be noted that the regulations may periodically change. A brief examination of the table shows that the regulations vary by country and may be more or less strict than the WHO guidelines. For example, in the case of NO_2, over an hourly period the WHO guideline is 200 $\mu g/m^3$ but the variation for this pollutant is from 75 to 400 $\mu g/m^3$. For particulate matter equal to or less than 10 microns (PM_{10}), there is no WHO guideline, but regulations vary from 50 to150 $\mu g/m^3$ over a 24-hour period. By contrast, for O_3 there is no hourly or 24-hour WHO guideline, but there is an 8-hour guideline of 120 $\mu g/m^3$, with national regulations varying from 120 to 160 $\mu g/m^3$.

2.3.4 The ability to conform to these national 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 1 hour, 8 hours, 24 hours or a year.

2.3.5 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.

2.3.6 In response to the recommendations of Agenda 21[2] of the United Nations (UN) Plan of Implementation of the 2002 World Summit on Sustainable Development, the Strategic Framework was set up. This Strategic Framework for Air Quality Management in Asia aims to provide a regional approach to improving urban local air quality by facilitating the setting of local air quality priorities and providing direction on institutional development and capacity enhancement. The Strategic Framework is being proposed by the Air Pollution in the Megacities of Asia (APMA) project and the Clean Air Initiative for Asian Cities. APMA is a joint project of the UN Environment Programme, the WHO, the Stockholm Environment Institute and the Korea Environment Institute. APMA covers the megacities in Asia, defined as those with a population of more than ten million.[3] This Strategic Framework recommends the use of the WHO Air Quality Guidelines for the setting of standards and averaging times.

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[2] Agenda 21: Earth Summit — The United Nations Programme of Action from Rio, April 1993, ISBN: 9211005094.

[3] Bangkok, Beijing, Calcutta, Chongqing, Guangzhou, Hong Kong, Kathmandu, Manila, Mumbai, New Delhi, Osaka, Seoul, Shanghai, Singapore, Taipei, and Tokyo.

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

Country/ Organization	Pollutant (averaging period)	Sulphur dioxide			Nitrogen dioxide			Carbon monoxide		Ozone			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
		$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$	$\mu g/m^3$
WHO	WHO Guidelines	—	125	—	200	—	40–50	30	10	—	120	—	—	—
EU	Air Quality Framework Directive	350	125	20	200	—	40	—	10	—	120	—	50	40
Australia	National Environmental Protection Measure for Ambient Air Quality	520	200	50	220	—	50	—	10	200	—	—	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	National Ambient Air Quality Objectives, Canadian Environmental Protection Act, June 2000	900	300	60	400	200	100	35	15	160	—	50		
China	Ambient Air Quality Regulations GB3095 — 1996	500	150	50	150	100	50	10	—	160	—	—	150	100
India	G.S.R.6(E), [21/12/1983] — The Air (Prevention and Control of Pollution) (Union Territories) Rules, 1983	—	80	60	—	80	60	4	2	—	—	—	100	60
Japan	Ministry of the Environment Environmental Quality Standards	260	100	—	75–110	—	—	12	23	120	—	—	—	—
South Africa	SANS 1929 Guidelines**	—	125	50	200	—	40	30	10	200	120	—	75	40
Switzerland	Swiss Luftreinhalteverordnung (LRV)	—	100	30	—	80	30	—	—	120	—	—	50	20
U.S.A	NAAQS		360	80	—	—	100	40	10	240	160	—	150	50

$\mu g/m^3$ = micrograms per cubic metre.

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

** The South African Air Quality Standard (SANS 1929) was published in October 2004 ahead of a new Air Quality Act. At the moment, it is not known how it will be incorporated into the Act and how it will be applied.

2.3.7 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.

2.3.8 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.

2.3.9 For example, in the U.K., although the government is committed to the mandatory EU local air quality regulations, it has also set national objectives in its Air Quality Strategy. These targets have a different legal status from the EU Limit Values, but they form part of a joint Department for Transport/Department for Environment, Food, and Rural Affairs (DfT/DEFRA) Public Service agreement and help underpin decisions on the future development of aviation in the U.K.

2.3.10 Since December 1997 each local authority in the U.K. has been carrying out a review and assessment programme of local air quality in its area. This involves measuring air pollution and trying to predict how it will change in the next few years. The aim of the work is to ensure that the National Air Quality Objectives are achieved throughout the U.K. These Objectives have been put in place to protect human health and the natural environment. If a local authority identifies any areas where the Objectives are not likely to be achieved, it must declare an Air Quality Management Area there. This area could be just one or two streets or it could be much bigger. The local authority can then form a Local Air Quality Action Plan to improve the local air quality.

2.3.11 Within the EU, local air quality is also regulated by the Framework Directive 96/62/EC[4] on local air quality assessment and management. Daughter Directives then develop the stringencies and provide further detail where it is needed. The Daughter Directive relevant to local air quality at airports is 99/30/EC,[5] which covers SO_2, NO_2 and NO_x, PM_{10} and Pb. These EU Directives are in line with the WHO recommendations for Europe.[6]

2.3.12 Historically, many of the existing large hub airports have evolved from smaller airfields so that their positioning and the proximity of urban/residential areas have been difficult to manage. For example, in Hong Kong, the old Kai Tak Airport, which had an extremely challenging approach over densely populated areas, has been replaced by an entirely new facility. The new Hong Kong International Airport has been deliberately built away from main centres of population so that aircraft do not have to take off and land over densely populated urban areas, and the new night-time approaches are over water rather than over centres of population. This has a benefit from both a noise and local emissions perspective, although in the particular case of Hong Kong, the Advisory Council for the Environment did not find a connection between the relocation of the airport and local air quality.[7] Where regions have the space or perhaps geography to accommodate such planning and can subsequently prevent encroachment by incompatible development, it is clearly beneficial. Further local emissions reductions have been made by building an extensive public transport network so that road vehicles need not be the primary method of airport access for the travelling public.

2.3.13 The U.S. EPA regulates local air quality through the Clean Air Act and the NAAQS, as previously discussed. Areas which have pollutant concentrations that exceed the NAAQS, or contribute to an exceedance of the standards in a neighbouring area, are designated as a non-attainment area. Air quality monitoring is used to determine compliance with the NAAQS and establish the geographic limits of these non-attainment areas.

2.3.14 The consequence of non-attainment is that States must submit State Implementation Plans (SIP) identifying specific measures for improving local air quality and achieving attainment of the NAAQS. Regulated entities within the non-attainment area, as well as land-use and transportation planning authorities, must then adhere to the SIP. Failure to do so incurs sanctions imposed by the U.S. EPA, usually in terms of civil penalties and/or in the form of a ban on further development and building of a particular new emissions source.

2.3.15 In addition to PM_{10}, the U.S. EPA also has an NAAQS regulating particulate matter equal to or less than 2.5 microns ($PM_{2.5}$). The $PM_{2.5}$ regulations are for a 24-hour period and annual mean time periods. The regulations allow

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4. Council Directive 96/62/EC of 27 September 1996 on ambient air quality assessment and management (OJ L 296, 21.11.1996, pp. 55–63).

5. Council Directive 99/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air.

6. *Air Quality Guidelines for Europe,* 2nd Edition, WHO Regional Publications, European Series, No. 91.

7. ACE Paper 25/2004*, Impact of Aircraft Emissions on Air Quality.*

only one exceedance of the 24-hour standard in a calendar year and no exceedance of the annual standard. Notably, at the time of the introduction of the $PM_{2.5}$ regulation there were more commercial service airports in $PM_{2.5}$ non-attainment areas (e.g. 53, not including general aviation or military airports) than there were in PM_{10} non-attainment areas (e.g. 38).

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 (e.g. boilers, generators, incinerators) and road vehicles; and

b) ***National regulations*** (in some States called "standards") establishing ambient pollutant concentrations for local air quality conditions (e.g. local air quality limit values).

2.4.2 This distinction 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 continue to be a relatively small contributor to regional pollution although 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 which 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 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 and smoke for a reference landing and take-off (LTO) cycle up to 915 m (3 000 ft) in height above the runway.

2.4.5 Presently, there is no ICAO standard for aircraft engine PM, though many national regulatory schemes contain ambient limits for that pollutant. Until recently, there was also no reliable and repeatable way to measure PM emissions from aircraft engines, but research on this subject is now ongoing. Finally, there are no ICAO standards applicable to any emissions from turboprop, piston engine and helicopter aircraft or smaller business jets.

2.4.6 The ICAO aircraft engine 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, with a production cut-off of 31 December 1999. In 1999,[8] ICAO tightened the NO_x

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[8] Percentage reductions quoted refer to reductions at an engine OPR of 30. Reductions at other engine OPR may vary from these values.

standard by about 16 per cent on average for engines newly certified from 31 December 2003. In October 2004, the ICAO Council ratified the CAEP decision for a further tightening of the NO_x standard so that the standard, which became effective in 2008, is now 12 per cent more stringent than the levels agreed in 1999. For the engines to which they apply, the combined effect of these changes is a 40 per cent tightening of the original ICAO NO_x emissions standards.

2.4.7 As a result, the emissions certification regime has gradually become more stringent, and engine manufacturers have greatly improved the average margin to the ICAO standards. However, the tendency towards the more efficient higher OPR engines means that absolute NO_x emissions from an updated fleet may not decrease by the same percentage as the change in the ICAO NO_x standard.

2.4.8 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 standard. 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 (e.g. there is no requirement for an emissions check after engine maintenance/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.

2.4.9 There are also ICAO standards regarding the reduction of smoke to non-visible levels, again using manufacturer demonstration by type testing described previously. ICAO standards also require that fuel not be vented from the main propulsion engines during normal engine shutdown. At present there are no ICAO standards related to aircraft APU.

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 is 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 the engine performance characteristics alone (e.g. in grams per kilowatt-hour). This is 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[9] 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 Ground support equipment 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 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.

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[9] The "New European Drive Cycle".

2.4.13 Hence, while aircraft, road vehicles and airside vehicles are regulated using specified procedures (e.g. 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 to 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. The reduction of the EU NO_2 limit values from 200 $\mu g/m^3$ in 1985[10] to 40 $\mu g/m^3$ in 1999,[11] along with further subsequent reductions enabled in the EU Daughter Directive 99/30/EC, are examples. In 99/30/EC, the annually averaged NO_2 limit of 40 $\mu g/m^3$ had a 50 per cent margin of tolerance when it was introduced in 2001 and then reducing annually by equal percentages to a margin of zero by 2010, so that the stringency gradually increases over the ten-year period. Given the continued expansion of most industry sectors, technological improvements to airport-related emissions sources must be made if these 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 U.S. are two examples.

2.6 REGULATORY RESPONSES

2.6.1 The introduction and expansion of all industry sectors has led to local air quality regulations that are designed to protect public health and the environment. Further growth and expansion means that it will become increasingly necessary for all sectors to improve their performance and either reduce their net emissions or else their emission rate as a function of productivity. This can be seen in the even more stringent NO_x standards in both the motor vehicle and aviation industries. In addition, a steadily improving understanding of the impact of various pollutants on public health means that the emphasis may shift from one emission or pollutant to another. So far, this has lead to an increase in stringency for local air quality regulations.

2.6.2 The introduction and tightening of the U.S. NAAQS and EU Air Quality Framework Directive for PM_{10}, and increasing interest in $PM_{2.5}$ are also resulting in considerable activity within ICAO CAEP. A prerequisite for ICAO standards is a repeatable and reliable means of measurement — which for the small particle sizes of aircraft engine exhaust does not yet exist. Once measurement systems are developed, the current SN measurement may be replaced with a PM-based parameter which better represents current relatively low levels of carbon-based particulate emissions from aircraft engines. In a longer timescale, ICAO standards for volatile particle precursors from HC may also be considered, but again reliable measurement methods will be required. Of additional concern is the emission of volatile particle precursors from sulphur. While this can be controlled by fuel sulphur content, measurement of engine emissions is in its infancy and direct ICAO emissions standards would be feasible only on a longer timescale.

2.6.3 Looking forward, CAEP is anticipating further stringency increases in ICAO aircraft engine emissions standards by LTO. In particular, NO_x will be examined, although potential reductions will be assessed against trade-offs

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[10] *Air Quality Standards for Nitrogen Dioxide, Directive* 85/203/EEC, 7 March 1985.

[11] *Limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air,* Directive 99/30/EC.

with noise, fuel consumption and cost. Engine technology has reached a stage of maturity such that there are few developments which can be made and have wholly beneficial effects. 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 as well as allowing for better informed forecasts and scenarios in aviation-related air quality over the next 20-year timescale.

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 (or 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 (e.g. 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. 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 (e.g. 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 (e.g. 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 (e.g. fuel farms).

c) ***Updates.*** The frequency of inventory updates influences the design of the inventory and any applied databases or data tables (e.g. 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 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;

   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 (e.g. 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) particulate matter (PM), fraction size $PM_{2.5}$ and PM_{10}; and

e) sulphur oxides (SO_x).

3.3.2 Carbon dioxide (CO_2) is sometimes included in inventories (using the total fuel burn as a basis for calculation). It has to 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. HAPs research is at an early stage and it should be noted that knowledge of emission factors is therefore 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;

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;

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 (e.g. 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 are typically comprised of the following:[1]

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.

3.4.3 Aircraft handling emissions sources are typically comprised of the following:

a) ***Ground support equipment.*** 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.

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.

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[1] 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.

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

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

d) ***Airport maintenance.*** All activities for the maintenance of airport facilities (cleaning agents, building maintenance, repairs, greenland maintenance) 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 are comprised of the following:[2]

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).

3.4.6 The mass of emissions from each of these source categories is considered (to the extent 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 (e.g. an airshed) may be developed. The relevant governmental bodies (e.g. 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 double-counting of emissions. Depending on the chosen assumptions (e.g. 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.

3.6 QUALITY ASSURANCE

3.6.1 Depending on the local situation, developing an emissions inventory can be a complex exercise which 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.

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

3.6.2 **Missing information.** Due to the lack of availability of certain data (i.e. 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 (i.e. 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 an 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 (e.g. 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 the 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 (e.g. 5, 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.

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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 that 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 (sometimes referred to as 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 (e.g. 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 Section 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 emission index 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 and HC, 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 TIM-specific fuel flow yields a mode-specific emission rate in units of grams per LTO. For more accurate inventories, adjustments to these values are necessary to take account of different power settings, installation effects, etc.

2. AIRCRAFT ENGINE EMISSIONS CERTIFICATION

2.1 For emissions certification purposes, ICAO has defined a specific reference LTO cycle below a height of 915 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 much 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 915 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]

2.4 The certification LTO cycle characteristics selected were derived from surveys in the 1970s. They reflected peak traffic operations (i.e. 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.

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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.

2.5 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 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 ten) 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 and NO_x, 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 (i.e. “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 some certified engines, mode-specific smoke numbers have been reported).

2.11 The emissions certification values previously described are provided in the ICAO EEDB, both as individual engine data sheets and also 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 www.caa.co.uk/srg/environmental and is periodically updated. An example of an engine emissions data sheet 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 (i.e. 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 Figure 3-A1-1 and described in the subsequent sections.

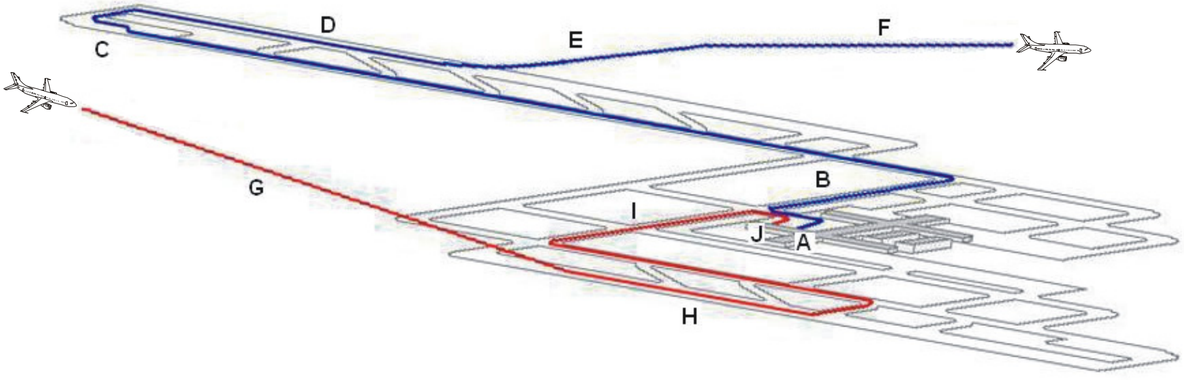

Figure 3-A1-1. Operational flight cycle

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 (i.e. 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 (i.e. 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 onboard 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 (e.g. 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 which 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 and in most instances 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 (e.g. 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 (e.g. 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 as listed and described in Table 3-A1-2 are to some degree independent of each other, i.e. 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, as well cannot be mixed with other options or approaches; 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% V2525 and 50% CFM56-5B5P)		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 UNFCC 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	Option B Derived from ICAO EEDB through BFFM2 curve-fitting method	Refined values using actual performance and operational data derived from the air carrier
Start-up emissions	Not considered		Consider including — see 6.53 to 6.59		Consider including — see 6.53 to 6.59
Engine deterioration	Do not consider — see 6.44 to 6.52		Do not consider — see 6.44 to 6.52		Do not consider — see 6.44 to 6.52

5. AIRCRAFT FLEET AND MOVEMENTS

5.1 Aircraft fleet is a generic description to describe 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 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.

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 (e.g. 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 (e.g. 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 contains Table B-1 which lists 52 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-3 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-3, 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-3, 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 (e.g. LTO) and type of aircraft at an airport over a specified period (e.g. 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 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). The data included in this document were current at the time of writing. The UNFCCC will provide updates to this table on an ongoing basis, and the most current table should be used whenever possible (http://www.ipcc-nggip.iges.or.jp/). If using new data from the UNFCCC website, CH4 and NMVOC data will require summing in order to obtain a value for HC. 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, and 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 (e.g. 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 inaccuracy, 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 U.S. 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, which 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 U.S. scheduled airlines and 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 BACK Aviation Solution’s World Fleet Registration database contains additional airline fleet information such as all worldwide commercial aircraft currently in use and other various aircraft parameters (see Attachment C for a list of useful fields). For emissions inventory purposes, the most important parameters from the BACK database (or other similar databases) are the aircraft identifiers, tail number, engine model, number of engines and aircraft type.

5.16 Bucher & Company’s JP Airline-Fleets International Database (JPFleets) is another publicly available database that provides aircraft type/engine combinations for major commercial airlines worldwide (see Attachment C for a list of useful data fields).

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

5.18 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 (e.g. 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.

5.19 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. For these cases, databases such as BACK, JPFleets and others can be used to develop distributions of engines based on reported airline and aircraft categories.

5.20 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 in order to minimize uncertainties.

Advanced aircraft movements

5.21 The requirements for aircraft movements needed for the advanced approach is nearly identical to 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

5.22 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 UID.

5.23 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. So 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 SN, based upon the standardized LTO cycle as set out in Annex 16, Volume II, and published originally in Doc 9646 (1995) and website amendments. ICAO provides the emissions certification data on the worldwide web at www.caa.co.uk/. 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.

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. Aircraft engine EI 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 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.

6.5 The Swedish Defence Research Agency (FOI) is the keeper of a database of EI 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 EI 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 found at http://www.foi.se/FOI/templates/Page____4618.aspx.

6.6 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, recommendations for the use of their data to conduct simple emissions inventories using suggested TIM. All material is openly available for download at www.bazl.admin.ch → For Specialists → Environment → Pollutant Emissions →Aircraft Engine Emissions.

Emissions calculations — simple approach (option A)

Emission indices

6.7 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 five pollutant species for each of the listed aircraft.

6.8 The emission factor is provided in terms of kg of each emissions species per LTO cycle per aircraft. 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

6.9 For NO_x, HC, CO, 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:

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

6.10 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.

6.11 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:

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

6.12 There is no provision for the calculation of PM emissions in the simple approach (option A).

Emissions calculation — simple approach (option B)

Aircraft time-in-mode (TIM)

6.13 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 2.1 through 2.8). 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.

6.14 While ICAO default TIM is applicable primarily to regulated engines, there may other default TIM available for other engine types (i.e. unregulated turbofan engines, turboprop engines, piston engines or helicopters). Sources of such information include national aviation or environmental authorities.

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

Emissions calculation methodology for NO_x, CO and HC

6.15 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.

6.16 To determine the NO_x, CO or HC 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.

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

where:

Ei_j = total emissions of pollutant i (e.g. NO_x, CO or HC), in grams, produced by aircraft type j for one LTO cycle;

Ei_{ijk} = emission index for pollutant i (e.g. NO_x, CO or 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 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;

Ne_j = number of engines used on aircraft type j.

6.17 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.

6.18 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 U.S. EPA conducted a survey of sulphur content for commercial aviation jet fuel, which resulted in a U.S. 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:

$$E_k = \sum (TIM_k * 60) * (Er_k) * (Ne_k) \qquad \text{Eq. A1-4}$$

where:

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

Ne_k = number of engines used on aircraft type k;

Er_k = 1 * (FF_k);

where:

Er_k = emission rate of total SO_x in units of grams of SO_x emitted per second per operational mode for aircraft k;

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

6.19 ICAO does not have emissions certification standards for PM emissions. However, CAEP has developed and approved the use of an interim First Order Approximation (FOA) method to estimate total PM emissions from certified aircraft engines. At the time of publication of this document, FOA, version 3, was the most up to date and is provided in Attachment D to this appendix. FOA3.0 provides expressions of volatile PM from fuel organics and sulphur content, as well as a relationship between SN and non-volatile PM mass. CAEP is committed to continually updating the interim FOA methodology as data and scientific advancements become available, until such time as it can be replaced by fully validated and verified measurement data. The FOA methodology is to be used for emissions inventory purposes only within the vicinity of airports. The FOA methodology should not be relied upon where accurate, validated data are required.

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. Also refer 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 (cf. Section 3). 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 for primarily 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 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 (e.g. 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 emission indices can be calculated using the BFFM2 curve fitting methodology. A twin quadratic methodology has been developed, and it 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-A1-2).

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.

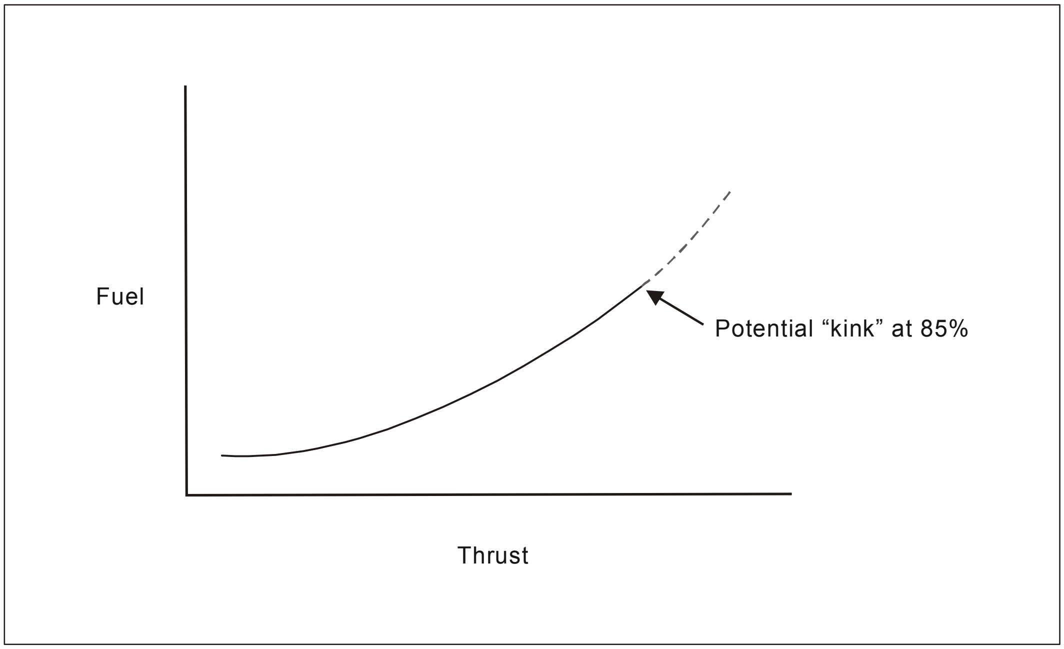

Figure 3-A1-2. Diagrammatic illustration of twin quadratic curve fit

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 (e.g. 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 6.29.

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 section 6.34.

Application of additional parameters that may influence emissions, if appropriate

Important caveats for modellers using advanced methods

6.37 Unlike 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 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 emission indices should be calculated using a fuel flow method. One documented[6] fuel flow method is the Boeing fuel flow method 2 (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 emission indices 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 emission indices 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 of 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.

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[6] SAE AIR5715.

6.42 The calculation of the emission indices 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 emission indices. 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.

Engine deterioration

6.44 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 provides the following guidance regarding how and when to apply deterioration in performing airport inventories.

6.45 In-service airframe and engine deterioration for the purposes of airport inventories (i.e. 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, HC or smoke number.

6.46 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.

6.47 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 (i.e. actual engine operational data or calibrated/validated on actual in-service data), implicitly (i.e. 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.

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

6.48 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.

6.49 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 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 and throttle settings in the LTO cycle. The deterioration factors are considered smaller that the inherent conservatism already existing in the method, and application of deterioration factors is therefore not recommended.

6.50 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.

6.51 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.

6.52 Fuel consumption deterioration should be applied only to modelling in the vicinity of airports (i.e. 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

6.53 During the starting sequence there is 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

6.54 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. From 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.

6.55 Pre-ignition emissions would be purely fuel hydrocarbons 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;

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

Engine post-ignition

6.56 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. 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.

6.57 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 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.

6.58 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.

6.59 ICCAIA has performed a detailed analysis of engine starting data from GE, RR, P&W and IAE 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:

$$\text{Starting HC emissions (grams)} = \text{rated take-off thrust (kN)}/2 + 80 \qquad \text{Eq. A1-5}$$

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).

Advanced calculation methodology for NO_x, CO and THC

6.60 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.

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

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

where:

E_{ij} = total emissions of pollutant i (e.g. NO_x, CO or 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 or HC), in grams of 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 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;

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

Emissions calculation — sophisticated approach

Parameters

6.62 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 6.35 to 6.52 could be considered based on the guidance provided in Table 3-A1-2.

6.63 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;

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;

f) airport infrastructure and constraints (e.g. runway length).

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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.

6.64 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 (e.g. reduced thrust take-off procedures);

f) approach and climb profiles;

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

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

6.65 Using actual performance and operational data, engine emission factors can be calculated using programmes such as the Boeing fuel flow method 2 or the Deutsches Zentrum für Luft- und Raumfahrt method.

Sophisticated calculation methodology for NO_x, CO and THC

6.66 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.

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

where:

E_{ij} = total emissions of pollutant i (e.g. NO_x, CO or 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 or 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 the 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;

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

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 for 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
PM_{10} emissions	25 g	40 g

7.6 The fuel burn and emissions values given in 7.5 are based on averaged APU-specific proprietary data from the manufacturer, though do not represent any specific APU type. The operational times noted are based on

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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 (e.g. A330, A340, A380, B747, B767-200ER, B763, B764, B777, IL96). Short-haul would include all other aircraft.

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 to the default values listed in Table 3-A1-3. If information on actual APU operating 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 the 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 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 EI 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 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.

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

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

Advanced approach

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

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; and
PM_{10} use the simple approach outlined above.

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-A1-9). APU fuel/CO_2, NO_x, HC and CO 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.

Sophisticated approach

7.16 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.

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)	50	90	105
Smaller (100 ≤ seats < 200), newer types	75	100	125
Smaller (100 ≤ seats < 200), older types	80	110	140
Mid-range (200 ≤ seats < 300), all types	105	180	200
Larger (300 ≤ seats), older types	205	300	345
Larger (300 ≤ seats), newer types	170	235	315

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	0.452	0.530
Smaller (100 ≤ seats < 200), newer types	0.364	0.805	1.016
Smaller (100 ≤ seats < 200), older types	0.565	1.064	1.354
Mid-range (200 ≤ seats < 300), all types	0.798	1.756	2.091
Larger (300 ≤ seats), older types	1.137	2.071	2.645
Larger (300 ≤ seats), newer types	1.210	2.892	4.048

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)	0.107	0.044	0.042
Smaller (100 ≤ seats < 200), newer types	2.662	0.094	0.091
Smaller (100 ≤ seats < 200), older types	0.105	0.036	0.036
Mid-range (200 ≤ seats < 300), all types	0.243	0.070	0.059
Larger (300 ≤ seats), older types	0.302	0.153	0.125
Larger (300 ≤ seats), newer types	0.180	0.078	0.076

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)	1.019	0.799	0.805
Smaller (100 ≤ seats < 200), newer types	3.734	0.419	0.495
Smaller (100 ≤ seats < 200), older types	1.289	0.336	0.453
Mid-range (200 ≤ seats < 300), all types	0.982	0.248	0.239
Larger (300 ≤ seats), older types	5.400	3.695	2.555
Larger (300 ≤ seats), newer types	1.486	0.149	0.192

7.17 The sophisticated approach requires a 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 EI from the manufacturers to give a more reliable result.

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

Emissions mass = time-in-mode x fuel flow x EI, for each mode and each emissions species Eq. A1-8

7.19 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 up the emissions calculated for each aircraft APU operation, the total mass of each emissions species can be calculated for the emissions inventory.

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Attachment A to Appendix 1

ICAO ENGINE EXHAUST EMISSIONS DATA BANK

SUBSONIC ENGINES

ENGINE IDENTIFICATION: Trent 895
UNIQUE ID NUMBER: 5RR040
ENGINE TYPE: TF

BYPASS RATIO: 5.7
PRESSURE RATIO (π_{oo}): 41.52
RATED OUTPUT (F_{oo}) (kN): 413.05

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NOx	SMOKE NUMBER
D_p/F_{oo} (g/kN) or SN	1.7	23.1	78.6	6.9
AS % OF ORIGINAL LIMIT	8.6 %	19.6 %	63.9 %	42.8 %
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_{oo})	TIME minutes	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg)			SMOKE NUMBER
				HC	CO	NOx	
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_{oo} (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_{oo} 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.

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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)[2]					Fuel consumption (kg/LTO/aircraft)
		CO_2[3]	HC	NO_x	CO	SO_2[4]	
Large commercial aircraft[5] Source: ICAO (2004)[6]	A300	5 450	1.25	25.86	14.80	1.72	1 720
	A310	4 760	6.30	19.46	28.30	1.51	1 510
	A319	2 310	0.59	8.73	6.35	0.73	730
	A320	2 440	0.57	9.01	6.19	0.77	770
	A321	3 020	1.42	16.72	7.55	0.96	960
	A330-200/300	7 050	1.28	35.57	16.20	2.23	2 230
	A340-200	5 890	4.20	28.31	26.19	1.86	1 860
	A340-300	6 380	3.90	34.81	25.23	2.02	2 020
	A340-500/600	10 660	0.14	64.45	15.31	3.37	3 370
	707	5 890	97.45	10.96	92.37	1.86	1 860
	717	2 140	0.05	6.68	6.78	0.68	680
	727-100	3 970	6.94	9.23	24.44	1.26	1 260
	727-200	4 610	8.14	11.97	27.16	1.46	1460
	737-100/200	2 740	4.51	6.74	16.04	0.87	870
	737-300/400/500	2 480	0.84	7.19	13.03	0.78	780
	737-600	2 280	1.01	7.66	8.65	0.72	720
	737-700	2 460	0.86	9.12	8.00	0.78	780
	737-800/900	2 780	0.72	12.30	7.07	0.88	880
	747-100	10 140	48.43	49.17	114.59	3.21	3 210
	747-200	11 370	18.24	49.52	79.78	3.60	3 600
	747-300	11 080	2.73	65.00	17.84	3.51	3 510
	747-400	10 240	2.25	42.88	26.72	3.24	3 240
	757-200	4 320	0.22	23.43	8.08	1.37	1 370
	757-300	4630	0.11	17.85	11.62	1.46	1 460
	767-200	4 620	3.32	23.76	14.80	1.46	1 460
	767-300	5 610	1.19	28.19	14.47	1.77	1 780
	767-400	5 520	0.98	24.80	12.37	1.75	1 750
	777-200/300	8 100	0.66	52.81	12.76	2.56	2 560
	DC-10	7 290	2.37	35.65	20.59	2.31	2 310
	DC-8-50/60/70	5 360	1.51	15.62	26.31	1.70	1 700
	DC-9	2 650	4.63	6.16	16.29	0.84	840
	L-1011	7 300	73.96	31.64	103.33	2.31	2 310

Aircraft[1]		LTO emission factors/aeroplane (kg/LTO/aircraft)[2]					Fuel consumption (kg/LTO/aircraft)
		CO_2[3]	*HC*	*NO_x*	*CO*	*SO_2*[4]	
Large commercial aircraft[5] Source: ICAO (2004)[6]	MD-11	7 290	2.37	35.65	20.59	2.31	2 310
	MD-80	3 180	1.87	11.97	6.46	1.01	1 010
	MD-90	2 760	0.06	10.76	5.53	0.87	870
	TU-134	5 860	35.97	17.35	55.96	1.86	1 860
	TU-154-M	7 040	17.56	16.00	110.51	2.51	2 510
	TU-154-B	9 370	158.71	19.11	190.74	2.97	2 970
Regional jets/business jets > 26.7 kN thrust	RJ-RJ85	950	0.67	2.17	5.61	0.30	300
	BAE 146	900	0.70	2.03	5.59	0.29	290
	CRJ-100ER	1 060	0.63	2.27	6.70	0.33	330
	ERJ-145	990	0.56	2.69	6.18	0.31	310
	Fokker 100/70/28	2 390	1.43	5.75	13.84	0.76	760
	BAC111	2 520	1.52	7.40	13.07	0.80	800
	Dornier 328 Jet	870	0.57	2.99	5.35	0.27	280
	Gulfstream IV	2 160	1.37	5.63	8.88	0.68	680
	Gulfstream V	1 890	0.31	5.58	8.42	0.60	600
	Yak-42M	1 920	1.68	7.11	6.81	0.61	610
Low thrust jets (Fn < 26.7 kN) Source: FAEED222[7]	Cessna 525/560	1 060	3.35	0.74	34.07	0.34	340
Turboprops Source: FOI[8]	Beech King Air[9]	230	0.64	0.30	2.97	0.07	70
	DHC8-100[10]	640	0.00	1.51	2.24	0.20	200
	ATR72-500[11]	620	0.29	1.82	2.33	0.20	200

Notes.—

1. Equivalent aircraft are contained in Table B-3.

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 ICAO Annex 16, Volume II," by D.H. Lister and P.D. Norman.
   — ICAO Annex 16, Volume II, 2nd edition (1993).

3. CO_2 for each aircraft based on 3.16 kg CO_2 produced for each kg of fuel used, then rounded to the nearest 10 kg.

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 with the most LTOs as of 30 July 2004 (except 747-300 — see text). This approach, for some engine types, may underestimate (or overestimate) fleet emissions which are not directly related to fuel consumption (e.g. NO_x, CO, HC).

6. ICAO (International Civil Aviation Organization) Engine Exhaust Emissions Data Bank (2004) based on average measured certification data**.** Emission factors apply to the LTO cycle only. Total emissions and fuel consumption are calculated based on ICAO standard time-in-mode and thrust levels.

7. U.S. Federal Aviation Administration (FAA) Emissions and Dispersion Modelling System (EDMS) non-certified data.

8. FOI (The Swedish Defence Research Agency) turboprop LTO emissions database non-certified data.

9. Representative of turboprop aircraft with shaft horsepower (SHP) of up to 1 000 SHP/engine.

10. Representative of turboprop aircraft with shaft horsepower of 1 000 to 2 000 SHP/engine.

11. Representative of turboprop aircraft with shaft horsepower of more than 2 000 SHP/engine.

Table B-2. Engine designation by aircraft

Aircraft	ICAO engine	Engine UID
A300	PW4158	1PW048
A310	CF6-80C2A2	1GE016
A319	CFM56-5A5	4CM036
A320	CFM56-5A1	1CM008
A321	CFM56-5B3/P	3CM025
A330-200/300	Trent 772B-60	3RR030
A340-200	CFM56-5C2	1CM010
A340-300	CFM56-5C4	2CM015
A340-500/600	TRENT 556-61	6RR041
707	JT3D-3B	1PW001
717	BR700-715A1-30	4BR005
727-100	JT8D-7B	1PW004
727-200	JT8D-15	1PW009
737-100/200	JT8D-9A	1PW006
737-300/400/500	CFM56-3B-1	1CM004
737-600	CFM56-7B20	3CM030
737-700	CFM56-7B22	3CM031
737-800/900	CFM56-7B26	3CM033
747-100	JT9D-7A	1PW021
747-200	JT9D-7Q	1PW025
747-300	JT9D-7R4G2(66%) RB211-524D4(34%)	1PW029(66%) 1RR008(34%)
747-400	CF6-80C2B1F	2GE041
757-200	RB211-535E4	3RR028
757-300	RB211-535E4B	5RR039
767-200	CF6-80A2	1GE012
767-300	PW4060	1PW043
767-400	CF6-80C2B8F	3GE058
777-200/300	Trent 892	2RR027
DC-10	CF6-50C2	3GE074
DC-8-50/60/70	CFM56-2C1	1CM003
DC-9	JT8D-7B	1PW004
L-1011	RB211-22B	1RR003
MD-11	CF6-80C2D1F	3GE074

Aircraft	ICAO engine	Engine UID
MD-80	JT8D-217C	1PW018
MD-90	V2525-D5	1IA002
TU-134	D-30-3	1AA001
TU-154-M	D-30-KU-154-II	1AA004
TU-154-B	NK-8-2U	1KK001
RJ-RJ85	LF507-1F, -1H	1TL004
BAE 146	ALF 502R-5	1TL003
CRJ-100ER	CF34-3A1	1GE035
ERJ-145	AE3007A1	6AL007
Fokker 100/70/28	TAY Mk650-15	1RR021
BAC111	Spey-512-14DW	1RR016
Dornier 328 Jet	PW306B	7PW078
Gulfstream IV	Tay MK611-8	1RR019
Gulfstream V	BR700-710A1-10	4BR008
Yak-42M	D-36	1ZM001
Cessna 525/560	PW545A or similar	FAEED222
Beech King Air	PT6A-42	PT6A-42
DHC8-100	PW120 or similar	PW120
ATR72-500	PW127F or similar	PW127F

Table B-3. Representative aircraft

Generic aircraft type	ICAO	IATA aircraft in group
Airbus A300	A30B	AB3
	A306	AB4
		AB6
		ABF
		ABX
		ABY
Airbus A310	A310	310
		312
		313
		31F
		31X
		31Y
Airbus A319	A319	319
	A318	318
Airbus A320	A320	320
		32S
Airbus A321	A321	321
Airbus A330-200	A330	330
	A332	332
Airbus A330-300	A330	330
	A333	333
Airbus A340-200	A342	342
Airbus A340-300	A340	340
	A343	343
Airbus A340-500	A345	345
Airbus A340-600	A346	346
Boeing 707	B703	703
		707
		70F
		70M

Generic aircraft type	ICAO	IATA aircraft in group
Boeing 717	B712	717
Boeing 727-100	B721	721
		72M
Boeing 727-200	B722	722
		727
		72C
		72B
		72F
		72S
Boeing 737-100	B731	731
Boeing 737-200	B732	732
		73M
		73X
Boeing 737-300	B733	737
		73F
		733
		73Y
Boeing 737-400	B734	737
		734
Boeing 737-500	B735	737
		735
Boeing 737-600	B736	736
Boeing 737-700	B737	73G
		73W
Boeing 737-800	B738	738
		73H
Boeing 737-900	B739	739
Boeing 747-100	B741	74T
	N74S	74L
	B74R	74R
	B74R	74V

Generic aircraft type	ICAO	IATA aircraft in group
Boeing 747-200	B742	742
		74C
		74X
Boeing 747-300	B743	743
		74D
Boeing 747-400	B744	747
		744
		74E
		74F
		74J
		74M
		74Y
Boeing 757-200	B752	757
		75F
		75M
Boeing 757-300	B753	
Boeing 767-200	B762	762
		76X
Boeing 767-300	B763	767
		76F
		763
		76Y
Boeing 767-400	B764	
Boeing 777-200	B772	777
		772
Boeing 777-300	B773	
		773
Douglas DC-10	DC10	D10
		D11
		D1C
		D1F

Generic aircraft type	ICAO	IATA aircraft in group
Douglas DC-10	DC10	D1M
		D1X
		D1Y
Douglas DC-8	DC85	D8F
	DC86	D8L
	DC87	D8M
		D8Q
		D8T
		D8X
		D8Y
Douglas DC-9	DC9	DC9
	DC91	D91
	DC92	D92
	DC93	D93
	DC94	D94
	DC95	D95
		D9C
		D9F
		D9X
Lockheed L-1011	L101	L10
		L11
		L15
		L1F
McDonnell Douglas MD11	MD11	M11
		M1F
		M1M
McDonnell Douglas MD80	MD80	M80
	MD81	M81
	MD82	M82
	MD83	M83
	MD87	M87
	MD88	MD88
McDonnell Douglas MD90	MD90	M90

Generic aircraft type	ICAO	IATA aircraft in group
Tupolev Tu134	T134	TU3
Tupolev Tu154	T154	TU5
Avro RJ85	RJ85	AR8
		ARJ
BAe 146	B461	141
	B462	142
	B463	143
		146
		14F
		14X
		14Y
		14Z
Embraer ERJ145	E145	ER4
		ERJ
Fokker 100/70/28	F100	100
	F70	F70
	F28	F21
		F22
		F23
		F24
		F28
BAC 111	BA11	B11
		B12
		B13
		B14
		B15
Donier Do 328	D328	D38
Gulfstream IV/V		GRJ
Yakovlev Yak 42	YK42	YK2

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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 (e.g. 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 (e.g. B738)
FAACarr = Abbreviation for air carrier name
FltNo = Flight number
Freq = 1/0 code showing days of the week that that flight flies that time slot and city pair
ATACarr = Carrier name in Air Transport Association 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 U.S.
LveCntry = Origin country or State if the origin is in the U.S.
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 BACK WORLD FLEET REGISTRATION DATABASE

Aircraft type
Aircraft serial number
Aircraft manufacturer
Registration/tail number
Engine manufacturer
Engine model
Number of engines
Aircraft noise class (stage)
Equipment category
Equipment type (LAR code)
Equipment type (IOAG code)
Aircraft equipment model
Operator category
Operator name
Operator IATA code
Operator ICAO code
Wingspan (m)
Wing area (square metres)
Overall length (m)
Belly volume (cubic metres)
Fuel capacity
Maximum take-off weight (kg)
Maximum payload (kg)
Maximum landing weight (kg)
Range with maximum fuel (km)
Range with maximum payload (km)

3. 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

4. USEFUL DATA FIELDS IN THE JP AIRLINE FLEETS DATABASE

Operator name
Operator IATA code
Operator ICAO code
Aircraft tail number
Aircraft type and subtype
Month and year of manufacturing
Construction number
Previous identity
Number of engines
Manufacturer of engines
Exact type of engines
Maximum take-off weight (kg)
Seat configuration (or other use than for passenger services)

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Attachment D to Appendix 1

FIRST ORDER APPROXIMATION V3.0 METHOD FOR ESTIMATING PARTICULATE MATTER EMISSIONS FROM AIRCRAFT ENGINES

1. NOMENCLATURE

AFR	Air-to-fuel ratio (mass basis)
BPR	Bypass ratio
CI	Carbon index. A measure of the black carbon mass per standard volume of flow. The volume is in standard cubic metres Standard atmosphere is defined as the volume occupied at 273.15 degrees Kelvin and 1 atmosphere of absolute pressure) (mg/m^3 produced by burning 1 kg of fuel).
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)
$EI_{PMvol–orgCFM56}$	Emission index for 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_{PMnvol}	Emission index for non-volatile particulate matter primarily consisting of black carbon (mg/kg of fuel)
$EI_{PMtotal}$	Total particulate matter emission index for both volatile and non-volatile components (mg/kg of fuel)
$EI_{PMvol–FSC}$	Emission index for volatile sulphate particulate matter due to fuel sulphur (mg/kg of fuel)
$EI_{PMvol–FuelOrganics}$	Emission index for organic volatile particulate matter primarily due to incomplete combustion of fuel (mg/kg of fuel)
HC	Total hydrocarbons
ICAO	International Civil Aviation Organization
FOA	First Order Approximation. FOA3.0 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)

LTO	ICAO landing and take-off cycle
MW_{out}	Molecular weight of SO_4^{-2} ($S^{VI} = 96$)
$MW_{Sulphur}$	Molecular weight of elemental sulphur ($S^{IV} = 32$)
PM	Particulate matter
Q_{core}	Exhaust volumetric flow rate as related to fuel burn (m^3/kg fuel)
Q_{Mixed}	Exhaust volumetric flow rate including that due to fuel burn and the bypass air (m^3/kg fuel)
SF	Scaling factor
SN	Smoke number. The methodology in this document is based on smoke numbers as defined in Appendix 2 of ICAO Annex 16.
SN_{mode}	Smoke number for one of the ICAO-defined modes (take-off, climb-out, approach or idle)
SN_{max}	Maximum smoke number
STP	Standard temperature and pressure as used in this document is 273.15 degrees Kelvin and 1 atmosphere of absolute pressure
ε	Fuel sulphur conversion efficiency (mass fraction)
δ	Ratio of $\mathrm{EI}_{\mathrm{PMvol-FuelOrganics}} = \frac{\mathrm{EI}_{\mathrm{PMvol-orgCFM56}}}{\mathrm{EI}_{\mathrm{HCCFM56}}}$ as derived for use in Equation 9 (mg/kg).

2. INTRODUCTION

2.1 FOA3.0 is a method for estimating the particulate emissions, both non-volatile (soot) and volatile, in the form of emission indices (EI) as mass emitted per kilogram of fuel.[1,2] Currently there are three components to the estimation process and each must be calculated separately, with the total EI being the sum of the parts. The basic technique for each component of particulate matter (PM) is as follows.

Non-volatile PM (EI_{PMnvol})

2.2 The calculation of non-volatile PM 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 carbon index (CI). The CI 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 CI and Q gives the EI with the unit of mass per kilogram of fuel burn. Units as reported in this document are mg/kg of fuel unless otherwise stated. The EI must be computed for the various power settings used in the vicinity of airports for EI_{PMnvol}.

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[1] CAEP, "Particulate Matter Characterization," Information Paper No. 6, Working Group 3 — Technical Emissions, ICAO Committee on Aviation Environmental Protection (CAEP) meeting, February 2007.

[2] ICAO, *Airport Air Quality Manual*, Doc 9889.

Volatile sulphate PM ($EI_{PMvol-FSC}$)

2.3 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). As such, the EI does not vary by power setting.

Volatile organic PM ($EI_{PMvol-FuelOrganics}$)

2.4 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 EI for the CFM56-2-C1 engine which was measured during NASA's Aircraft Particle Emissions Experiment 1 (APEX1).[3] The result is an EI that is both engine and power-setting specific for the volatile organic PM.

PM from engine lubricant

2.5 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

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 Committee on Aviation Environmental Protection as follows:

a) the addition of new engine data;

b) clarification for mixed turbofans as to whether the measurements were made on the engine core or over both the core and bypass flows;

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 which denotes that either the SN was not derived at that particular power setting or it was not reported since only the maximum is required. These guidelines were developed by Calvert[4] 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:

$$SF = \frac{SN_{mode}}{SN_{max}} \quad \text{(Eq. D-1)}$$

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[3] 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.

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

where:

SF = scaling factor;

SN_{mode} = SN for one of the modes (take-off, climb-out, approach or idle);

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
GE and CFM DAC engines	0.3	0.3	0.3	1.0

3.4 Using these SF values and Equation D-1, missing SN data can be reasonably 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 the missing SN in the ICAO EEDB, other concerns also exist. If an SN is listed as zero (0) by the manufacturers no attempt has been made to change the value. In these cases, non-volatile PM estimates will also be zero, which is unrealistic, but it was considered to be undesirable by the group to change any listed values. In some cases the SN for the idle power setting is listed with an asterisk (*) as a superscript. This indicates that the SN has been calculated at a power setting other than 7 per cent. Finally, if the value is preceded by the symbol “<” the provided value should still be used.

3.6 To assist in ongoing analysis, a separate table had been included in spreadsheet form (Calvert-method-Databank-Issue_15-C.xls) as the interim recommended values. Manufacturers are working to include, in the ICAO EEDB, all SNs for engines still in production, and those values will replace those presently included in the table.

Air-fuel ratio (AFR)

3.7 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 AFRs listed by ICAO power settings (mode)

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

Non-volatile PM (EI_{PMnvol})

3.8 The calculation of EI_{PMnvol} is accomplished by first computing the CI, which is based on a statistical correlation, with the ICAO SN being the independent variable. Derivation of the appropriate SN when the value is not available in the ICAO EEDB is described in 3.1 to 3.6. Also of note is that the statistical correlation equation that must be used has two forms depending on the value of the SN. The dividing line is an SN value of less than or equal to 30 or above 30.

3.9 The independent variable for the derivation of the flow rate is the AFR which was listed for each power setting (mode) in Table D-2. Of note is that two possible choices exist for the appropriate flow rate to use. This is due to SNs being listed either by core flow or mixed flow in the ICAO EEDB. The listing in the ICAO EEDB for engine type (TF or MTF) allows the choice to be easily made. However, the EEDB is undergoing changes and users should be careful in their choice.

3.10 The CI must then be multiplied by the appropriate flow rate to determine EI_{PMnvol}.

Volatile sulphate PM ($EI_{PMvol-FSC}$)

3.11 Fuel sulphur contents (FSC) can vary widely between different batches of aviation fuel and are not included in the ICAO EEDB. For application to the FOA airport, 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[5] with a global average of 0.03 weight per cent.[6] Using a conservative value of 0.068 weight per cent is currently recommended in the absence of more specific FSC data.

3.12 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 input 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,[7] the sulphur

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

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

[7] 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.

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.

Volatile organic aerosol ($EI_{vol–FuelOrganics}$)

3.13 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.[3] 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	$EI_{PMvol–orgCFM56}$ (mg/kg fuel)
Take-off	4.6
Climb-out	3.8
Approach	4.5
Idle	11.3

4. PM EI CALCULATION

Non-volatile PM (EI_{PMnvol})

4.1 The CI at STP for SN ≤ 30 is calculated from Equation D-2.[8]

$$CI = 0.06949(SN)^{1.234} \text{ mg/m}^3 \text{ based on 1 kg of fuel burn} \qquad \text{(Eq. D-2)}$$

4.2 For SN > 30 Equation D-3 should be used.

$$CI = 0.0297(SN)^2 – 1.803(SN) + 31.94 \text{ mg/m}^3 \text{ based on 1 kg of fuel burn} \qquad \text{(Eq. D-3)}$$

4.3 The exhaust volumetric flow rate at STP for the engine core is:

$$Q_{Core} = 0.776(AFR) + 0.877 \text{ m}^3\text{/kg} \qquad \text{(Eq. D-4)}$$

where AFR is the mode-specific value from Table D-2.

4.4 It should be noted that the constants in this equation have the units of m^3/kg of fuel. Similarly, constants used for other equations listed in this document will have units, and for a mixed (core and bypass) flow:

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[8] S.P. Girling et al., "Development and Characterization of a Smoke Generator for the Calibration of Aerosol Emissions from Gas Turbine Engines," *Aerosol Science and Technology*, 13:8-19, 1990.

Q_{Mixed} = 0.7769 (AFR)(1+BPR) + 0.877 m^3/kg (Eq. D-5)

EI_{PMnvol} = (CI)(Q) mg/kg fuel (Eq. D-6)

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

4.5 The EI for sulphate PM is calculated from:

$$EI_{PMvol\text{–}FSC} = (10)^6 \left[\frac{(FSC)(\varepsilon)(MW_{out})}{MW_{Sulphur}}\right] \text{mg/kg} \qquad \text{(Eq. D-7)}$$

where:

MW_{out} = 96 (SO_4^{-2}) and $MW_{Sulphur}$ = 32. The values of FSC and ε are user-defined with default values as previously defined.

Volatile organic PM ($EI_{PMvol–FuelOrganics}$)

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

$$EI_{PMvol\text{–}FuelOrganics} = \frac{EI_{PMvol\text{–}orgCFM56}}{EI_{HCCFM56}} \left(EI_{HCEngine}\right) \text{mg/kg} \qquad \text{(Eq. D-8)}$$

Where $EI_{HCCFM56}$ is the ICAO total hydrocarbon emission index for the CFM56-2-C1 engine. $EI_{PMvol–orgCFM56}$ is the APEX1 measured volatile organics EI from Table D-3, and $EI_{HCEngine}$ is the EI_{HC} from the ICAO EEDB for the subject engine (the engine where the EI is being determined). Of note is:

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

b) the ratio of $EI_{PMvol–orgCFM56}$ and $EI_{HCCFM56}$ is a constant for each mode. Since only the modal value of the EI_{HC} for the subject engine changes, a simplification can be made to Equation D-8 which is easier to calculate. This results in:

   $EI_{PMvol–FuelOrganics}$ = (δ) ($EI_{HCEngine}$) mg/kg (Eq. D-9)

   where δ is constant ratio by mode. Values of this constant are given in Table D-4 for each mode.

Table D-4. Modal values for the ratio of $EI_{PMvol–orgCFM56}$ and $EI_{HCCFM56}$ in Equation D-8

LTO mode	δ (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 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-5.

Table D-5. 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 idle mode is used:

$$SN_{mode} = (0.3)(133) = 3.99.$$

5.3 To calculate non-volatile PM EI (EI_{PMnvol}) as a function of SN, since the SN < 30, Equation D-2 is used.

$$CI = 0.0694(3.99)^{1.234} = 0.383 \text{ mg/m}^3.$$

5.4 Based on the ICAO EEDB, the mixed exhaust volumetric flow rate should be used with a bypass ratio of 1.73. Using the idle AFR of 106 (Table D-2), the exhaust volumetric flow rate is calculated, via Equation D-5, as follows:

$$Q_{Mixed} = 0.776(106)(1+1.73) + 0.877 = 225.436 \text{ m}^3\text{/kg fuel.}$$

Hence:

$$EI_{PMnvol} = (0.383)(225.436) = 86.3 \text{ mg/kg or } 0.086 \text{ g/kg.}$$

5.5 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:

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

5.6 The $EI_{PMvol-FuelOrganics}$ 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:

$$\mathrm{EI}_{\mathrm{PMvol-FuelOrganics}} = \frac{11.3}{1.83}(3.33) = 20.6 \text{ mg/kg or } 0.021 \text{ g/kg.}$$

5.7 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:

$$\mathrm{EI}_{\mathrm{PMvol-FuelOrganics}} = (6.17)(3.33) = 20.5\ \mathrm{mg/kg}.$$

5.8 In summary, the example calculation results of applying FOA3 to the idle mode for the JT8D-217 series engine are:

EI_{PMnvol} = 86.3 mg/kg

$EI_{PMvol-FSC}$ = 49.0 mg/kg

$EI_{PMvol-FuelOrganics}$ = 20.6 mg/kg.

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

$EI_{PMtotal}$ = 86.3 + 49.0 + 20.6 = 155.9 mg/kg of fuel or 0.156 g/kg of fuel burn.

5.10 While the EI for sulphur does not change by power setting, the other EIs must be calculated for each mode. Table D-6 shows the results for all modes. Of note is that the maximum SN was used for the non-volatile PM EI estimates.

Table D-6. Values of EI_{PM} for the JT8D-217 series engine (mg/kg of fuel)

ICAO defined power setting (mode)	$EI_{PMnonvol}$	$EI_{PMvol-FSC}$	$EI_{PMvol-FuelOrganics}$	Total EI_{PM} by mode
Idle	86.3	49.0	20.6	155.9
Approach	67.6	49.0	90.0	206.6
Climb-out	161.7	49.0	32.7	243.4
Take-off	161.2	49.0	32.2	242.4

6. UNCERTAINTIES

6.1 As its title suggests FOA3.0 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;

    2) details of whether the bypass flow was included in the SN measurement;

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

    1) AFR;

    2) fuel sulphur content;

    3) S^{IV} to S^{VI} conversion factor;

    4) combustor technology;

c) extremely limited data on volatile organics;

d) no information on the effect of engine lubricants;

e) inaccuracies and measurement differences in reported data:

    1) Annex 16 states that measured SNs can vary by ±3;

    2) reported mass measurements vary considerably resulting in ranges of values.

6.2 The limitations of the EEDB are being addressed by the engine manufacturers through CAEP WG3. Values of engine AFR 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.

6.3 Since the inception of the FOA process and its development into FOA3.0, the methodology has continued to evolve and the estimate accuracy improved. The FOA process is not static and will continue to evolve until measurements are sufficient that the approximation is no longer needed. In the interim, CAEP and specifically the ad hoc PM working group will continue to review available information to improve the methodology and the input parameters to the degree possible.

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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
ALAQS-AV	Experimental, available to Eurocontrol member states and other users by special agreement.	www.eurocontrol.int
AEDT-EDMS 5.1	Application, publicly available	www.faa.gov
LASPORT 2.0	Application, publicly available	www.janicke.de

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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 comprised of 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.* Emissions from vehicles and machinery used to service the aircraft on the ground at the aircraft stand or maintenance area;

   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;

   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, as follows.

2.2 Many of the GSE are “non-road” vehicles that have been specially designed to provide services required for aircraft (e.g. 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, however, operate on an aircraft stand for some time and then use service roads to return to specific facilities (e.g. catering trucks, lavatory trucks, baggage tugs). 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.

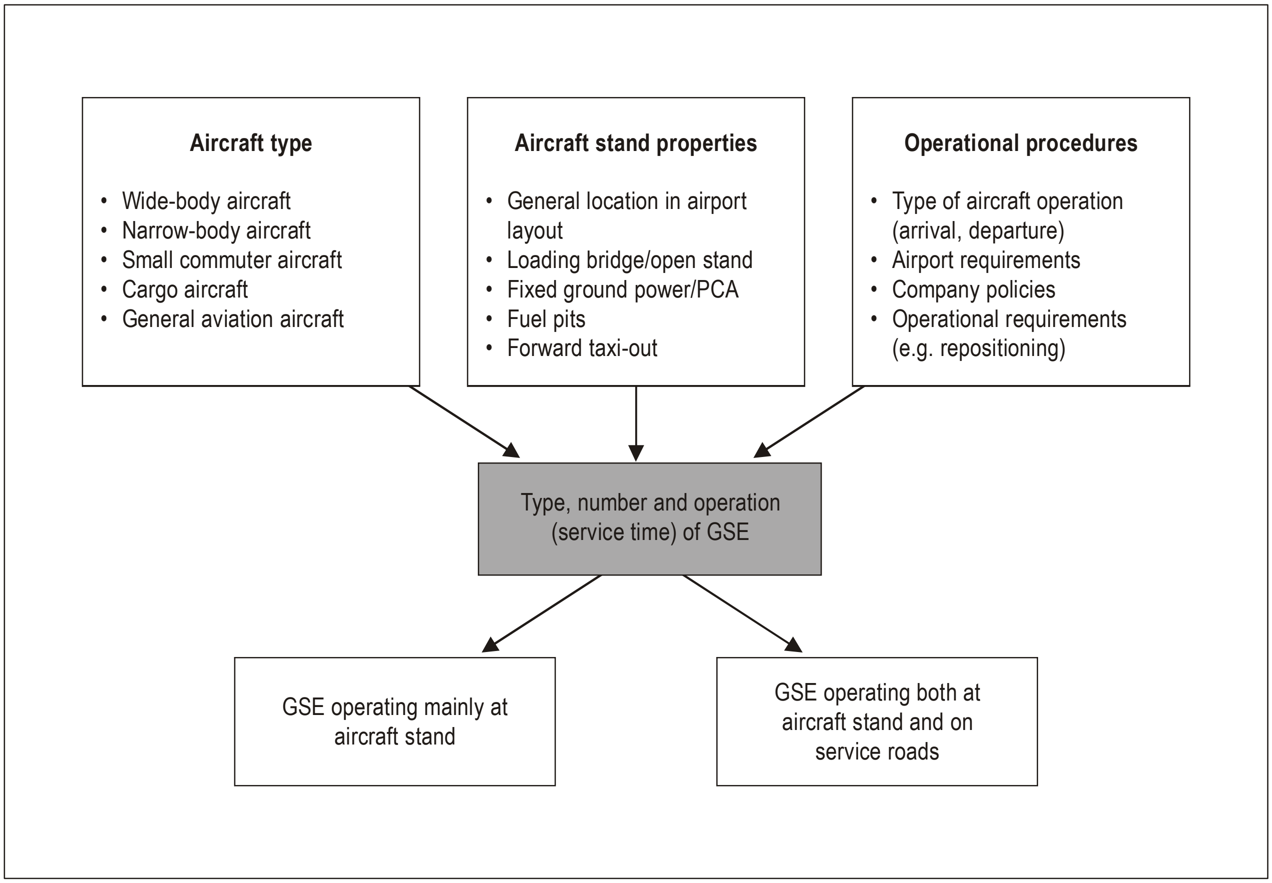

Figure 3-A2-1. Characterization of GSE operations

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

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 (e.g. whether a stand is used for cargo aircraft or for passenger aircraft).

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.

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	
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, CNG or gasoline; 10–25% load	Highly variable (distance rather than time)	Usually on-road certified engines

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 (e.g. 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

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 Aircraft might need air-conditioning 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 hertz (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

b) Government regulations (e.g. safety, operational requirements) and airport operator requirements (e.g. 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 (e.g. 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 (e.g. 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 8 minutes per cycle (instead of 6 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 (e.g. 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]

Pollutant	Unit	Narrow-body aircraft (single-aisle fixed-wing jet)	Wide-body aircraft (double-aisle fixed-wing jet)
NO_x	kg/cycle	0.400	0.900
HC	kg/cycle	0.040	0.070
CO	kg/cycle	0.150	0.300
PM_{10}	kg/cycle	0.025	0.055
CO_2	kg/cycle	18	58

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.

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

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

Pollutant	Diesel (g/kg)	Gasoline (g/kg)
NO_x	48.2	9.6
HC	10.5	45.5
CO	15.8	1 193.0
PM	5.7	—
CO_2	3150	3 140

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[1] Unique (Flughafen Zürich AG).

[2] Diesel and Gasoline: CORINAIR (other values may be used if deemed more appropriate).

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 (e.g. 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.

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

or

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

or

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

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;

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. 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 (e.g. for night stops).

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

where:

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

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 stair is operated 10 minutes for a B-737 size aircraft at an open (e.g. remote) stand upon arrival. The stair has a 45-kW engine, operated at 25 per cent load, with an NO_x EI of 6.0 g/kW-h 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/kW-h × 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 is required for computing aircraft refuelling emissions include:

a) amount of fuel, by fuel type (e.g. 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 (EI) 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.

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).

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

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

4.6 For example, if a total of 1 500 000 kg of Jet A-1 (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 A-1 x 0.85 x 0.01 g VOC/kg Jet A-1) + (1 500 000 kg Jet A-1 x 0.15 x 2 connections x 0.01 g VOC/kg Jet A-1) + (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 both propylene glycol 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[3] are generally based on the amount of de-icing fluid used, the percentage of the de-icing chemical (i.e. ethylene glycol) in the mixture and an emission factor. A U.S. 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. U.S. source of emissions data — de-icing/anti-icing activities

Substance	Source
Propylene glycol/ethylene glycol	FAA's *Air Quality Handbook*, Section H3.3.2.4 (Emission Indices)

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

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

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[3] At airports, there are two types of de-icing activities that 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).

where:

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

DF = amount of de-icing fluid (e.g. litres);

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

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

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

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/roadways, if applicable.

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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 (i.e. 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/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/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. However, the two which are most commonly cited in Europe and North America are those produced by the U.S. EPA and the European Environment Agency:

a) U.S. 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, 1995 (with supplements through 2004);

b) Coordinated Information on the Environment in the European Community — Air (Corinair) — CORINAIR *Emission Inventory Guidebook — 2006*: http://www.eea.europa.eu/publications/ EMEPCORINAIR4.

1.5 However, the methodological approaches set out in the documents cited 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 U.S. 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 (i.e. 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 and

PM_{10}. 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 gas (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 (i.e. horsepower-hours) of actual or estimated equipment usage (i.e. 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	
Anthracite	1985 National Acid Precipitation Program AP-42, Vol. 1, Tables 1.2-1 and 1.2-2 EPA's Factor Information Retrieval (FIRE) data system USGS COALQUAL database *CORINAIR Emission Inventory Guidebook — 2005*
Bituminous	AP-42, Vol. 1, Tables 1.1-3, 1.1-4 and 1.1-19 EPA's Factor Information Retrieval (FIRE) data system USGS COALQUAL database *CORINAIR Emission Inventory Guidebook — 2005*
Bituminous/subbituminous	AP-42, Vol. 1, Tables 1.1-3, 1.1-4 and 1.1-19 LIFAC Sorbent Injection Desulphurization Demonstration Project findings USGS COALQUAL database *CORINAIR Emission Inventory Guidebook — 2005*
Subbituminous	AP-42, Vol. 1, Tables 1.1-3, 1.1-4 and 1.1-19 EPA's Factor Information Retrieval (FIRE) data system USGS COALQUAL database *CORINAIR Emission Inventory Guidebook — 2005*
Fuel oil	1985 National Acid Precipitation Program AP-42, Vol. 1, Tables 1.3-1, 1.3-3, 1.3-4, 1.3-5, 1.3-6, and 1.3-7 EPA's Factor Information Retrieval (FIRE) data system *CORINAIR Emission Inventory Guidebook — 2005*
LPG	AP-42, Vol. 1, Table 1.5-1 B.H. Haneke — A National Methodology & Emissions Inventory, pg. 4 *CORINAIR Emission Inventory Guidebook — 2005*
Natural gas	AP-42, Vol. 1, Tables 1.4-1 and 1.4-2 *CORINAIR Emission Inventory Guidebook — 2005*

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

Fuel	Methodology	Source
Diesel fuel	U.S. EPA	AP-42, Vol. 1, Table 3.1-1
	USAF (distillate oil)	FAA's *Air Quality Handbook*, Table H-2 1985 National Acid Precipitation Program
Gasoline	USAF	FAA's *Air Quality Handbook*, Table H-2 NONROAD
	U.S. EPA	AP-42, Vol. 1, Table 3.1-1
Kerosene/naphtha (jet fuel)	USAF	FAA's *Air Quality Handbook*, Table H-2
LPG (propane or butane)	USAF	FAA's *Air Quality Handbook*, Table H-2 NONROAD
Natural gas	USAF	FAA's *Air Quality Handbook*, Table H-2
Residual/crude oil	USAF	FAA's *Air Quality Handbook*, Table H-2

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

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

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);

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 (i.e. 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	AP-42, Vol. 1, Table 2.1-12
	EPA's Factor Information Retrieval (FIRE) software *CORINAIR Emission Inventory Guidebook — 2005* (Group 9)

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

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

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);

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 (i.e. 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 apparatus. 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 (FBO).

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's *Air Quality Handbook*, Table H-5 (Jagielski, Kurt D., and Robert J. O'Brien, "Calculation Methods for Criteria Air Pollutant Emission Inventories") • *CORINAIR Emission Inventory Guidebook — 2005* (Group 6)
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's *Air Quality Handbook*, Table H-7 • *CRC Handbook of Chemistry and Physics*, 63rd Edition) • Occupational, Health & Safety Administration (OSHA) www.ohsah.bc.ca/index • *CORINAIR Emission Inventory Guidebook — 2005* (Group 6)

4.5 For demonstration purposes, estimates of VOC emissions from surface coating can be obtained using the following general equation that 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:

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

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);

ER = control equipment emissions reduction efficiency (%).

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 (i.e. 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 in 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:

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

where:

E_{VOC} = emissions of VOC;

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

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

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 of the litres 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 = 200 litres

200 litres x 0.87 kilograms/litre = 174 kilograms of VOC (i.e. 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 (e.g. VOC).

5.2 Fuel storage tanks can emit VOC from both "standing" (i.e. storage) and "working" (i.e. 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 (i.e. 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	AP-42, Fifth Edition, Volume 1, Chapter 7: Liquid Storage Tanks

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

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

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);

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:

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

6. FIRE TRAINING

6.1 At some airports, airport rescue and fire fighting (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, particulate matter 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 The FAA *Air Quality Handbook* is the most authoritative source of information for fire training activities and is not included within the CORINAIR 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’s *Air Quality Handbook*, Table H-3 (emission indices for uncontrolled fuel burning in training fires)
JP-5, tekflame	Exxon Mobil Chemical

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:

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

where:

E_{VOC} = emissions of VOC;

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

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 (i.e. 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 (i.e. 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. Comprised of both 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, urea, 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 which also 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 (i.e. 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-A3-8. An example calculation for aircraft de-icing can be found in Appendix 2, Section 5, and the calculation for airfield surface is conducted in the same manner.

Table 3-A3-8. Sources of emission rate data — de-icing/anti-icing activities

Substance	Source
Propylene glycol/ethylene glycol	FAA's *Air Quality Handbook*, Section H3.3.2.4 (emission indices)

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 (e.g. off-road or non-road vehicles) and vehicles that travel off-site (e.g. haul and dump trucks). Pollutant emissions also result from construction-related employee commute trips to and from a construction site.

8.2 Common U.S. sources of emission rate data for construction activities are provided in Table 3-A3-9.

Table 3-A3-9. Source of emission rate data — construction activities

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

8.3 For Europe, emission factors for these activities can be found in the *CORINAIR Emission Inventory Guidebook*[1].

8.4 For demonstration purposes, estimates of PM emissions from the working of a storage pile can be obtained using the following general equation that considers the throughput of the operation (i.e. 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.

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

where:

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

2 = number of drops material undergoes;

TH = total throughput;

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

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[1] The name of the *Corinair Emission Inventory Guidebook* has been changed to the *EMEP/EEA Air Pollutant Emission Inventory Guidebook*.

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 (i.e. 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 (i.e. bulldozer, articulated truck), the size of the equipment (i.e. 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 (i.e. hours) of operation.

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

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

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);

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 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 (i.e. 1.2 metric tonnes).

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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 (e.g. 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 (i.e. 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 (i.e. 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.

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 (i.e. district) and macro-scale (i.e. 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 (i.e. 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.

Geographic scope — road network extent

2.5 The geographic scope defines the road network and road types that are included in a vehicle traffic emissions inventory. The geographic scope is also used in conjunction with the chosen approach to identify the type of input data required for the inventory.

2.6 The geographic 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.

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 (i.e. such as vehicles from non-

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[1] Department for Transport (UK), *Project for the Sustainable Development of Heathrow: Air Quality Technical Report,* 19 July 2006, <www.dft.gov.uk/stellent/groups/dft_aviation/documents/divisionhomepage/612123.hcsp> (July 2011).

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 (i.e. temporal) scope defines the averaging period over which a vehicle traffic emissions inventory is to be calculated (e.g. 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 (e.g. 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 four categories:

a) passenger cars;

b) other light-duty vehicles (i.e. taxies, vans, limos);

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 of 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-dependant profiles for different road segments (e.g. to allow for morning/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 (i.e. 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 (e.g. idle, cruise, deceleration, acceleration, cold start, hot start and stabilized), fuel type/volatility, vehicle technology, age, inspection/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) U.S. EPA MOBILE6;

b) California's EMFAC2002;

c) CITEPA method based on COPERT-IV;

d) Eurocontrol ALAQS method based on COPERT-IV.

4. MODEL VARIATIONS OF POLLUTANT EMISSION FACTORS

4.1 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 (MOBILE6, CITEPA). These models estimate a number of exhaust pollutants including CO, HC, NO_x, PM, SO_x, select HAP and carbon dioxide CO_2. Evaporative emissions from fuel and PM emissions from brake- and tire-wear are also provided in many cases.

4.2 The pollutants relevant to road vehicle emissions are divided into legislated and non-legislated groups. The pollutant species that are typically modelled are shown in the Tables 3-A4-1 and 3-A4-2. When selecting a model it is important to note that some vehicle emissions models will report pollutants differently, e.g. some might provide a breakdown of hydrocarbons and volatile pollutants, while others might aggregate these as one pollutant. Among other pollutants that are not included, lead may need to be calculated if leaded fuel is still in use and if a leaded fuel emission factor is available.

4.3 Table 3-A4-1 indicates the pollutants that are subject to air quality legislation in one or more nations.

4.4 Some models are able to report an extended set of pollutants if the appropriate indices are available as shown in Table 3-A4-2.

Table 3-A4-1. Base pollutant set — legislated

Pollutant	Remarks
CO	
HC	Some models may provide results per component pollutant — see extended set of pollutants below.
NO_x (NO_2 + NO)	Some models may report NO_2 and NO separately.
SO_x	
PM_{10}	
$PM_{2.5}$	May be included in the report for PM_{10}.

Table 3-A4-2. Extended set — non-legislated

Pollutant	Remarks
1.3,-Butadiene	
Acetaldehyde	
Acrolein	
Benzene	
CO_2	Most models will calculate fuel burn (hence CO_2 can be derived) but because CO_2 is not an LAQ gas, it is included in the extended set.
CH_4	
Cu	
CHCO	
HCB	May be included in HC.
N_2O	
NH_3	
MTBE	
PAH : BaP, BbF, BkF, IndPy	May be included in HC.
PCDD-F	May be included in HC.
TSP	

5. CALCULATIONS

5.1 The following 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.

5.2 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.

5.3 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 (e.g. 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 (e.g. 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 (i.e. one hour, one week and one year).

Simple approach

5.4 For demonstration purposes, emissions estimates using the simple approach can be calculated using the following general equation:

$$E = RL \times NV \times EF \qquad \text{Eq. A4-1}$$

where:

E = emissions (e.g. grams);

RL = road length (e.g. kilometres);

NV = number of vehicles on the road by class, age and speed;

EF = emission factor considering vehicle class, age and speed (e.g. grams/vehicle-kilometre travelled).

5.5 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, (e.g. 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 (i.e. 15 metric tonnes).

Advanced approach

5.6 For demonstration purposes, urban driving emissions estimates using the advanced approach can be calculated using the following equation:

$$E_{total} = (RL_1 \times NV_1 \times EF_1) + (RL_2 \times NV_2 \times EF_2) + (RL_n \times NV_n \times EF_n) \qquad \text{Eq. A4-2}$$

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;

$F_{1..n}$ = emission factor considering vehicle class, age and speed (e.g. grams/vehicle-kilometre travelled).

5.7 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.

5.8 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. For the period of interest (24 hours), the average temperature is 21 degrees Celsius.

5.9 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 (i.e. 7.96 metric tonnes).

Sophisticated approach

5.10 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).

5.11 Assume that during the morning peak hour of a 24-hour 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.

5.12 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.

5.13 During the morning peak hour, the average temperature is 4 degrees Celsius and during the evening peak hour, the average temperature is 21 degrees Celsius. All other hours of the day, the temperature is 10 degrees Celsius.

5.14 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 (i.e. 1.47 metric tonnes).

5.15 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

5.16 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 (e.g. 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.

5.17 For demonstration purposes, emissions estimates for vehicles idling at curbsides and travelling/idling in parking lots can be calculated using the following general equation:

$$E_{total} = (TD_m \times NV_m \times EF_m) + (T \times NV_1 \times EF_1) \qquad \text{Eq. A4-3}$$

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_l = number of idling vehicles by class, age and speed;

EF_l = idle emission factor considering vehicle class, age and speed (e.g. grams/minute).

5.18 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 2 minutes. The average daily temperature is 21 degrees Celsius. 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).

Chapter 4

TEMPORAL AND SPATIAL DISTRIBUTION OF EMISSIONS

4.1 INTRODUCTION

4.1.1 At an airport, emissions occur at various locations and time periods depending on the purpose and operational characteristics of the source. For example, stationary sources such as generators or heating plants emit from fixed locations and may be continuous or intermittent. By comparison, aircraft emissions are more mobile, occurring at various locations on the airport, times of day and intensities. Aircraft emissions generated during take-off and landing operations also occur off the airport and up to the local mixing height, which is often assumed to be 1 000 metres or 3 000 ft in height. This results in the dispersion of emissions becoming not only a temporal distribution but a spatial three-dimensional (e.g. "3-D") consideration as well.[1] Other mobile sources are usually confined to a general area but move within the area and vary by time of day. The assessment of this variability of location and emissions density must be done by temporal and spatial distribution of the emissions. This is especially true if dispersion modelling is to be performed as part of the overall air quality analysis. Depending on the dispersion modelling source configuration (e.g. point, line, volume or area) different information may be needed for the emissions distribution. This chapter describes the emissions distribution process that occurs in the general vicinity of airports.

4.1.2 In summary, the objectives of the assessment of airport-related emissions distribution include:

a) determination of spatial (placement) emissions densities;

b) determination of temporal (time of day and total release time) emissions;

c) evaluation of areas of the airport that include specific pollutants;

d) determination of "hot-spot" areas on airport property; and/or

e) development of dispersion modelling input.

4.1.3 The process of emissions distribution is closely tied to the overall emissions inventory process and dispersion modelling, if conducted. Accordingly, frequent references to Chapter 3 will be made, rather than repeating the information.

4.1.4 Emissions distribution may occur at different times during the air quality analysis of airports or may not be done at all. For example, some airports complete this work as they complete the emissions inventory, combining the work effort. Other airports do not complete the emissions distribution until dispersion modelling begins. The reason for this is that an emissions inventory includes the total mass from the entire airport, broken down by source and pollutant types, and may be all that is required. Alternately, an allocated inventory places the emissions temporally and spatially, providing additional information that can be used for trend analysis, dispersion modelling input, or for mitigation of emissions distribution. The detailed data needed for this analysis also may not be available during the initial emissions inventory, which may delay the completion of the work.

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1. It should be noted that the term allocation is often used during airport analysis instead of the term distribution. However, allocation in a global sense can have a different meaning and as such is not used in this document.

4.1.5 In general, the distribution of airport-related emissions involves the following steps:

a) define the purpose of the distribution (i.e. emissions density, emissions variability or dispersion modelling);

b) collect source-specific, detailed spatial and temporal information;

c) perform quality assurance on spatial and temporal data;

d) allocate sources by specific area, time of day and duration of operation;

e) perform emissions inventory as described in Chapter 3 by source, area and time of day; and

f) aggregate and report results.

4.1.6 If the ultimate application of the data is for dispersion modelling, then the approach to assessing spatial and temporal distribution of the emissions is often dictated by the requirements of the dispersion model and the associated meteorological data. Typically, the concentrations at the output of the dispersion model will be required to show annual, eight- and 24-hour means with the number of times that the limits are exceeded in those time spans and is discussed in 4.2.4 to 4.2.6 of this chapter. The geospatial representation may also need to be compatible with a regional or national assessment, and care is needed to determine the correct basis so that delays do not occur.

4.2 GENERAL EMISSIONS DISTRIBUTION CONSIDERATIONS

4.2.1 Since emissions distribution determines the spatial representation of emissions, the first task is the collection of operational data and location information for each source on or near the airport. Typical airport emissions source pollutant species were previously described in Chapter 3, Section 3.3, and the sources were described in Chapter 3, Section 3.4. Distribution of emissions is often done in conjunction with the initial data collection for the emissions inventory as previously described in Chapter 3, but this is not always the case. The reason for performing the emissions distribution as a separate task is that for an emissions inventory, location and time of release do not matter and the work can be completed without distribution. As such, distribution can be completed at a later time if needed. In some locations, such as the U.S., an overall emissions inventory may be all that is needed unless increases in emissions occur or a major action is to be undertaken (e.g. new airport, runway or taxiway). In these cases, dispersion modelling is sometimes required and emissions distribution is generally completed in conjunction with the dispersion modelling task. If it is known that distribution will be required as the emissions inventory is undertaken, it is generally more effective to complete this work as part of the original task.

4.2.2 The additional information needed for spatial and temporal distribution can vary considerably from airport to airport. For example, the taxi time for an aircraft depends on runway and taxiway configurations, queue lengths, gate configurations and aircraft type. Because most airport operational and performance characteristics differ from one another, the time in the taxi mode will also vary and must be determined on a case-by-case basis. Best practice includes using airport-specific data whenever possible (i.e. use of the real taxiing time for each movement). Airport schedules also vary, resulting in the time periods in which the emissions actually occur being different. This results in data collection being required for each individual airport, although simplified procedures and assumptions can be used in some cases.

4.2.3 The data collection process often requires the air quality analyst to contact multiple entities to obtain the required information. Tables 4-1 and 4-2 list possible entities for obtaining this information, by emissions source type. To the extent possible, data must be specific by time and place for a typical operational day. Variations in these parameters occur but are sometimes difficult to quantify resulting in the assessment of “typical” or “average day” conditions being analysed most often. At some airports seasonal variations also occur and must be considered.

4.2.4 Each emissions source is allocated to a specific time period by location on the airport. The use of one-hour time periods over a 24-hour average day is most often used because of dispersion modelling requirements. The source may not operate for the entire hour and, in the case of mobile sources, may change locations at the airport. This must be considered during distribution. This can be done by allocating the emissions using fractions of the estimation period or by using factors. Either method will result in the same outcome.

Table 4-1. Sources of spatial data for emissions distribution

Emissions source	Possible entity for obtaining information
Airport runway/taxiway/gate geometry	Maps Orthophotos Airport layout plans (AIP) Geographic information systems (GIS) files Field surveys
Stationary sources	Maps GIS files Orthophotos Airport operation office Fixed-based operators Maintenance operation office Field surveys
Airside mobile sources	Master plan Noise reports Airport operation office Maintenance operation office Field surveys Handling companies/agents
Landside mobile sources	Master plan Noise reports Airport operation office Maintenance operation office Field surveys Regional authorities
Non-standard sources	Master plan Airport operation office Maintenance operation office Airport safety office Airport security Fixed-based operator surveys Field surveys

Table 4-2. Sources of temporal data for emissions distribution

Emissions source	Possible entity for obtaining information
Stationary sources	Master plan Noise reports Fuel delivery schedules/history Fuel-use records Airport operation office Airport maintenance office Fixed-based operator surveys
Aircraft	OAG Airport schedules Tower logs Airlines Cargo scheduling Noise reports Observations
Airside mobile sources	Aircraft scheduling Airlines Service providers Master plan Airport operation office Maintenance operation office Observations Handling companies
Landside mobile sources	Master plan Mass transit scheduling Parking lot counts Employee schedules Cargo scheduling Roadway traffic counts Speed limits Roadway speed measurement Airport operation office Maintenance operation office Airport security Observations/field survey
Non-standard sources	Master plan Airport operation office Maintenance operation office Airport safety office Airport security Fixed-based operator surveys Field surveys

4.2.5 When the purpose is for emissions distribution only, emissions are allocated to activity areas or grids for each time increment selected. The areas or grids defined will depend upon the source and its typical operation area (i.e. tugs used for aircraft pushback tend to remain in specified areas around the terminal gates). Final results can be by the hour, day, week, month or year, but as previously stated one hour is used most often due to dispersion modelling input needs. The end result can then be used to estimate emissions density changes on the airport, “hot-spot analysis”, emissions variability or comparison of trends.

4.2.6 When the purpose is for dispersion modelling, the required inputs for the dispersion model dictate where emissions are allocated. Common practice is to predict one-hour concentrations to determine the worst hour of the day or greatest consecutive period of hours depending on the pollutant and the applicable regulations. This provides local ambient concentrations that can be used to determine health or public welfare impacts. As previously stated, the most common time periods are one hour, eight hours, 24 hours and yearly. At EU airports, legislation requires the number of occurrences of concentration levels (over various time steps as expressed previously, e.g. 24-hour/eight-hour/one-hour average) per year. While this occurs during dispersion modelling, it must be considered.

4.3 SPATIAL DISTRIBUTION[2]

4.3.1 The overall process discussed in Chapter 3 still applies. The difference is that the overall inventory is broken into smaller inventories that are specific to a particular location. As stated by the U.S. EPA, “Because air quality modelling strives to replicate the actual physical and chemical processes that occur in an emissions inventory domain, it is important that the physical location of emissions be determined as accurately as possible. In an ideal situation, the physical location of all emissions would be known exactly. In reality, however, the spatial allocation of emissions in a modelling inventory only approximates the actual location of emissions.” The approximation required is not just a U.S. problem, but occurs at all airports. This is very true for airports where activities vary day to day. However, the spatial emissions density can still be determined for the overall average. The process first begins by deciding on the areas, cells or zones where emissions are to be allocated, depending on the intended purpose of the results and the requirements of the model used. The size of the areas, cells or zones is also a function of the operational area of the source, as previously mentioned. Distribution can be done by establishing a series of similarly shaped cells over the airport or by determining activity areas for each source. Cells are often used in conjunction with emissions density charts to show changes in overall emissions density in the vicinity of the airport. This is a strong aid for the airport planner to evaluate where “hot spots” occur and helps to determine where control measures may be needed. Cell-based representation also fits closely with dispersion analysis where the modelled concentration levels would be used in conjunction with land-use charts, maps of population, housing type, sensitive zones, etc.

4.3.2 On the other hand, distribution by activity zones allows the airport to evaluate emissions related to those particular activities. These activity zones could be the gate area, the airfield, the parking lots, a roadway network, unloading zones, etc. As before, the accuracy of allocating to each zone depends on how well the source can be characterized. Each zone’s emissions would allow characterization of that zone and comparison of alternate programmes for reducing these emissions for the specific activity. In the case of dispersion modelling the zones could be related to evaluation of methods to reduce potential impacts on health or public welfare at the local level.

4.3.3 Spatial distribution is straightforward for stationary sources and can easily be developed. The stationary source emissions are determined by the time of use but do not move. Mobile sources create difficulties because the moving source may cross several delineated spatial boundaries unless an activity zone is specifically defined for this source. This is especially true for moving GSE where guidelines may be necessary to ensure a reliable and consistent spatial distribution. When the cell approach is used, the partial emissions for the operation must be computed for each cell. This results in the combination of time and space parameters. A common approach is to determine the time in a particular cell by use of the emission index and allocate the emissions for that cell. This procedure was described in

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[2] In the context of this manual, the terms “allocation” and “distribution” are used interchangeably.

Chapter 3. This process must be completed for all mobile sources entering the defined area and summed with the stationary sources in the area. The sum of all sources, for each specific pollutant, results in the emissions density for that defined area.

4.3.4 It is important to remember that spatial distribution provides only emissions density information. Emissions variability requires the use of temporal distribution, and the two combined provide an even stronger tool for the analyst.

4.4 TEMPORAL DISTRIBUTION

4.4.1 Temporal distribution provides a measure of emissions variability, by duration. As stated by the U.S. EPA, “Because air quality modelling attempts to represent the actual physical and chemical processes as they occur over a specific duration of time, it is important that the temporal allocation of emissions be as accurate as possible. Temporal allocation can be thought of as an accounting of emissions variation over time. The simplest temporal allocation is for a steady-state emissions source that continually releases emissions at the same rate all the time. Under actual conditions, however, steady-state emission sources are quite rare. Instead, under actual conditions, emissions sources may operate only in the winter, not operate on Sundays, or their activity may peak during certain hours of the day. Temporal allocations allow emissions variability to be correctly modelled during the desired modelling periods. The desired modelling periods will vary depending upon the purpose of the inventory.”

4.4.2 Temporal distribution requires the time of day of the activity to be determined. For example, a heating plant may run continuously and emissions will be constant for the entire day and can be easily allocated over the day. This would result in activity factors being the same for each hour and a constant emissions density for this stationary source. However, mobile sources such as aircraft do not have continuous activity and often do not last for an entire hour. This makes distribution more difficult. This is compounded by the source moving between defined areas as previously discussed. For these sources, care must be taken to define the times of use by zone or defined area. In the extreme case, activity profiles may be needed for each major taxi-route and considered as a separate zone. The time a source is in a zone can be related to the speed of the mobile source and the distance travelled in each defined area, that is:

Time in zone = distance travelled in zone/speed of mobile source.

4.4.3 If the speed varies in the zone, this process may need to be further subdivided and the total determined. Often, an average speed is assumed in order to simplify the process. Also, the path the mobile source traverses while in the zone must be determined. When roadways, taxiways, runways or defined routes are involved the process is well-defined. When the path is not well-defined, approximations must be made. For example, a car travelling in a parking lot may be assumed to travel one-half the total possible distance on entry and then one-half the total possible distance during egress. Once time has been determined in the defined area, the emissions estimation process becomes that described in Chapter 3.

4.4.4 It can be seen that other difficulties may occur for sources with no defined path at all. In these cases observation may be needed to determine a representative time. A simplified procedure could also be used based on past studies for particular types of equipment (e.g. GSE). Data of this type are presented in Chapter 3, Appendix 2. For minor stationary sources such as de-icing, fire training and engine testing, some simplifications could be made to allocate the emissions temporally and spatially. (For example, meteorological data can be used to define when de-icing is used.)

4.5 USE OF COMPUTER MODELS

4.5.1 Air quality computer models that have been developed for airport analyses often permit both spatial and temporal input and output as elements of the emissions inventories. Such models include EDMS (U.S. FAA), LASPORT and ALAQS-AV (Eurocontrol).

4.5.2 During the input data development for these models, the process previously described will often be needed since the models may not have algorithms for all sources to allow spatial and temporal determination. A GIS-based model should facilitate the spatial distribution process through its highly visual interface; an example is shown in Figure 4-1 taken from the Arcview-based ALAQS-AV. LASPORT and EDMS also have GIS capabilities. It should be noted that any graphical user interface-based programme will support the spatial determination more easily and, with proper input, assist in the temporal distribution. The user should consult the appropriate model user's guide for further information.

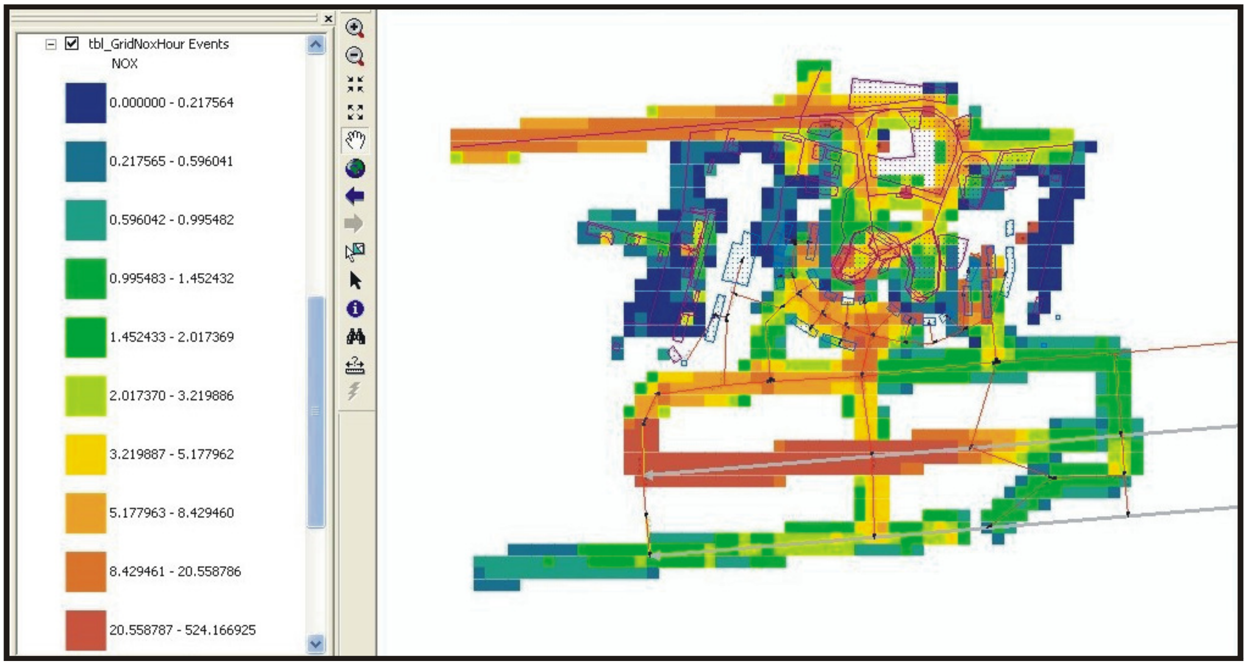

Figure 4-1. Example of 2-D geospatial emissions inventory

4.6 DATA FORMATTING AND REPORTING

4.6.1 It is often essential to use a matrix-type approach when reporting spatial and temporal emissions results. Figure 4-2 shows an example (U.S. EPA). In this figure, it can be seen that sources 23 and 24 are continuous emitting sources while source 25 represents a source with temporal emissions variability. From this type of analysis, emissions for any hour can be easily determined. For example, source 24 emits 417 pounds from 2:00 to 3:00 p.m. This same matrix approach may also be used for spatial reporting or for each individual source in a single table, a combination of spatial and temporal data. In some models such matrixes can be obtained as an output.

4.6.2 Once the data are in this format, graphics can also be used to display the results and more easily identify trends. For example, Figure 4-3 is the plot of source 25 that was shown in Figure 4-2. It can be seen that the source is utilized in the afternoon but much less at other times of day. This could be used for spatial distribution and with 3-D graphics as well, resulting in much easier comprehension by the reviewer.

4.6.3 Graphical displays may be used to show the geo-spatial distribution, usually in 2-D density grids, but careful use of 3-D techniques could also be envisaged for sources such as aircraft as illustrated in Figure 4-4.

Hour	**…**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**…**	**Total**
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
23	…	435	435	435	435	435	435	435	435	435	435	435	435	435	435	…	10005
24	…	417	417	417	417	417	417	**417**	417	417	417	417	417	417	417	…	**10008**
25	…	508	763	847	847	847	847	847	847	847	847	763	508	254	85	…	9996
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

Pounds per hour released

Sources

Figure 4-2. Diurnal profile file

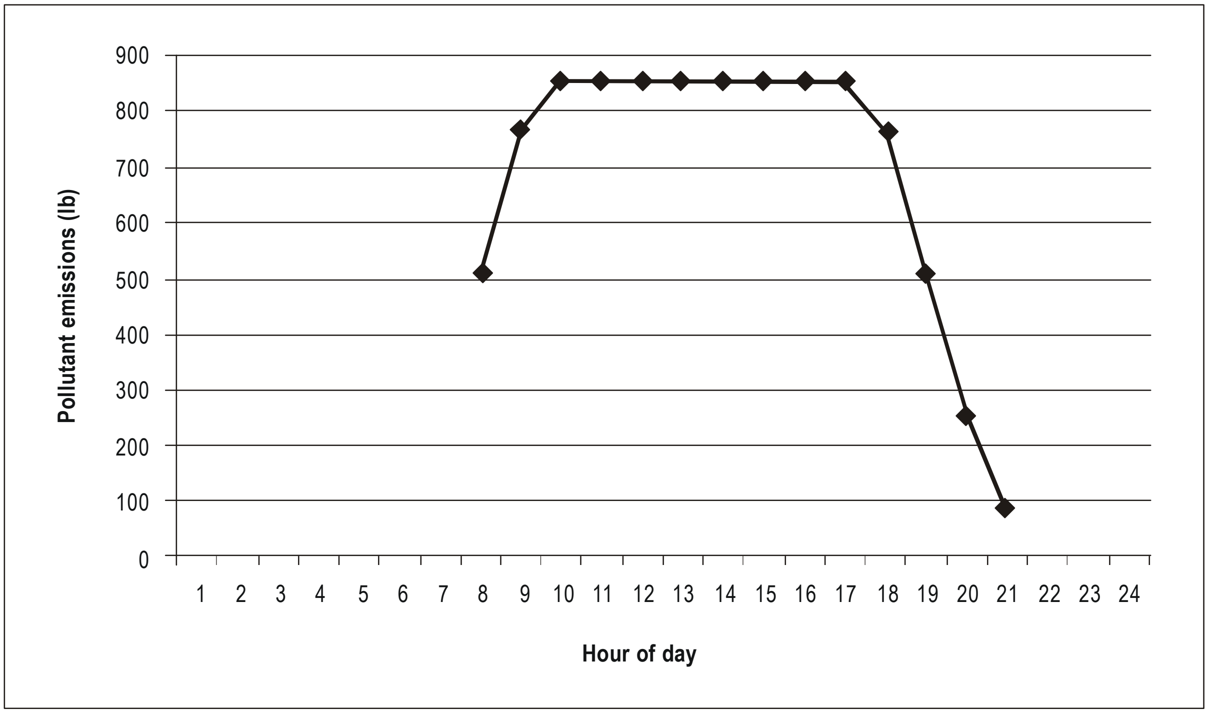

Figure 4-3. Diurnal profile plot

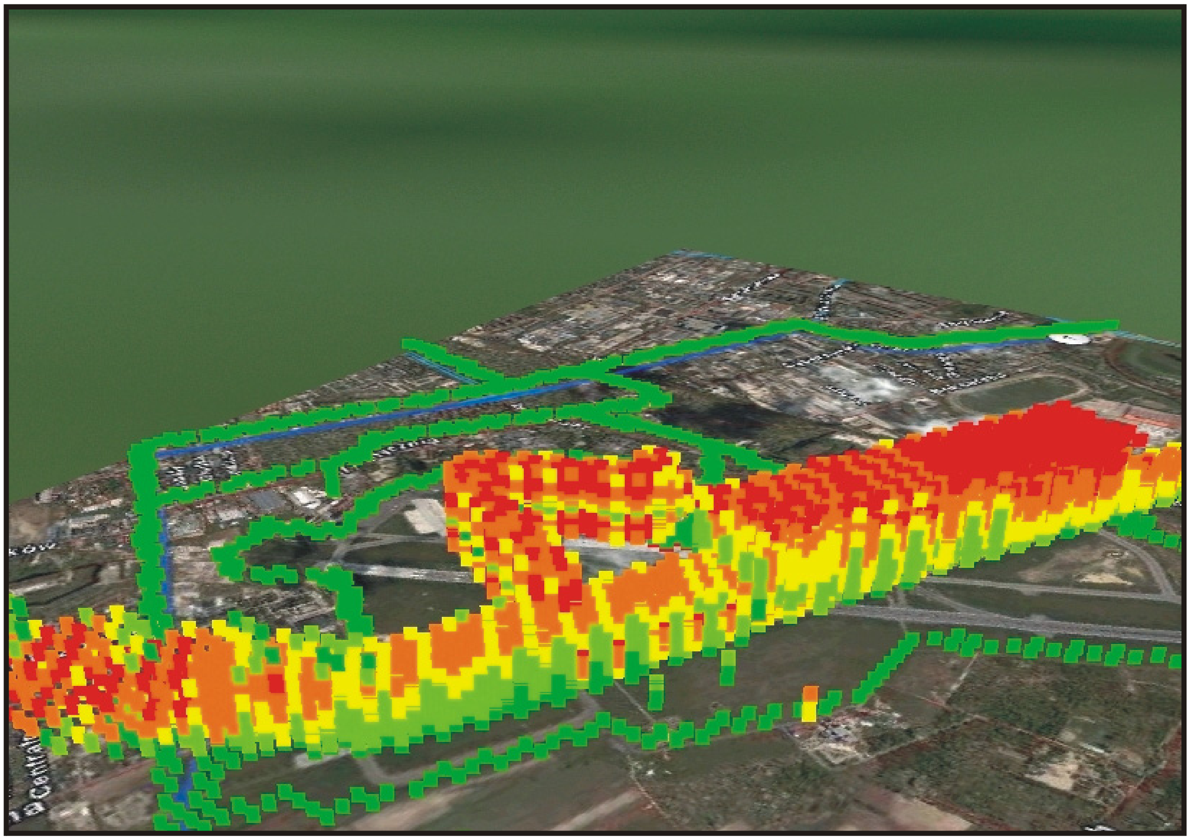

Figure 4-4. Example of 3-D geospatial emissions inventory

Chapter 5

DISPERSION MODELLING

5.1. INTRODUCTION

5.1.1 In Chapter 3, guidance on estimating the mass emitted for various pollutants was discussed. However, the total mass emitted does not account for mixing in the atmosphere, which determines local concentrations, or how much mass is mixed in the air at any given time. Additional modelling is required to estimate these local ambient concentrations.

5.1.2 A trace substance that has been released from a source into the free atmosphere will be transported by the mean wind field and dispersed by atmospheric turbulence. This process is referred to as atmospheric dispersion. Dispersion can be more rigidly defined[1] as "the scattering of the values of a frequency distribution from an average." It then follows that atmospheric dispersion modelling is the mathematical simulation of the scattering or mixing process in the ambient atmosphere. The trace substances most often evaluated are regulated atmospheric pollutants and were delineated in Chapter 3, 3.4, for airport sources. In an airport-related dispersion calculation, the atmospheric mixing of these trace substances or pollutants that are emitted from local sources is modelled based on scientific principles and the resulting concentration distributions (usually near the ground) are predicted. The results, or predicted atmospheric concentrations, form the basis for local air quality (LAQ) impact studies and are used to show compliance with required regulations and/or standards.

5.1.3 This chapter presents the need for dispersion modelling in the vicinity of airports, provides a brief overview of dispersion models, summarizes typical practices that occur during atmospheric dispersion modelling at airports and examines how predicted concentrations are used to estimate impacts. The chapter has been laid out to follow that of Chapter 3, that is, the required modelling will be discussed in terms of the simple, advanced, and sophisticated approach.

5.2 EXTERNAL REQUIREMENTS AND DRIVERS

5.2.1 This section discusses the need for dispersion modelling and the external drivers that both cause and affect this need. As described in detail in Chapter 2, air quality assessments for proposed actions at airports are often necessary to comply with:

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

b) increased awareness of health impacts, leading to the production of new regulations, including the addition of new pollutant species;

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

d) greater public expectations regarding air quality levels;

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[1] Merriam-Webster Online Dictionary, <http://www.merriam-webster.com/dictionary/dispersion> (July 2011).

e) public relations exercises carried out by airport and environmental lobbies; and

f) legislative requirements of various countries and regions.

5.2.2 Emissions modelling to meet these requirements has been previously discussed. Emissions modelling, a prerequisite to dispersion modelling, allows the change in emissions to be reviewed temporally and spatially. However, direct impacts are more related to the ambient concentrations and not just the mass of emissions emitted. Ambient air quality standards, real impacts and health impacts are better evaluated by the use of ambient concentrations than with mass emitted. As previously described, atmospheric mixing of emissions results in ambient concentrations most often used to determine local impacts. Measurements, described in Chapter 6, can be very costly, define only the concentration at a point in space for each measurement and do not readily reveal the fractional contribution from each contributing source. Dispersion modelling allows the evaluation of local air quality to be done at a reasonable cost. Regardless, the need for dispersion modelling is to determine the ambient mixing as a part of the overall analysis process.

5.2.3 Beyond the evident need for dispersion modelling, legislation or ordinances often mandate that the estimation process be used. The regulations resulting from these legal requirements may also specify how the dispersion modelling must be accomplished or how variables are considered. The analyst is prompted to review any related requirements to ensure the process occurs as mandated.

5.3 GENERAL DISPERSION CONCEPTS

5.3.1 This section provides a brief overview of the basic physical concepts included in dispersion modelling and the process required. References are included to allow interested parties to explore these concepts in more depth than presented here. Understanding how the models work should lead to more appropriate use of the models.

5.3.2 When a trace element or pollutant is emitted from a source, its final fate is determined by the characteristics of the pollutant, source characteristics, atmospheric motion and local topography. Each of these parameters plays an important role in the local concentrations. A pollutant that is released in its final form is called a primary pollutant. Primary pollutants that are very slow to react with other gases in the atmosphere are called passive pollutants. Primary pollutants such as carbon monoxide (CO) are often called inert because of the very long reaction time and residence time in the atmosphere. Secondary pollutants are formed in the atmosphere when the original precursor emitted undergoes chemical reactions or other conversion processes in the atmosphere and forms a new pollutant. The pollutant is termed secondary since the final composition is not as released from the source. Ozone (O_3) is a secondary pollutant.

5.3.3 The pollutant source affects the local concentrations due to the location of the release, the total mass flow rate and the dynamics of the exhaust air due to the effect on the atmospheric dispersion in addition to the atmospheric motion. Atmospheric motions determine the overall direction in which the emissions travel and are primarily responsible for the mixing with the ambient atmosphere (dispersion), thereby creating a pollutant “plume” (or “puff”). The direction of the plume is determined by the large-scale motion, such as the mean wind flow, while mixing is more related to small-scale eddies in the flow, referred to as turbulence. Likewise terrain characteristics and local building structures will have an effect on local area concentrations due to changes in the wind patterns and the generation of turbulence. All of these parameters affect atmospheric dispersion and lead to a three-dimensional, generally time-dependent concentration distribution of the emitted trace substance (pollutant). Likewise other substance-specific processes may have an effect such as dry and wet deposition.

5.3.4 The quantities that determine atmospheric dispersion resulting in a local concentration can be grouped as follows:

a) Q1 source parameters (location, shape, dynamics of the exhaust air);

b) Q2 emissions parameters (emissions strength of each trace substance for each source);

c) Q3 substance parameters (e.g. conversion or deposition properties);

d) Q4 atmospheric parameters (e.g. wind speed, wind direction, turbulence properties and temperature); and

e) Q5 terrain parameters (e.g. surface roughness, terrain profile, obstacles).

5.3.5 Not all of the above parameters are independent and most of the parameters are time-dependent. It is evident that the parameter set includes additional information than is required for emissions calculations, even when emissions allocation has been conducted as described in Chapter 4.

5.3.6 At airports, the relevant sources can be grouped as follows:

a) S1 aircraft, including auxiliary power units (APUs);

b) S2 aircraft handling sources (e.g. ground support equipment (GSE), aircraft fuelling, airside vehicles);

c) S3 stationary and area sources (e.g. power plants, fire training); and

d) S4 airport access traffic (e.g. landside motor vehicles).

5.3.7 The dispersion methodologies used are of course only for those sources directly included in the model. Regional or background contributions also add to the total local concentration to produce the total concentration. The total concentration is needed to compare to the applicable criteria or standards. These background sources can be substantial and come from sources at varying distances from the airport. How background sources and the resulting concentrations are accounted for needs to be considered based on the spatial resolution of the modelling area and data sources to be used, such as long-term ambient monitoring stations. This stands in contrast to noise assessments, where the airport contribution is usually by far the dominating component. To account for the overall concentration the background concentration must be added to the concentration predicted by the models. This results in:

$$c_t = c_s + c_b \qquad \text{Eq. 5-1}$$

where:

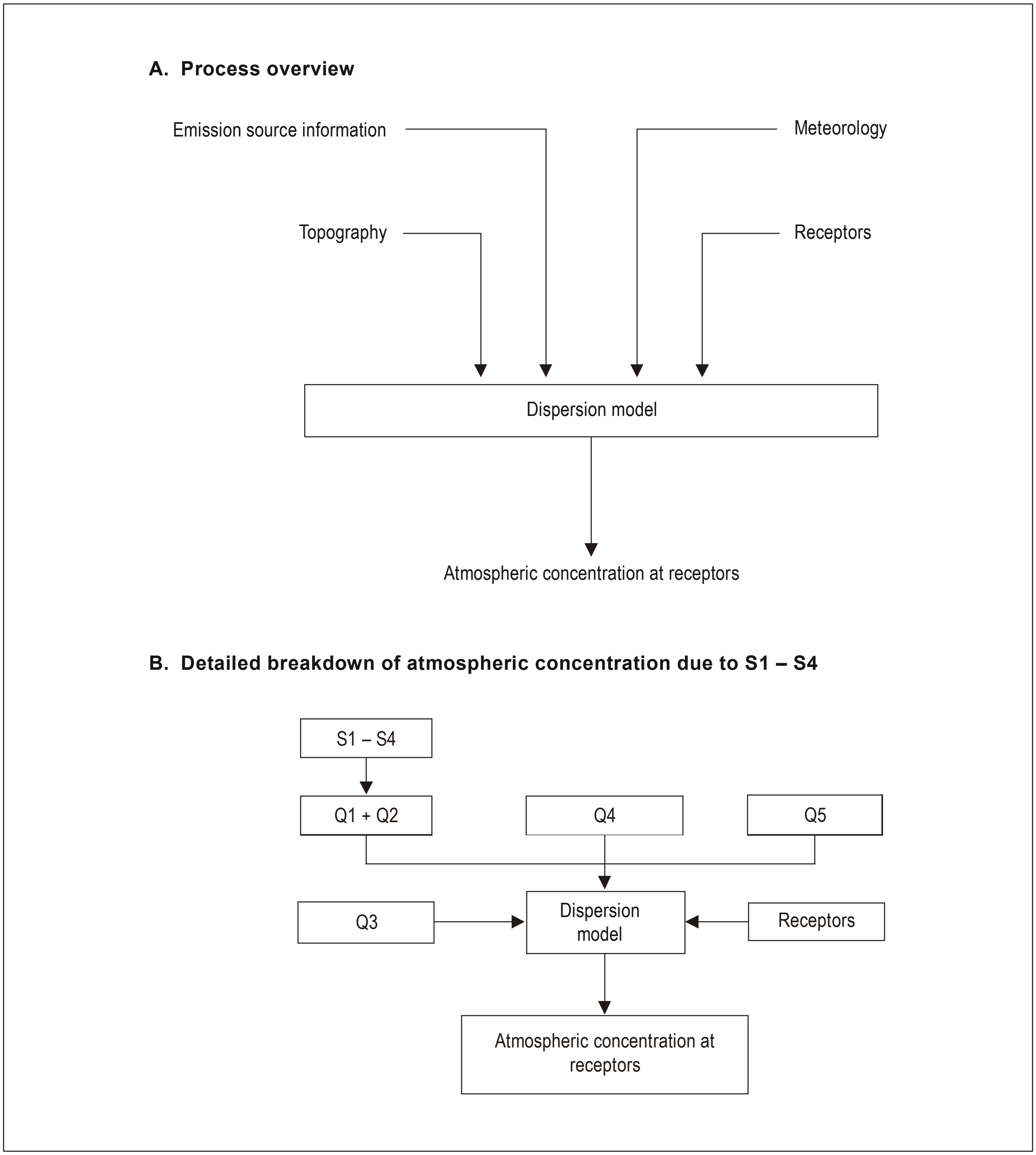
c = concentration with the subscripts t, s and b representing total, source and background, respectively.

5.3.8 The summation in Equation 5-1 represents the concentration at a point in space from all sources and is the value that is compared to applicable ambient air quality standards. Of note is that concentration, c, is pollutant-specific, that is, pollutants of different species cannot be added.

5.3.9 Figure 5-1 shows an overview of the modelling process (A) and the detailed steps required (B).

5.3.10 Several approaches to dispersion modelling have been applied at various airports around the world to predict local concentrations. As the science continues to evolve, so will the airport models. As such, this chapter will concentrate on the common methodologies currently used rather than on specific models.

5.3.11 The actual formulation for these models may vary. To assist the reader in a more comprehensive understanding of dispersion model methodologies, model formulations are briefly discussed in Appendix 1. Computer models in common use for airport dispersion modelling are listed in Appendix 2.



A. Process overview

B. Detailed breakdown of atmospheric concentration due to S1 – S4

Figure 5-1. Inputs and outputs of dispersion modelling[2]

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[2] J. Draper et al., *Air Quality Procedures for Civilian Airports and Air Force Bases, Appendix I: Dispersion Methodology*, FAA-AEE-97-03, Arlington, VA., April 1997.

5.4 REQUIRED MODEL INPUTS

5.4.1 This section provides information on variables needed to perform a dispersion analysis. While this is a general overview to provide an understanding for the reader, variables required will vary by modelling method (simple, advanced, sophisticated) and the specific model used. Additionally, each airport is unique and this large variability, the differences in the availability of data, and the desired final product also result in different data sets for each airport.

Information on emissions sources

5.4.2 A brief overview of the information that will be needed to complete the concentration analysis is included in this section.

Airport emission sources

5.4.3 Air pollution sources at airports are many and varied. In order to perform concentration modelling, for each source studied, the emissions strength of each of the modelled substances must be available. A detailed description of the emissions sources found at an airport is given in Chapter 3.

Airport temporal and spatial considerations (e.g. taxiways, runways, gates)

5.4.4 When performing an emissions inventory, spatial and temporal allocations are not always required or completed. However, spatial and temporal allocations are of prime importance during dispersion modelling since local concentrations will be calculated. These local concentrations depend upon the distance to a source and its time of operation. This requires not only the emissions data, but explicit detail on when, where and in which way the emissions occur. Airport spatial and temporal variation was previously discussed under emissions distribution in Chapter 4.

5.4.5 Dispersion modelling often relies on Cartesian coordinates (x, y, z) where x and y are the horizontal distances and z is the vertical distance from an established datum point. A common practice, for easy transfer to maps, is to set the positive y axis in the north direction. A thorough understanding of the airport operation is required for detailed dispersion modelling (see Chapter 4). For all but the simple approach, all source locations must be established (see Chapter 4) and for dispersion modelling a new component, the receptor, must be added as discussed in 5.4.16. The receptor location must be exactly specified, as with the source, leading to the use of coordinates such as the Cartesian coordinate system. The defined receptor location determines where the concentration will be predicted using the dispersion models. This is most often at locations of frequent human use. Some dispersion models are based on specific time periods since their dispersion parameters change with time after release. This is often an internal parameter, transparent to the user, and can be adapted, based on the output needs, to compare to ambient air quality standards.

Emission factors

5.4.6 Emission factors are needed to determine the rate of release of emissions from each source. Emission factors are both source- and pollutant-specific. The reader is referred to Chapter 3 for a complete discussion of emission factors.

Meteorology

5.4.7 Meteorology is an essential input for the dispersion calculation. Without an input for the local weather, it is not possible to perform dispersion modelling except in simple cases. For all modelling of any sophistication, the parameters for the planetary boundary layer (PBL) must be known. As with other variables, the degree of sophistication of the modelling process can vary but a general listing of needs is discussed here. Additionally, some common sources of these data are listed in Appendix 3 to this chapter.

Wind data

5.4.8 Horizontal wind speed (velocity) and direction generated by the geostrophic wind component and altered by local surface characteristics and other parameters such as terrain is of primary importance in all but the simple case. In the advanced and sophisticated approach, local climatology must be established in more detail and may include wind data from multiple elevations and/or vertical wind gradients. Often these historical data are available from existing records (see Appendix 3). The wind speed and direction will vary due to surface characteristics and topography, local buildings, surface cover and nearby influences such as large bodies of water. These factors might be taken into account to establish a suitable wind field depending on model requirements.

Turbulence and atmospheric stability

5.4.9 The atmospheric stability can be simply defined as the turbulent status of the atmosphere and has a significant effect on the dilution rate of pollutants. Turbulence refers to the small motions of the atmosphere, generally circular in nature and referred to as eddies. These eddies vary dramatically in size depending on atmospheric stability. Small eddies can “rip” apart the plume and cause mixing with the local air while large eddies tend to move the entire plume.

5.4.10 Turbulence can be characterized in several ways including empirical methods (e.g. the Pasquill-Gifford stability classes), the flux Richardson number, the gradient Richardson number or the Monin-Obukhov length. While each requires different inputs to determine, the basic meteorological information needed is wind speed by height (wind shear), temperature by height (lapse rate), wind velocity fluctuations and surface characteristics. Turbulence is often broken into the categories of stable (vertical mixing of pollutants is hindered), neutral (vertical motion of the atmosphere is neither hindered nor enhanced), and unstable (vertical motion of the atmosphere is enhanced).

Upper-air data

5.4.11 In the advanced and complex analysis it is recognized that the atmospheric conditions change with height. To account for this change, meteorological data at greater heights (up to some hundred metres) than surface data are often used, although some models can approximate the change with height based on surface data and use boundary layer parameterization. If the measured data are used, these data come from acoustic soundings, release of balloons with instrument packages, and reports by aircraft.

Temperature

5.4.12 The ambient temperature has an effect on the rate of chemical reactions and may be needed in the sophisticated approach. The change of temperature with height (lapse rate) may be needed by models to assist in determining atmospheric stability and could be needed for both the advanced and sophisticated approach.

Cloud cover

5.4.13 Cloud cover has the direct effect of changing the albedo and is often used indirectly for atmospheric stability in the advanced approach.

Derived parameters (model-specific)

5.4.14 Many parameters may be important depending upon the model chosen (e.g. sensible heat flux, surface friction velocity, convective velocity scale, vertical potential temperature gradient, Monin-Obukhov length, and the Bowen ratio). Often these parameters can be derived from the basic meteorological data listed above. The parameters are not described here, but if not computed directly by the dispersion model selected, the user should take great care to understand these parameters and how they may be derived.

Surface roughness

5.4.15 Different types of surfaces change the frictional characteristics of the surface and affect the vertical wind profile and the turbulence characteristics. For airports this is often a vegetative flat relief near the runways, but the location and height of buildings such as the terminal, tree lines and, for some airports, significant changes in the surface profile must all be determined. After this determination, charts may be used to determine the value of the surface roughness parameter (z_0) to be included in the model. Table 5-1 shows an example of values that can be selected. Of note is that this is a parameter and not the true length of the objects on the surface.

Table 5-1. Surface roughness length, z_0, for typical surfaces[3]

Terrain description	z_0 (m)
Water	0.0001
Grassland (winter)	0.001
Grassland (summer)	0.1
Cultivated land (winter)	0.01
Cultivated land (summer)	0.2
Swamp	0.2
Desert shrubland	0.3
Deciduous forest (winter)	0.5
Deciduous forest (summer)	1.3
Coniferous forest	1.3
Urban	1.0–3.0

Receptors

5.4.16 A receptor is a location in space that may represent human occupation or simply a location of interest. Receptors can also simply be a predetermined grid of a specific size, centred on an established airport reference point. Airport receptor locations may be defined on or off the airport. These are chosen by a review of the airport with particular

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[3] D.B. Turner, *Workbook of Atmospheric Dispersion Estimates, An Introduction to Dispersion Modelling*, 2nd Ed., Lewis Publishers, Boca Raton, FL., 1994.

interest in locations where normal human activity occurs or in other locations, for example, nature reserves. The choice of receptor locations will result in modelled concentrations at these points used to determine the overall impact at that location.

Background concentrations

5.4.17 As previously discussed (Equation 5-11), background concentrations are due to sources not considered during the modelling process. These concentrations must be added, on a pollutant-specific basis, to the model results to obtain the total concentration of any pollutant. Background concentrations are generated by nearby roadways, industry, commercial operations, residential areas and long-range transport. Background concentrations are most often determined by long-term measurement stations in the area since the sources are too numerous to be modelled during an airport evaluation. The averaged upwind concentration at the airport is often used and may be temporally allocated to account for diurnal changes in the other local sources. Depending on the pollutant, significant percentages of the overall (measured) concentrations may be from background concentrations sometimes brought into the study area from large distances.

Atmospheric chemistry

5.4.18 As previously mentioned, pollutants may react with other components in the atmosphere after being emitted by the source. This causes a change in precursors and creates new pollutants. This is particularly important for aircraft emissions where secondary gas and particulate matter pollutants are created. This is an advanced topic and will most often be built into the model used or may even be ignored depending upon the scope of the study. Chemical reactions are always ignored in the simple approach defined here. In the case where atmospheric chemistry is not explicitly considered, ratios based on historic data can be applied and this is defined in this document as the advanced approach. For example, the ratio of NO to NO_2 is important. Historic data may provide a typical ratio. This ratio can then be applied to the NO_x prediction (NO + NO_2) which is predicted by models without chemical algorithms. If not performed by the model, speciation of hydrocarbons may also be approximated in this manner based on the total hydrocarbon prediction and historic data.

5.4.19 Chemical reactions proceed at different rates and are affected by ambient concentrations, transport time, and ambient conditions with all being considered in the sophisticated approach. The time for the reaction to occur is different for each pollutant, and the reaction rate is necessary for dispersion modelling of reactive pollutants.

5.5 DISPERSION CALCULATION

5.5.1 Appendix 1 to this chapter contains a very general overview of the dispersion methodologies while Appendix 2 lists the models commonly used for airport analysis. It is not the purpose of this chapter to provide detailed directions on the use of these methodologies or concepts, and the reader is directed to the appropriate texts or user manuals for the specific methodology/method chosen. The fundamentals of the simple, advanced and sophisticated approach are described in this section. The choice of which method is best suited for the analysis will depend on the data available and the desired use of the results.

Analysis and level of effort

5.5.2 As the analyst proceeds from the simple to the advanced approach and then to the sophisticated approach, the data requirements increase as well as the analysis time. However, the accuracy increases with the additional effort required if the input data are of good quality. The simple approach should be conservative in nature while the advanced and sophisticated approaches will provide results that permit the impact analysis to be more realistic. Table 5-2 shows the input variables that may be needed if the simple, advanced or sophisticated approach is chosen. Exact needs are determined by the model selected.

Note.—The designation 1 in the simple approach refers to the rollback model approach while 2 is a conservative analysis often referred to as the "worst-case" analysis.

Table 5-2. Input data needed depending upon the approach taken

Key parameters	Simple approach	Advanced approach	Sophisticated approach
Emissions	As described in Chapter 3.		
Spatial resolution	For case 1: No differentiation; airport as one "emissions bubble". For case 3, very large mesh size using a single source location such as runways.	Defined receptor positions with spatial resolution on a coarse grid (e.g. not less than 500-m mesh size).	Defined receptor positions with fine grid on a 10- by 10-m mesh size, but not more than 500- by 500-m mesh size.
Temporal resolution	Annual total.	Monthly or daily resolution.	Hourly or smaller resolution.
Meteorological	1. No weather data. 2. Wind speed is 1 m/s. Wind direction very stable atmosphere for ground level sources, and no plume rise is used to predict a conservative estimated (often referred to as "worst-case") concentration calculated at the receptor. Mixing height not considered.	Climatological data for multiple parameters ranging from an hourly to daily average Turbulence as a single parameter such as a stability classification generally from only wind speed and cloud cover considerations. Average mixing height for area generally assumed to be 914 metres (3 000 ft).	Detailed climatological data on a small time scale including upper air and specific mixing height data. Multiple derived parameters requiring additional data such as cloud cover and temperature gradients.
Surface roughness	Assume all area is flat and grass.	Consideration of major topographical features.	Consideration of topographical features, ground cover and local buildings.
Receptor information	General locations at ground level.	Specific locations at ground level.	Specific locations with varying horizontal and vertical locations.
Background concentration	1. Not considered. 2. Single value for airport area.	Single value for airport area.	Temporal and spatial considerations included.
Atmospheric chemistry	None.	Typical (analytical) transformation ratios from established studies.	Detailed reaction rate constants with consideration of local ambient concentrations of reacting chemical species.

5.5.3 It is again noted that many models will not support all variables or require very specific information, and it is the responsibility of the analyst to determine which variables are required by any model.

Simple approach

5.5.4 The simple approach can be thought of in two distinct ways:

a) use of a rollback model in which airport data are lacking except for the overall change in operations; and

b) a simplistic so called "worst-case" analysis.

As in Chapter 3 for emissions, the simple approach is recommended only when limited data are available or for initial assessments.

Rollback approach

5.5.5 The rollback approach is the most simple and requires the least data and, as such, can be performed very quickly. It also represents the greatest error. In this approach, which is not actually dispersion modelling, known emissions and concentrations are scaled according to overall changes in the aircraft operations. This assumes all other sources grow or decrease at the same rate as the aircraft operations. Equation 5-2 represents the idea numerically:

$$\Delta_2 = \Delta_1(O_2/O_1) \tag{Eq. 5-2}$$

where:

Δ_2 = total emissions or local area concentration at time 2;

Δ_1 = total emissions or local area concentrations at time 1;

$O_{1,2}$ = aircraft operations in LTOs for times 1 and 2, respectively.

"Worst- case" analysis

5.5.6 In this analysis, wind speed is assumed to be the smallest value that provides reasonable answers in a model, typically a constant 1 m/s. The wind is also assumed to be from a direction that produces the greatest concentration at the receptor location. The atmospheric stability is considered to be very stable for ground level sources and the mixing height is not considered. Background concentrations are assumed to be a single, conservative value. Use of these parameters results in a so-called "worst-case" analysis in that in reality the concentrations would rarely, if ever, be this high. These assumptions lead to the logic that if criteria or standards are not shown to be exceeded in this conservative estimation where predicted concentrations are most likely at a level greater than would normally occur, then there is not a substantial impact. Simple models can be used and, as such, this method can be coded into a spreadsheet (such as the use of the Gaussian formulation included in Appendix 1) or graphs and tables may be used. Simple computer models may also be used. The advantage is only a small set of data is needed and quick results. The disadvantage is a very conservative prediction that overestimates impacts.

Advanced approach

5.5.7 In this approach, computer-coded models are a must. Specific models may be required by the reviewing agency. Some models are available in the open domain, or proprietary models may be purchased. Each model will have a user guide and most will have a technical manual for the interested analyst. The analyst must completely review the user manual and be sure of the input. The old adage "garbage in equals garbage out" is very true in this case, and the result, even for the most complete model, is only as good as the input data used. Some models may include an interactive graphical user interface (GUI) to allow input to be more easily included. If not, input files will have to be created. Some models may have the needed emission factors (or, in the case of aircraft, emission indices) included to also make input easier. In these cases the emissions inventory may also be accomplished directly in the model. If this information is not included, the emissions inventory will have to first be completed externally. Temporal and spatial allocation may occur at the emissions inventory phase or postponed until the dispersion analysis.

5.5.8 These models may be the same as in the sophisticated approach with the difference being a greater use of default values for input variables, less complete operational data, non-varying background concentrations, and a lesser degree of spatial and temporal definition. Model inputs contain a large number of “default” values, that is typical values for airports but not actual for the defined airport. Typical models used in the advanced approach for modelling in the vicinity of airports include ALAQS-AV, AEDT/EDMS,[4] ADMS-Airport[5] and LASPORT.[6]

Sophisticated approach

5.5.9 This approach requires the most extensive data collection effort to define inputs. Default values are replaced with real data and this is especially true of meteorological input. Operational data are very complete with a much greater emphasis on spatial and temporal resolution. The models may be the same as in the advanced approach but with the actual data and a much greater use of options. Typical models used in the sophisticated approach for modelling in the vicinity of airports include ALAQS-AV, AEDT/EDMS, ADMS-Airport and LASPORT.

Hybrid approach

5.5.10 As with emissions, the three basic approaches can be mixed according to need and available data. The simple approach, because of the large simplifications that are made, does not lend itself to the hybrid approach except in very special situations. The advanced and sophisticated approaches are often mixed. This is especially true when the same model is used first with a high number of default input values for a high-level assessment and then refined to allow more detailed modelling.

5.6 MODEL OUTPUTS

5.6.1 Each model has different outputs but some are common to all models. The first is an echo file of the input data when computer models are used. This is an important component of the output because it allows the user to check the input data to:

a) be sure of the accuracy of input;

b) make sure the model has interpreted the data input correctly (very important for fixed-field inputs);

c) evaluate derived parameters by the model which will be reported with the input; and

d) allow the analyst to store the results and later understand the inputs used.

5.6.2 The most important output of course from all models is the calculated concentrations. The concentrations will be output as a certain time average (e.g. annual mean or series of daily means), possibly supported by some statistics (e.g. percentiles or exceedance frequencies) or even by complete time series (e.g. hourly means at given receptor points). The units of the concentrations will typically be either parts-per-million (ppm) or micrograms per cubic-metre (μg/m^3). In the case of particulate matter, only μg/m^3 is valid. The calculated or predicted concentrations including background should then be compared to the ambient air quality standards or criteria with the correct time frame and units.

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[4] U.S. EPA, AERMOD, AERMIC Dispersion Model, <http://www.epa.gov/scram001/7thconf/aermod/mod-desc.txt> (July 2011).

[5] CERC, ADMS,< http://www.cerc.co.uk/environmental-software.html> (July 2011).

[6] Janicke Consulting, LASPORT 2.0, A program system for the calculation of airport-induced pollutant emissions and concentrations in the atmosphere, Germany, 2009, <http://www.janicke.de/en/lasport.html> (July 2011).

5.6.3 Some models may also include graphical outputs to assist in determining problem areas or to allow a visualization of changes, for example, during mitigation modelling. In the sophisticated approach, multiple derived parameters will also be available in the output.

5.7 MODELLING APPLICATION AND INTERPRETATION OF RESULTS

5.7.1 The analyst should be aware of the fidelity of the results. This depends on the model used, the accuracy of the input data, and any assumptions applied.

Uncertainty in dispersion modelling

5.7.2 Since air pollution dispersion models vary from the simple to the very complex, there is a large difference in the uncertainty from model to model. Hanna[7] points out that total model prediction uncertainty is a combination of parameters including model physics errors, natural or stochastic uncertainty and data errors. As the number of parameters increases, the natural or stochastic uncertainty decreases and the model's representation of the physical reality becomes better. This leads to more complex models and a greater need for high-fidelity input data. However, as the number of input parameters increases, the input data errors may increase. Poor input data could cause the more complex model outputs to be equal to or even inferior to more simplistic models. In addition, model adjustments based on limited data sets can lead to additional error.

5.7.3 This makes it extremely difficult to quantify the uncertainty. Models may perform well in predicting the maximum occurrences but may do poorly when trying to predict concentrations in time and space when compared to measurements.

5.7.4 Limit values and required model results often refer to statistical quantities like percentiles, long-time averages like annual means, or maximum concentrations independent of their specific occurrence in time or their accurate location. A model may yield reliable results with respect to these quantities even if it shows poor performance in a point-by-point comparison, for example, with a measured time series at a given location.

Verification based on measurements

5.7.5 Complex dispersion models are applied in the form of computer programs. In view of quality assurance it is required to verify and validate such programs. The verification checks whether the program correctly implements the mathematical formulation (algorithms) of the model. The validation then checks how well the model and program respectively describe the reality, usually by a comparison with measured data sets.

5.7.6 For the validation it is important that these data sets are sufficiently complete, i.e. that the validation test can be performed with the smallest amount of additional assumptions. If assumptions are required or if assumptions have been implemented in the model or the program, it is of importance whether they are based on general grounds or adjusted, for example, to a specific airport or situation. With regard to input data, complex models are usually better able to account for specific airport details and are thus more flexible for validation against measured data.

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[7] S.R. Hanna, "Plume dispersion and concentration fluctuation in the atmosphere," *Encyclopedia of Environmental Control Technology*, Volume 2, *Air Pollution Control*, Gulf Publishing Company, Houston, Texas, 1989.

Comparison to applicable standards and criteria

5.7.7 The term impact has been used throughout this chapter. This is because impacts are most often evaluated by comparing the predicted concentrations from the dispersion models to standards and/or criteria which most often are time-averaged concentrations based on health effects. The use of these standards has been addressed in earlier chapters and will not be repeated here. However, it is important to realize the connection between dispersion modelling and impact assessment. Results from the emissions inventory do not allow this direct impact analysis. It has also to be considered that usually only by conducting dispersion modelling of all contributing sources plus the inclusion of all background concentrations will results be produced that may be directly compared to applicable standards. Modelling uncertainties must still be considered with respect to reporting direct impacts.

Use of multiple runs during mitigation considerations

5.7.8 Both the emissions inventory and the dispersion analysis results may be used for mitigation purposes. The big difference, as noted in the preceding section, is that the dispersion analysis results that compare the existing case and multiple future scenarios allow evaluation of changes in local area concentration and, therefore, of changes in impacts that are health-related.

Future advancement in models

5.7.9 As the understanding of the emission and dispersion of airport-related source systems increases, models will be improved to reflect and incorporate these advancements.

5.7.10 In addition to model development, a combination of microscale (the ones discussed here) and regional modelling are occurring to allow evaluation of the impact at larger distances from the airport and a more detailed consideration of background concentrations at the airport.

5.7.11 As advancements occur, agencies and airport authorities will be faced with the need to evaluate and implement modelling practices that provide the best impact analysis for the airport. As such, this field is dynamic and any documents such as this one will need to be evaluated over time for possible updating.

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Appendix 1 to Chapter 5

OVERVIEW OF DISPERSION MODELLING METHODOLOGIES

1. Dispersion modelling is a relatively new science and development is continuing. In 1895, Reynolds produced a paper discussing laminar to turbulent flow in pipes, which has been considered by some to be the starting point of dispersion modelling. Taylor produced one of the first papers on turbulence in the atmosphere in 1915 and in 1921 produced the "Taylor theory of turbulent diffusion" which provided a basis for describing dispersion with constant eddy diffusivity. Development continued and in 1962 Pasquill published the landmark book "Atmospheric Diffusion".[1] This work summarized what had been done to that time and is the basis of modern Gaussian plume models based on the horizontal and vertical spread of the plume being determined experimentally as a function of atmospheric stability and distance, the now well-known sigma values. The sigma values are in reasonable agreement with the Taylor theory.

2. There are different types of dispersion modelling methodologies for a dispersion calculation, with different features and capabilities. In the 1960s work on dispersion modelling continued to expand and formalize the dispersion modelling process including plume rise considerations. This resulted in the basis of the Lagrangian (moving coordinate axis) and Eulerian (fixed axis) modelling known today. The science has become an accepted approach to prediction of concentrations of pollutants in the vicinity of airports which is directly connected with the impact on public health and welfare. Performance of dispersion modelling requires key variables to be carefully assembled and various methodologies have occurred. A very brief description of each is included here.

Gaussian formulation

3. The Gaussian formulation is still used more than any other approach. This Lagrangian approach assumes downwind dispersion to be a function of stability class and downwind distance and applies the Gaussian probability density function to account for plume meandering and diffusion. It was released in various forms by the U.S. EPA as part of the UNAMAP series in the late 1960s and developments still are ongoing worldwide. It can be applied to plumes or individual puffs and as such provides needed flexibility for local air quality modelling. It has been adapted for point, line and area sources. In its basic point source form, for a plume, the concentration (c) is predicted with the following mathematical expression:

$$c(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}$$

where:

Q = source strength;

u = wind speed;

H = stack height;

σ_y, σ_z = horizontal and vertical dispersion coefficients.

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[1] F. Pasquill, *Atmospheric Diffusion: the dispersion of windborne material from industrial and other sources*, D. Van Norstand Company Ltd. London 1962.

4. Of note is that x, the distance downwind, is included implicitly in the horizontal and vertical dispersion coefficients that increase with downwind distance.

5. More recent Gaussian model formulations have used a bi-Gaussian distribution in the vertical to better account for vertical mixing in convective conditions. This results in more accuracy but also a more complex model.

Eddy diffusivity based on mass conservation formulation

6. In this Eulerian approach, the approximate solution of the mass conservation governing equations is used with simplifying assumptions that relate turbulent fluxes $< u'c' >$ to concentration gradients, $\partial c/\partial x_i$ by including an eddy diffusivity term, K_i. This results in:

$$< u'c' > = -K_i \left(\frac{\partial \mathrm{c}}{\partial x_{\mathrm{i}}}\right)$$

This approach is used for widely or uniformly distributed pollutants where large individual plumes are not dominant. This occurs for such pollutants as carbon monoxide. This approach has been applied in regional modelling in the form:

$$\frac{\partial c_i}{\partial t} + u_x \frac{\partial c_i}{\partial x} + u_{\mathrm{y}} \frac{\partial c_i}{\partial \mathrm{y}} + u_z \frac{\partial c_i}{\partial z} = \frac{\partial}{\partial x}\left(K_x \frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial c_i}{\partial z}\right)$$

$$+R_i(c_1, c_2, \ldots, c_n) + E_i(x, y, z, t) - S_i(x, y, z, t)$$

where:

u_x, u_y, u_z = velocity;

c_i = concentration of i^{th} species;

R_i = chemical generation rate of species i;

E_i = emissions flux;

S_i = removal flux.

Box model

7. The box model is a simplistic mathematical representation of a defined, well-mixed volume of air (the box) that includes inputs and outputs into the volume. Since the box is well mixed, the output concentration is equivalent to the concentration inside the box. Multiple boxes may be used in the horizontal or vertical with the output of one box representing the input of the next in a grid approach. Chemical reactions can be considered in each box. This allows the mass conservation formulation to be used for each box in this Eulerian method.

Trajectory models

8. These models, based on the Lagrangian approach, provide an approximate solution by using the governing equations of mass conservation and a coordinate system that moves with the average wind velocity. This approach implies that parcel integrity is reasonably maintained for the length of time of model simulation and assumes

that horizontal wind shear, horizontal turbulent diffusions and vertical advective transport are negligible. This model is not generally accepted for general use for regulatory applications in the U.S.

Mass and momentum models

9. In this type of model, governing equations of mass and of momentum are applied using first order principles. For example, approaches may begin with the fundamental Navier-Stokes equation and include turbulence based on Reynolds averaging. The result is more scientifically rigorous with complex procedures that avoid the K-theory simplification but are often computer and data intensive and specific to a particular case. As such, this category of models tends to be more research-oriented and not in common use.

Lagrangian particle models

10. In contrast to Gaussian models, which are based on an analytical solution of the classical dispersion equation, and Eulerian models, which solve this equation numerically, Lagrangian particle models simulate the transport process itself.

11. Out of the huge number of particles (gas, aerosol, dust) usually emitted by a source, only a representative, small sample is considered. The sample size is typically of the order of some million particles, depending on the problem and available computer resources. The trajectory of each of these particles is calculated on the computer by a stochastic process (Markov process in phase space). From these trajectories the three-dimensional, time-dependent, non-stationary concentration distribution is derived.

12. The core of a Lagrangian particle model, as for example specified in the guideline VDI 3945/3 (English/German, see www.vdi.de), does not contain tuneable parameters. It relies on meteorological parameters that can be determined without dispersion experiments. Timescales typically range from some minutes to one year with a time resolution down to some seconds; spatial scales range from some metres to some 100 kilometres.

13. Increased research and application to atmospheric physics started about twenty years ago, and Lagrangian particle models have become more widely used with increased computer speeds and memory storage. Today the technique is routinely applied in air quality control.

Plume-in-grid approach

14. This method is a hybrid between the Lagrangian and Eulerian approaches. The Eulerian approach is adapted by using trajectory models or Gaussian dispersion techniques to preserve concentrations of trace species to overcome the deficiencies regarding instant mixing of pollutants in the grid.

Closure models

15. In Eulerian models, vertical diffusion must be addressed. Two different turbulence closure schemes are typically used: local closure and non-local closure. Local closure assumes the turbulence is similar to molecular diffusion while non-local closure assumes the turbulent flux to be similar to mean quantities at different layers and an exchange of mass is allowed. Closure models are often discussed in terms of first-order for prognostic equations for the mean variables (i.e. wind or temperature) or higher order models which are more complex. This type of modelling is closely related to eddy diffusivity models previously described.

Statistical models

16. This idea is based on statistical analysis of ambient pollutant measurements and other emissions information. This approach is best used when detailed source information is available because with these models there is difficulty applying results as location parameters change. One subset of this type of modelling is receptor modelling which has been used to predict particulate matter in the U.S. and in the U.K. Receptor modelling uses multivariate statistical methods to identify and quantify the apportionment of air pollutants to their sources.

17. In summary, this partial listing of procedures is meant to provide a background for the discussion of dispersion modelling allowing the analyst to better understand the process.

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Appendix 2 to Chapter 5

COMMONLY USED DISPERSION MODELS IN THE VICINITY OF AIRPORTS

1. It is not the purpose of this appendix 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-A2-1 shows computerized dispersion modelling packages that have commonly been used at airports. Of note is that there are many models that have been used and the table is not all-inclusive.

Table 5-A2-1. Commonly used dispersion models at airports

Airport air quality model	*Fundamental type of dispersion model*	*Model information*
AEDT/EDMS	Bi-Gaussian	Sponsoring organization: United States Model developer: FAA
ADMS-Airport	Bi-Gaussian	Sponsoring organization: United Kingdom Model developer: CERC
ALAQS-AV	Bi-Gaussian/Lagrangian	Sponsoring organization: France Model developer: Eurocontrol
LASPORT	Lagrangian	Sponsoring organizations: Germany and Switzerland Model developer: Janicke Consulting

3. Obvious in all of these 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.

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.

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Appendix 3 to Chapter 5

CLIMATOLOGICAL INFORMATION SOURCES

1. Dispersion modelling using the advanced or sophisticated approach requires detailed meteorological data. Care should be taken in selecting these data. Short-term data may not accurately display trends and may not be representative of the seasonal variations, dominant wind patterns or diurnal variations.

2. According to the World Meteorological Organization (WMO) (http://www.wmo.int/pages/index_en.html) "more than 10 000 manned and automatic surface weather stations, 1 000 upper-air stations, over 7 000 ships, more than 100 moored and 1 000 drifting buoys, hundreds of weather radars and over 3 000 specially equipped commercial aircraft measure key parameters of the atmosphere, land and ocean surface every day." Information is available for multiple years and databases have been established prior to 1950.

3. The World Data Centre for Meteorology, with 52 centres in 12 countries, represents a huge number of monitoring stations worldwide (http://www.ncdc.noaa.gov/oa/wdc/index.php).

4. Individual countries may also maintain the required climatological data for a region or country. These include the British Atmospheric Data Centre (http://badc.nerc.ac.uk/home/index.html) in the U.K. and the National Climatic Data Center (NCDC) (http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html) in the U.S. For example NCDC has directly downloadable surface data, upper-air data and other useful information in multiple formats. Of importance are the historical records over many years that help to avoid errors due to incorrect input parameters. The data are available from the 1800s to the present for over 8 000 locations in the U.S. and 15 000 worldwide stations depending on the data needed.

5. Climatological data can be found at many universities worldwide as well, and they often provide unique data for a region. It is suggested that the analyst explore this possibility for obtaining information.

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 airport locations attempt to quantify airport-related emissions 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.

6.2 REQUIREMENTS AND DRIVERS FOR AIR QUALITY MEASUREMENTS

6.2.1 Chapter 2 of this manual describes the general local air quality regulatory framework and the drivers influencing the aviation industry to provide information or undertake action related to air quality. 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 (e.g. for baseline assessment or in the context of expansion projects).

6.2.3 ***Voluntary programmes.*** For example, public and community concerns often trigger the need for measurements to obtain actual information about air quality in the local vicinity. Alternatively, an airport may voluntarily conduct measurements and report as part of their environmental policy and management activities.

6.2.4 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 (e.g. 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) external factors;

c) measurement locations (with respect to the airport premises);

d) measurement methods;

e) management planning.

6.3.2 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.

External factors

6.3.3 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.

6.3.4 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 may already be in place that is operated by local authorities or other entities. In this case it would be advisable to coordinate or even harmonize potential measurement plans to avoid duplication of similar or identical measurements or to avoid inconsistencies or even 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 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.

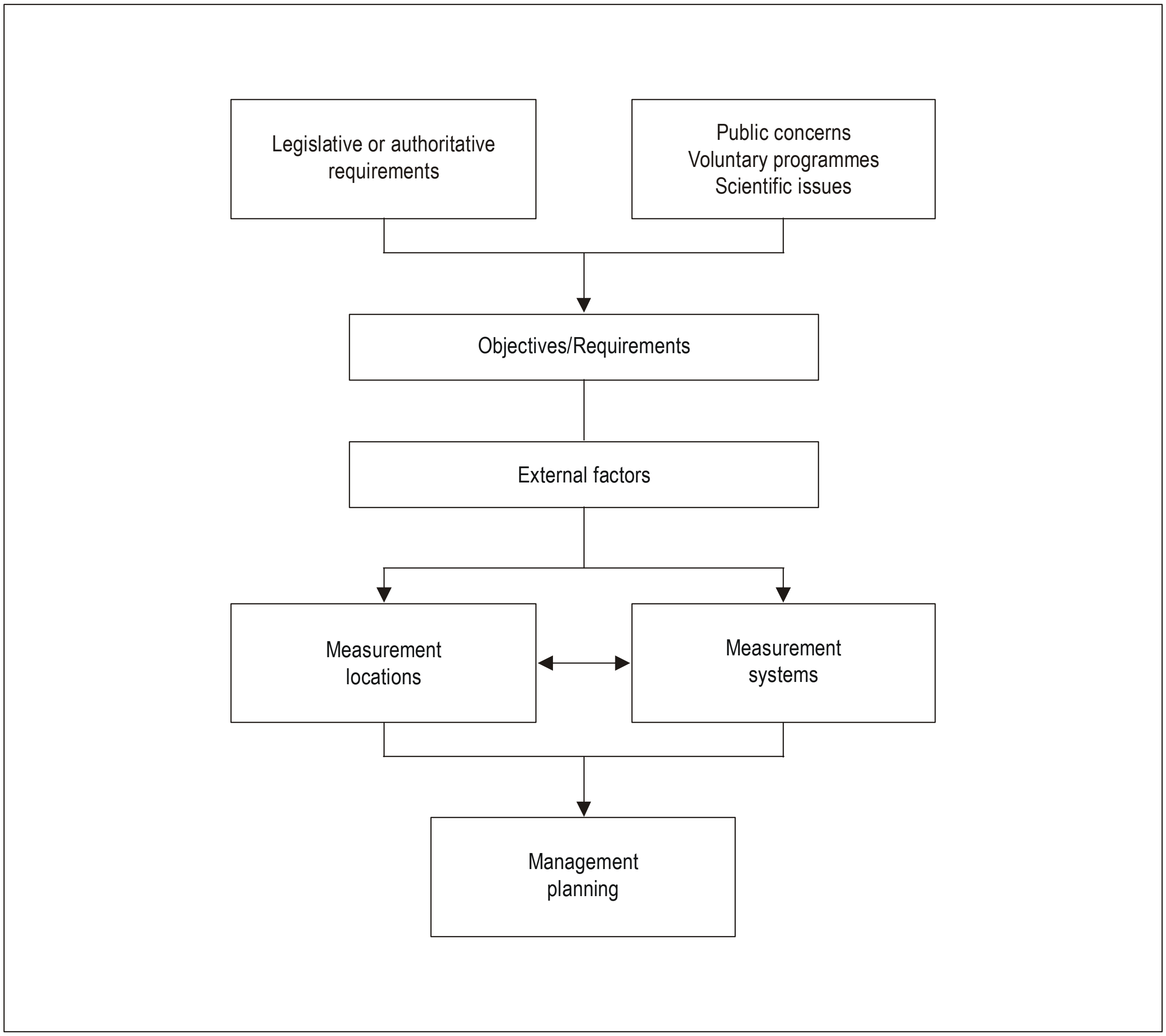

Figure 6-1. Measurement plan elements

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.

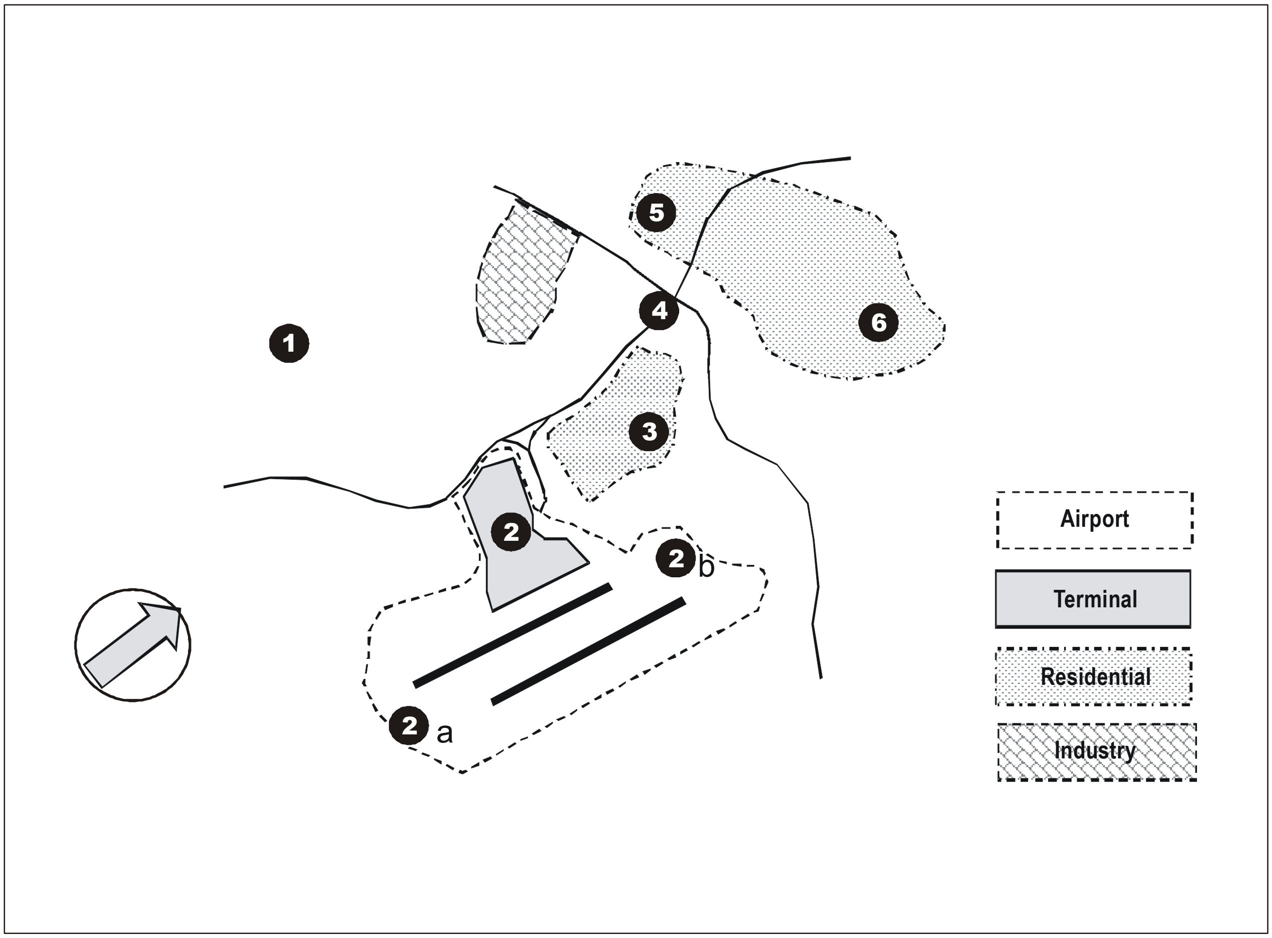

Figure 6-2. Generic measurement site selection plan
(circled arrow: prevailing wind direction)

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, while air quality measurements in the airport region should be performed with passive systems.

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 2 a and 2 b) 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.

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;

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 (e.g. 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 (e.g. 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 by means of printed or electronic reports. In addition, communication to authorities or local stakeholder 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;

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;

e) meteorological data (e.g. wind speed and direction).

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 (e.g. 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 (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, e.g. samples can be analysed every few seconds or minutes.	Intervals are usually long (e.g. two-week intervals) or only one-time measurements.
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 a 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.

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 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-week, month-of-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 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.

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 Source apportionment is the use of monitored or modelled concentrations, with or without meteorological data, to determine the sources, source types and/or source locations that contribute substantially to measured values. The spatial gradient and time-series analyses discussed above are possible source apportionment methods. Others include the chemical mass balance or the positive matrix factorization.

6.4.12 The use of monitored data to determine sources that contribute to the measurements is referred to as receptor modelling. The receptor (monitoring station) data are analysed along with either wind speed and wind direction data or assumed source-type emissions profiles and characteristics to tease out information about which sources or source types are generating the emissions that get measured at the station.

6.4.13 Measurements at a point do not allow one to distinguish from 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 (e.g. an airport).

Handling of missing data

6.4.14 Local or national guidelines usually set forth the required conditions under which measured time series are valid. For longer-term measurements (e.g. annual), a maximum number of days without data is allowed where 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.

6.4.15 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 may be a number of guidelines available, which could include but are not limited to, manufacturer specifications, local or national guidelines or international guidelines (International Standards Organization). 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, e.g. 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 (e.g. 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 (e.g. reference gases) are used, they must be quality assured or certified (e.g. 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 has to 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 (e.g. 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.

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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 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 grater set splits the light stepwise into the different spectra. The resulting spectrum is now compared with a reference spectrum and the difference calculated to a polynomial. 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 U.S. 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.

O_3 analyser

1.5 In the O_3 analyser, two air samples are collected. The first one passes through a catalyst which 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

1.6 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 (e.g. 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 (e.g. 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 which are used.

3.3 The data obtained from traditional measurement methods permit control of compliance with current air quality standards and limit values. Data on ambient pollutant concentrations, however, do not allow for 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 permits assessing 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.

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Appendix 2 to Chapter 6

EXAMPLES OF MEASUREMENT METHODS

Table 6-A2-1. Examples of measurement methods (from Europe and the U.S.)

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	
Lead	Gravimetric	
Carbon monoxide	Gas filter correlation Non-dispersive infrared spectroscopy (EU)	
Ozone	Ultraviolet photometry	DOAS

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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 (e.g. vehicle) or it can also include infrastructure measures (e.g. insulation, road layout).

7.2.4 "Operational measures" refer to those measures that would be implemented by the operator of the equipment in question, whether 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	• 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 • Reduced intensity of hot fire practices.	• Emissions-related licensing fees
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)	
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.

Mitigation option requirements

7.2.6 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;

d) potential Interdependencies.

7.2.7 ***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.

7.2.8 ***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.

7.2.9 ***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.

7.2.10 ***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

7.2.11 It is recommended that a management approach (plan-do-check-act) as outlined in the following paragraphs be adopted.

7.2.12 ***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.

7.2.13 ***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.

7.2.14 ***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.

7.2.15 ***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?

7.2.16 ***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.

7.2.17 ***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.

7.2.18 ***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.

7.2.19 The design and development of measures are processes that include a number of 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.
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 using 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.
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.

7.3 MITIGATION OPTIONS

7.3.1 Emissions management measures applicable to sources at airports may be grouped into four broad categories while the emissions sources are also grouped into four main categories. Table 7-1 provides a matrix with the source groups and measures categories and provides examples of possible measures. 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.

7.3.2 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.

7.3.3 The measures selected for use at a particular airport are best determined based on local considerations and in cooperation with appropriate stakeholders in the operation and use of the airport. Best practices will continue to evolve, and the airport authority should continue to evaluate opportunities and to engage and challenge the local stakeholders to contribute their fair share toward reducing airport-related emissions.

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Appendix to Chapter 7

REFERENCES

ICAO, 2002, *Operational Opportunities to Minimize Fuel Use and Reduce Emissions* (Cir 303). Circular 303 documents practices that all aviation stakeholders can consider in order to reduce fuel consumption and the resultant emissions. The circular outlines principles of fuel savings by identifying operational opportunities and techniques for minimizing aircraft fuel use that in turn reduce the amount of emissions from these sources.

ICAO, 2002, *Airport Planning Manual* (Doc. 9184, Part 2). Chapter 3 of Doc 9184, Part 2, outlines emissions control measures that airport operators themselves, or in cooperation with aircraft operators, can employ for aircraft, ground support vehicles and airport facilities.

Airports Council International (ACI), 2008, *ACI Policy and Recommended Practices Handbook.* Section 6.2 of this Handbook describes emissions and local air quality and illustrates potential measures to reduce emissions at source.

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, etc.

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 interdependences are not discussed further in this chapter which concentrates solely on aircraft operations.

8.1.3 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 (915m)) in the "operational LTO flight cycle" detailed in Chapter 2, 2.2.

8.1.4 Note that the impact of an aircraft's emissions plume, at or above 3 000 ft, on NO_2 ground-level concentrations is very small even in a very conservative analysis,[1,2] and 1 000 ft is the typical limiting altitude for ground-level NO_2 concerns.[3]

8.1.5 Interrelationships between noise, NO_x and fuel burn/CO_2 emissions are often complex and can be unclear and difficult to understand. As a result, they require careful evaluation to assess the results of changes to operating practices before operational or regulatory decisions are made. There may also be interrelationships between environmental impacts and other factors, such as airport or airspace capacity, that must be determined before any changes are contemplated.

8.1.6 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.

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[1] Roger L. Wayson, and Gregg G. Fleming, "Consideration of Air Quality Impacts by Aeroplane Operations at or above 3000 ft AGL," FAA-AEE-00-01, DTS-34, U.S. Department of Transportation, Federal Aviation Administration, September 2000.

[2] U. Janicke, E. Fleuti, and I. Fuller. "LASPORT — A Model System for Airport-related Source Systems Based on a Lagrangian Particle Model," *Proceedings of the 11th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Cambridge, England, 2007, <http://www.harmo.org/conferences/proceedings/_Cambridge/topicIndex.asp?topicID=9> (July 2011).

[3] ICAO, *Effects of PANS-OPS Noise Abatement Departure Procedures on Noise and Gaseous Emissions* (Cir 317), International Civil Aviation Organization, 2008.

8.1.7 As regulatory and operational pressures to reduce the environmental impacts of aircraft operations become more intense, the trade-offs arising from these interrelationships tend to be encountered more often and become more difficult to address.

8.2 RECOMMENDATIONS FOR EVALUATING INTERDEPENDENCIES

8.2.1 The identification and calculation of environmental impacts and interrelationships can be both complex and obscure. It 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.

8.2.2 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.

8.2.3 For local air quality effects, the variations identified for emissions inventories are not necessarily consistent with differences in local air quality impacts because the position of the aircraft source in relation to the receptor is highly relevant due to dispersion of the emissions, as well as ambient meteorological conditions. As a result, an overall reduction in an emissions inventory may not always result in a reduction of local air quality impacts — this is especially true if all the reduction occurs at altitude.

8.2.4 Analysing noise interrelationships is again a complex issue, and different techniques can result in differences in noise exposure at different points along, or to the sides of, the flight path (sometimes of a different sign). Note that for turboprop, or other propeller-driven aircraft, the results may well be asymmetric due to the direction of rotation of the propellers, and the impacts of this need careful consideration when analysing the trade-offs for any mitigation technique.

8.2.5 Policy decisions may be set by regulators or individual airport and aircraft operators. It is also important to be aware of legal constraints and other international, national and local environmental policies that may themselves determine the controlling environmental factor to be optimized at the potential expense of other issues.

8.2.6 Note that ICAO PANS-OPS defines the principle that the aeroplane operator should develop no more than two noise abatement procedures for each aeroplane type. It recommends that one procedure should provide noise benefits for areas close to the aerodrome and the other for areas more distant from the aerodrome. This requirement can also set a constraint on what is achievable.

8.2.7 It is primarily for the reasons outlined above that it is important to involve all relevant stakeholders: aircraft and airport operators, aircraft and engine manufacturers, airports, air navigation service providers (ANSPs), policy makers and regulators, in the assessment process as early as possible.

8.2.8 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 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, e.g. 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	NOx (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 even further.

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, e.g. 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, e.g. 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, although the impacts on noise are complex, and increases in power will 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. The effects on noise footprint areas may increase, however, due to the lateral attenuation characteristics of an ascending noise source being less affected by the proximity of the ground.[4]

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.

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.

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[4] ICAO, *Recommended Method for Computing Noise Contours around Airports* (Doc 9911), International Civil Aviation Organization, 2008.

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 constraint precludes 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 AGL will have little impact on changes in ground-level concentrations.

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)[5]	Reductions prior to joining the ILS glideslope	Reduced	Little or no difference (Note 1)	Procedures need to be agreed and established first. Greatest benefit will occur when initiated at higher altitudes with more advanced navigation equipment. May impact capacity (Note 2).
Tailored arrivals[6]	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 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 considerations (e.g. 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.[7] In

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[5] Eurocontrol, *Continuous Descent Approach — Implementation Guidance Information*, Eurocontrol, May 2008.

[6] R. Mead, *Tailored Arrivals Overview*, Boeing, 2007, <www.tailoredarrivals.com> (July 2011).

[7] ICAO, *Operational Opportunities to Minimize Fuel Use and Reduce Emissions* (Cir 303), International Civil Aviation Organization, February 2004.

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.

8.6 SPECIFIC EXAMPLES — ICAO CIRCULAR 317

8.6.1 This section contains some examples from analyses carried out by members of ICAO CAEP WG2, using a number of different aircraft types for a non-constrained, non-specific airport. Changes have been assessed for:

a) NO_x emissions to both 1 000 ft and 3 000 ft;

b) total CO_2 (and hence fuel burn) to a common point after the top of climb (note that the fuel burn to 3 000 ft varies with type and sector distance, but varies between about 2.5 per cent (for very long flights) to about 25 per cent (for very short flights) of the total fuel for the sector);

c) maximum “close-in” noise difference and maximum “distant” noise difference along with the crossover point (distance from brake release) where the noise difference changes sign;

d) number of procedures for eight different aircraft types.

8.6.2 This information is intended only to give a guide to the types of interrelationships that may be encountered in actual operations and should not be seen as representative for all aircraft, even of the same type, at all airports.

8.6.3 Full details of the results of this study are published in Circular 317, though summaries of the environmental interrelationships for three techniques are given here to illustrate the type of trade-offs that may be required.

8.6.4 Figures 8-1 to 8-6 give the impacts of three different operational changes on eight aircraft types. The “aircraft ID” number used in the figures is that given in Table 8-4.

Effect of cut-back height

8.6.5 The effect of cut-back height can be seen in the results of the analysis of the comparison of a cut-back from take-off power to maximum climb limited thrust (MCLT) at 1 500 ft relative to a cut-back initiated at 800 ft.

8.6.6 The results show that low-level NO_x emissions are generally increased, while fuel burn and CO_2 emissions are slightly reduced. Close-in noise is also increased while distant noise is reduced to a lesser amount after a crossover point that is relatively close to the airport. See Figures 8-1 to 8-2.

Effect of cutback sequence

8.6.7 The effects of different cut-back sequences are illustrated in Figures 8-3 and 8-4, where the base procedure is to initiate acceleration and flap retraction at 800 ft, followed by cut-back to MCLT when flap retraction has been completed. The alternative procedure entails cut-back to MCLT at 800 ft before acceleration and flap retraction are initiated.

8.6.8 The results show that, in general, NO_x emissions are reduced, with a slight increase in CO_2 emissions (less than 1 per cent). Close-in noise is reduced while distant noise is increased after a crossover point that is, again, relatively close to the airport.

Flap retraction height

8.6.9 The effect of flap retraction height is illustrated in Figures 8-5 and 8-6, where cut-back to MCLT at 800 ft, but delaying acceleration and flap retraction initiation until 3 000 ft, is the base procedure. The alternative procedure is to cut back to MCLT and initiate acceleration and flap retraction at 800 ft.

8.6.2 The results show that, in general, NO_x emissions are significantly increased, with a slight reduction in CO_2 emissions. Close-in noise is increased while distant noise is reduced after a crossover point that is relatively further away from the airport.

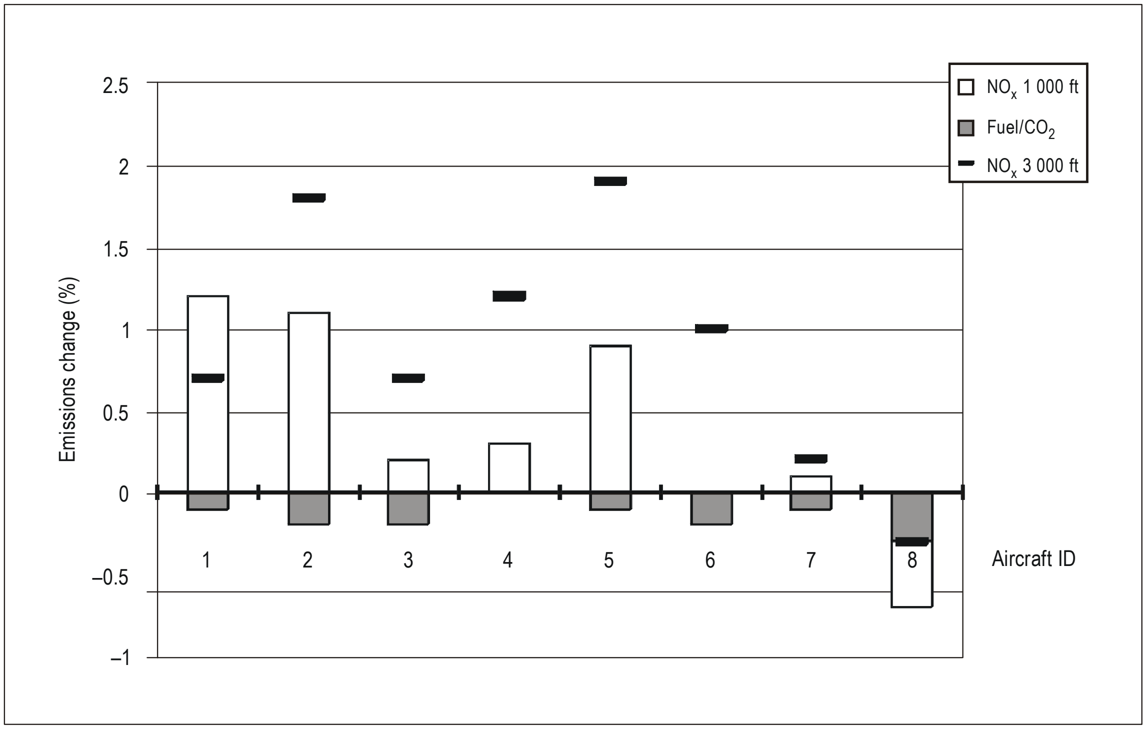

Figure 8-1. Emissions impacts of different cut-back heights

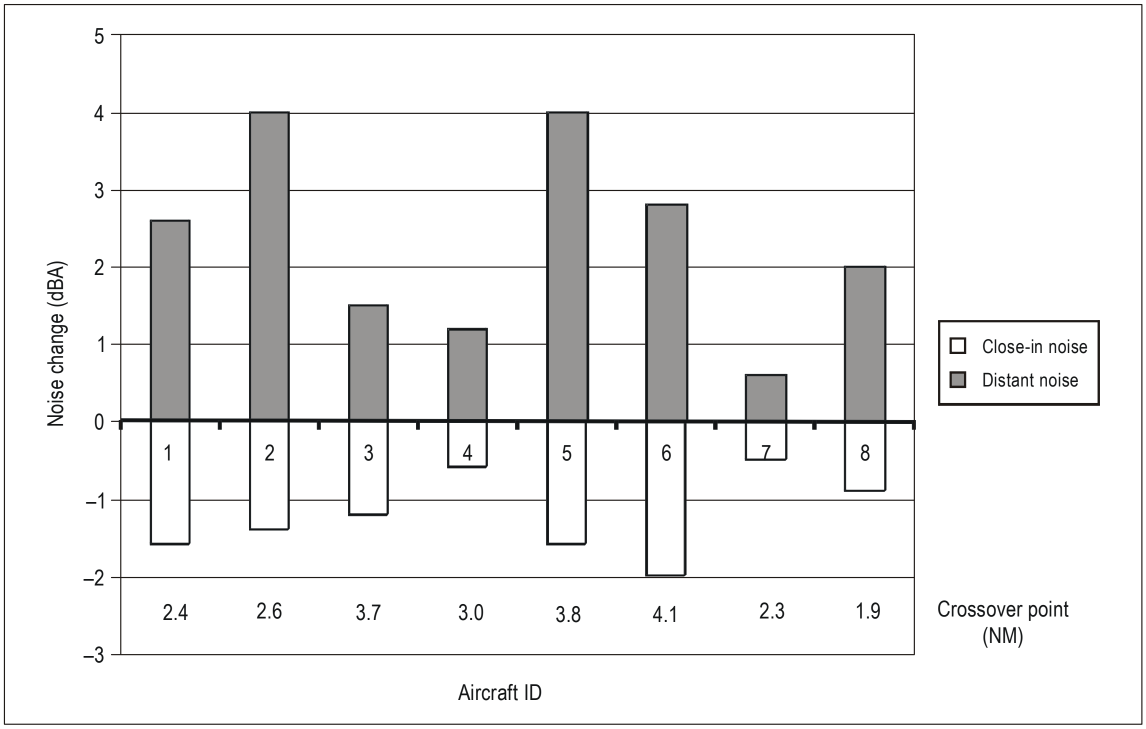

Figure 8-2. Noise impacts of different cut-back heights

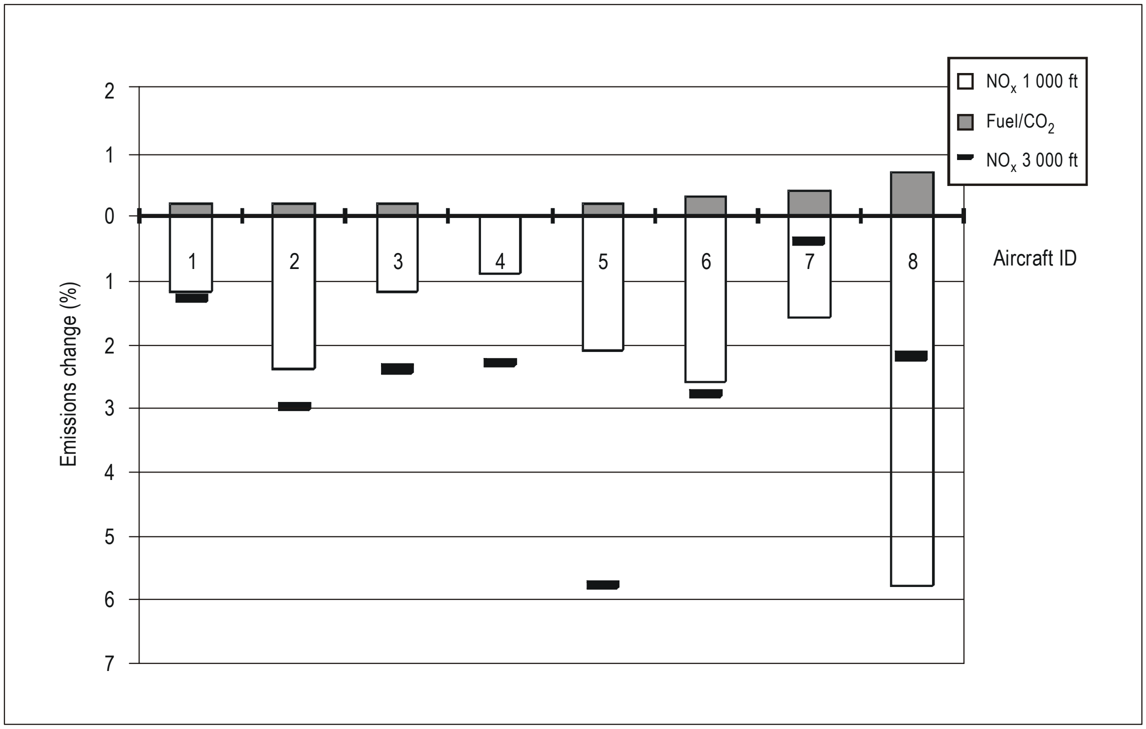

Figure 8-3. Emissions impacts of different cut-back sequences

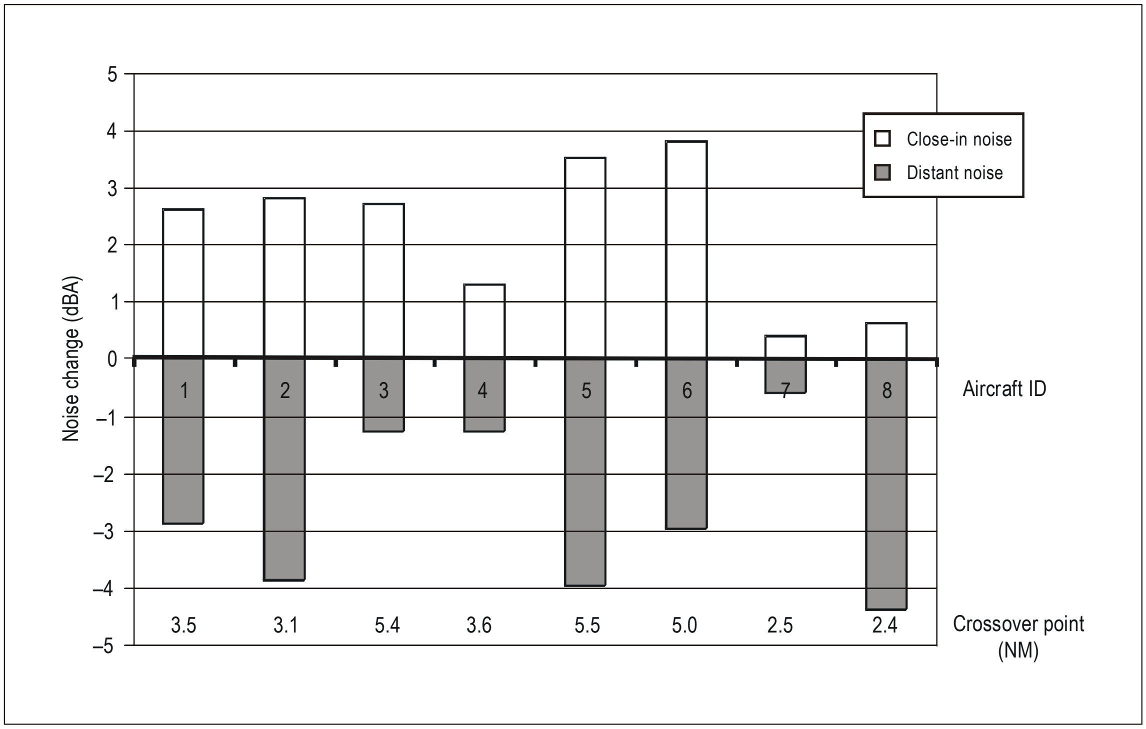

Figure 8-4. Noise impacts of different cut-back sequences

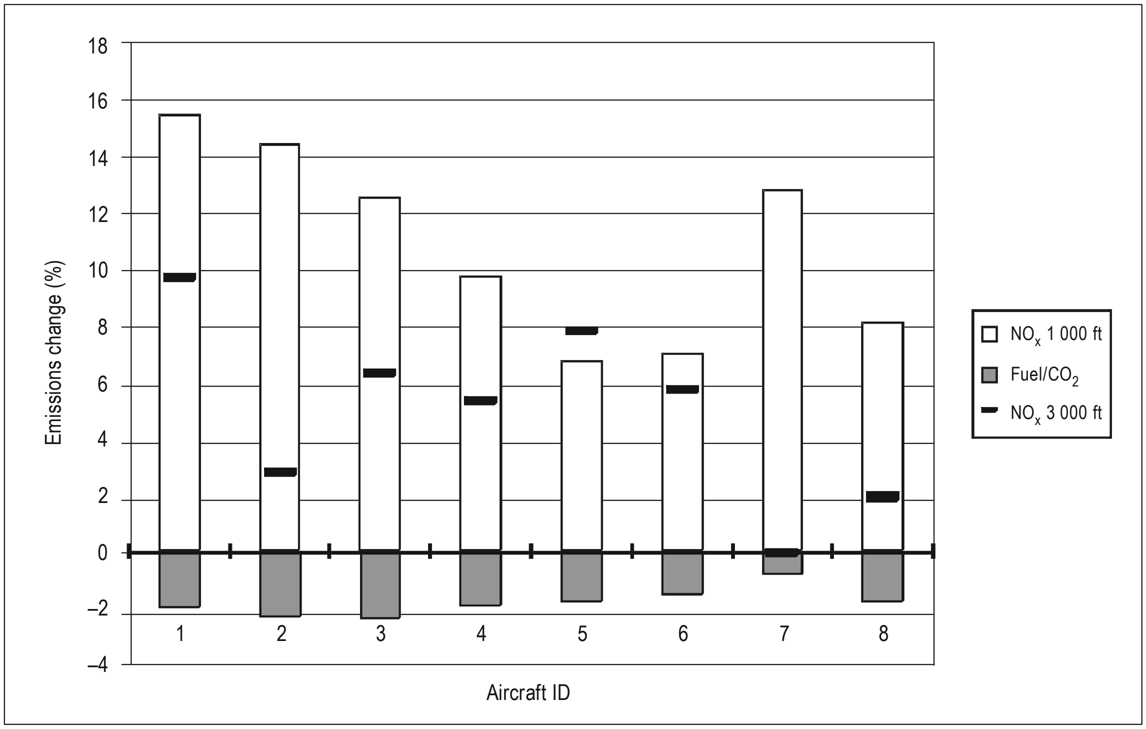

Figure 8-5. Emissions impacts of different flap retraction heights

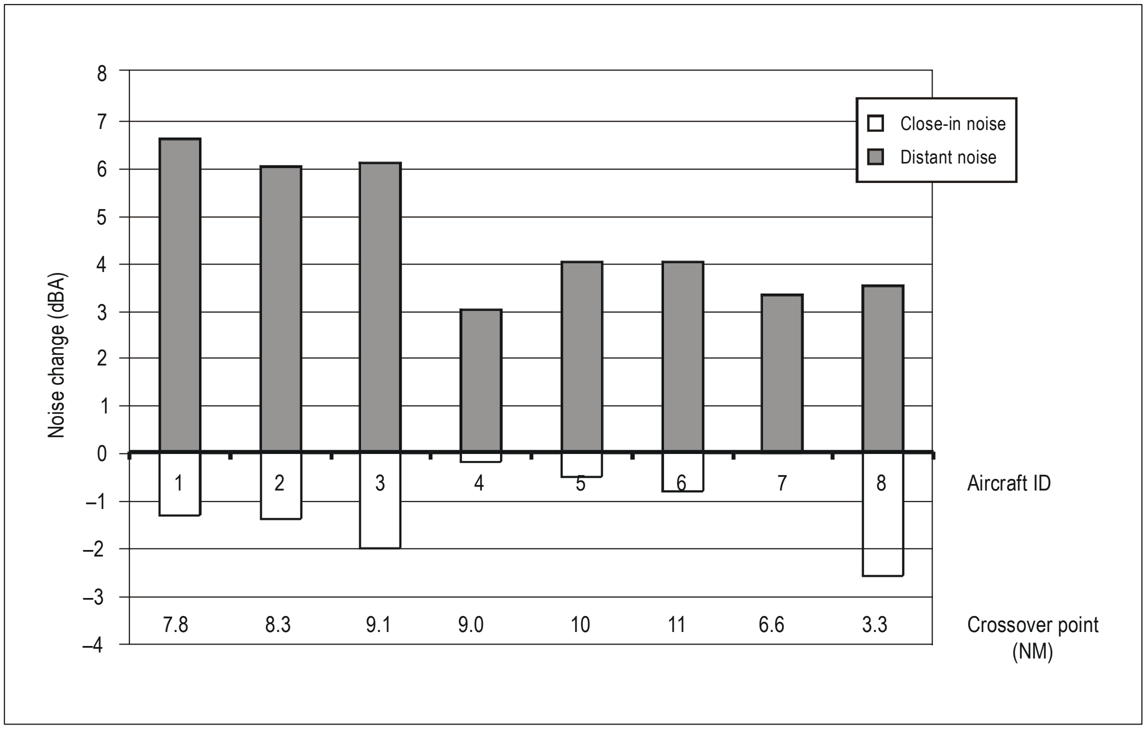

Figure 8-6. Noise impacts of different flap retraction heights

Table 8-4. Aircraft types used in the Circular 317 study
(ID refers to the aircraft ID number used in Figures 8-1 to 8-6)

ID	Aircraft type
1.	Airbus A320-214, CFM56-5B4/P Take-off weight 77 000 kg 12% reduced take-off thrust
2.	Boeing 737-700, CFM56-7B24 Take-off weight 70 000 kg 10% reduced take-off thrust
3.	Airbus A330-223, PW4168A Take-off weight 233 000 kg 12% reduced take-off thrust
4.	Airbus A340-642, Trent 556 Take-off weight 368 000 kg 12% reduced take-off thrust
5.	Boeing 767-400, CF6-80C2B8F Take-off weight 204 000 kg 10% reduced take-off thrust
6.	Boeing 777-300, Trent 892 Take-off weight 300 000 kg 10% reduced take-off thrust
7.	Bombardier CRJ900ER, CF4-8C5 Take-off weight 37 000 kg 10% reduced take-off thrust
8.	Dassault Falcon 2000EX, PW308C take-off weight 19 000 kg Full take-off thrust

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