Thesis

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Methodologies for Aviation Emission Calculation –

A comparison of alternative approaches towards 4D global inventories

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LIST OF ABBREVIATIONS

A glossary of symbols and units used in formulae is found in Appendix A.

AERO	Aviation Emissions and Evaluation of Reduction Options
AMOC	ATFM Modelling Capabilities
ANCAT	Abatement of Nuisances Caused by Air Transport
APU	Auxiliary Power Unit
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BADA	Base of Aircraft Data
BMAP	Boeing Mission Analysis Program
BPR	Bypass-ratio
BTS	Bureau of Transportation Statistics
CAS	Calibrated Airspeed
CARAT	Computer Aided Route Allocation Tool
CAEP	Committee on Aviation Environmental Protection
CFDR	Computer Flight Data Recorder
CFMU	Central Flow Management Unit of EUROCONTROL
DTI	United Kingdom Department of Trade and Industry (DTI)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOT	Department of Transportation
DOC	Direct Operating Costs
EC	European Community
ECAC	European Civil Aviation Conference
EDMS	Emissions and Dispersion Modeling System
EI	Emission Index
ETMS	Enhanced Traffic Management System
FATE	Four-dimensional Calculation of Aircraft Trajectories and Emissions
FL	Flight Level
FAA	Federal Aviation Administration
FSU	Former Soviet Union
GA	General Aviation
GANOX	Global Aircraft Emissions of NO_x
GAEC	Global Atmospheric Emissions Code
GDP	Gross Domestic Product

IATA	International Air Transport Association
ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organization
IEA	International Energy Association
IFR	Instrument Flight Rules
INM	Integrated Noise Model
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
LMI	The Logistics Management Institute
LRC	Long Range Cruise
LTO	Landing and Take-off
MIT	Massachusetts Institute of Technology
MMU	Manchester Metropolitan University
MRC	Maximum Range Cruise
MTOW	Maximum Take-off Weight
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory of the Netherlands
OAG	Official Airline Guide
OEW	Operational Empty Weight
OPR	Overall Pressure Ratio
PIANO	Project Interactive Analysis and Optimisation
UTC	Coordinated Universal Time
PM	Particulate Matter
RF	Radiative Forcing
ROC	Rate-of-Climb
SAE	Society of Automotive Engineers
SAGE	System for Assessing Aviation's Global Emissions
SARS	Severe Acute Respiratory Syndrome
SN	Smoke Number
TEM	Total Energy Model
TET	Turbine Entry Temperature
TSFC	Thrust Specific Fuel Consumption
UHC	Unburned Hydrocarbons
UV	Ultra-violet
VFR	Visual Flight Rules
VOC	Volatile Organic Compounds
WWLMINET	World Wide LMI Network

PREFACE

The thesis deals with the production of emission inventories for global aviation. Results of such calculations, which can be performed at four-dimensional resolution, are typically used in models of the global atmosphere to determine the effects of aviation on climate change. The thesis was composed in cooperation between Berlin University of Technology, Institute of Aeronautics and Astronautics, and the German Aerospace Center (DLR) in Cologne, Section Air Transport and Airport Research.

Chapter 1 contains general information on gaseous emissions of modern transport aircraft and their potential effects on global warming. Chapter 2 covers the "state-of-the-art" in inventory production with an emphasis placed on alternative approaches regarding the following aspects:

- The processing of flight schedules, flight plans and radar trajectories to create a movements database for global aviation.
- Methods for aircraft performance calculation to determine the fuel consumption in various flight phases.
- Correlation methods to calculate in-flight engine emissions and
- The usage of the above mentioned methods to produce emission inventories of global aviation at three- or four-dimensional resolution.

Furthermore, simplifications and sources of errors are identified and assessed both qualitatively and quantitatively on the basis of scientific literature.

Based on the interrelations mentioned above, chapter 3 gives an overview on specific inventories produced in recent years. A comparison in terms of methodology and results is performed. The chapter covers inventories for global aviation composed in the 1990s (NASA, DLR-2, ANCAT/EC-2) and – in more detail – inventories from the last 5 years (NASA 1999, AERO2k and SAGE). A comparison of results is performed for aviation fuel-use and emissions of nitric oxides (NO_x), carbon monoxide (CO) and unburned hydrocarbons (HC).

1 AVIATION EMISSIONS – AN OVERVIEW

1.1 INTRODUCTION

The transport sector creates social and economic benefits at the cost of adverse environmental impacts. Air transport is no exception in this respect. In the past 30 years, air transport growth rates have shown a close link to the growth of the world GDP. Aviation facilitates travel, tourism and the expansion of trade in an ever globalizing world. Aircraft and airline industries are major direct and indirect employers. On the other hand, negative effects of aviation include noise from aircraft, land use for airports and the associated infrastructure, the use of limited resources like fossil fuels and gaseous emissions from fuel burn. Although noise and local air quality around airports seem to be of primary concern to the public, the steady growth of aviation gives rise to worries about its contribution to climate change.

Emissions from aircraft include greenhouse gases like carbon dioxide (CO_2) and water vapour (H_2O). Aviation emissions of carbon dioxide (CO_2) may be small compared to those of other sectors. In absolute values, however, "they are still roughly equivalent to the carbon emissions of industrialized countries such as Canada and the UK"[1]. Furthermore, aircraft emit nitrogen oxides (NO_x) into the troposphere and lower stratosphere, where they influence ozone (O_3) and methane (CH_4) concentrations via chemical processes. Condensation trails and aviation induced cirrus clouds have been in the focus of meteorologists in recent years and may also contribute to global warming.

It's the rapid and continuous growth of air transport that justifies special attention to its adverse effects. Although significant technological progress in the fields of engine and airframe technology has been made, overall emissions of the airline industry are still on the rise. With sustainability becoming a key word (at least a target) in many fields of society, "the environmental sustainability of the airline industry is at least in doubt"[2].

Aviation emission inventories are required for any research on the interrelation between aircraft emissions and climate change. They provide input data for scientific computer models of the atmosphere used to analyse the relevant chemical processes. Resulting from a better understanding of atmospheric reactions, technological, operational or political actions may be taken in order to minimize the adverse effects of aviation. Although the thesis deals with inventory production from an engineering perspective, the following paragraphs provide an overview on the interrelations mentioned above.

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[1] Upham et al. (2003), p. 4

[2] Upham et al. (2003), p. 239

1.2 EMISSIONS FROM AVIATION

Gaseous emissions from aviation aren't limited to aircraft exhaust. In studies about local air quality at airports, the following sources of emissions need to be considered:

- Emissions from aircraft operations.
- Emissions from road or rail traffic at the airport.
- Emissions from the airport infrastructure.

Global aviation emission inventories focus mainly on emissions at altitude. As a consequence, only aircraft operations are assessed in the following paragraphs.

1.2.1 EMITTED SPECIES

Aircraft emissions result from the combustion of fuel with air in the main engines and the Auxiliary Power Unit (APU) both in flight and during ground operations. A schematic of the combustion process is shown in Figure 1.

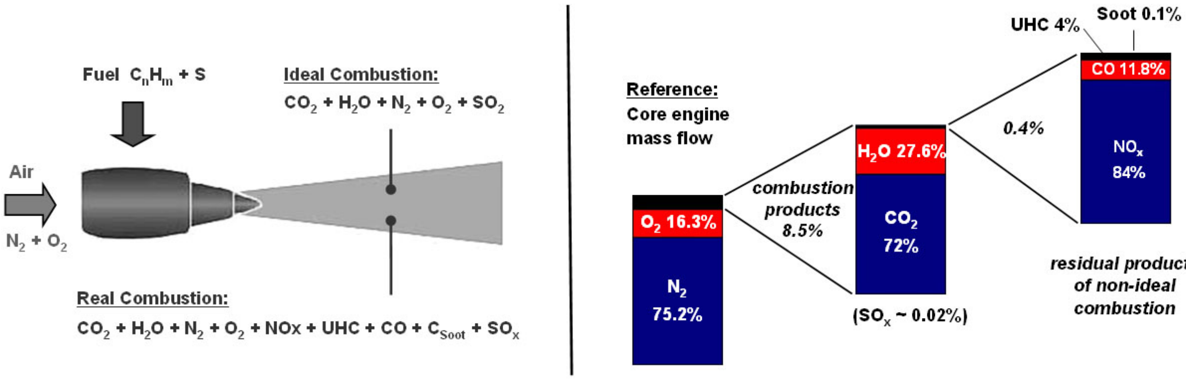

Figure 1: Combustion process (left) and proportions of emissions in cruise flight (right) [IPCC (1999), p. 235]

Kerosene-based fuels like JET A-1 are used by most commercial transport aircraft, i.e. jets and turboprops[3]. Main products from the combustion are *carbon dioxide (CO_2)* and *water vapour (H_2O)*, the proportions of which depend on the carbon to hydrogen ratio of the specific fuel. In a simplified approach one can assume a mean formula of $C_{12}H_{23}$ for JET A-1[4]. An ideal combustion of 1 kg of such fuel results in 3.156 kg CO_2 and 1.237 kg H_2O. In reality, JET A-1 is a complex mixture of hydrocarbons with further additives and the combustion process in an engine is not ideal. Table 1 shows the most prominent emissions from aircraft and respective emission indices averaged for aviation in 2002.

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[3] Other aviation fuels like Avgas are typically used in piston-engined aircraft.

[4] See Rachner, M. (1998): *Die Stoffeigenschaften von Kerosin JET A-1*, DLR-Mitteilung 98-01, quoted in Eyers et al. (2004), p. 31

Species	Emission index [g/kg]	Emission rate [Mt/year]
CO_2	3154	492
H_2O	1237	193
NO_x	13.2	2.06
CO	3.25	0.507
HC	0.4	0.063
Soot	0.025	0.0039

Table 1: Mean emission indices for civil aviation in 2002 [Eyers et al. (2004), p. 90]

Whereas CO_2 and H_2O emissions are basically functions of fuel flow, things are more complicated for other exhaust gases. Since the combustion process in aircraft engines is not ideal, *unburned hydrocarbons (H_xC_y, often termed HC or UHC)* and *carbon monoxide (CO)* are produced during engine operation. Both pollutants result from incomplete combustion, their amount in the exhaust being dependent on the specific engine, its power setting and ambient engine inlet conditions. As shown in Table 1, mean emission indices for CO and HC are in the range of 3 g and 0.4 g per kg fuel respectively. CO and HC are mostly produced at low power settings, when fuel/air mixing processes are rather inefficient. On the contrary, *nitric oxide (NO) and nitrogen dioxide (NO_2) – together referred to as NO_x* – are mainly produced at high power levels. An average NO_x emission index was calculated to be 13.2 g per kg fuel for aviation in 2002.

Emissions from aircraft engines include *particulate emissions (soot)*, which may contribute to a visible plume. Soot consists of around $2.6 \cdot 10^{14}$ carbonaceous particles per kg fuel with diameters typically in the range of 10-30nm[5]. Besides, small and liquid particles (2-10nm diameter) form in the exhaust plume during cruise flight, initially from H_2SO_4, condensable hydrocarbons, chemi-ions and water[6]. Furthermore, due to the sulphur content in the fuel there are *sulphur oxides (SO_x)* in the exhaust – mainly sulphur dioxide (SO_2), but also sulphur trioxide (SO_3). After some cooling and in combination with H_2O the SO_x may partly be transformed into sulphuric acid (H_2SO_4). SO_x production for a specific fuel can be assumed to depend on fuel flow only and is typically measured in mass units of SO_2. The maximum sulphur content in kerosene according to international regulations is 0.3 mass percent with actual values often below this limit. For a sulphur content of between 0.001 and 3 g per kg fuel one can expect a SO_x production during combustion of 0.6-1 g/kg[7].

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[5] See Eyers et al. (2004), p. 91 and Kärchner, B. (1999): Aviation-produced Aerosols and Contrails, Surveys Geophys., quoted in Schumann (2002), p. 3

[6] See Schumann (2002), p. 5

[7] See Schumann (2002), p. 2

1.2.2 ENGINE TECHNOLOGY – STATE OF THE ART

The fuel efficiency of transport aircraft has been improved considerably since the introduction of turbojet powered aircraft in the late 1950s. Responsible for any progress in this field are improvements in airframe technology and – to a greater extent – engine technology. Modern aircraft engines feature high overall pressure ratios (OPR) and turbine entry temperatures (TET), resulting in higher thermal efficiencies compared to their predecessors. High bypass-ratios (BPR) of up-to-date engines ensure a greater propulsive efficiency through a reduction of the jet velocity. Above mentioned developments together with advances in airframe technology (lighter materials and superior aerodynamics) helped to cut an aircraft's fuel consumption per passenger kilometre by more than 50% in the past 40 years.

Figure 2 is based on Rolls-Royce data and shows the development of fuel consumption for selected jet engines and aircraft over time. Although a steady progress in terms of fuel efficiency can be noted, it is obvious from the figure below, that the rate of improvement tends to slow down in recent years[8].

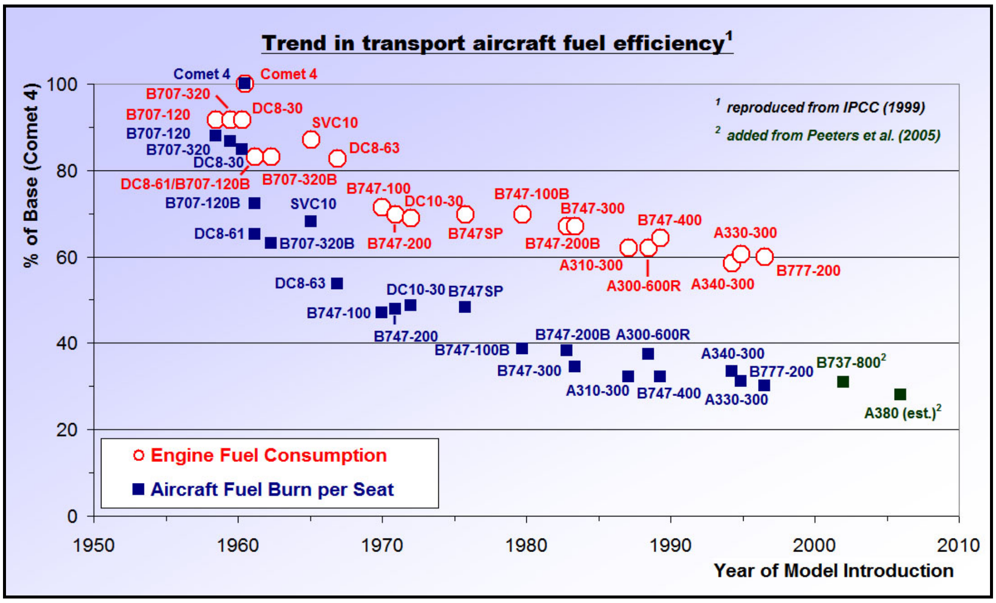
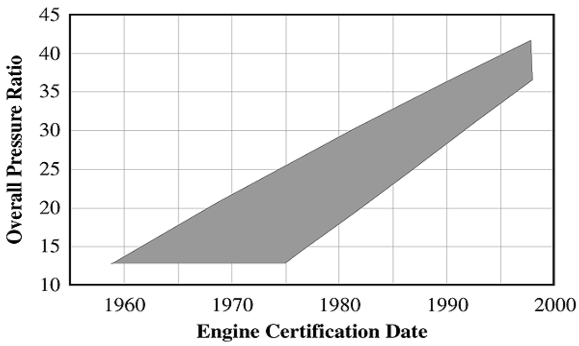


Figure 2: Development of fuel efficiency [IPCC (1999), p. 298]

Progress in fuel efficiency translates into corresponding reductions of engine emissions, at least of the main combustion products. As already mentioned in chapter 1.2.1, the output of carbon dioxide (CO_2) and water vapour (H_2O) is roughly proportional to fuel consumption, as are sulphur dioxide (SO_2) emissions. However, emissions of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and particles (soot) depend on the specific combustion technology and are more difficult to quantify from a general perspective.

[8] A detailed discussion of Figure 2 is found in Peeters et al. (2005).



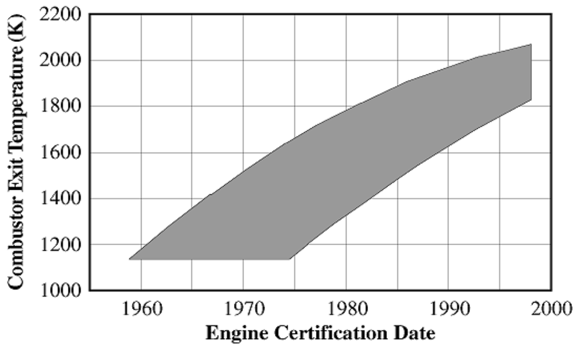


Figure 3: Development of OPR and TET [IPCC (1999), pp. 231-232]

The output of species resulting from incomplete combustion (i.e. CO and HC) could be reduced significantly by improved fuel/air mixing systems and combustor technology incorporated into high-bypass-engines of the late 1960s and 70s. This trend continued in later years, resulting in today's levels of HC and CO emissions, which can be considered low even at critical (i.e. low) power settings of the engine[9]. Combustors developed in the timeframe mentioned above also eliminated the visible smoke trails following early turbojet aircraft, while emissions of soot particles were reduced further in later years.

Unfortunately, NO_x emissions could not be cut by similar levels. On the contrary, the more fuel efficient engines introduced in the 1970s and 80s had higher NO_x emission levels than their predecessors. Taking a simplified approach to the topic, the NO_x produced during engine operation increases with both temperature and pressure in the combustor. The higher either of these factors, the higher the NO_x output per kg fuel. Improvements in combustor technology can reduce NO_x emission indices for any given temperature and pressure. However, both peak-cycle-temperatures and overall-pressure-ratios of modern engines are on the rise (see Figure 3). As a consequence, the gains in terms of fuel efficiency do not necessarily translate into a reduction of NO_x emissions. They can even result in a net rise in the output of NO_x, if engines on similar technology levels are compared[10].

This important connection between fuel consumption and NO_x still holds good for the most advanced engines available today. Furthermore, combustor designs with focus on reduced NO_x emissions may face performance issues as well as tradeoffs with respect to CO and HC emissions. Considerable research efforts on NO_x emissions in recent years have shown that such tradeoffs can be reduced to a minimum. Design improvements in combustor technology over the last 20 years helped to reduce NO_x formation by nearly 50% (yet starting from high levels), while engine peak temperatures were rising by approximately 300°C[11].

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[9] See IPCC (1999), p. 236 and Upham et al. (2003), p. 165

[10] See IPCC (1999), p. 237

[11] Ruffles, 1998, quoted in Upham et al. (2003), p. 166

Table 2 compares Rolls-Royce engines from different generations and may serve as an example of the progress made in the past. Listed are thrust-specific emissions of major pollutants during a standardized landing and take-off cycle (see chapter 1.2.3). All devices have a comparable take-off thrust of between 230 and 265kN. RB211-524D4 engines power older Boeing 747-200 aircraft, whereas the 747-400 can be equipped with the RB211-524H. Trent 556 engines are found on the Airbus A340-600. Whereas HC, CO and smoke emissions could be reduced dramatically, the NO_x reduction achieved is comparatively small.

Engine	*Year*	*LTO-Fuel (kg)*	*HC (g/kN)*	*CO (g/kN)*	*NO_x (g/kN)*	*Smoke (SN)*
Trent 556	2002	843	0,2	16,6	67,2	3,7
RB211-524H	1990	977	2,5	23,8	107,6	5,0
RB211-524D4	1977	1016	114,1	176,7	93,8	13,4
Note: All emission data are characteristic values for the ICAO landing and take-off (LTO) cycle.						

Table 2: Emissions of different generation Rolls-Royce engines [ICAO (1995)]

With no replacement for gas turbine engines in sight, evolutionary advances in engine technology and airframe design will continue to reduce the emissions per aircraft in the foreseeable future. However, technology floors may soon be reached concerning some critical engine design parameters: Further improvements in thermal efficiency through both increased temperatures and pressures seem reasonable, yet are dependent on “materials with improved temperature properties and turbine components with better cooling characteristics”[12]. As far as propulsive efficiency is concerned, an increase of the bypass-ratio (BPR) to values above 10 may be restricted by a couple of issues including aerodynamic penalties, limited space for the engines below the wings and the possible need for a gear-box between turbine and fan with appropriate drawbacks in terms of weight and efficiency. As a consequence, it is highly likely that future improvements in fuel efficiency and emission reductions of CO_2 and H_2O will not be at the scale we have seen in the last 40 years[13].

It’s the connection between fuel efficiency and CO_2 on the one hand and NO_x emissions on the other hand, that makes projections into the future a difficult task. According to ICAO predictions, the fuel efficiency of production aircraft in 2050 may be 40-50% better than in 1997 with NO_x levels on average 10-30% below current standards[14]. In an alternative ICAO scenario assuming a future research focus on NO_x rather than fuel consumption, we might as well see greater NO_x reductions (more than 50% below current standards by 2050), yet at the cost of lower advances in fuel efficiency.

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[12] Upham et al. (2003), p. 168

[13] See Upham et al. (2003), p. 168

[14] See IPCC (1999), p. 242

1.2.3 EMISSION STANDARDS & LEGISLATION

Aircraft engines have to comply with emission standards defined by the ICAO in Annex 16 Volume II to the Convention on International Civil Aviation. The standards contain upper limits for CO, HC, NO_x and soot emissions during a standardized landing and take-off (LTO) cycle and apply to all newly manufactured turbojet and turbofan engines. As part of the certification process, emission data for new engines are provided by the engine manufacturer. All data collected is publicly available in the ICAO Engine Exhaust Emissions Databank[15]. Soot emissions are classified by the so called smoke number (SN) and appropriate limits were put into practice in the year 1983. The standards for gaseous emissions apply to engines with a take-off-thrust of more than 26.7kN at ISA sea level static conditions and took effect in 1986 with limits for NO_x tightened on several occasions.

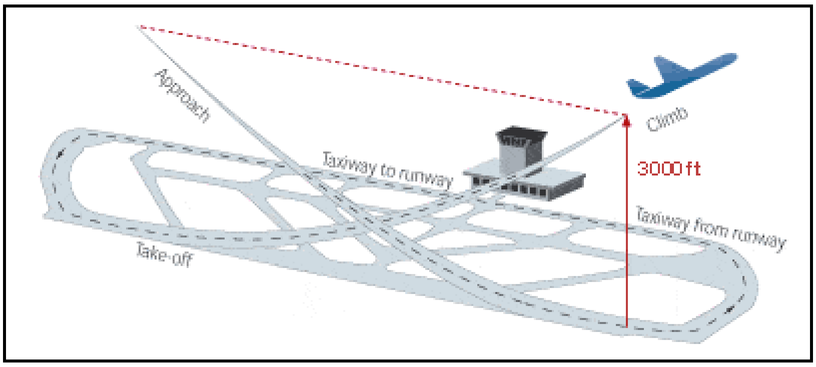

Figure 4: ICAO landing and take-off (LTO)-cycle [http://www.adv-net.org]

The ICAO standards were created to control local air quality in the vicinity of big airports. As a consequence, a landing and take-off cycle (see Figure 4) was defined to simulate the conditions for aircraft movements below 3000 ft altitude, i.e. during approach, taxi, take-off and climb. The LTO-cycle defines standard thrust settings and times for the four modes of operation, while the appropriate emissions are measured at the nozzle exit. Emissions during cruise flight are not covered by existing standards. All measurements are conducted during ground tests in accordance with the procedures described in Annex 16. The thrust settings to be applied and the appropriate times-in-mode are summarized in the table below.

	Take-off	Climb	Approach	Taxi / Idle
Thrust setting [% F_{00}]	100%	85%	30%	7%
Time [min]	0.7	2.2	4.0	26.0

Table 3: Thrust settings and times-in-mode for ICAO LTO cycles [ICAO (1993), p. 6]

[15] ICAO Engine Exhaust Emissions Databank, First Edition 1995, ICAO Doc 9646-AN/943; subsequent updates are provided online (see www.caa.co.uk).

As part of the certification process, one or more engines of a type are tested by the manufacturer. Emission indices of HC, CO and NO_x in g per kg of fuel are reported for each mode as well as the maximum smoke number (SN). Fuel flow in kilograms per second is also measured and used to calculate the total gross emission D_p of each gaseous pollutant over the LTO cycle as a whole. By a set of formulae described in Annex 16, measured values are corrected to reference conditions, i.e. ISA sea level static conditions except that the reference absolute humidity was chosen to be 0.00629 kg water/kg dry air[16].

The thrust specific value D_p/F_{00} in g/kN is determined as the mean value of all engines tested, with F_{00} being the maximum rated thrust of the engine. An additional statistical coefficient – dependent on the number of engines tested – is applied, which ensures at a 90% level of confidence that the mean emissions of all engines of a certain type do not exceed the values calculated. The resulting and corrected LTO emissions D_p/F_{00} are called characteristic values and must meet regulatory values defined for each pollutant in Annex 16.

The ICAO limits for each pollutant are as follows[17]:

- Regulatory Smoke Number: $83.6 \cdot \left(F_{00}\right)^{-0.274}$ or a value of 50, whichever is lower;
- Regulatory HC Level: $\frac{D_p}{F_{00}} = 19.6$ [g/kN];
- Regulatory CO Level: $\frac{D_p}{F_{00}} = 118$ [g/kN];
- Regulatory NO_x Level: *dependent on date of manufacture, pressure ratio and maximum thrust of the engine;*

NO_x limits vary linearly with the pressure ratio π_{00} of the engine which is defined as the "ratio of the mean total pressure at the last compressor discharge plane of the compressor to the mean total pressure at the compressor entry plane (...)."[18] Regulatory NO_x limits were strengthened several times in the past. As a consequence, they also depend on the date of manufacture of an engine and – for the latest standards – on maximum take-off thrust. Further strengthening of emission levels in the future is being proposed by the Committee on Aviation Environmental Protection (CAEP) and may also cover emissions during cruise flight. Figure 5 on the following page shows the different NO_x emission standards in place today with CAEP/6 being the latest standard incorporated into Annex 16.

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[16] See ICAO (1993), p. 23

[17] See ICAO (1993), p. 7

[18] See ICAO (1993), p. 1

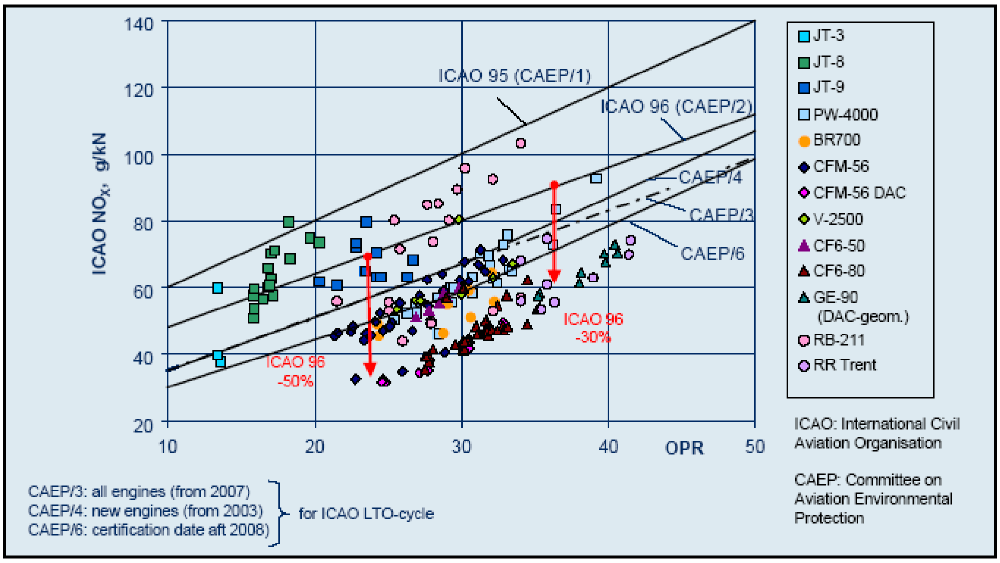

Figure 5: NO_x emission standards[19] [Donnerhack (2005)]

While the ICAO regulations set upper limits for engine emissions, policy makers in some countries aim to create further incentives for airlines to use the best available engine technology. Such *market-based approaches* include emission dependent landing fees, which have already been put into practice at some airports and will be briefly discussed below. Furthermore, emission dependent en-route charges and emissions trading of airline CO_2 and other gases are currently being discussed in Europe[20]. As a result of such approaches, the pressure on engine manufacturers to provide low-emission technology is increased.

Comparable to well established noise dependent landing charges, *fees dependent on engine emissions* have been introduced at certain airports in Switzerland, Sweden and the UK. Zurich became the first airport to introduce an emission charge in 1997; a similar charge was established at a number of airports including London Heathrow in the following years. Confronting local pollution issues (particularly ozone formation, see chapter 1.3.1), nitric oxides (NO_x) and – in some cases – hydrocarbons (HC) are addressed by the charges. Current landing fee models are based on an engine's thrust-specific LTO emissions of NO_x. Unlike in the ICAO standards, no consideration is given to the engine's pressure ratio. Aircraft are ranked according to their emission factors and grouped into different emission classes. Dependent on the emission class, rebates on the landing fee are granted or a certain supplement is to be paid. A standardized approach towards NO_x-dependent landing fees was adopted as an ECAC recommendation in 2003[21].

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[19] The figure includes the CAEP/4 standards for engines with a maximum rated thrust of more than 89.0 kN.

[20] See Wit et al. (2005), p. 2

[21] Recommendation ECAC/27-4, see http://www.ecac-ceac.org

1.3 ADVERSE EFFECTS OF AIRCRAFT EMISSIONS

1.3.1 LOCAL AIR QUALITY

Besides aircraft noise and 3rd party risk through potential accidents, air quality problems are amongst the local issues resulting from aviation. Emissions from aircraft engines, fuel handling, road traffic and the airport infrastructure may result in poor air quality in the vicinity of airports. Particularly affected are the personnel working at the airport site, but also residents living close to the airport. Whereas aircraft are the predominant source of emissions at the airport itself, road traffic is usually the largest polluter in residential areas even in the vicinity of large airports.

Permanent surveillance of air quality at major airports has shown that *national limits are often exceeded* for certain pollutants, most prominently nitric oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC)[22], and particles (PM_{10}). NO_x and VOCs are precursors of ground-level ozone (O_3), hence an elevated O_3 level may result through a chemical reaction with oxygen at the presence of sunlight. Species like sulphur dioxide (SO_2), hydroxyl radicals, nitrous and nitric acids may also affect local air quality, although the contribution of aviation towards these pollutants is believed to be negligible[23]. Determining the effects of aircraft amongst other emission sources in the vicinity of airports is a complicated task and beyond the scope of this thesis. There is no doubt, however, that airports as major transport hubs have a negative, though highly localized effect on air quality.

Respiratory complaints are the main effects related to elevated concentrations of NO_x, VOCs, O_3 and PM_{10}. Whereas health studies of airport workers showed an association with respiratory symptoms like chronic obstructive pulmonary disease or asthma, investigations in residential areas around London Heathrow and Amsterdam Schiphol failed to show a clear respiratory effect to the population that could not be explained by differences in lifestyle[24]. Of course, exposure of pollutants in the general population may vary dependent upon a number of factors including air and ground traffic at the airport, the distance of residential areas from the airport site, the orientation of the runways and wind directions.

VOCs and particle emissions are known to have *cancer-causing properties*, yet only few studies of cancer amongst the general population around airports exist. VOCs are also the main contributors to the odour nuisance associated with airports. On a regional level, SO_2 together with NO_x may contribute to *acidification and eutrophication*.

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[22] VOC are combinations of carbon with other elements (e.g. hydrogen or oxygen).

[23] See IATA (2004), p. 18

[24] See Upham et al. (2003), p. 67

1.3.2 GLOBAL ATMOSPHERIC EFFECTS

Besides air quality issues at airports, it's the global atmospheric impact of aviation which has been discussed amongst scientists since the 1970s. As mentioned in chapter 1.2.1, carbon dioxide (CO_2) and water vapour (H_2O) make up 71% and 28% of aviation's emissions respectively (by mass), with NO_x being the most prominent factor amongst the remaining 1%. At typical cruise altitudes of between 10 and 12 km and particularly in the heavily occupied airspace of the Northern Hemisphere, aircraft emissions alter the concentration of atmospheric gases and influence atmospheric chemistry. Together with anthropogenic emissions from other sources aviation is believed to disturb the energy balance of the earth and may contribute to climate change.

The atmospheric effects of aircraft emissions can be grouped into three categories[25]:

- Direct emissions of greenhouse gases (CO_2 and H_2O).
- Emissions that contribute to the production of greenhouse gases (NO_x).
- Substances or particles that influence the formation and properties of clouds.

1.3.2.1 DIRECT EMISSIONS OF GREENHOUSE GASES

Carbon dioxide (CO_2) is a greenhouse gas with exceptionally high photochemical and thermodynamic stability. As a consequence, it has a lifetime of several 100 years. Through atmospheric exchange processes CO_2 emissions get distributed over the whole atmosphere. According to Schumann, the concentration of atmospheric CO_2 has increased since 1850 by about 80 μmol/mol due to anthropogenic emissions. The contribution of aircraft CO_2 from the last 40 years is estimated to be in the order of 1.4 μmol/mol. At present times, the aviation sector contributes 1.6-2.2% to all anthropogenic CO_2 emissions or 10-13% to the CO_2 from all transportation sources[26].

Another greenhouse gas is *water vapour (H_2O)* and the respective emissions may also contribute to global warming. However, H_2O emissions from aviation are small compared to the water evaporating at the Earth's surface. Aviation induced H_2O is mainly emitted into the troposphere, where it is removed by precipitation within 1-2 weeks. Some H_2O is released into the stratosphere, where it has a larger residence time. Stratospheric H_2O emissions may also have an effect on the reduction of stratospheric O_3 via chemical reactions, yet these processes are of negligible importance compared to other effects of aircraft emissions[27].

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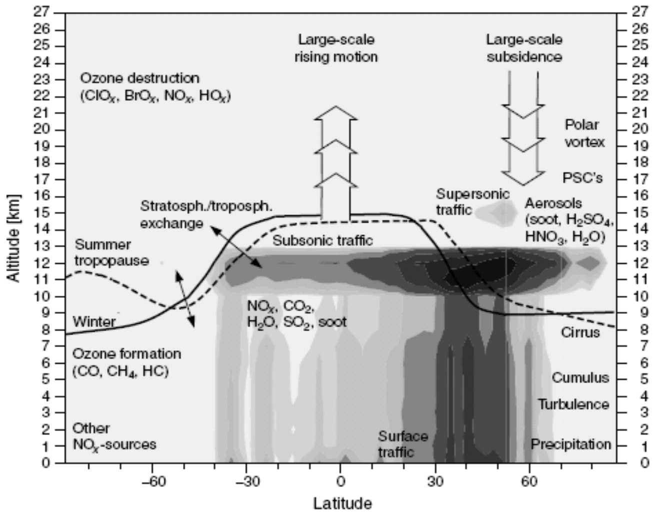
[25] See IPCC (1999), p. 187

[26] Values for 1992, see Schumann (2002), p. 3

[27] See Schumann (2003), p. 5

1.3.2.2 EFFECTS OF AIRCRAFT NO_X EMISSIONS

Aviation-induced *nitrogen oxides (NO_x)* make up 2% of all anthropogenic NO_x emissions. The peculiarity of aircraft emissions at altitude results from low background concentrations of NO_x in the upper troposphere and lowermost stratosphere. At cruise altitudes in northern mid-latitudes aircraft increase the NO_x concentration by up to 20%, whereas the increase is lower outside this region (see Figure 6)[28]. Furthermore, the residence time of NO_x near the tropopause is 10 times higher than at ground level, with most NO_x being converted to HNO_3 within days or weeks. These issues lead to a significant influence of aircraft emissions on atmospheric chemistry. Most importantly, ozone (O_3) and methane (CH_4) concentrations are altered via several chemical reactions and transport processes.



Legend:

The darker the shaded area the higher the NO_x emission rate.

Figure 6: NO_x emission rates from aircraft [Schumann (2002), p. 2]

While ozone in the mid and upper stratosphere (15-50km altitude) provides a protective shield against UV radiation, it is also a greenhouse gas and, as such, most effective around the tropopause level. Tropospheric O_3 has a lifetime in the order of weeks and is influenced by the emissions of today's subsonic air traffic, since *its formation rate increases with NO_x concentration*. Carbon monoxide (CO), methane (CH_4) and other hydrocarbons in the atmosphere are oxidised and produce the hydroperoxy radical (HO_2). Hence, a reaction of nitric oxide (NO) and HO_2 forms nitrogen dioxide (NO_2). The NO_2 may photodissociate and set free atomic oxygen (O), which reacts with O_2 forming O_3. These processes take place in the natural atmosphere, but aviation NO_x is believed to catalytically enhance the production process. The resulting O_3 increase from aircraft was calculated to be 6% at cruise altitudes in the most frequented airspace of the Northern Hemisphere[29].

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[28] See IPCC (1999), p. 31

[29] Referring to the region 30-60° N latitude, 9-13km altitude; see IPCC (1999), p. 31

Besides increasing the O_3 concentration, aircraft emissions may also influence atmospheric methane (CH_4). Direct emissions of CH_4 are negligible, but via complex reactions and transport processes NO_x emissions may cause a *slight decrease in CH_4 over the whole atmosphere*. In principle, aircraft NO_x emissions increase the amount of OH radicals, which are set free in the above mentioned reaction of HO_2 with NO. The OH radicals react with carbon monoxide and cause a reduction of the CO concentration at flight altitudes. Due to a lifetime of CO in the order of months and atmospheric mixing processes, the CO reduction is also notable at lower altitudes. In the warm air near the ground OH radicals from other sources may react with both CO and CH_4. As CO levels have decreased, they are believed to react with CH_4 to a greater extent and hence reduce the amount of CH_4 molecules. Since methane is a greenhouse gas with long lifetime, a uniform reduction in atmospheric CH_4 concentration may result. It must be noted, however, that the calculated decrease of about 2% from aviation is small compared to a 2.5 times increase in atmospheric CH_4 since industrialization[30].

1.3.2.3 EFFECTS OF PARTICLES & CONTRAILS

The mass of *soot and sulphate particles* in the engine plume is of small magnitude compared to particulate emissions from ground based sources, e.g. volcanic eruptions. By number, however, they significantly alter the aerosol concentration in the upper troposphere. Furthermore, the background concentration of particles at cruise altitude is low and the residence time much longer than near the Earth's surface. The direct radiative effect of particles is comparatively small, but they may influence ozone production, change cloud properties or trigger the formation of cirrus clouds. Scientific knowledge in this field is limited and the increase in cirrus cover in the last decades need not be attributable to aircraft particles[31].

Condensation trails (contrails) of aircraft are visible, line-shaped ice clouds resulting from the condensation and freezing of water vapour on particles. They form at low ambient temperature, when the warm and moist engine exhaust mixes with cold air and saturation with respect to liquid water is reached in the plume. Contrails usually have a short lifetime, but they may persist for hours or even longer, dependent mainly on ambient air temperature and humidity. By the uptake of further H_2O persistent contrails may grow and form large-spread cirrus-like clouds. From an analysis of satellite pictures and calculations, a 0.75% mean cover from line-shaped contrails could be determined at daytime over Central Europe, around 0.07% in the global day and night average[32]. However, persistent contrails may finally spread by diffusion and wind-shear to form cirrus clouds that can no longer be identified as being produced by aircraft.

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[30] See Schumann (2002), pp. 4-5 and IPCC (1999), p. 44

[31] See Schumann (2005), p. 12

[32] See Schumann (2005), pp. 10-11

1.3.2.4 AVIATION'S INFLUENCE ON CLIMATE CHANGE

Climate change in the context of the thesis refers to any human influence on the Earth's radiative balance that may alter global or regional long-term weather properties. Greenhouse gases warm the Earth's surface and troposphere by absorbing and reemitting outgoing radiation. The cloud cover affects the energy and water budgets of the Earth and influences climate in more than one way. Clouds absorb or reflect both solar radiation to Earth and infrared radiation back to space. An increased cirrus cover is known to lower the temperature range on the surface and may on average increase surface temperature. Aerosols in the atmosphere also affect climate by absorbing and reflecting solar energy[33].

The Earth's mean surface temperature has increased by 0.6 ± 0.2 °C during the 20th century[34]. It is difficult, however, to separate anthropologic from natural effects and determine their respective impacts on observable parameters. In order to quantify and compare various influences, the *concept of radiative forcing* may be used as a metric.

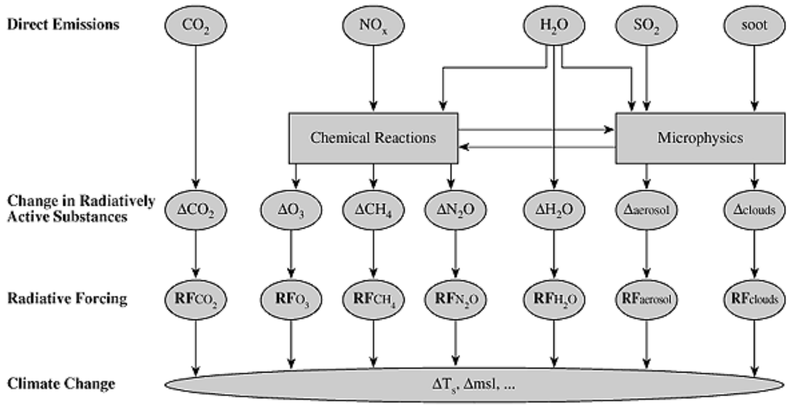

Figure 7: The effects of aircraft emissions on climate change [IPCC (1999), p. 189]

Radiative forcing – in units of watts per square metre (W/m²) - can be described as a measure of the effects of perturbations to the planetary radiation balance. More exactly, it is "the net radiative flux change at the top of the atmosphere calculated in response to a perturbation such as a change in gas concentration or cloud cover (...)."[35] Usually determined as a global and annual mean value, positive radiative forcing causes a warming of the Earth system. An approximately linear relationship can be assumed between the change in radiative forcing (ΔRF) and the global mean surface temperature change (ΔT_S). Figure 7 shows a schematic of aviation's effects in terms of radiative forcing and climate change.

[33] See Schumann (2002), pp. 5-6

[34] See IPCC, Climate Change 2001 – the Scientific Basis, Cambridge 2001, quoted in Upham et al. (2003), p. 80

[35] See Schumann (2002), p. 7

By the means of a 3D radiative transfer model the Intergovernmental Panel on Climate Change (IPCC) calculated radiative forcing for aviation in their landmark report "Aviation and the Global Atmosphere" (IPCC, 1999). Best estimates for aircraft related effects were given, with CO_2, O_3 and contrails being the most influencing factors. According to the report, aviation caused a radiative forcing of +0.05 W/m² in the base year 1992, around 3.5% of the global mean radiative forcing from anthropogenic sources. The uncertainties in such calculations are high since scientific knowledge of atmospheric processes is limited. The level of understanding is particularly low regarding aviation's influence on cirrus clouds, hence no estimate of this effect's forcing (and just a possible range) was given in the IPCC report.

Various Chemical Transport and Climate Chemistry Models were used in the European TRADEOFF project to calculate aviation's radiative forcing for the year 2000 (see Figure 8). Based on the latest knowledge of atmospheric processes, the study indicates an overestimation of contrails in the IPCC report. The effects of aviation induced cirrus clouds are still subject to debate, yet they may be of significant magnitude[36]. The total radiative forcing from aviation was calculated to be +0.05 W/m², about the same value as estimated by the IPCC for 1992. It should be noted that all values are global averages and – due to inhomogeneous distributions of the species – forcings of opposite signs do not necessarily cancel.

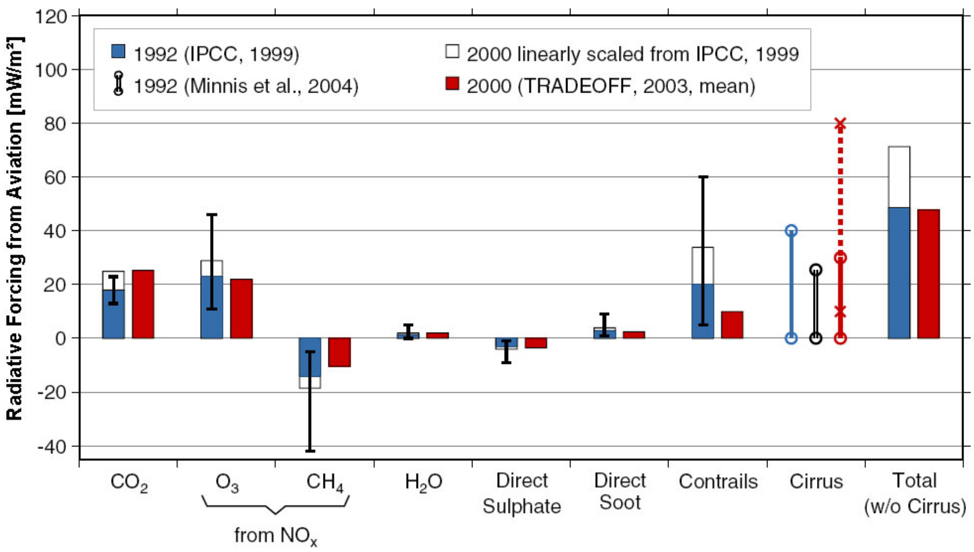

Figure 8: Radiative forcing estimates for aviation [Sausen et al. (2005), p. 556]

As will be discussed in the following chapter, the climatic influence of aviation will most likely grow both in absolute values and as a fraction of total anthropogenic forcing. The IPCC predicts a forcing of 0.19 W/m² in a central scenario for aviation in 2050 – about 4 times the current value and a prospective 5% contribution to the total anthropogenic influence[37].

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[36] See Sausen et al. (2005), p. 559

[37] See IPCC (1999), pp. 209-211

1.4 AVIATION TRENDS

Aviation growth rates regularly exceed those of the world economy. Since the 1970s, passenger numbers have doubled every 12-15 years. According to ICAO statistics, 1.887 billion passengers and 3,442 billion passenger-kilometres were flown by commercial airlines in 2004. In the wake of the events of September 11th, 2001 and the SARS crisis in Asia, passenger growth has slowed down slightly to an average 4.4% increase per annum between 1994 and 2004. In the same timeframe revenue passenger-kilometres grew by 5.1% per year, while cargo traffic (in ton-kilometres) shows growth rates in the order of 6-7%[38]. Market forecasts by Airbus and Boeing predict a continuous growth of similar magnitude in the next 20 years[39].

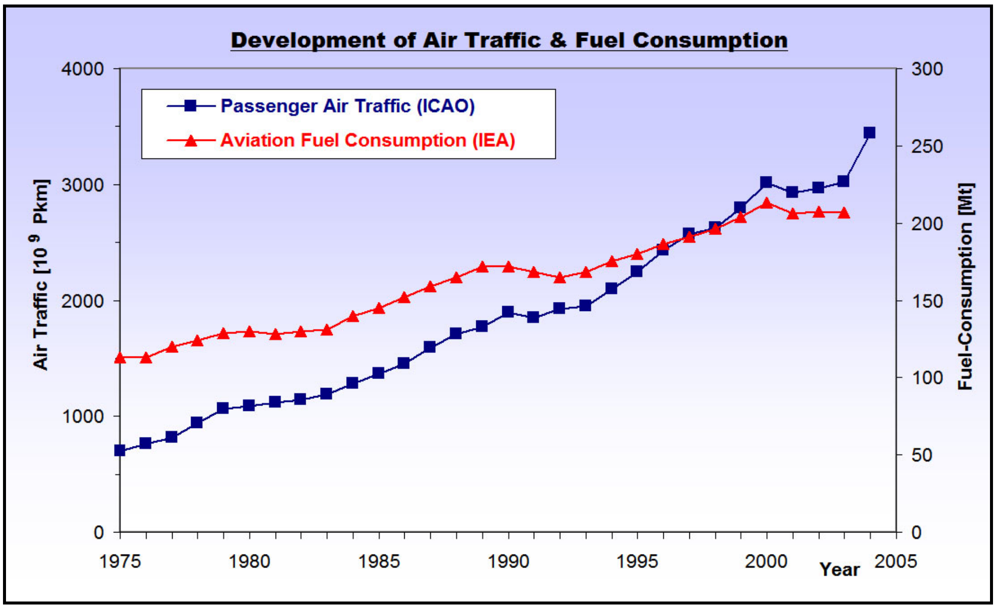

Figure 9: Development of Air Traffic and Fuel Consumption [ICAO, IEA]

Concerning the ecologic impact of aviation on a global level, the *fuel consumption of the world fleet* is a major factor. Figure 9 compares the development of passenger-kilometres travelled with the amount of aviation fuel sold according to statistics of the International Energy Agency (IEA). As can be concluded from the figure, the fuel use of aviation is increasing, however at lower rates than transport performance. It should be noted that the IEA values comprise various fuel and kerosene types for civil and military aviation including fuel amounts used for ground-based engine tests or other purposes[40]. With civil aviation being by

[38] See Grunewald et al. (2005), pp. 29-34

[39] 5.3% (Pkm) / 5.9 % (tkm) annual growth from 2004-2023 according to Airbus (2004), p. 2
4.8% (Pkm) / 6.2% (tkm) annual growth from 2005-2024 according to Boeing (2005), p. 3

[40] See UBA (2003), pp. 7-9

far the largest consumer of such fuels, the above mentioned comparison is justified[41]. Taking into account the technological progress described earlier in this chapter, the following interrelations become visible:

- The fuel consumption of newly developed aircraft is declining due to progress in engine and airframe technology.
- The average fuel consumption of the world fleet of aircraft is reduced when new aircraft (partially) replace older models.
- The growth rate of air traffic is higher than the world fleet's improvement rate in terms of average fuel consumption.

Due to the environmental impacts of aircraft emissions discussed earlier in chapter 1.3, this development cannot be considered sustainable from an ecologic point of view. Aircraft emissions of CO_2 and H_2O are proportional to fuel consumption and can be assumed to follow the respective trend. Calculations of the world fleet's NO_x output also indicate an increase over the years (see chapter 3.3). Put differently, *the technological progress in the field of emissions reduction technologies is being outpaced by aviation growth.* It remains open to question, whether these interrelations can be influenced to the positive. Political and market based approaches like those mentioned in chapter 1.2.3 might help to reduce aviation's environmental impacts in the future.

[41] 156 Mt of fuel burn can be attributed to civil aviation in 2002, see Eyers et al. (2004), p. 90; 207 Mt of aviation fuel were sold in 2002 according to IEA statistics.

2 METHODOLOGY OUTLINE FOR INVENTORY PRODUCTION

2.1 INTRODUCTION TO EMISSION INVENTORIES

An emission inventory can be defined as *"the summation of the quantity of emissions for a specific element or compound from various emitters"*[42]. Inventories for aviation are typically compiled on an annual basis and on local or global scales. Whereas local emission inventories focus on air quality aspects in the surroundings of airports, global inventories are used to determine the impact of aircraft on climate change. The development of global inventories for aviation has traditionally been driven by atmospheric scientists, who use the results to model atmospheric chemistry and transport processes. Emissions of carbon dioxide (CO_2), water vapour (H_2O) and nitric oxides (NO_x) are covered as the most influencing substances on global warming, supplemented by hydrocarbons (HC), carbon monoxide (CO) or particulate emissions (by mass and number) dependent on the specific focus of an inventory[43].

The thesis concentrates on *global emission inventories*, which are mostly calculated at a three-dimensional resolution. They provide gridded data, i.e. the mass of aircraft emissions as functions of latitude, longitude and altitude. The latest data-sets feature a four-dimensional resolution in space and time, which improves the usability of the results for the purpose of climate research. Emission inventories for global aviation are available from different sources, most prominently the U.S. National Aeronautics and Space Administration (NASA), the Abatement of Nuisances Caused by Air Transport (ANCAT) / European Community (EC) Working Group and the German Aerospace Center (DLR).

Commonly used inventories for present-day aviation include:

- The ANCAT/EC-2 inventory for 1991/92 by Gardner et al. (1998),
- The DLR-2 inventory for 1991/92 by Brunner et al. (1998),
- NASA data for 1992 and 1999 by Baughcum[a] et al. (1996) and Sutkus et al. (2001),
- The EC initiated AEOR2k inventory for 2002 by Eyers et al. (2004).

Another set of inventories for the years 2000-2004 is being prepared by the Federal Aviation Administration (FAA). More information on specific inventories is presented in chapter 3. Figure 10 shows the distribution of NO_x emissions from aviation, the sketch being composed from a four-dimensional DLR inventory for scheduled aviation in March 1992.

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[42] Bromberg, S.: The Underappreciated Emission Inventory, Environmental Manager, August 1997, quoted in Patterson (2005), p. 8

[43] See IPCC (1999), p. 295

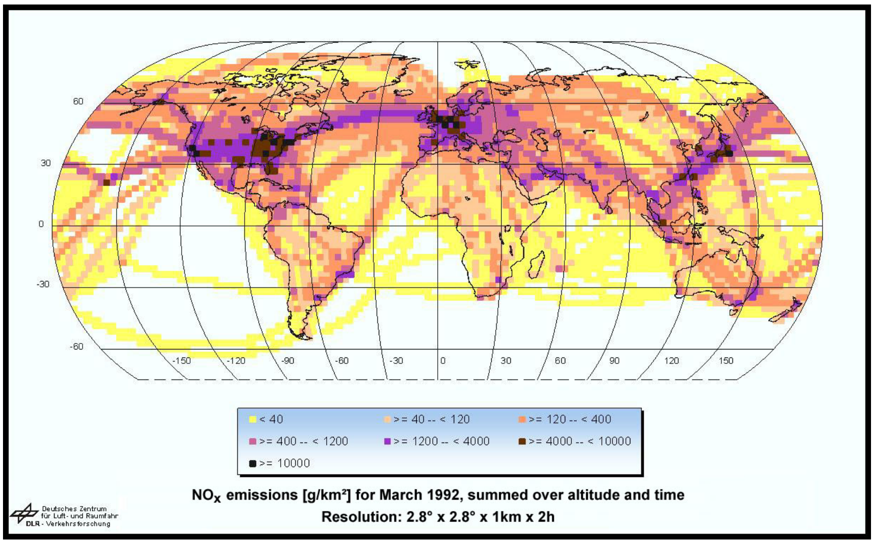

Figure 10: Global NO_x inventory for scheduled aviation in March 1992 [DLR]

The inventories mentioned above are based on *similar, yet not identical assumptions and methodologies*. In order to calculate aircraft emissions, a "bottom-up" approach is typically followed (see Figure 11). Global flight operations are collected in an aircraft movements database, which may consist of Air Traffic Control (ATC) data or flight schedules. Aircraft/ engine combinations in service are identified and assumptions on the flight paths are made to approximate an aircraft's trajectory. For each single flight, the fuel burned along its flight path is calculated using aircraft and engine performance data. The respective engine emissions are determined by an emission model, taking into account ambient atmospheric conditions. Finally, the results are placed on a three-dimensional world grid.[44]

Using the "bottom-up" approach, it is obvious that for *an ideal inventory of aviation fuel burn and emissions*, the following information would be required:

- Movements and trajectory information for all flights worldwide, including scheduled, non-scheduled, military and general aviation.
- Detailed performance data for all aircraft and engines in service.
- Detailed data on the emission characteristics of all engines in service (for all operating points and flight phases).

Since the above mentioned data are only partially available, simplifying assumptions are to be made in several areas. Keeping in mind the limits of data availability on the one hand and processing power on the other hand, the current "state-of-the-art" in inventory production will be discussed in the following chapters.

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[44] See IPCC (1999), pp. 298-299

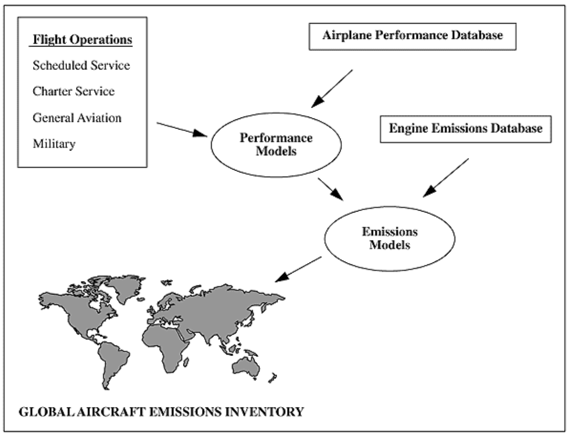

Figure 11:

The “bottom-up” approach for inventory calculation

[IPCC (1999), p. 299]

Whereas movements data for civil air traffic can be obtained from various sources, the respective data is hardly available for military aviation (for reasons of national security). As a consequence, *a combination of “top-down” and “bottom-up” approaches* is typically used to account for military flight movements. In a first step, the activity for each military aircraft needs to be determined. This can be done by estimating the number of flights per aircraft type from an analysis of the national fleets and their respective utilizations. Estimated or actual performance data can be used to derive generic mission profiles for a set of typical missions. Assuming one of these profiles for each flight, fuel burned and emissions are calculated. Since the horizontal distribution of the emissions is unknown, the calculation results may be allocated to military airspace and manoeuvres areas, the regions around airbases or countries’ boundaries. The limited data availability for such studies results in a considerably lower resolution and accuracy of the results. As a consequence, inventories for military aviation are mostly produced separately from their civil aviation counterparts.[45]

Besides historical or present-day data, gridded inventories are also available *for a number of future scenarios*, e.g. for the years 2015 (by NASA, ANCAT and DLR), 2020 (NASA) and 2025 (AERO2k). In principle, these inventories use the same methodologies as described above for civil and military aviation. Air traffic in future years may be predicted using a base year inventory and assuming regional growth rates for aircraft movements or transport performance. Furthermore, predictions on the future fleet of aircraft in terms of performance and emission characteristics are to be made.[46]

Since fuel burn and emissions from civil aircraft exceed those from military aviation by a considerable margin, the thesis concentrates on the classical “bottom-up” approach. It focuses on present-day and historical inventories for civil aviation and explains their methodologies. Results for both civil and military inventories will be discussed in chapter 3.

[45] See IPCC (1999), pp. 299-300 and Eyers et al. (2004), pp. 41-47

[46] See IPCC (1999), pp. 301-302

2.2 ELEMENTS OF INVENTORY PRODUCTION

2.2.1 PROCESSING OF MOVEMENTS DATA

2.2.1.1 CONTENTS AND SOURCES OF MOVEMENTS DATA

A movements database contains all flight operations considered relevant for an inventory. The specific contents depend on the data sources available and the level of detail that should be achieved when modelling each flight. The construction of a movements database for global aviation requires a great share of the total workload for inventory production. As will be described below, large amounts of information are to be analysed, filtered and processed.

The minimum data-set required for each flight includes departure and arrival airports, the weekly frequency of the flight and the aircraft type. Such information can be gathered from flight schedules. Separate databases may be used to obtain the airports' coordinates and to assign an engine type to each aircraft. This is essential in order to model each flight on a world grid and to calculate the respective emissions. The latest methodologies make use of additional information, most prominently:

- Departure and arrival times for each flight, which are required to create a four-dimensional inventory.
- A number of waypoint coordinates for each flight, used to model an aircraft's trajectory.

Whereas departure and arrival times are included in flight schedules, waypoint coordinates need to be obtained from Air Traffic Control (ATC) organizations. Table 4 summarizes the above mentioned data requirements.

Source of Information	Extracted Data	Optional Information
Flight schedules (e.g. OAG, BACK Aviation)	Flight ID Departure and arrival airports Weekly frequency Aircraft type	Departure and arrival times
ATC data (e.g. FAA, EUROCONTROL)	Flight ID Departure and arrival airports Weekly frequency Aircraft type	Departure and arrival times Waypoint coordinates & times
Airports Database	Airport codes and coordinates	
Fleet Database	Aircraft / engine combinations	

Table 4: Information requirements for a typical movements database

Flight schedule databases for global aviation are available commercially e.g. from the Official Airline Guide (OAG) or BACK Aviation. These databases contain information on scheduled air traffic including departure and destination airports, departure and arrival times as well as the aircraft type in service. Major limitations when using scheduled data are:

- No unscheduled, military or general aviation flights are included.
- Schedules may not correspond to "real-world" air traffic, i.e. flights may be cancelled or added, arrival and departure times may vary, the aircraft type may be replaced.
- No trajectory information is available.

Air Traffic Control (ATC) data provide more detailed and reliable information, however they may not be available for every country in the world. ATC data either consist of flight plans, which have to be filed for every IFR flight, or a combination of flight plans and radar trajectories. Air Traffic Management (ATM) organizations like EUROCONTROL's Central Flow Management Unit (CFMU) collect *regional flight plan data*. Since flight plans include waypoints in combination with estimated flight levels and times, they can be used to reconstruct an aircraft's trajectory. European flight plans provided by the CFMU cover all flights to and from every ECAC member state. The so-called AMOC data (Air Traffic Flow Management Modelling Capabilities) provided by EUROCONTROL consist of four-dimensional trajectories which were calculated from flight plan information[47].

Depending on the capabilities and policies of ATC organizations*, radar trajectories* may be more difficult to acquire. Such data cover the movements of all flights detected by ATC radars, mostly in the form of waypoint coordinates and times. Information may not be available for areas without radar coverage. Besides, data of military flights are not provided by ATC authorities for reasons of national security. As far as data quality is concerned, radar trajectories must be regarded as the preferred source of information. The FAA's Enhanced Traffic Management System (ETMS), as an example, provides flight plans and radar tracks for North America and parts of Western Europe (including the United Kingdom)[48].

Whereas the early generations of emission inventories rely entirely on flight schedules, the latest methodologies like AERO2k use ATC data wherever available. Flight plans and four-dimensional radar trajectories from ETMS can be used in combination with AMOC trajectories from EUROCONTROL. Air traffic movements in the remaining parts of the world are supplemented by scheduled information. Following this approach, detailed information on both scheduled and unscheduled (IFR) flights are available for North America and Europe, while unscheduled movements are not available for countries outside these areas.

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[47] See Michot et al. (2003), p. 90

[48] ETMS data is maintained by the Volpe Centre in Cambridge, Massachusetts, see FAA (2003), p. 6

2.2.1.2 DATA SELECTION AND PROCESSING

OAG flight schedules for a period of one week consist of around 500.000 entries in a 350 megabyte Microsoft Access database, while ATC data including trajectory information may make up even larger data-sets. It is obvious, that tools for automatic importation, filtering, standardization and merging of data need to be used. Furthermore, a reasonable selection of data collection periods is common practice for inventory production. For the AERO2k inventory, as an example, ATC data was collected for 6 representative weeks of the year, i.e. 42 days that account for the seasonal, weekly and diurnal variation in air traffic. Inventories for the remaining year were calculated from the data collected using trends extracted from BACK Aviation's flight schedules[49].

Filtering of Flight Schedules

Schedules as provided by OAG usually support travel planning and do not represent aircraft movements. The data includes duplicate listings of certain flight segments as well as legs of trips offered by other means of transportation (such as rail services with a flight number). While the latter are marked and can be filtered out easily, some logic needs to be implemented to account for duplicate entries of actual flight movements. In the terminology used by NASA, such duplications are classified as

- codeshare,
- starbust and
- effectivity duplications[50].

Codeshare duplications are flight segments listed under more than one airline code and flight number due to a codeshare agreement between two or more airlines. While the latest OAG schedules include information on the operating carrier of a flight (which enables simple filtering routines), older data need to be checked for duplicate flights with the same airport-pair served, same times of departure and arrival, same day in the week and aircraft type. Expert knowledge is required, since some head-to-head competition flights may be filtered out erroneously following the logic described above[51].

Furthermore, flight segments of one- or multi-stop itineraries of an airline may be listed under different flight numbers. A flight from Hamburg to New York via Frankfurt may be listed as flight number 123, while flight number 321 represents a flight from Munich to New York via

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[49] Trends were determined as functions of season, day in the week and country, see Eyers et al. (2004), p. 20

[50] See Sutkus et al. (2001), p. 13

[51] See Sutkus et al. (2001), p. 13

Frankfurt. The Frankfurt-New York leg may hence be double counted, even though just one physical flight is taking place. These *starbust duplications* are removed by determining flight segments of one airline with the same airport pair, same departure and arrival time, same day and equipment[52].

Double entries of a third type are classified as *effectivity duplications*. They account for changes of flight numbers within a month due to minor schedule modifications. Flights may erroneously be double counted if the number of connections between airports is determined. However, effectivity dates of flight numbers are included in the database. In the NASA inventory for 1999, only flights effective on the 16th of a month are considered for the inventory in order to avoid duplications due to schedule modifications[53].

Processing of ATC Data

Both flight plan and trajectory information from ETMS and AMOC data are of limited quality, i.e. the data-sets may include duplicates, incomplete, inconsistent or redundant information. As a consequence, *checks and assessments* are required before the data can be used for inventory production. The processing of flight plan and radar data includes:

- The substitution of missing data (e.g. departure / arrival airports, times etc.) from other available sources.
- The identification and removal of inconsistent or redundant information.
- An assessment of each flight's trajectory.

The trajectory of each flight is given in the form of waypoints which are connected by straight lines or great-circle segments. *Trajectories based on ETMS data often need to be smoothed*, i.e. kinks and altitude spikes need to be removed. Trajectory kinks may result from the limited accuracy of radar stations and are particularly striking, if closely spaced waypoints originate from different radar centers. Two successive waypoints may be replaced by a single "averaged" position which gives the effect of a smoothed trajectory. Care must be taken in departure and arrival flight phases (where the ground speed is typically low) in order not to remove waypoints resulting from holding or flight manoeuvres[54]. Similarly, altitude spikes may be identified and smoothed by defining a maximum rate-of-climb (ROC) value between successive waypoints[55].

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52 See Sutkus et al. (2001), p. 14

53 See Sutkus et al. (2001), p. 15

54 Ground speed is reported by ETMS or calculated from the waypoint coordinates and times, see Michot et al. (2003), pp. 73-77

55 See FAA[a] (2005), pp. 20-25 and Michot et al. (2003), pp. 77-78

2.2.1.3 MERGING OF DATA FROM VARIOUS SOURCES

Since data from multiple sources may be used for an inventory, problems regarding the conversion of data formats may arise. Besides the technical implementation of a common database, a harmonization of contents is required. This includes most prominently:

- The *implementation of common standards* in terms of airport and airline codes, flight identification and abbreviations for aircraft types,
- The *conversion of local times* from flight schedules to coordinated universal time (UTC),
- *The linking and merging of information* from various sources.

IATA (three-letter) and ICAO (four-letter) codes are *common identifiers* for airports and may be used inconsistently in the data provided by different sources. An airports database is required which identifies the appropriate airport, supplies a common airport code and which may also provide the airport's coordinates. Similar procedures are to be followed for other information extracted from more than one source (e.g. airline codes and flight-id). It is worth noting that IATA codes are no unique identifiers, hence a conversion table between IATA and ICAO codes cannot be provided without some implemented "intelligence"[56].

Since various ATC and scheduled data may be used, flights are often covered (completely or partially) by more than one source of information. These flights need to be identified as the same aircraft movement and a standard set of information for each flight needs to be defined. This could involve the selection of data from a preferred source or merging of information from more than one source. It is obvious that linking and merging of information is the more complicated, the more sources of information are used.

Merging of Trajectories

In the AERO2k inventory, as an example, AMOC and ETMS data are used to provide movements data supplemented by flight schedules from BACK Aviation. Since both AMOC and ETMS data include trajectories for transatlantic flights, a common trajectory needs to be defined for each of these aircraft movements (see Figure 12). For this purpose, all flights are divided in three "zones", i.e. departure, en-route and arrival zone. Departure and arrival zones are defined as parts of a trajectory within 30NM of the airport at altitudes below 15,000 ft. As will be described below, checks of data quality are performed separately for each zone in all sources available. The data with the highest quality are used to provide the merged departure, en-route or arrival trajectory.

[56] See Eyers et al. (2004), p. 15

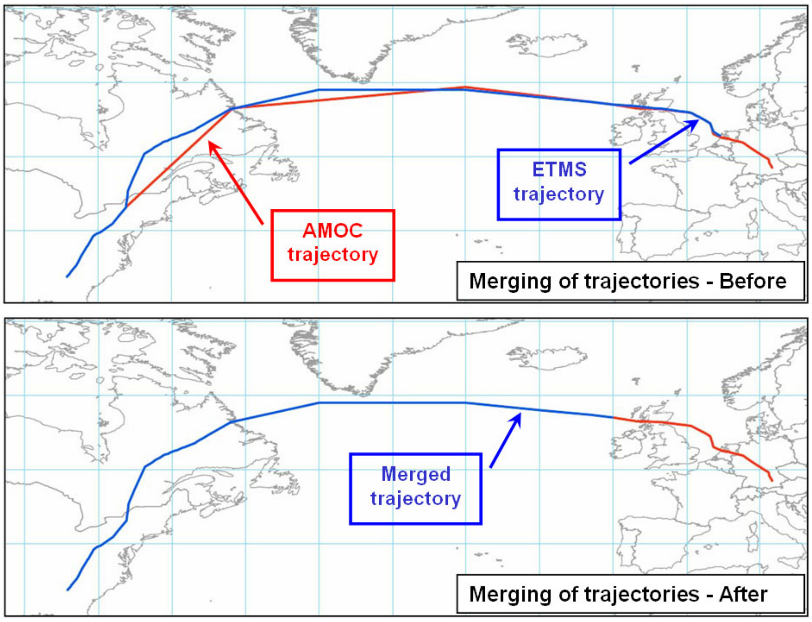

Figure 12:

Merging of trajectories in AERO2k

[Eyers et al. (2004)]

In AERO2k, the *assessment of departure and arrival zones* of each trajectory includes the following tasks:

- The data are checked for a valid departure or arrival airport.
- The distance from the airport to the closest trajectory point is determined and should be less or equal than 20 NM.
- The altitude of the first trajectory point should be lower or equal to 3000 ft.[57]

Depending on the result of the assessment, the trajectory is marked as complete (C) or incomplete (I). Similarly, the en-route trajectory is assessed by checks for sensible speed and rate-of-climb values and is marked either as fine (F) or dubious (D). Since these checks are performed separately for all data sources available, the data with the highest quality in each zone can be identified. This source will then contribute its zone to the merged trajectory. In case of similar quality, the source with the highest number of waypoints is preferred[58].

Different methods exist to create a *trajectory for scheduled flights* (without ATC data available). Whereas older methodologies assume a great-circle between departure and arrival airports in combination with a standard altitude profile, the latest methodologies make use of more accurate methods. Routings can be based on existing ETMS or AMOC trajectories or a deviation from the great-circle[59]. More information on these topics is found in chapter 3.2.

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[57] See Michot et al. (2003), pp. 49-50

[58] See Michot et al. (2003), pp. 49-50 and 78-79

[59] See Michot et al. (2003), pp. 89-100 and FAA[a] (2005), p. 27

2.2.2 AIRCRAFT REPRESENTATION

2.2.2.1 DETERMINATION OF THE ENGINE TYPE

Since modelling aircraft emissions requires performance data, both aircraft and engine types need to be assigned to each aircraft movement. The aircraft type is extracted from radar and flight plan data and included in the movements database. The engine type may be part of the database, but can also be assigned at a later stage. It is determined using a fleet database, most commonly JP airline-fleets, CASE by the Airclaims Company or BACK's World Fleet Registration Database. These data provide the engine for each aircraft's tail sign. Since the tail sign may not be available for the greater part of global aircraft movements, a simplified approach can be followed instead. In the NASA inventories, for example, the engines were allocated using "majority rules" criteria: the most prevalent engine of an aircraft type is assigned to the aircraft's movement, this being done on an airline-to-airline basis[60].

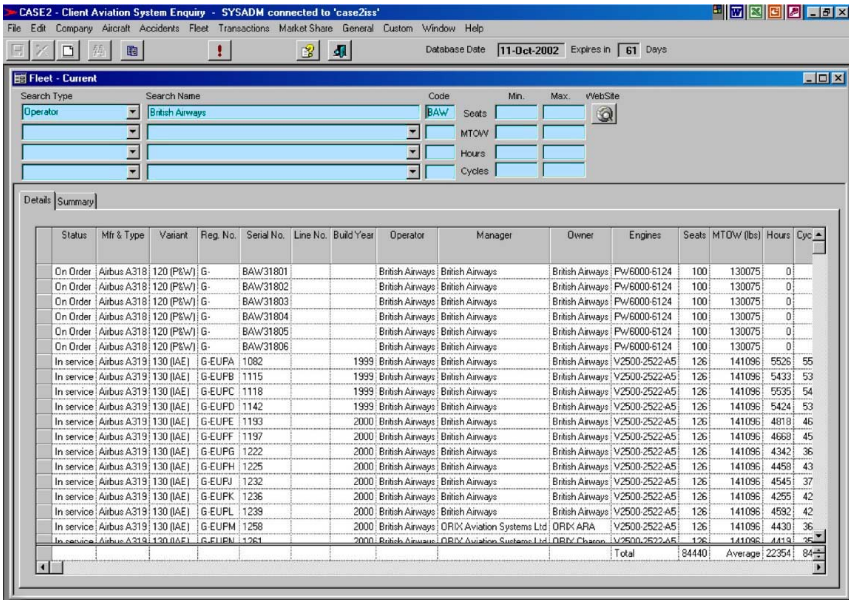

Figure 13: CASE fleet database by Airclaims Limited [Screenshot]

It should be noted, however, that more than 300 civil aircraft types or variants are in service today, not including airline-specific subvariants[61]. Most aircraft are available from the manufacturer with more than one engine option. As a consequence, it is impractical to model both performance and emissions of every aircraft/engine combination identified. In most methodologies, a smaller number of aircraft/engine combinations are defined as representative. Aircraft and engines for which no performance data is available are allocated a representative type with similar performance, fuel consumption and emissions.

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[60] See Sutkus et al. (2001), p. 16

2.2.2.2 SELECTION OF REPRESENTATIVE AIRCRAFT

Representative aircraft should cover the whole variety of aircraft in service considering at least the following distinctive features[62]:

- Seat capacity and/or maximum take-off weight (MTOW),
- Engine technology,
- Configuration.

Since many inventories do not include general aviation or VFR traffic, smaller single engine turboprops, helicopters and piston-engined aircraft are sometimes omitted (as in AERO2k) or represented by a small number of generic types (NASA). More emphasis must be put on a proper representation of large jet aircraft, which account for the greatest distance travelled and hence the largest percentage of aviation emissions. Amongst aircraft of similar capacity, engine technology and configuration, those types with the largest fleet in service are usually chosen as representative aircraft. Of course, the availability of performance data is another prerequisite in the selection process. A number of around 40 representative aircraft (as in AERO2k) is commonly believed to represent the global fleet with sufficient accuracy.

2.2.2.3 SELECTION OF REPRESENTATIVE ENGINES

Since in-flight performance and emissions depend on the aircraft / engine combination, representative engines are to be chosen for each representative aircraft. Particularly emissions may vary considerably with the engine type. Different approaches were followed in past inventory methodologies to account for these circumstances:

- A generic engine may be defined and modelled for each representative aircraft (as in the ANCAT/EC-2 inventory).
- One of the “real” engines available for an aircraft is selected as representative (as in AERO2k).

In case an existing engine is modelled, this could be the most common type amongst an aircraft’s engine options. Alternatively, the most representative type in terms of emissions could be determined in a selection process based on the ICAO emissions databank. In the AERO2k project, average NO_x emission indices of an aircraft’s engine options were calculated for the LTO thrust settings and weighted by the number of engines in service. The engine with the closest fit to these average values was selected as representative[63].

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[61] See Eyers et al. (2004). p. 22

[62] See Eyers et al. (2004), p. 23

[63] However, this principle was not strictly followed, see Eyers et al. (2004), p. 26

2.2.2.4 AIRCRAFT / ENGINE COMBINATIONS

Aircraft and engine types together define aircraft / engine combinations for which performance and emission calculations are carried out. Besides the criteria discussed above, an element of expert judgement is required when it comes to selecting representative aircraft and engines. 40 combinations represent the global fleet in the AERO2k inventory, including 26 large jet aircraft (with more than 100 seats), 10 regional jets and turboprops supplemented by 4 different business jets[64]. Table 5 shows the large jets used for AERO2k with their respective engines. An even greater number of 120 aircraft / engine combinations were considered in the NASA inventory for 1999[65].

ICAO code	Representative Aircraft	Representative Engine	ICAO code	Representative Aircraft	Representative Engine
A306	Airbus A300-600R	2 x PW4x62	B737	Boeing B737-600	2 x CFM56-7B26
A310	Airbus A310-300	2 x PW4x62	B738	Boeing B737-800	2 x CFM56-7B26
A319	Airbus A319	2 x CFM56-5C4	B742	Boeing B747-200B	4 x JT9D-7R4G2
A320	Airbus A320-200	2 x CFM56-5C4	B744	Boeing B747-400	4 x PW4x62
A321	Airbus A321-100	2 x CFM56-5C4	B752	Boeing B757-200	2 x PW2040
A330	Airbus A330-300	2 x CF6-80E1A3	B763	Boeing B767-300ER	2 x PW4x62
A340	Airbus A340-300	4 x CFM56-5C4	B772	Boeing B777-200	2 x PW4090
A340 (R)*	Airbus A340-300	4 x D-30KP-2	BA11	Rombac 1-11	2 x SPEY Mk511
B703	Boeing B707-320C	4 x D-30KP-2	L101	Lockheed L1011	3 x JT9D-7J
B712	Boeing B717-200	2 x BR700-715C1-30	DC9	Douglas DC9-34	4 x JT8D-15
B722	Boeing B727-200A	3 x JT8D-15	MD11	McDonnell Douglas MD-11	3 x PW4x62
B732	Boeing B737-200	2 x JT8D-15	MD80	McDonnell Douglas MD-82/88	2 x JT8D-15
B734	Boeing B737-400	2 x CFM56-3C-1	MD90	McDonnell Douglas MD-90-30	2 x CFM56-5C4
* Representative type for large four-engine Russian types similar to A340;					

Table 5: Representative large jet aircraft and engines in AERO2k
[Eyers et al. (2004), p. 27]

[64] See Eyers et al. (2004), p. 28

[65] See Sutkus et al. (2001), p. 20

2.2.3 AIRCRAFT PERFORMANCE MODELS & FUEL PROFILING

2.2.3.1 GENERAL INFORMATION ON FUEL PROFILING

Determining the fuel consumption of each aircraft movement is the prerequisite for emission calculations. Besides the total fuel consumption of a mission, the actual fuel flow throughout the flight is required for a three- or four-dimensional emission inventory. Various models exist that simulate aircraft performance and calculate such fuel profiles.

The fuel consumption of a given aircraft/engine combination is basically *a function of aircraft weight, speed and altitude*. However, aircraft weight is debited as fuel is burned and speed and altitude may vary even in cruise flight. Figure 14 shows a specific range chart taken from the performance documentation of an Airbus A330-200 aircraft with Rolls-Royce engines. The Figure gives the specific range of the aircraft, i.e. the reciprocal of fuel consumption measured in nautical miles per pound of fuel burned, as a function of Mach number and gross weight. It should be noted that the altitude is held constant at FL370 in the chart.

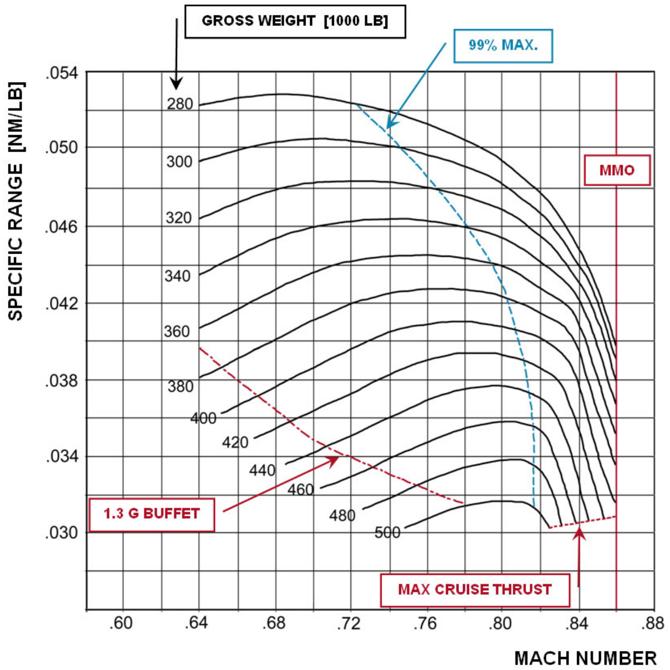


Figure 14:

Specific Air Range of an Airbus A330-200 at 37,000 ft altitude

[TU Berlin (2002)]

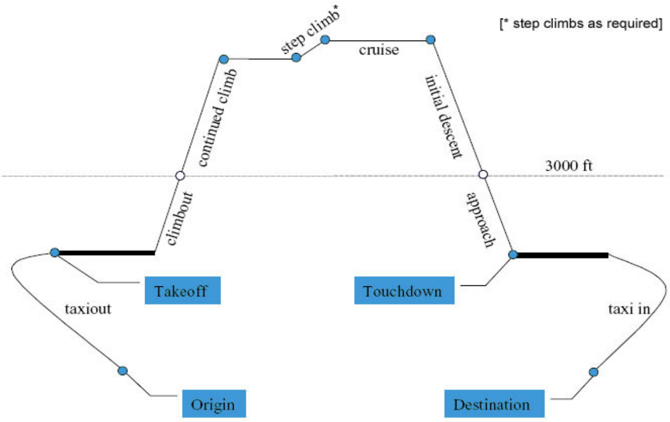
Performing *fuel burn calculations for global aviation* turns out problematical. Performance data are required for all representative aircraft/engine combinations. Furthermore, aircraft weight and speed are not included in the movements database while routing and altitude information may not be available for all flights[66]. Each flight phase needs to be modelled in detail (see Figure 15) while assumptions on the missing parameters need to be made.

[66] Ground speeds given from radar data or calculated from waypoint coordinates and times do not provide the resolution and reliability required for performance calculations; see Norman and Eyers (2004), p. 18

Figure 15:

Schematic of typical flight phases for performance calculations

[Middel / de Witte (2001), p. 22]



Different approaches in terms of performance modelling have been followed in the latest inventories. *Aircraft manufacturers* have reliable and detailed performance models of their aircraft, but these data are not readily provided for external use. In the NASA inventories, which were created in cooperation with Boeing, such information has been utilized together with an in-house performance software (Boeing Mission Analysis Program, BMAP). As an alternative, *commercial performance software* like “PIANO” or “Pacelab Mission” may be used for inventory production[67]. Such tools are able to evaluate every flight phase from first principles and produce the desired fuel profile for a single aircraft movement. PIANO has been used for the ANCAT/EC-2 and AERO2k projects. In order to automate the process of fuel calculation, performance look-up tables for each aircraft/engine combination were created which are then used by an inventory data integration software (see chapter 2.2.4.4).

Similar calculations can be performed using *the Base of Aircraft Data (BADA)* that is available free-of-charge from EUROCONTROL[68]. BADA, which will be discussed later in this chapter, provides a comprehensive database for aircraft performance modelling in combination with a well documented methodology for fuel flow calculations. As a consequence, it can be implemented easily into any inventory software. In the FAA’s SAGE inventories, BADA is used as the performance model for in-flight fuel burn calculations.

For ground operations and flight phases below 3000 ft altitude, methodologies based on *ICAO’s engine exhaust emissions database* may be used. For a standardized landing-and-take-off (LTO) cycle, both fuel use and emissions are available for every jet engine in service. The underlying assumptions include static sea level conditions and were already discussed in chapter 1.2.3. While standardized times-in-modes are applied for engine certification, airport-specific timings may be used for inventory production. In the AERO2k inventory, as an example, performance tables created by PIANO were used to determine the fuel use above 3000 ft altitude, while ICAO data was used below this threshold.

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[67] For PIANO: see http://www.piano.aero; for Pacelab Mission: see http://www.pace.de

[68] See http://www.eurocontrol.int/eec/public/standard_page/ACE_bada.html

2.2.3.2 ASSUMPTIONS FOR PERFORMANCE CALCULATIONS

When using performance models to calculate the fuel burned during the flight, a number of input parameters are required for each aircraft movement. In order to keep the complexity of performance calculations within manageable limits, standard values and procedures need to be specified, concerning at least the following factors:

- Aircraft masses, i.e. payload, fuel reserves, take-off mass,
- Mission rules, i.e. flight phases, altitude profile and speed schedules,
- Environmental parameters like winds and the atmospheric model assumed.

Since an *aircraft's mass or weight*[69] determines its performance in all flight phases, the take-off weight is the first parameter to be specified when it comes to performance calculations. At take-off, an aircraft's mass comprises the operational empty weight (OEW) of the aircraft, the fuel amount carried including all reserves and the payload. While empty weight, fuel capacity and maximum take-off weight (MTOW) of an aircraft are known parameters, assumptions on the actual payload and fuel reserves need to be specified for the purpose of inventory production. A payload mass corresponding to 60.9% of the maximum capacity was assumed in AERO2k, this being an ICAO-determined average value for scheduled air traffic[70]. In the NASA inventory for 1999, a 70% passenger load factor was assumed for passenger aircraft, while average payloads were determined separately for large cargo aircraft[71].

The *trip fuel required to perform a given mission* is basically a function of aircraft mass and mission distance. It is calculated from the performance data available. Besides the regular mission fuel, an additional fuel amount – often a certain percentage of the trip fuel – is carried as a contingency. Another reserve fuel quantity is the fuel amount for diversion to an alternate airport. Mandatory requirements are varying from country to country and may also be subject to airline policies. As a consequence, reserve fuel policies need to be set for the purpose of inventory calculation. In AERO2k for example, aircraft are assumed to carry 5% of the trip fuel as a contingency plus diversion fuel specified separately for long haul and short haul flights. Long haul flights carry reserves for a 200 NM flight to an alternate airport and 30 minutes of holding at low altitudes. For short haul flights a 100 NM diversion and 45 minutes low altitude hold are taken into account[72].

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69 'Weight' is often used synonymously to 'mass' in aviation. Common abbreviations for aircraft weights (OEW, MTOW) are used in the text, even though these quantities are (strictly speaking) masses.

70 See Eyers et al. (2004), p. 30

71 See Sutkus et al. (2001), pp. 21-22

72 See Eyers et al. (2004), p. 31

If no trajectory information is available from the movements data, an *altitude profile* needs to be assumed for performance calculations. A standard profile based on typical airline policies was used for the NASA inventories (see Figure 16). As can be seen from the schematic, a continuous climb cruise is assumed, i.e. an optimal cruise profile for minimal fuel consumption. In reality, however, a constant altitude cruise or step-climbs may be required by Air Traffic Control which would result in slightly higher fuel consumption.

A more accurate modelling of the flight can be reached by *utilizing trajectory data from ATC radars*. The altitude from waypoint coordinates may be used to assign multiple cruise flight levels and hence reproduce a realistic step-climb profile. Such waypoint information is used in AERO2k to model the cruise segment whenever the corresponding data are available[73]. It should be noted, however, that coverage, reliability and resolution of such data are limited and usually not sufficient to provide altitude information for flight phases other than cruise[74].

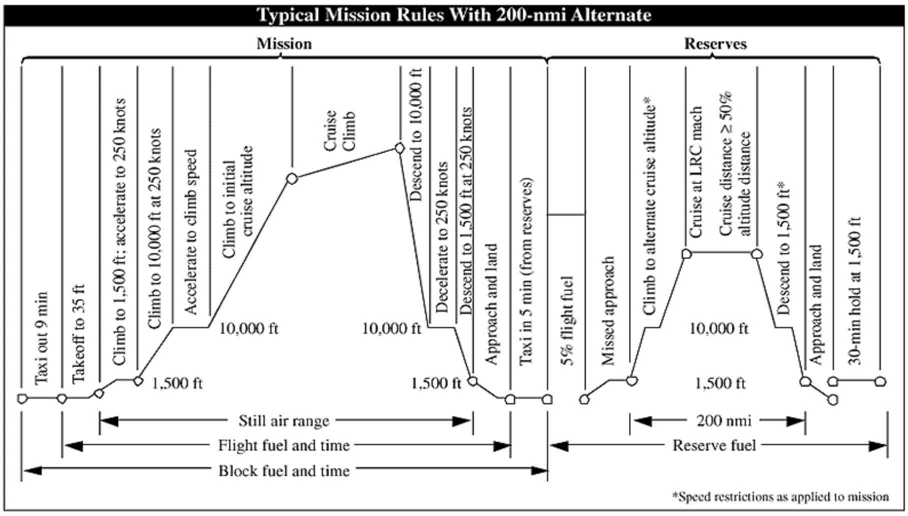

Figure 16:

Mission rules for NASA inventories

[IPCC (1999), p. 300]

Similar to the altitude profile, the *speeds maintained by aircraft in different flight phases* need to be defined by the performance model. Ground speeds given from radar data or calculated from waypoint coordinates and times do not provide the required accuracy for performance calculations.[75] As a consequence, speed schedules need to be described which – in reality – depend on aircraft performance, airline policies and restrictions imposed by national air traffic rules. For the cruise segment, different Mach numbers may be assumed ranging from a constant Mach number up to Maximum Range Cruise (MRC) or Long Range Cruise (LRC) policies. In AERO2k, a Long Range Cruise Mach number is assumed by default[76].

[73] See Eyers et al. (2004), p. 29

[74] See FAA[a] (2005), pp. 36-37

[75] See Norman and Eyers (2004), p. 18

[76] At the LRC Mach number, the specific air range is 1% lower than at the MRC Mach number;
Both LRC and MRC Mach numbers vary with gross weight and altitude, see Eyers et al. (2004), p. 31

Regarding *environmental properties*, ISA (International Standard Atmosphere) conditions are assumed for performance calculations. ISA defines air temperature, pressure and temperature as well as other atmospheric parameters as functions of altitude. Neither local deviations from ISA conditions nor winds are considered in the up-to-date methodologies.

Neglecting the effects of temperatures and winds on fuel consumption are amongst the largest sources of uncertainty in current inventories for global aviation[77]. Methodologies to account for head- and tailwind components as well as cross-winds exist, but are typically not included in performance calculation tools as described below. However, more refined flight planning software as used by airlines consider various meteorological effects based on real-time or statistical weather information. Even though considering meteorological conditions for emission inventories would significantly enhance the complexity of the calculations, such features are discussed to be implemented in future versions of SAGE[78].

2.2.3.3 PERFORMANCE EVALUATION WITH BADA

The **B**ase of **A**ircraft **Da**ta (BADA) is an aircraft performance database maintained by the EUROCONTROL Experimental Centre. Designed to simulate aircraft movements in Air Traffic Management (ATM) environments it can be used to calculate the fuel burn along a flight path. The database is updated annually and available free of charge for scientific purposes. The latest version 3.6 includes detailed information on 91 supported aircraft types, gathered from reference sources like flight and operating manuals. Another 204 aircraft can be represented (through equivalences) by one of the aforementioned types.

The database consists of ASCII files containing performance and operating parameters for all aircraft supported directly. The core data is stored in the following files:

- Operations Performance Files (*.OPF) incl. aircraft-specific performance parameters,
- Airline Procedure Files (*.APF) with aircraft-specific operational data,
- Performance Table Files (*.PTF) with a summary of an aircraft's performance.

The *.PFT files provide look-up tables for cruise, climb and descent performance at different flight levels. For detailed performance calculations, on the other hand, only the *.OPF and *.APF files are required. The *.OPF files include a total of 51 parameters per aircraft which specify the aircraft's mass and flight envelope together with its aerodynamic and engine capabilities (see Table 6)[79].

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[77] See Baughcum[a] et al. (1996), pp. 50-52

[78] See FAA[a] (2005), p. 36

[79] See EUROCONTROL (2004), p. C-34

Category	Parameter and Description
aircraft type	n_{eng} – number of engines [-] engine type – Jet/Turboprop/Piston wake category – Heavy/Medium/Light
mass	m_{ref} – reference mass [t] m_{min} – minimum mass [t] m_{max} – maximum mass [t] m_{pyld} – maximum payload [t]
flight envelope	v_{MO} – max. operating speed [kt] M_{MO} – max. operating Mach number [-] h_{MO} – max. operating altitude [ft] h_{max} – max. altitude at MTOW and ISA [ft] G_W – weight gradient on max. altitude [ft/kg] G_t – temp. gradient on max. altitude [ft/C]
aero-dynamics	S – reference wing surface area [m²] $C_{D0,CR}$ – parasitic drag coefficient (cruise) [-] $C_{D2,CR}$ – induced drag coefficient (cruise) [-] $C_{D0,AP}$ – parasitic drag coefficient (approach) [-] $C_{D2,AP}$ – induced drag coefficient (approach) [-] $C_{D0,LD}$ – parasitic drag coefficient (landing) [-] $C_{D2,LD}$ – induced drag coefficient (landing) [-] $C_{D0,\Delta LDG}$ – parasitic drag coef. (landing gear) [-] C_{M16} – Mach drag coefficient [-] $(V_{stall})_i$ – stall speeds for TO,IC,CR,AP,LD [kt] $C_{Lbo(M=0)}$ – Buffet onset lift coef. [-] **jets only** K – Buffeting gradient [1/M] **jets only**

Category	Parameter and Description
engine thrust	$C_{Tc,1}$ – 1st max. climb thrust coefficient [N] $C_{Tc,2}$ – 2nd max. climb thrust coefficient [ft] $C_{Tc,3}$ – 3rd max. climb thrust coefficient [1/ft²] $C_{Tc,4}$ – 1st thrust temperature coefficient [°C] $C_{Tc,5}$ – 2nd thrust temperature coefficient [1/°C] $C_{Tdes,low}$ – low alt. descent thrust coefficient [-] $C_{Tdes,high}$ – high altitude descent thrust coef. [-] h_{des} – transition altitude [ft] $C_{Tdes,app}$ – approach thrust coefficient [-] $C_{Tdes,ld}$ – landing thrust coefficient [-] $V_{des,ref}$ – reference descent speed [kt] $M_{des,ref}$ – reference descent Mach number [-]
fuel flow	C_{f1} – 1st TSFC coefficient [kg/min/kN] C_{f2} – 2nd TSFC coefficient [kt] C_{f3} – 1st descent fuel flow coefficient [kg/min] C_{f4} – 2nd descent fuel flow coefficient [ft] C_{fer} – cruise fuel flow correction coefficient [-]
ground operation	TOL – take-off length [m] LDL – landing length [m] span – wingspan [m] length – aircraft length [m]
Note: Units shown are valid for jet aircraft only; Some units may vary for turboprop and piston aircraft.	

Table 6: Operations Performance Parameters in BADA [EUROCONTROL (2004), p. C-23]

The *.APF files supplement the data by providing typical speeds or mach numbers for climb, cruise and descent conditions. This information can be used to calculate a flight's speed schedule. As an example, Table 7 shows the speeds assumed for cruise flight. Furthermore, a Global Parameter File (BADA.GPF) is provided containing non-aircraft-specific parameters like maximum accelerations, holding speeds and speed coefficients.

The BADA data in combination with the underlying performance model can be used to calculate lift and drag as well as thrust and fuel flow in all flight phases. The model is believed to be most accurate for cruise conditions[80]. In SAGE, as an example, the BADA methodology is utilized for cruise flight modelling, while a combination of BADA and other models is applied for the other modes (see chapter 3.2.3). Since the thesis cannot cover the BADA methodology as a whole, only the most fundamental equations are presented in the following paragraphs. More detailed information is found in the User Manual[81].

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[80] See FAA[a] (2005), p. 6

[81] EUROCONTROL (2004): User Manual for the Base of Aircraft Data (BADA), Revision 3.6

Given aircraft-specific values in APF files
$v_{cr,1}$ – standard cruise speed (CAS) between 3,000 ft and 10,000 ft
$v_{cr,2}$ – standard cruise speed (CAS) between 10,000 ft and Mach transition altitude
M_{cr} – standard cruise Mach number

Altitude Band	Speed
0 – 2,999 ft	170 kt
3,000 – 5,999 ft	min ($v_{cr,1}$, 220kt)
6,000 – 13,999 ft	min ($v_{cr,1}$, 250kt)
14,000 ft – transition altitude	$v_{cr,2}$
above transition altitude	M_{cr}

Table 7: BADA speed schedule for cruise flight [EUROCONTROL (2004), p. C-28]

In principle, the aircraft model in BADA assumes the aircraft as a point mass. It balances the rate of work done by forces acting on the aircraft and the rate of increase in potential and kinetic energy. This approach, mostly referred to as a Total Energy Model (TEM), is represented by the following equation[82]:

(1) $$(T-D)\cdot v_{TAS} = m\cdot g\cdot\frac{dh}{dt} + m\cdot v_{TAS}\cdot\frac{dv_{TAS}}{dt}$$ *("Total Energy Equation")*

where: T = thrust [N] *D = aerodynamic drag [N]*

m = aircraft mass [kg] *v_{TAS} = true airspeed [m/s]*

g = gravitational acceleration [m/s²] *h = altitude [m]*

Equation (1) includes three independent variables which represent typical aircraft control inputs: thrust T, true airspeed v_{TAS} and rate-of-climb (or descent) dh/dt. Controlling any two of these, the third variable can be calculated. When modelling a cruise flight segment, the Total Energy Equation can be used to calculate thrust, while speed and rate-of-climb are given from other sources. In case a constant altitude cruise is assumed, the rate-of-climb becomes zero. In SAGE, the rate-of-climb is determined from trajectory information included in the movements database while cruise speeds are gathered from BADA speed schedules. As will be shown below, the thrust calculated by the above equation is required to determine fuel flow and fuel consumption in the flight chord considered.

The ISA standard atmosphere is typically assumed for BADA calculations, although a temperature deviation from ISA could be specified. Air temperature and density vary with altitude and can be calculated from ISA assumptions. Mach numbers from the BADA speed schedule can be converted to true airspeeds by the following equation:

(2) $$v_{TAS} = M\cdot a = M\cdot\sqrt{\gamma\cdot R\cdot T^{*}}$$ *, where:*

γ = isentropic expansion coefficient for air *a = local speed of sound [m/s²]*

R = universal gas constant for air [m²/Ks²] *T^{*} = local temperature [K]*

[82] See EUROCONTROL (2005), p. C-6

Since the aerodynamic drag is required in equation (1), lift and drag coefficients C_L and C_D as well as the respective forces are calculated using the following equations:

(3) $$C_L = \frac{2 \cdot m \cdot g}{\rho \cdot V_{TAS}{}^2 \cdot S \cdot \cos\phi}$$

(4) $$C_D = C_{D0,CR} + C_{D2,CR} \cdot C_L{}^2$$

(5) $$L = \tfrac{1}{2} \cdot C_L \cdot \rho \cdot v_{TAS}{}^2 \cdot S$$

(6) $$D = \tfrac{1}{2} \cdot C_D \cdot \rho \cdot v_{TAS}{}^2 \cdot S$$

where: ρ = *air density [kg/m³]*

$C_{D0,CR}$ = *parasitic drag coefficient [-]*

ϕ = *bank angle [-]*

$C_{D2,CR}$ = *induced drag coefficient [-]*

S = reference wing surface area [m²]

Wing area and drag coefficients are given from the BADA *.OPF file. It should be noted that equation (3) assumes a flight path angle of zero, while a bank angle correction can be applied if necessary. Equation (4) is valid for all flight phases except approach and landing, for which similar equations with other coefficients are provided[83].

The thrust specific fuel consumption η in [kg/min/kN] can be determined as a function of airspeed. With the thrust calculated from equation (1), the nominal fuel flow f [kg/min] is determined utilizing aircraft-specific fuel flow coefficients:

(7) $$\eta = C_{f1} \cdot \left(1 + \frac{v_{TAS}}{C_{f2}}\right)$$

(8) $$f_{cr} = \eta \cdot T \cdot C_{fer}$$

where: C_{f1} = *1st thrust specific fuel consumption coefficient [kg/min/kN]*

C_{f2} = *2nd thrust specific fuel consumption coefficient [kt]*

C_{fer} = *cruise fuel flow correction coefficient [-]*

For simplicity, equation (7) is shown in the version for jet aircraft only, while equation (8) is restricted to the cruise flight phase. Similar equations are utilized for the other flight modes. The absolute amount of fuel burned in a flight chord can be calculated by multiplying fuel flow with time.

In the above equations, aircraft mass is assumed constant; hence an iterative approach is required for performance calculations: Starting at a given gross weight, fuel consumption is calculated for a sufficiently small flight segment. For the following segment, equations (1) through (8) are applied again, while the aircraft mass is debited by the amount of fuel burned in the previous flight chord[84].

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[83] See EUROCONTROL (2004), p. C-17

[84] See FAA[a] (2005), p. 42

2.2.3.4 PERFORMANCE EVALUATION BY SOFTWARE

Project Interactive Analysis and Optimisation (PIANO)

PIANO is the name of a software offered by Lissys Limited for Apple's OS X operating system. Utilized in the ANCAT/EC-2 and AERO2k inventories, it has a tradition of being used for inventory production. The *"**P**roject **I**nteractive **A**nalysis a**n**d **O**ptimisation"* programme is a preliminary design tool for civil subsonic aircraft that includes performance analysis features and a database of existing aircraft. With customers in the aircraft industry like Airbus and Boeing as well as engine manufacturers like Rolls-Royce, PIANO is typically used for:

- Preliminary sizing and analysis of aircraft (incl. geometry, mass, aerodynamics),
- Studying the application of engines to existing and projected aircraft,
- Flight performance evaluation for aircraft/engine combinations and
- Evaluation of Direct Operating Costs (DOC) and aircraft emissions[85].

More than 260 aircraft and engine parameters may be defined from scratch or existing models may be modified. An aircraft definition in PIANO typically uses around 50-60 parameters. The software includes a database of more than 250 aircraft types, modelled at different levels of detail. The database was derived from various sources, ranging from press releases of the industry up to explicit aerodynamic, engine and performance data. Although PIANO isn't a flight planning tool, it features a powerful flight profile analysis.

Performance calculations are derived from first principles i.e. are based on aircraft mass, aerodynamics and engine parameters. The programme's source code is provided to selected customers, however subject to a confidentiality agreement. For a given aircraft/engine combination, the user may analyse the performance for a complete mission or separately for each flight phase. A standard mission in PIANO consists of a climb phase from sea level to initial cruise altitude, a cruise phase and a descent back to sea level. The ISA standard atmosphere is used throughout the programme, while a temperature difference to ISA may be specified. Allowances for take-off, approach and taxi are calculated or specified by the user. Given take-off weight or mission distance, the programme produces detailed tables of altitude, distance and fuel-burn versus time (see Figure 17). Non-standard missions can be analysed as a sequence of user-defined flight manoeuvres. Furthermore, PIANO is able to calculate emissions of NO_x, CO and HC for a single aircraft movement using the Boeing-2 fuel flow method[86].

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[85] See http://www.piano.aero

[86] See http://www.piano.aero

PIANO was used as the performance model for the *production of the AERO2k emission inventory*. For this purpose, all aircraft/engine combinations chosen as representative for the global fleet were defined as PIANO models. For each of these aircraft, the software produced performance look-up tables, which were used by the AERO2k data integration software to calculate the fuel profile of each flight. Separate tables were created for the climb, cruise and descent flight phases. The cruise data tables include values of engine fuel flow as functions of altitude, Mach number and gross weight[87].

```
Climb from 1500.feet to:   35000.feet                     Alt.     Time      Dist.      Burn     FN/eng    R.o.C.    NOx
------------------------------------------------        (feet)    (sec)   (n.miles)    (lb.)     (lbf.)   (f.p.m)   (lb.)
Time                  26.03      minutes
Fuel burn             3979.      lb.                     1500.       0.       0.0        0.     12605.     2390.     0.0
Distance              163.1      n.miles                 2655.      29.       2.1      113.     12287.     2329.     1.6
                                                         3810.      60.       4.3      227.     11988.     2272.     3.2
Initial mass          162039.    lb.                     4966.      90.       6.6      339.     11708.     2218.     4.8
Airspeed schedule     250.kcas,  275.kcas, 0.750 mach    6121.     122.       9.0      452.     11434.     2164.     6.3
Delta-ISA             +0.        deg.C.                  7276.     154.      11.4      564.     11164.     2110.     7.8
                                                         8431.     188.      14.0      676.     10900.     2055.     9.2
NOx emissions         42.96      lb.                     9586.     222.      16.7      788.     10641.     2000.    10.7
HC  emissions         0.18       lb.                    10741.     278.      21.4      966.     10156.     1941.    12.9
CO  emissions         8.68       lb.                    11897.     314.      24.7     1079.      9923.     1883.    14.3
------------------------------------------------       ............................. etc ............................
```

Figure 17: Sample report for the climb phase in PIANO [http://www.piano.aero]

Boeing Mission Analysis Program (BMAP)

Data on aircraft performance may also be available from other sources like aircraft or engine manufacturers, universities and research institutes. *Boeing proprietary performance data* on 120 aircraft/engine combinations were used in NASA inventory for 1999, including information on all Boeing models and many non-Boeing aircraft. A number of performance tables were created for each representative aircraft using the **B**oeing **M**ission **A**nalysis **P**rogram (BMAP). The information provided by these tables contains the following data[88]:

- Time, distance flown and fuel burned as functions of gross weight and altitude for climbout, climb and descent flight phases.
- Specific Air Range [NM/kg fuel] as function of aircraft gross weight, Mach number and altitude for cruise conditions.
- Constant fuel burn rates based on typical mission allowances for taxi-in, taxi-out and approach phases.

The Long Range Cruise (LRC) Mach number can be determined from another set of tables as function of gross weight and altitude. Based on the aforementioned data, the data integration tool determines the fuel flow for each flight condition by interpolation routines.

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87 See Norman and Eyers (2004), pp. 8-9;
More information on the AERO2k performance look-up tables has not been published.

88 See Sutkus et al. (2001), p. 21

2.2.4 EMISSION MODELS

2.2.4.1 GENERAL INFORMATION ON EMISSION CALCULATIONS

The methods used to calculate in-flight emissions of aircraft engines depend on the combustion product investigated. Emissions of carbon dioxide (CO_2), water vapour (H_2O) and sulphur oxides (SO_x) can be assumed to be proportional to fuel consumption. Emissions of nitric oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC) and particles are influenced by a number of parameters, most prominently the power setting of the engine, flight speed, altitude and ambient atmospheric conditions. More complicated procedures are required to account for these species. Figure 18 gives an overview on calculation methods covered by this thesis.

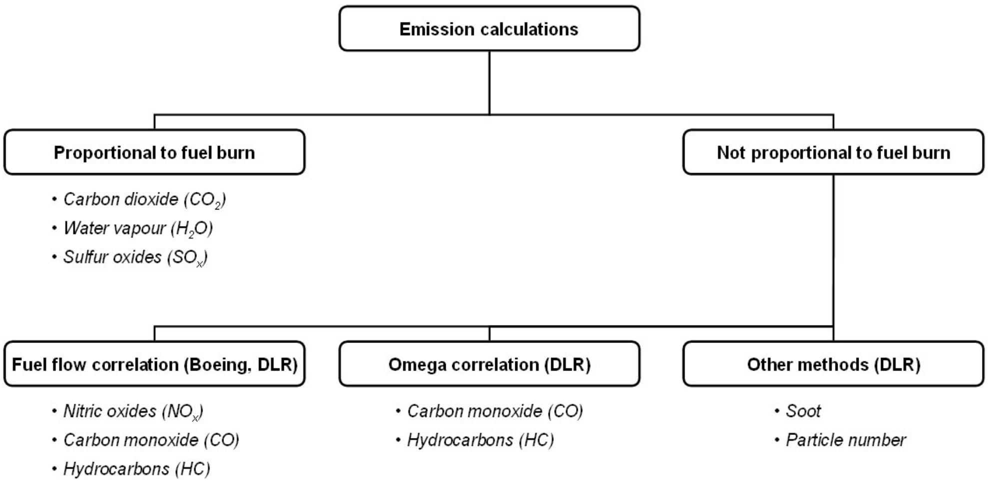

Figure 18: Overview on methods for emission calculation

As already discussed in chapter 1.2.3, emission indices for partially and unburned species are available from the ICAO emissions databank[89]. However, the ICAO data do not cover emissions at cruise flight. The common task of the methods shown above is to predict engine emissions at cruise flight based on reference emission indices from engine test runs at sea level static conditions.

The methods shown in Figure 18 will be discussed on the following pages. It should be noted that fuel flow methods for NO_x are used by all inventories covered by this thesis. The NASA and SAGE inventories use the Boeing-2 fuel flow method, which also calculates emissions of CO and HC. In AERO2k, a fuel flow method developed by the German Aerospace Center (DLR) is applied for NO_x while the Omega method is used for CO and HC emissions. Estimations of particulate emissions are given in AERO2k based on DLR data.

[89] For particulate emissions, only the so-called Smoke Number (SN) is available; see chapter 1.2.3

2.2.4.2 EMISSIONS OF CO_2 AND H_2O

The main products resulting from the combustion of jet fuel are carbon dioxide (CO_2) and water vapour (H_2O). The relation of CO_2 to H_2O in the exhaust depends on the carbon to hydrogen ratio of the fuel. Given a chemical mean formula for jet fuel and assuming complete oxidation, the mass of CO_2 and H_2O in the exhaust can be calculated. Resulting from the assumption of an ideal combustion, emissions of these species are proportional to fuel burn.

Emission indices (EI) in grams per kilogram fuel were determined in various studies on jet fuel properties. Selected results are shown in Table 8. As can be seen from the table, the emission indices calculated differ by less than 0.2%. The values from Hadaller and Momenthy (1989) were used in the NASA and SAGE inventories.

Emitted substance	Emission index [g/kg] [Rachner (1998)][90]	Emission index [g/kg] [Nüßer and Schmitt (1990)][91]	Emission index [g/kg] [Hadaller and Momenthy (1989)][92]
Carbon Dioxide (CO_2)	3156	3154	3155
Water (H_2O)	1237	1239	1237
Sulphur oxides (SO_x)	-	-	0.8*
	** dependent on the sulphur content in the specific fuel; see chapter 1.2.1*		

Table 8: Emission indices for CO_2, H_2O and SO_x from various studies

The assumption of an ideal combustion should provide enough accuracy for most purposes. In the strict sense, however, partially or unburned species like carbon monoxide (CO) and hydrocarbons (H_xC_y, often termed HC) need to be considered by subtracting their mass from the ideal CO_2 and H_2O values. Since the carbon to hydrogen ratio of the HC in the exhaust is unknown, these species are usually neglected. CO emissions were considered in AERO2k where the emission index for CO_2 was calculated by formula (1), taking into account the different molar mass of the combustion products[93].

$$(1) \qquad EICO_2 = EICO_{2,ideal} - \frac{44}{28} \cdot EICO$$

In AERO2k, the ideal emission indices for CO_2 and H_2O were taken from Rachner (1998). It is obvious that a reliable CO estimation is required if the above formula is meant to improve the accuracy of CO_2 results. Methods to predict the EICO will be discussed below.

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[90] Quoted in Eyers et al. (2004), p. 31

[91] Quoted in Nüßer and Schmitt (1996), p. 25

[92] Quoted in Sutkus et al. (2001), pp. 22-23

[93] See Eyers et al. (2004), p. 32

2.2.4.3 FUEL FLOW METHODS FOR NO_x, CO AND HC

The Principle of Fuel Flow Methods

Emissions of NO_x depend on pressure, temperature and time of residence in the hot flame region of the combustor and vary with the power setting of the engine and ambient atmospheric conditions. A number of semi-empirical methods exist which predict in-flight emissions based on reference emission indices measured at sea level static conditions. Most methods concentrate on pressure and temperature in the combustion zone as the most influencing parameters. The so-called P3T3 approach is commonly used by engine manufacturers, yet it requires the knowledge of combustor inlet pressures and temperatures[94].

Since such data are treated as company secrets of the manufacturers, fuel flow methods were developed by Boeing and the German Aerospace Center (DLR)[95]. Both methods calculate emissions of NO_x as function of engine fuel flow, ambient atmospheric conditions and flight speed. They are based on the idea that emission indices at various conditions are correctable to reference conditions and may collapse into a single function of corrected fuel flow. The common principle of these methods is to determine a ratio of emission indices at flight conditions versus reference conditions, which eliminates – for a given engine – the influence of geometric engine parameters. This scheme is represented by formula (2)[96]:

$$\text{(2)} \quad \frac{EINOx}{EINOx_{ref}} = f\left(\frac{p}{p_{ref}}, \frac{T}{T_{ref}}, \frac{w_{fuel}}{w_{fuel,ref}}\right) \cdot F(H)$$

where: *EINOx = emission index for NO_x [g/kg]*

p = ambient static or total pressure, dependent on method [Pa]

T = ambient static or total temperatures, dependent on method [K]

w_{fuel} = engine fuel flow [kg/s]

F(H) = humidity correction factor [-]

While the Boeing-2 method and the equivalent DLR approach share the above principle, they differ in the way the parameters are manipulated. Furthermore, the Boeing-2 method is also applicable for CO and HC emissions whereas the German Aerospace Center suggests an alternative approach for CO and HC which will be discussed later in this chapter. Keeping in mind the similarity of both methods available, the Boeing approach exemplifies fuel flow methods for the purpose of this thesis and will be discussed in detail.

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94 See Norman et al. (2003), pp. 25-29

95 Baughcum[a] et al. (1996) and Deidewig et al. (1996)

96 See Norman et al. (2003), p. 30

The Boeing-2 Fuel Flow Method

The ICAO emissions database, which provides the reference values for the Boeing-2 method, includes fuel flow and emission indices for four power settings of an engine. In a first step of the calculation process, all fuel flows from the database are corrected for effects resulting from the installation of the engine on an airframe.

(3) $$RW_{ff} = RW_{ff,u} \cdot r$$

where: RW_{ff} = *fuel flow at ref. conditions adjusted for installation effects [kg/s]*

$RW_{ff,u}$ = *fuel flow at reference conditions from the ICAO database [kg/s]*

r = correction factor suggested by Boeing [-]

The correction factor is provided for each of the four thrust settings covered by the ICAO database. Table 9 shows the values of these parameters as suggested by Boeing.

	Take-off	Climb	Approach	Taxi / Idle
Thrust setting [% F_{00}]	100%	85%	30%	7%
Correction factor r [-]	1.010	1.013	1.020	1.100

Table 9: Correction factor for ICAO fuel flow values [Baughcum[a] et al. (1996), p. D-4]

Reference functions for NO_x, CO and HC emission indices (EI) versus fuel flow are required for sea level static conditions. From experience, linear relationships between the logarithms of fuel flow and emission indices can be assumed. As shown in Figure 19, a regressed linear fit is developed for NO_x, whereas a bilinear approach is applied for CO and HC[97].

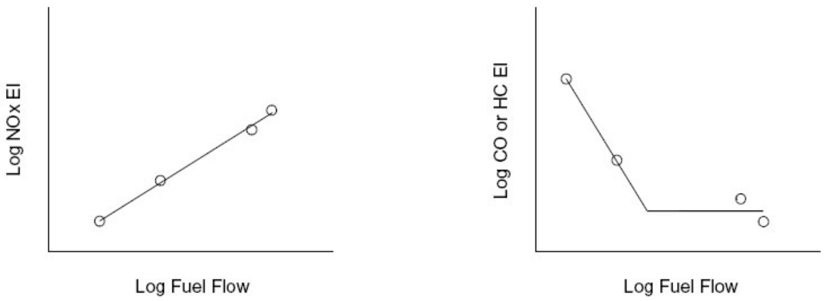

Figure 19: Emission indices versus fuel flow in the Boeing-2 method [FAA[a] (2005), p. 43]

The relationships developed above need to be used to determine emission indices for actual fuel flows in cruise flight. Since the diagrams developed from ICAO values are valid for sea level static conditions, actual fuel flow values are corrected to reference conditions using the following equations.

[97] See Baughcum[a] et al. (1996), p. D-5 and FAA[a] (2005), p. 43

(4) $$W_{ff} = \frac{W_f}{\delta_{amb}} \cdot (\theta_{amb})^{3.8} \cdot \exp(0.2 \cdot M^2)$$

with: $\delta_{amb} = \frac{P_{amb}}{101.3}$ and $\theta_{amb} = \frac{T_{amb}}{288.15}$

where: *W_{ff} = actual fuel flow at reference conditions [kg/s]*

W_f = actual fuel flow at altitude [kg/s]

P_{amb} = ambient pressure at altitude [kPa]

T_{amb} = ambient temperature at altitude [K]

M = Mach number [-]

It should be noted that the above formulae are quoted from U.S. literature, except that U.S. units were transferred to S.I. standards. Using the corrected fuel flow determined by equation (4), the corresponding emission indices are obtained via the plots in Figure 19. In a last step, these indices are re-corrected to flight conditions using equations (5) – (7):[98]

(5) $$EIHC = REIHC \cdot \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}}$$

(6) $$EICO = REICO \cdot \frac{\theta_{amb}^{3.3}}{\delta_{amb}^{1.02}}$$

(7) $$EINOx = REINOx \cdot \sqrt{\frac{\delta_{amb}^{1.02}}{\theta_{amb}^{3.3}}} \cdot \exp(H)$$

with: $H = (-19.0) \cdot (\omega - 0.0063)$

where: *EIHC = emission index for HC at flight conditions [g/kg]*

EICO = emission index for CO at flight conditions [g/kg]

EINOx = emission index for NO_x at flight conditions [g/kg]

REIHC = emission index for HC at reference conditions [g/kg]

REICO = emission index for CO at reference conditions [g/kg]

REINOx = emission index for NO_x at reference conditions [g/kg]

H = humidity correction factor and ω = specific humidity

The equations to calculate the specific humidity ω are not shown for simplicity, but can be found in Baughcum et al. (1996). The resulting emission indices may be used to determine absolute emissions at flight altitudes. For this purpose, the fuel burned in a flight segment is multiplied by the emission index.[99]

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98 See Baughcum[a] et al. (1996), p. D-5

99 See Baughcum[a] et al. (1996), p. D-6

2.2.4.4 OTHER METHODOLOGIES FOR EMISSION CALCULATIONS

DLR Omega Method

Whereas Boeing suggests the use of fuel flow correlation methods for CO and HC, the German Aerospace Center (DLR) uses an alternative method, which will be discussed briefly in the following paragraphs[100]. Emissions of CO and HC result from incomplete combustion and are mostly produced at low power settings of the engines, where the efficiency of the combustion process is low. The combustion efficiency can be correlated with a parameter Ω, which is the reciprocal value of the simplified combustor loading parameter Θ.[101]

Ω is given by the following equation:

$$(8) \qquad \Omega = \frac{w_{air}}{V_C \cdot p_3^{1.8} \cdot \exp\left(\frac{T_3}{300K}\right)}$$

where: *w_{air} = air flow through combustor [kg/s]* *V_C = combustor volume [m³]*

T_3 = combustor inlet temperature [K] *p_3 = combustor inlet pressure [Pa]*

The principle of the so-called Omega correlation is the use of EICO and EIHC versus Ω as a reference function for sea level static conditions. More exactly, a parameter $\Omega \cdot V_C$ is utilized for this purpose, since the volume of the combustor V_C is an unknown constant. Corrections are to be applied to account for changing evaporation properties at altitude. The method results in equations for CO and HC emission indices of the following scheme[102]:

$$(9) \qquad EICO, EIHC = f(\Omega \cdot V_C) \cdot \left\{ \frac{T_3}{T_{3,ref}} \cdot \frac{p_{3,ref}}{p_3} \right\}^c$$

where: *$T_{3,\,ref}$ = combustor inlet temperature at reference conditions*

$p_{3,\,ref}$ = combustor inlet pressure at reference conditions

Altitude emission indices of CO and HC can hence be determined as functions of $\Omega \cdot V_C$, given reference emission indices for sea level static conditions. Compared to a fuel flow correlation, the Omega method may describe the physical processes more accurately. A drawback is the need for a detailed engine simulation in order estimate combustor inlet properties.

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[100] Döpelheuer, A. (1997): Berechnung der Produkte unvollständiger Verbrennung aus Luftfahrttriebwerken, quoted in Plohr (2004), pp. 5-7

[101] See Plohr (2004), p. 5

[102] See Plohr (2004), p. 6

DLR Soot Method

The German Aerospace Center (DLR) has developed methods to calculate emissions of soot by mass and number. The formation of soot, which is mostly taking place at high power levels, is a complex process and influenced by various engine design parameters. Reliable estimations of soot emissions are difficult since the ICAO emissions database includes the smoke number instead of an emission index for soot (see chapter 1.2.3)[103].

A semi-empirical correlation method with variable reference functions was developed in Döpelheuer (1997)[104], which determines in-flight emissions of soot from smoke number measurements at sea level static conditions. This method was termed *DLR soot method* for the purpose of this thesis. Without going into detail, the following tasks are performed:

- The soot concentration C_{Soot} [mg/m³] is estimated from smoke number measurements at sea level static conditions.
- A reference function of C_{Soot} versus combustor inlet temperature T_3 is determined for sea level static conditions (separately for each engine type considered).
- Actual emission indices are calculated from the reference functions using correction factors for combustor inlet pressure p_3, flame temperature T_{fl} and equivalence ratio Φ.

The DLR Soot method was extended in Döpelheuer (2002)[105] in order to provide estimations of the number of particles emitted. The number of particles is calculated based on a statistical distribution of particle size, which can be modelled as function of engine parameters. Furthermore, a model of diameter-dependent soot density is necessary. The method requires reference distributions of particle size, which vary with engine type and are not available for a large number of engines. However, an *average characteristic of particle number concentration* could be developed, which gives the number of particles per gram soot as a function of altitude. This relation was used in AERO2k to determine the number of particles emitted. It should be noted that the accuracy of such estimations is low and – in the strict sense – the approach towards particle numbers is not suited to deliver viable results for individual flights. On the other hand, the calculations performed in AERO2k represent the best estimates possible from the data available[106].

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[103] The smoke number (SN) is determined from collecting soot on white filter paper and evaluating the intensity of light reflection, see ICAO (1993), p. 7

[104] Döpelheuer, A. (1997): Berechnung der Produkte unvollständiger Verbrennung aus Luftfahrttriebwerken, quoted in Plohr (2004), pp. 7-8

[105] Döpelheuer, A. (2002): Anwendungsorientierte Verfahren zur Bestimmung von CO, HC und Ruß aus Luftfahrttriebwerken, Forschungsbericht 2002-10, quoted in Plohr (2004), pp. 8-9

[106] See Plohr (2004), p. 9

2.2.5 EMISSION ALLOCATION & DATA INTEGRATION

2.2.5.1 EMISSION ALLOCATION

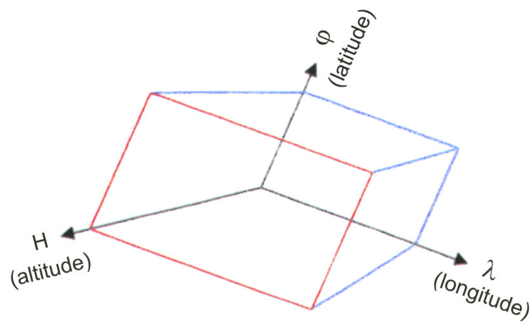
The output of an emission inventory is gridded data, i.e. aggregated fuel burn and emissions per grid cell in a three-dimensional coordinate system. Such data may be used to study the distribution of different species in the atmosphere, most prominently in models of atmospheric chemistry. Additional day and time coding can provide a fourth dimension, which may be of interest for the assessment of processes requiring the presence of sunlight.

For the purpose of inventory production, the earth is idealised as a sphere. Spherical coordinate systems are utilized based on longitude and latitude; these are supplemented by an altitude coordinate which is oriented orthogonally to the earth's surface. Based on this coordinate system, the three-dimensional airspace is divided into cells, which are assumed to span the whole globe from ground level up to a maximum altitude of 15-22 km (see Figure 20).

Figure 20:

Schematic of a three-dimensional grid cell

[Pabst and Brunner (2003), p. 22]



Consequently, fuel burn and emissions of each flight need to be calculated and *allocated to a grid cell*. This can be done using formulae of spherical geometry, which enable the calculation of distances and angles on a spherical surface[107]. In principle, an aircraft's ground track is approximated by connecting two consecutive waypoint locations by a great-circle[108]. In combination with the altitude information given from waypoint or profile data, the three-dimensional flight path of the aircraft is determined. For the purpose of emission allocation, the intersections of the flight path with the grid cell boundaries are determined by their three-dimensional coordinates. Given the intersection points, the length of the flight segment inside a grid cell is calculated and so are, in a next step, fuel burn and emissions for this segment. The process is repeated for all flights from the movements database and the respective emissions per grid cell are summed[109]. In the latest inventories, the total distance travelled per grid cell is also recorded in order to assist with the evaluation of contrail-related effects.

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[107] See Priebs (2003), chapter 3

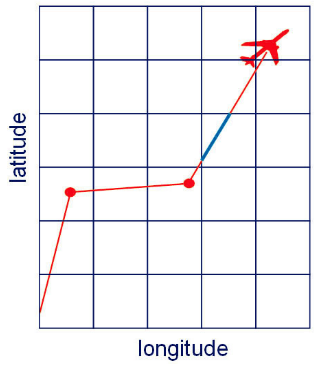
[108] A great-circle is the shortest connection between two locations on the surface of a sphere.

[109] See Middel and de Witte (2001), pp. 49-50

Figure 21:

Two-dimensional schematic showing the distance travelled per grid cell

[Eyers (2004)]



The resolution of the world grids can be chosen arbitrarily. The following resolutions were used for past inventories of aviation emissions:

- The 2.8° latitude x 2.8° longitude x 1 km altitude resolution used in various DLR inventories (the so-called “T42 grid”).
- The 1° latitude x 1° longitude x 1 km altitude resolution used in the NASA, SAGE and ANCAT/EC-2 inventories.
- The 1° latitude x 1° longitude x 500 ft altitude resolution utilized for AERO2k.

Each grid cell is identified via three indices for latitude, longitude and altitude. In the 1° x 1° x 1km grid, for example, the index describing the longitude of the cell is typically a positive number between 1 (longitude of -180°) and 360 (longitude of +180°). Similarly, the latitude index runs from 1 (latitude of -90°) to 180 (latitude of +90°). Assuming a maximum altitude of 20km, an altitude index between 1 (ground level to 1km) and 20 (19-20km) may be used. *Four-dimensional inventories* are produced to enable detailed assessments of diurnal cycles. For this purpose, a time grid is used at resolutions typically in the range from 6 hours up to 1 hour. The times an aircraft entered a grid cell, left the grid cell or the arithmetic mean between the aforementioned times can be calculated; they can be used to allocate an additional time code to the emissions produced within a grid cell[110].

In principle, higher resolutions provide higher fidelity of the output results. It should be noted, however, that the accuracy of trajectory modelling is limited. Given the idealizations typically made for flight profile modelling and the accuracy of ATC waypoint data, an altitude resolution of 500 ft can already be regarded as questionable. Altitude information from ATC data is mostly provided in the form of flight levels with three significant figures (e.g. FL 395 representing 39,500 ft altitude). However, a vertical separation of 1000 ft is usually required by Air Traffic Control, resulting in typical cruise altitudes spaced 1000 ft apart[111].

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[110] See Pabst and Brunner (2003), pp. 22-33 and Eyers et al. (2004), Appendix

[111] See Eyers et al. (2004), Appendix

2.2.5.2 DATA INTEGRATION

In the previous chapters, techniques have been presented for the development of a movements database and the calculation of fuel burn and emissions along a generic flight path. In order to produce an emission inventory for global aviation, computer code is required which performs these calculations for each flight and allocates the results to a three-dimensional world grid. In principle, the *following tasks are performed* by such software:

- Selection of a flight from the movements database.
- Calculation of take-off weight as function of trip distance.
- Calculation of fuel flow and recalculation of aircraft gross weight in discrete steps along the flight path.
- Calculation of engine emissions along the flight path.
- Allocation of fuel burn and emissions to a three-dimensional world grid with or without additional time coding.

The above tasks are performed iteratively for each flight of the movements database. Supporting look-up tables of aircraft performance and emissions may provide pre-processed data which can be utilized for the above purposes by interpolation routines. Depending on the specific performance and emission models, the contents of the look-up tables may vary. Additional databases may be required to determine the three-dimensional coordinates of airports or to assign representative aircraft and engines to each flight (see chapter 2.2.1).

Figure 22 shows a schematic of the AERO2k data integration tool and its interaction with data from various sources.

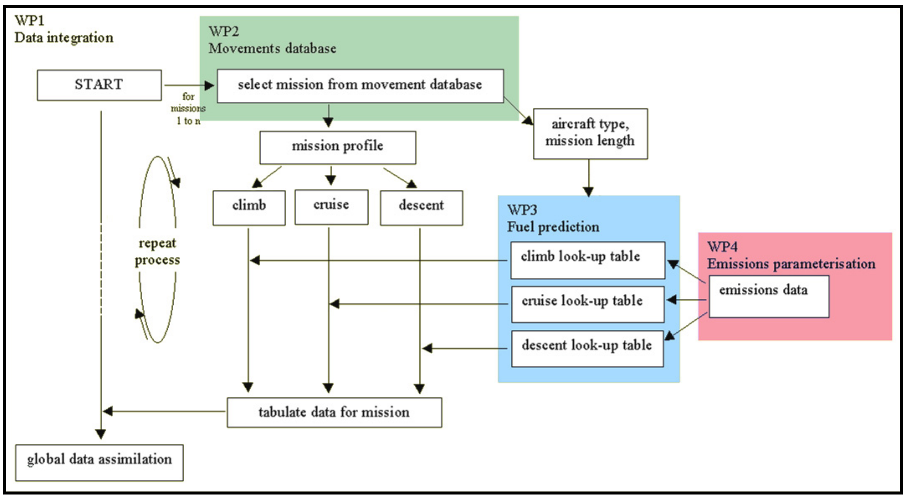

Figure 22: Schematic of AERO2k methodology [Eyers et al. (2004), p. 40]

As can be seen from Figure 22, separate look-up tables for climb, cruise and descent flight phases are utilized in AERO2k in order to simplify performance and emission calculations. These tables contain performance and emissions data for each representative aircraft/engine combination. The performance related contents were produced by the PIANO aircraft performance software. The cruise data tables, for example, give engine fuel flow as function of altitude, Mach number and aircraft gross weight[112]. Besides, pre-generated emission indices are provided as function of fuel flow, Mach number and altitude. These contents were calculated in VARCYCLE – an engine performance program developed by the German Aerospace Center (DLR) – using the DLR fuel flow, Omega and Soot methods. More detailed information on the AERO2k methodology is found in chapter 3.2.2.

Alternative Approaches towards Data Integration

The architecture of data integration systems may differ from the AERO2k approach; it depends on the methodologies used for calculation purposes, the computer power available and general design "philosophies". In the NASA inventories, for example, the Boeing-developed ***G****lobal* ***A****tmospheric* ***E****missions* ***C****ode (GAEC)* was utilized for data integration and emission allocation. Whereas the performance data used by GAEC is of similar form as in AERO2k (see chapter 2.2.3.4), the program performs emission calculations without relying on pre-generated tables. Instead, the algorithms of the Boeing-2 fuel flow method were integrated into GAEC[113]. It should be noted that unlike the NASA inventories, AERO2k uses a mix of methods for emission calculations. The DLR Omega and Soot methods require detailed engine simulation, a factor which may have prevented a more integrated approach.

Given the steady progress in the field of computer technology, an even greater integration of tasks becomes possible. In the SAGE inventories, a *dynamic fuel burn and emission module* is used for performance and emission calculations based on the BADA methodology and the Boeing-2 fuel flow method[114]. As described in chapter 2.2.3.3, performance calculations in BADA require the calculation of lift, drag and thrust along a flight path in order to determine engine fuel flow. It is obvious that such software requires more processing power compared to an approach based on interpolation and look-up tables. On the other hand, the error associated with interpolation routines is avoided. As for most methodologies, no descriptions of hardware requirements or processing times are given in the documentation published by the developers of SAGE[115].

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[112] See Norman and Eyers (2004), pp. 8-9

[113] See Baughcum et al. (1994), pp. 25-26 and Baughcum[a] et al. (1996), p. 13

[114] See FAA (2003), pp. 38-42

[115] FAA (2003), FAA[a] (2005), FAA[b] (2005), FAA[c] (2005), FAA[d] (2005)

2.3 UNCERTAINTIES AND ERROR ANALYSIS

2.3.1 BACKGROUND ASSUMPTIONS AND SIMPLIFICATIONS

Simplifications for modelling aviation emissions result from the lack of specific data or are made deliberately in order to keep the complexity of an inventory within manageable limits. In this chapter, the most significant assumptions will be summarized and discussed.

Typical assumptions for global emission inventories include the following aspects[116]:

- No consideration of winds,
- Standard atmospheric conditions,
- Flights with a standard payload, no fuel tankering,
- No consideration of delays and holdings,
- Simplified routing and trajectory modelling,
- No aircraft and engine deterioration.

Winds alter an aircraft's speed relative to the ground – an effect which could be considered at the price of more complex performance modelling. Methodologies to account for wind effects exist (e.g. by using equivalent headwinds in combination with meteorological statistics) and are considered to be included in future versions of SAGE[117]. As to *atmospheric conditions*, ISA standard temperatures and pressure are utilized by all inventories discussed in this thesis. Suitable statistics on regional deviations from ISA conditions may exist, but are currently neglected in order to simplify the modelling process[118].

The remaining factors in the above list could only be modelled in detail, if reliable information were available on a global basis. However, no actual *payloads or fuel amounts* carried by individual flights are available from ATC data or other sources. As a consequence, inventories typically assume an average payload and do not account for fuel tankering. Ground-based (taxi) *delays* may be approximated by the use of aircraft-specific times-in-modes, whereas airborne delays are more difficult to consider. "Racetrack" manoeuvres during holding may partially be visible in 4D radar trajectories, but the temporal resolution of such data does not provide enough information to accurately model the manoeuvres. Apart from the effects implicitly included in radar data, most methodologies do not consider delays.[119]

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[116] See Eyers et al. (2004), pp. 78-81

[117] See FAA[a] (2005), p. 36

[118] See Eyers et al. (2004), p. 79-80

[119] SAGE partially accounts for airborne delays by means of a queuing model, see FAA[a] (2005), p. 29

Regarding routing and trajectory modelling, vast improvements have been made in the past 5 years. Older inventories assumed standard altitude profiles and great-circle routes between city-pairs, resulting in an underestimation of flight distances by more than 10%[120]. "Real" trajectories given by 20-30 waypoints per flight can be obtained from ATC organizations and were used in more recent inventories. The *aircraft and engine deterioration* issue in the above list sums up various effects of deteriorating components on fuel burn and emissions. Such effects are difficult to be explicitly accounted for due to lack of reliable data[121].

All simplifications discussed in the previous paragraphs amount to an underestimation of actual fuel burn and emissions. Given the absence of reference data on a global level, a quantification is difficult. Various assessments and uncertainty analyses have been performed for inventories, either as parametric studies or by comparing samples of results with airline data. Table 10 summarizes the outcome of a parametric study for the NASA inventories. In this assessment, the Boeing Mission Analysis Program (BMAP) was used to analyse selected missions and determine the effects of selected assumptions. All missions are *round-trips* between city-pairs on great-circle routes. Wind and temperature effects were assessed on the basis of statistical data from different seasons[122].

Changes to assumptions	Average fuel burn increase	Maximum fuel burn increase
No winds to actual winds	1.89% [B747, Route A] 1.15% [B747, Route B] 0.44% [B747, Route C] *four seasons average*	2.62% [B747, Route A] *autumn winds*
Standard temperature to actual temperatures	0.46% [B747, Route A] 0.29% [B747, Route B] 0.67% [B747, Route C] *four seasons average*	0.72% [B747, Route A] *summer temperatures*
Payload: increase of passenger load factor from 70% to 75%	n/a	0.80% [B747, Route A] 2.54% [B737, Route D]
Payload: no additional cargo to volume limited cargo of typical density	n/a	7.68% [B747, Route A]
No fuel tankering to actual practice	4.04% [B737, Route D] *averaged over a four-leg mission*	8.15% [B737, Route D] *first leg of a four-leg mission*
Notes: All missions are round-trips on the following routes: Route A = Los Angeles – Tokyo, Route B = New York – London, Route C = New York – Rio de Janeiro, Route D = Los Angeles – San Francisco.		

Table 10: Effects of model assumptions in NASA inventories [Baughcum[a] et al. (1996), pp. 48-61]

[120] The error in fuel burn and emissions may be lower, see IPCC (1999), p. 306

[121] See Eyers et al. (2004), p. 81

[122] See Baughcum[a] et al. (1996), pp. 48-61

The results from Table 10 are not necessarily representative for global aviation. However, some general conclusions can be drawn from the data and from comparable results from other sources:

Neglecting winds for emission inventories leads to an underestimation of actual fuel burn in the order of 1-2% on average, with higher deviations on certain routes. The assumption of standard temperatures, however, should not affect the results by a significant margin (<1%). Furthermore, fuel tankering may be responsible for large deviations of fuel burn in the order of 4-8% on certain routes. According to Eyers et al. (2004), the overall effect of fuel tankering on global fuel consumption is considerably smaller (around 0.5%). Delays are believed to be responsible for 1% of aviation fuel use, while aircraft and engine deterioration may contribute another 0-3%[123]. Summarizing the above paragraphs and taking into account the high sensibility of fuel consumption towards load factor variation, the aforementioned assumptions should result in a systematic underprediction of total fuel use in the order of 5-10%.

2.3.2 FLIGHT UNCERTAINTIES & MODULE VALIDATION

Unfortunately, additional errors may be introduced by incomplete movements data, by faulty aircraft representation or implicit assumptions within performance and emission models.

As has been described in chapter 2.2.1, a *movements database* may incorporate data from various sources. Experience from past inventories has shown that the effort required in order to identify and remove duplicate flights from different sources is high. Whereas remaining duplicates in the movements data may lead to an overestimation of actual fuel use and emissions, this effect is typically overcompensated by an incomplete coverage of global air traffic[124]: Radar data offer the largest coverage of both scheduled and unscheduled aircraft movements. However, such data are not globally available and no information on military flights is provided by ATC organizations. Flight schedules can be used in order to model civil aircraft movements in areas without radar coverage. Scheduled data, on the other hand, do not provide complete coverage of charter and cargo flights, particularly regarding smaller airlines and domestic air traffic.

No suitable reference is available in order to quantify the effects of missing flight information on a global level. In the words of Attilio Costaguta, chief of the ICAO statistics section: "While in terms of revenue-tonne kilometres, ICAO has a fairly good coverage, this is not the case for aircraft movements. Data for smaller regional or domestic airlines are generally not submitted to ICAO."[125]

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[123] See Eyers et al. (2004), pp. 79-81

[124] See Eyers et al. (2004), p. 57

[125] Costaguta (2001), quoted in Eyers et al. (2004), p. 57

Whereas incomplete movements data are likely to contribute to an underestimation of aviation fuel burn and emissions, the selection of representative aircraft/engine combinations and inherent simplifications within performance or emission models may influence the results in any direction. *Modular analyses* and validation studies are required in order to assess the accuracy of performance and emission models. For aircraft performance, reference data may include fuel burn and flight profile data from aircraft computer flight data recorders (CFDR)[126]. Results from emission models can be compared to measurements conducted on engines in an altitude test facility (ATF) or to calculations from comparable models[127].

A discussion of validation studies and findings on this modular level is beyond the scope of this thesis. From inherent model assumptions and simplifications, it is obvious that some scattering of the results cannot be avoided when compared to reference data. Care must be taken in order to minimize systematic errors; these will sum up to larger deviations when a method is applied to several million flights in an emission inventory.

2.3.3 SYSTEM VALIDATION

Unlike modular validation, system validation involves the analysis of aggregated data for a large number of flights. Unfortunately, no suitable reference is available for the emissions of aviation and only limited data are available for fuel burn or distance travelled.

Global and yearly *statistics of aviation fuel production* can be gathered from the International Energy Agency (IEA). A comparison of inventory results with IEA data is found in chapter 3.3. However, IEA statistics do not reflect the actual fuel amount which is consumed in flight. As a consequence, they may provide a rough guidance for calculation results but are no suitable reference for scientific validation[128].

More accurate error analyses can be performed on lower aggregate level by a *comparison of inventory results with airline data*. In the United States, major airlines are obliged by law to report their fuel use, distance travelled and number of flights to the US Department of Transportation (DOT). Comparisons of reported airline fuel use with corresponding calculations have been performed for the NASA inventories. These studies by Sutkus et al. (1999) and (2001) revealed an underprediction of actual fuel use in the order of 15-20%[129]. The studies were restricted to US airlines and, in the strict sense, the results are valid for the NASA inventories only. Considering the improvements achieved in the latest methodologies, the figure of inaccuracy may be slightly lower for AERO2k and SAGE.

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[126] See FAA[c] (2005), pp. 7-8

[127] See Norman et al. (2003), pp. 23-24

[128] See Baughcum[b] et al. (1996), p. 64

[129] See IPCC (1999), p. 308

3 COMPARISON OF METHODOLOGIES

Whereas the previous chapter has explained the bottom-up approach towards aviation emission inventories, chapter 3 discusses specific inventories produced in the past. Both methodologies and results are discussed and compared. The focus is on the very latest inventories calculated in the last 5 years. However, the "classical generation" of emission inventories from the 1990s is also introduced shortly in the following paragraphs.

3.1 AVIATION EMISSION INVENTORIES – THE "CLASSICAL GENERATION"

3.1.1 HISTORY OF AVIATION EMISSION INVENTORIES

The development of emission inventories for aviation has always been driven by scientists, who use the results to model atmospheric chemistry. Of particular interest have been the effects of aircraft NO_x emissions on ozone production both in the troposphere and – through a potential fleet of supersonic aircraft – in the stratosphere. In the earliest studies of aviation emissions dating from the 1970s and 80s, one- and two-dimensional distributions of global emissions were obtained (e.g. by latitude and altitude). It was not until the 1990s, that three-dimensional inventories were calculated for various research programs, most prominently:

- The U.S. Atmospheric Effects of Stratospheric Aircraft (AESA) Program,
- The German "Schadstoffe in der Luftfahrt" Program,
- The European AERONOX Program[130].

In these programs, inventories of fuel burn and emissions of NO_x were produced by the U.S. National Aeronautics and Space Administration (NASA) and – in a common project – by the German Aerospace Center (DLR) and the Abatement of Nuisances Caused by Air Transport (ANCAT) / European Community (EC) Working Group. Whereas the uncertainties of the very first results were high and the results differed by a large percentage, methodology improvements have since been made resulting in more accurate and reliable results. Revised inventories were produced by NASA, DLR and ANCAT in the late 1990s covering air traffic in the 1976-1992 timeframe. Forecast scenarios for the year 2015 have also been calculated, but are not discussed any further. For the purpose of this thesis, the revised NASA, DLR and ANCAT inventories are termed "classical generation" and their methodologies are briefly discussed below. Another inventory for 1992 has been developed for the Dutch Aviation Emissions and Evaluation of Reduction Options (AERO) project. The AERO inventory is intended to serve as a basis for scenario analyses rather than focusing on atmospheric chemistry.

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[130] See IPCC (1999), pp. 295-296

3.1.2 NASA INVENTORIES FOR 1976, 1984 AND 1992

Three-dimensional inventories of aircraft fuel burn and emissions have been developed by NASA for the years 1976, 1984 and 1992. Detailed calculations were performed for scheduled aviation in a typical bottom-up approach[131]. Separate studies were carried out for military, charter and general aviation as well as for unreported traffic in the Former Soviet Union (FSU) and China[132]. Military aviation was accounted for by estimating the flight activity of each type of military aircraft by country. The methodologies to create the scheduled aviation inventories for 1976, 1984 and 1992 are similar to the methodology of the NASA inventory for 1999, which will be discussed in more detail in chapter 3.2.

For the scheduled aviation inventories, a *movements database* was created exclusively from flight schedules. The schedules were obtained from the Official Airline Guide (OAG) for each month of the year 1992 and four months of the years 1976 and 1984. Duplicates were filtered out of the database and an aircraft/engine substitution was performed in order to represent the global fleet by a number of characteristic types. 76 aircraft/engine combinations were declared representative for the 1992 inventory, mainly jet aircraft supplemented by three generic turboprops. For the 1984 and 1976 inventories, a smaller number of 36 and 27 aircraft/engine combinations were used respectively[133].

Look-up tables of *aircraft performance* were created for each representative aircraft/engine combination using Boeing-proprietary performance data and Boeing's Mission Analysis Program (BMAP). Emissions were determined by the Boeing-2 fuel flow method based on reference emission indices obtained from the ICAO engine database and – for turboprop engines – from engine manufacturers[134].

A Boeing-developed *emission allocation software* (Global Atmospheric Emissions Code, GAEC) was utilized for inventory production. Using the data tables mentioned above, GAEC calculates fuel burn and emissions of NO_x, CO and HC assuming great-circle routes between city-pairs. A 70% passenger load factor was assumed for take-off weight calculations while airport coordinates were determined by an airports database. Mission rules and altitude profile used for the NASA inventories have already been shown in Figure 16 on page 33. Three-dimensional results of fuel burn and emissions were finally allocated to a global grid at a 1° latitude x 1° longitude x 1km altitude resolution[135].

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[131] Baughcum[a] et al. (1996) and Baughcum[b] et al. (1996)

[132] Metwally (1995) and Mortlock and van Alstyne (1998), quoted in IPCC (1999), p. 299

[133] See Baughcum[a] et al. (1996), p. 10 and Baughcum[b] et al. (1996), pp. 9 and 12

[134] See Baughcum[a] et al. (1996), pp. 11-15

[135] See Baughcum[a] et al. (1996), p. 13

3.1.3 ANCAT/EC-2 INVENTORY FOR 1991/1992

Both the ANCAT/EC-2 and the DLR-2 inventories are based on the same movements data, but differ in the way performance and emission calculations were carried out[136].

The *ANCAT movements database* consists of ATC flight plans supplemented by schedules from the ABC Travel Guide (ABC), the Official Airline Guide (OAG), the Aeroflot time table and a German study of domestic air traffic in China. The data collected covers the months of July and October 1991 as well as January and April 1992. Unlike in the NASA inventories, both scheduled and unscheduled air traffic were considered in a bottom-up approach. Since ATC data at the time was not available for the United States, unscheduled traffic in this country was accounted for by factoring up the frequency of domestic flights by 10%. Military aviation was treated separately in an ANCAT study. Military emissions were calculated from an analysis of the world's fleet composition and were allocated to countries' boundaries[137].

In the ANCAT/EC-2 inventory, the PIANO software was used for *fuel profiling* based on performance data of 20 representative aircraft which were modelled as carrying generic engines of a certain thrust and technology level. Unlike in the NASA inventories, only jet aircraft movements were accounted for. Typical fuel profiles were generated for each representative aircraft covering the entire flight cycle including step-climbs in cruise. The DLR fuel flow method was used to calculate emissions of NO_x. Fuel burn and emissions during ground operations were estimated based on the ICAO emissions database and the respective certification timings. As in the NASA inventories, fuel burned and emissions of NO_x were placed on a global grid at a 1° latitude x 1° longitude x 1km altitude resolution[138].

3.1.4 DLR-2 INVENTORY FOR 1991/1992

For the DLR-2 inventory, a *simplified flight model* was developed by the DLR Institute of Propulsion Technology consisting of the aircraft performance module BLOCKFUEL and the VARCYCLE engine and emission model. Fuel and emission profiles were calculated for 34 representative aircraft/engine combinations and various mission ranges. Take-off, climb and descent were modelled via iterative step-by-step techniques while the Breguet range formula was used to calculate fuel consumption in cruise flight. A correction was applied to the results in order to model a constant altitude cruise[139].

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[136] Gardner et al. (1998) and Brunner et al. (1998);
These inventories are titled ANCAT/EC-2 and DLR-2 as opposed to a first edition named DLR/ANCAT-1.

[137] See IPCC (1999), p. 299

[138] See IPCC (1999), pp. 299-300

[139] See Brunner et al. (1998), pp. 3-8 and 13-15

Take-off weight calculations were performed for a 100% load factor while reserve fuel quantities were neglected for compensation. To account for the taxi phases, 10 minutes of engine operation at idle thrust were considered before take-off and 5 minutes after each flight. The DLR fuel flow and Omega correlation methods were applied for emission calculations[140].

The *emission allocation software* GANOX (Global Aircraft Emissions of NO_x) was developed by the DLR Institute of Transport Research and was taken to create the DLR-2 inventory using the ANCAT movements database. Great-circle routes were assumed between city-pairs and the aforementioned profiles were utilized by GANOX via interpolation routines. Fuel burned and emissions of NO_x, CO and HC were finally allocated to a three-dimensional world grid at a 2.8° latitude x 2.8° longitude x 1km altitude resolution[141].

Based on the methodology of DLR-2, a number of other inventories aiming at specific tasks were produced by the DLR. To enable detailed trend analyses, emission inventories for scheduled international air traffic were developed for each year between 1982 and 1992, based on yearly ICAO statistics. Inventories for total scheduled aviation were produced for the years 1986, 1989 and 1992, based on ABC flight schedules for a week in September. Furthermore, a four-dimensional inventory covering scheduled aviation in March 1992 was calculated to assess the diurnal variation of aviation emissions. For this purpose, the improved allocation software *FATE (Four-dimensional Calculation of Aircraft Trajectories and Emissions)* was developed by the DLR Institute of Transport Research. The inventory for March 1992 was based on ABC flight schedules and assumed great-circle routes between city-pairs. Results were presented on a 2.8° latitude x 2.8° longitude x 1km grid at a temporal resolution of 2 hours. Unlike previous methodologies, FATE calculated distance travelled and time spent in each grid cell besides emissions of NO_x, CO and HC[142].

It should be noted that FATE has the capability to consider waypoints from ATC trajectories and to calculate emissions at higher resolutions than used for the above purpose (e.g. 1° latitude x 1° longitude x 1km altitude at a temporal resolution of 1 hour). Since the above mentioned publications, further improvements have been implemented in FATE. 40 aircraft/ engine combinations including turboprops are available in the current version and particulate emissions can be calculated by mass. However, these features have not yet been used for global inventories[143]. Table 11 on the following page summarizes this chapter in order to give an overview on emission inventories from the “classical generation”.

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[140] See Brunner et al. (1998), p. 15

[141] See Brunner et al. (1998), pp. 13-17

[142] See Brunner et al. (1998), pp. 16-17 and 30-31

[143] A European inventory for jet aircraft emissions in 1998 has been produced based on EUROCONTROL data, see Brunner et al. (2002), p. 2

		NASA *[Baughcum et al.[a, b] (1996)]*	**ANCAT/EC-2** *[Gardner et al. (1998)]*	**DLR-2** *[Brunner et al. (1998)]*
General information	*Years*	1976, 1984, 1992, forecast for 2015	1991/92, forecast for 2015	1991/92, forecast for 2015
	Coverage	Scheduled aviation, Charter aviation*, FSU/China unreported flights*, Military aviation*	Scheduled and unscheduled aviation, Military aviation*	Scheduled and unscheduled aviation, Military aviation (from ANCAT/EC-2)*
Movements data	*Sources*	OAG flight schedules	ATC flight plans, ABC and OAG flight schedules, Aeroflot timetable, Assessment of aviation in China.	See ANCAT/EC-2
	Data collection period	Each month of 1992, 4 months of 1976 and 1989	4 months of 1991/92	See ANCAT/EC-2
	Contents of database	Scheduled information (no waypoints/trajectories)	Scheduled information (no waypoints/trajectories)	See ANCAT/EC-2
Performance	*Representative AC/Eng combinations*	27 / 36 / 76 for 1976 / 1984 / 1992 (jets and generic turboprops)	20 (jets only)	34 (jets only)
	Performance data, Performance model	Boeing proprietary data, Boeing Mission Analysis Program (BMAP)	PIANO aircraft models, PIANO performance software	DLR aircraft models, DLR BLOCKFUEL/VARCYCLE software
	Selected mission assumptions	Great-circle routes, 70% passenger load factor, Continuous climb cruise	Great-circle routes, Cruise with step-climbs	Great-circle routes, 100% load factor, no reserve fuel, Constant altitude cruise
Emissions	*Emission data, Emission model*	ICAO emission indices + industry data, Boeing-2 fuel flow method (NO_x, CO, HC)	ICAO emission indices, DLR fuel flow method (NO_x)	ICAO emission indices, DLR fuel flow method (NO_x), DLR Omega method (CO, HC)
Results	*Allocation software*	Boeing GAEC	unknown	DLR GANOX / FATE
	Species covered	Fuel burned, NO_x, CO, HC	Fuel burned, NO_x	Fuel burned, NO_x, CO, HC
	Resolution	3D data in a 1° x 1° x 1km world grid	3D data in a 1° x 1° x 1km world grid	3D data in a 2.8° x 2.8° x 1km world grid, 4D data in a 2.8° x 2.8° x 1km x 2h grid**
		** Estimated in separate studies*	*** 4D inventory for scheduled aviation in March 1992*	

Table 11: Comparison of "classical generation" inventory methodologies

3.2 THE LATEST METHODOLOGIES IN DETAIL

3.2.1 NASA INVENTORY FOR 1999

3.2.1.1 GENERAL INFORMATION

The *"Scheduled Civil Aircraft Emission Inventories for 1999" [Sutkus et al. (2001)]* were prepared by the Boeing Commercial Airplane Group, Seattle, as part of the NASA's Ultra Efficient Engine Technology (UEET) program. Three-dimensional data of aircraft fuel burned and emissions of NO_x, CO and HC were determined for each month of the year 1999. Based on the methodology of NASA's 1992 inventory – with some minor modifications – the Boeing/ NASA inventory represents a conservative approach towards global aviation emission modelling.

The 1999 inventory covers scheduled civil air traffic only and does not account for unscheduled aircraft movements, i.e. general aviation, charter and military flights. The gridded results are made available to atmospheric scientists including the NASA Global Modeling Initiative (GMI). As mentioned before, data for the unscheduled components of air traffic can be estimated separately. For the year 1999, however, such data is not available[144].

3.2.1.2 PROCESSING OF MOVEMENTS DATA

The NASA inventory uses *flight schedules from the Official Airline Guide (OAG)* as single source for its movements database. Unlike the 1992 NASA inventory where monthly schedules were used, OAG data were purchased quarterly for January, April, July and October only. Since each dataset includes projections for the following three months, full coverage of the year was obtained[145]. In order to reduce the amount of data to be processed, a seven day period from the 16th through the 22nd was chosen as representative for each month. The results in terms of fuel burned and emissions for this week were finally divided by seven and multiplied by the number of days in the month to obtain monthly totals.

From the OAG schedule, duplicate entries were filtered out in a semi-automatic process. Following the logic described earlier in chapter 2.2.1, codeshare and starbust duplications as well as effectivity duplications were accounted for and removed from the database. The filtering process is similar but not identical to the one used for previous NASA inventories in order to minimize the need for interfering and judgement by the analyst[146].

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[144] See Sutkus et al. (2001), p. 6

[145] The OAG data purchased by Boeing included four months-projections into the future; projected data for a three months period were used for the inventory; see Sutkus et al. (2001), p. 10

[146] See Sutkus et al. (2001), pp. 12-13

The information extracted from the OAG database included airline and airplane code, origin and destination airports and the weekly frequency of the flight. The *Airline Fleet Database from the Airclaims Company* was used to determine the engine type for each aircraft movement – unlike the approach in previous NASA inventories where Boeing's Jet Track database was utilized. The engine type for each aircraft was allocated using a "majority rules" criteria i.e. the most numerous engine on a given aircraft type in a given airline's fleet was allocated to an aircraft movement. Since the global aircraft fleet is changing continuously, an up-to-date version of the fleet database from the 16th of each month was used for the allocation[147].

On the so-called *preliminary schedule database* an airplane/engine substitution was performed. If performance data for an aircraft/engine combination was not available, it was replaced by aircraft/engine combinations with similar characteristics. 120 representative aircraft/engine combinations including all Boeing models were considered for the inventory. While this results in a comparably large coverage of the global fleet of jets, turboprop-powered aircraft are represented by three generic models for small, medium and large airplanes. As can be seen in the schematic below, the *final schedule database* contained the movements data utilized for inventory calculation[148].

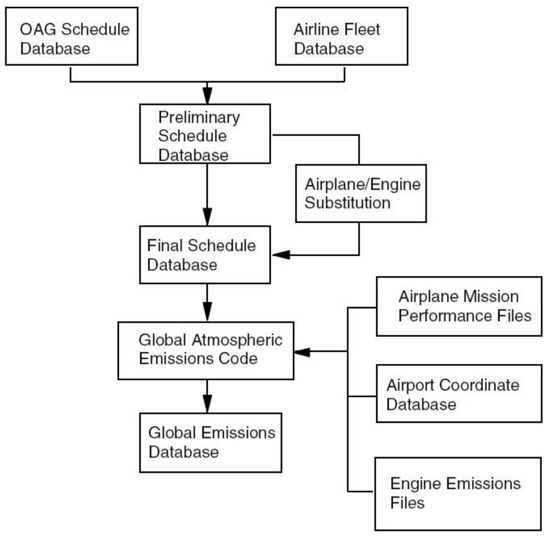

Figure 23:

Schematic of NASA emission inventory calculation

[Sutkus et al. (2001), p. 9]

Calculations of both fuel consumption and emissions for each flight were performed using the Boeing proprietary *GAEC (Global Atmospheric Emissions Code)* allocation software. Apart from the movements database discussed above, the input data included aircraft mission performance files, engine emission data as well as airport coordinates extracted from an airport database[149].

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[147] See Sutkus et al. (2001), pp. 16-18

[148] See Sutkus et al. (2001), pp. 18-19

[149] See Sutkus et al. (2001), pp. 24-25

3.2.1.3 FUEL BURN AND EMISSION CALCULATIONS

Boeing proprietary performance data were used to calculate the fuel burned during the flight. Performance data files were created for each representative aircraft/engine combination using the Boeing Mission Analysis Program (BMAP). Each data file contained a set of performance tables covering the whole operating envelope of an aircraft (see chapter 2.2.3).

As in most methodologies, ISA standard atmospheric conditions were assumed for performance calculations. For every aircraft movement, great-circle routes between origin and destination airports were chosen in combination with the altitude profile shown below. The load factor utilized for take-off weight calculations was assumed to be 70% for all passenger and combi aircraft. While smaller cargo aircraft were also modelled as carrying a passenger load, average payloads for some large freighters (Boeing 747, Douglas DC-10, McDonnell Douglas MD-11 and Lockheed L-1011) were used for the purpose of performance calculations. These payloads were determined separately by aircraft type based on loading data reported on the United States Department of Transportation (DOT) Form T-100[150]. While take-off weight calculations assumed city pairs at sea level, performance calculations considered origin and destination airports at their respective altitudes. Cruise flight is modelled as continuous climb cruise starting and ending at typical westbound cruise altitudes[151].

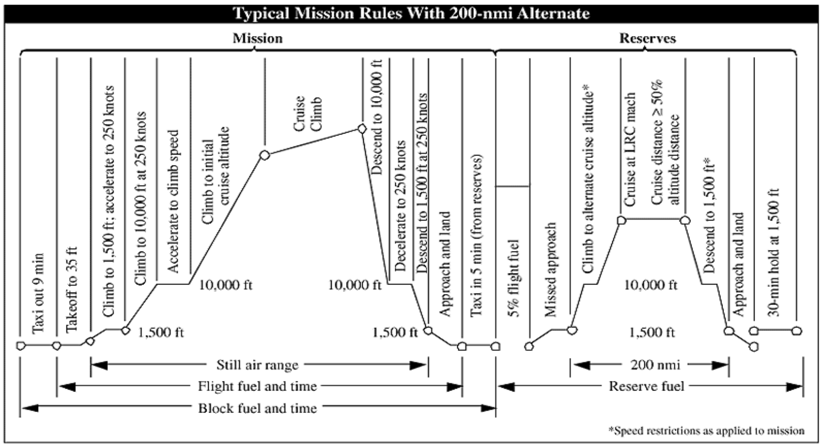

Figure 24:

Mission profile in NASA inventories

[IPCC (1999), p. 300]

Emissions were determined by the *Boeing-2 fuel flow method,* an empiric correlation method calculating in-flight emissions of NO_x, CO and HC based on fuel flow, atmospheric conditions and reference emission indices from engine certification tests at sea level static conditions (see chapter 2.2.4). Emission indices for jet engines were gathered from the ICAO engine emissions database. For turboprop engines, the respective information was obtained directly from the engine manufacturer[152].

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[150] Used for US domestic flights as well as flights from and to the US; see Sutkus et al. (2001), p. 21

[151] See Sutkus et al. (2001), p. 51

[152] See Sutkus et al. (2001), p. 24

3.2.1.4 SUMMARY OF RESULTS

In order to obtain the *global emissions database*, fuel burned and emissions for each flight were placed on a global grid at a 1° longitude x 1° latitude x 1 km altitude resolution, reaching from the Earth's surface up to 22 km of altitude. Emissions of all aircraft movements in a month are summed up; hence all results obtained represent monthly totals[153].

Fuel use of scheduled aviation in 1999 was calculated to be $1.28 \cdot 10^{11}$ kg. Global NO_x emissions (as NO_2) were calculated as $1.69 \cdot 10^9$ kg, while HC and CO emissions made up $1.89 \cdot 10^8$ kg and $2.58 \cdot 10^{10}$ kg respectively. Aircraft emissions of CO_2, H_2O and SO_2 can be determined from fuel consumption. The emission indices recommended by NASA are based on a Boeing study of jet fuel properties and are shown in Table 12.

Emitted substance	Emission index [g/kg]
Carbon Dioxide (CO_2)	3155
Water (H_2O)	1237
Sulfur oxides (as SO_2)	0.8

Table 12: NASA emission indices for CO_2, H_2O and SO_2 [Sutkus et al. (2001), p. 23]

3.2.1.5 CONCLUSION

Compared to previous NASA inventories, *minor improvements* were implemented into the methodology of the 1999 NASA inventory. The explicit modelling of typical cargo payloads has improved the accuracy of performance calculations. Moreover, the number of representative aircraft/engine combinations was increased and is larger than in any other inventory covered by this thesis. As in all methodologies from the "classical" generation, however, great-circle routes were assumed between city-pairs. Given the similarity with previous NASA inventories, the 1999 results are well suited for trend analyses (see chapter 3.3)[154].

A major drawback, however, is the *incomplete coverage of global aviation*. Whereas previous NASA inventories were supplemented by studies of charter, military and General Aviation, only scheduled air traffic was accounted for in the 1999 inventory. Furthermore, no estimates of particle emissions were given and the output data does not contain any four-dimensional results. In all the aforementioned aspects, the AERO2k and SAGE inventories must be regarded as superior. Summarizing the above paragraphs, the 1999 NASA inventory represents a conservative approach towards aviation emission inventories.

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[153] See Sutkus et al. (2001), p. 25

[154] See Sutkus et al. (2001), p. 47

3.2.2 AERO2K – INVENTORY FOR 2002

3.2.2.1 GENERAL INFORMATION

The *AERO2k emission inventories* were developed as part of the European Community's 5th Framework Programme in a common project by QinetiQ, EUROCONTROL, Manchester Metropolitan University (MMU), the National Aerospace Laboratory (NLR) of the Netherlands and the German Aerospace Center (DLR). Calculations were performed separately for civil and military aviation. The coverage of the civil aviation inventories was restricted to IFR flights. As a consequence, most unscheduled commercial aircraft movements are included while General Aviation is not[155].

Emissions of CO_2, H_2O, NO_x, CO and HC were calculated together with fuel-use and distance travelled per grid cell. Unlike in previous inventories, estimates for particulate emissions were given for civil aviation. Both particulate emissions and distance flown are intended to be used by meteorologists in studies on contrails and cirrus clouds. Besides three-dimensional inventories for each month of 2002, four 6-hourly inventories were published for civil aviation in order to show the diurnal variation of emissions over a 24 hours period. Furthermore, a scenario for 2025 was developed based on demand and technology forecasts by Airbus and the United Kingdom Department of Trade and Industry (DTI)[156].

In its overall approach, the AERO2k methodology for civil aviation is similar to the methodology of previous projects. A schematic of the calculation process is shown in Figure 25. All gridded results for both historical and forecast inventories are available online.[157]

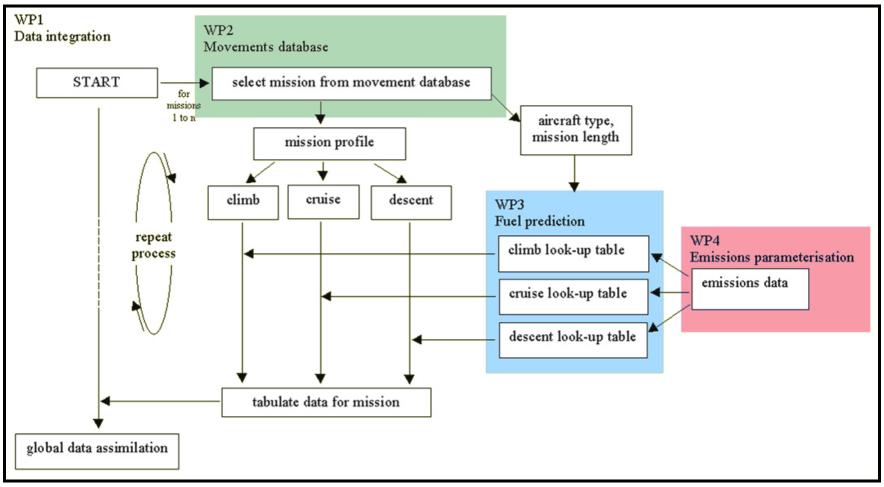

Figure 25: Schematic of AERO2k methodology [Eyers et al. (2004), p. 40]

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155 The coverage of unscheduled flights varies for reasons of data availability, see Eyers et al. (2004), p. 20

156 See Eyers et al. (2004), p. 11

157 See http://www.cate.mmu.ac.uk/aero2k.asp

3.2.2.2 PROCESSING OF MOVEMENTS DATA

The *AERO2k movement inventory* was compiled by EUROCONTROL and stored in an Oracle 9i database. Four-dimensional flight trajectories consisting of 20-30 waypoints per flight were collected for six representative weeks of the year 2002. The selection of the representative weeks was based on an analysis of diurnal, weekly and seasonal variations in air traffic. The data were obtained from ETMS radar data for North America and European AMOC flight plan data from the Central Flow Management Unit (CFMU). While data from these sources are believed to cover more than 70% of global air traffic, movements for the rest of the world were supplemented from BACK Aviation’s flight schedules. Six weekly movement inventories were created, whereas inventories for the remaining days of the year were derived from the data collected using trends extracted from flight schedules[158].

In addition, a toolset was developed to automate the importation, filtering and harmonization of data using airports and airline databases as well as a global time zone converter. Flight and trajectory information were stored in separate tables within the movements database. The parallel use of ETMS and AMOC data required *extensive data checks and assessments* before merging trajectory information from both sources. In a first step, checks were performed separately for ETMS and AMOC data. This included the identification and removal of inconsistent information, “smoothing” of the trajectories and an assessment of each trajectory’s quality separately for departure, cruise and arrival zones of each flight (see chapter 2.2.1). Duplicate flights were identified by various criteria using a temporary merge table. *While merging AMOC and ETMS data,* the source with the highest data quality was used to provide departure, cruise and arrival trajectories for each flight. In case of similar data quality, the source with the highest number of waypoints was preferred[159].

Scheduled flights from BACK’s database were similarly checked for duplicates and then merged with the combined AMOC/ETMS data. A trajectory for these flights was obtained by “copying” an existing AMOC or ETMS flight between the same city-pair and using comparable equipment. If no such flight is available, a trajectory is created artificially. For this purpose, EUROCONTROL’s Computer Aided Route Allocation Tool (CARAT) was utilized to determine the shortest flight path between departure and arrival airports in the global route network. The altitude and speed profiles of such flights were based on statistical analyses of ETMS data for departure, cruise and arrival phases. These analyses were performed separately for various aircraft types and range groups[160].

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[158] See Eyers et al. (2004), p. 20

[159] See Michot et al. (2003), pp. 78-80

[160] See Michot et al. (2003), pp. 89-100

3.2.2.3 FUEL BURN AND EMISSION CALCULATIONS

Fuel burn and emission calculations for each flight were performed within the data integration module using a number of look-up tables. Fuel burn and emissions for the landing-and-takeoff (LTO) cycle were obtained from the ICAO emissions database. Airport-specific times-in-modes were developed by Manchester Metropolitan University (MMU). For climb, cruise and descent, look-up tables were produced by the PIANO aircraft performance software. These tables provide performance and fuel flow data for 40 representative aircraft/engine combinations as described earlier in chapter 2.2.3.

The principle of fuel prediction for a single flight can be described as follows[161]:

- Taxi-Out, take-off, climbout (up to 3000 ft): determine fuel burn from ICAO data using airport-specific times-in-modes.
- Climb: determine initial cruise altitude (ICA) from the movements data; calculate fuel use for climb using climb data tables.
- Cruise: select cruise fuel flow data from cruise data tables; calculate fuel burn for each cruise flight segment.
- Descent: determine final cruise altitude (FCA) from movements data, calculate fuel use for descent using descent data tables.
- Approach (from 3000 ft), landing, taxi-in: determine fuel burn from ICAO data using airport-specific times-in-modes.

The take-off mass of an aircraft was calculated assuming a load factor of 60.9%, this being an ICAO average value for scheduled air traffic. Typical reserve fuel policies were applied as described earlier in chapter 2.2.3. In order to use ICAO fuel burn and emissions for the LTO cycle (without further corrections), all airports were assumed at sea level.

Cruise flight was modelled using trajectory information from the movements database. The altitude information from waypoints was used to assign different cruise flight levels, leading to step-climb profiles for flights with an ETMS trajectory[162]. A constant cruise altitude was assumed for those trajectories that were artificially created. Aircraft mass was recalculated at top-of-climb and throughout cruise at each waypoint or every 300NM, whichever was the shorter distance[163]. A typical long range cruise (LRC) Mach number was assumed for the cruise segment (see chapter 2.2.3).

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[161] See Norman et al. (2004), p. 9

[162] No fuel allowances were considered for the step climbs themselves; see Eyers et al. (2004), p. 81

[163] See Eyers et al. (2004), p. 85

Emission indices for NO_x, CO, HC and particles were pre-generated for each representative aircraft/engine combination as function of engine fuel flow, Mach number and altitude[164]. These data were calculated in VARCYCLE – an engine performance program of the German Aerospace Center (DLR) – using the DLR fuel flow, Omega and Soot methods. An ideal combustion was assumed for H_2O emissions whereas partially burnt species were considered for the calculation of CO_2 (see chapter 2.2.4). Similarly to the performance data, the emission indices were included in look-up tables which were accessed by the data integration module using interpolation routines.

3.2.2.4 THE INVENTORY FOR MILITARY AVIATION

An emission inventory for military aviation was compiled as part of the AERO2k project. Movements data for military flights as well as performance and emission characteristics of military aircraft are hardly available. As a consequence, a simplified approach was developed by the NLR in order to estimate the respective emissions. Both the calculation and the presentation of the results were performed separately from the civil aviation inventory.

The *input data* included aircraft and engine types in service, the number of aircraft per country and typical missions performed by each aircraft type (e.g. escort, air to air combat, ground-attack). The utilization of each aircraft type (in terms of flying hours per year) was determined from published sources for some western countries and estimated for other parts of the world. For the USA and large European states, the location of military airspace and air force bases was determined as well as the aircraft fleet allocated to each base[165]. By means of US Air Force planning methods, the number of flights was estimated from aircraft utilization; a fraction of each fleet was assumed to undergo maintenance or be not operational for other reasons[166].

Flight profiles were determined for a limited number of aircraft-engine-mission combinations. 11 different mission types were declared representative for fixed-wing aircraft and another 6 for helicopters. The missions were initially defined according to standardised NATO and US-Navy descriptions by a sequence of generic values for power setting, speed and time (e.g. 20 minutes on station). For each representative aircraft/engine combination, these mission descriptions were converted into typical flight profiles. The profiles developed follow the scheme shown in Figure 26 and define altitude, speed, and throttle setting along a two-dimensional flight path[167].

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[164] See Norman et al. (2004), p. 8

[165] See Eyers et al. (2004), p. 42

[166] See Eyers et al. (2004), p. 44

[167] See Eyers et al. (2004), pp. 45-46

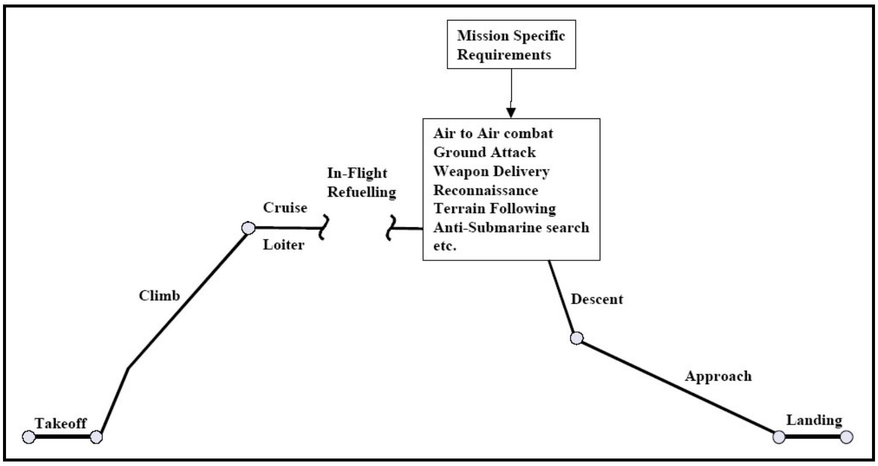

Figure 26: Mission design template for military flights [Eyers et al. (2004), p. 46]

Fuel burn and emissions along each profile were determined by the use of software. The E-MISSION program was utilized for this purpose, which is a combination of a military mission performance software and the NLR-developed Gas Turbine Simulation Program (GSP). Given the number of flights per aircraft type, typical missions for an aircraft type and the aforementioned mission profiles, an emission inventory can be calculated. Aircraft-specific conversion factors were utilized to determine results for non-representative aircraft[168].

The profiles calculated for each flight deliver an altitude distribution of fuel burn and emissions. The *geographic distribution* of the emissions in terms of longitude and latitude was initially unknown. A mixture of the following approaches was used to "spread" fuel burn and emissions horizontally over a region[169]:

- The emissions can be spread equally over the respective aircraft's home country. This approach does not require the location of air force bases in a country.
- Fuel burn and emissions can be linked to an aircraft's home base and spread over a concentric area around the base, dependent on the mission range of the aircraft.
- Fuel burn and emissions can be attributed to flights between air force bases and dedicated military airspace (within the range of a particular aircraft). A significant part of the emissions may be allocated to the military airspace.

Using a combination of the methods described above, the resulting fuel burn and emission aggregates were allocated to a three-dimensional world grid.

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[168] See Eyers et al. (2004), p. 46

The number of representative aircraft/engine combinations has not been published.

[169] See Eyers et al. (2005), pp. 46-47

3.2.2.5 SUMMARY OF RESULTS

The main output of AERO2k is the gridded data, which can be found on the webpage of Manchester Metropolitan University (MMU)[170]. Emissions of CO_2, H_2O, NO_x, CO and HC were calculated as well as particle emissions by mass and number. Both particle emissions and distance flown are intended to be used by meteorologists in studies on contrails and cirrus clouds.

The following inventories are available for civil aviation[171]:

- Three-dimensional gridded data at a 1° latitude by 1° longitude by 500 ft altitude resolution for each month of the year 2002 (12 tables).
- Three-dimensional gridded data at a 1° latitude by 1° longitude by 500 ft altitude resolution for four successive six-hour periods (4 tables).

The six-hourly tables enable an assessment of the diurnal variation of air traffic and emissions over a 24 hour period. These tables contain data for an average day calculated as the arithmetic mean of the seven day period from the 10th to the 16th of June 2002[172]. Furthermore, a three-dimensional inventory at a 1° latitude x 1° longitude x 500 ft altitude resolution has been created for military aviation containing annual data for 2002. This data covers fuel burn and distance flown per grid cell together with CO_2, H_2O, NO_x, CO and HC emissions. Unlike the civil inventories, the military data do not account for particulate emissions due to lack of data for military engines[173].

3.2.2.6 CONCLUSION

Compared to previous inventories, AERO2k features a number of major improvements. Unlike the NASA inventories, it accounts for both scheduled and unscheduled traffic in a typical bottom-up approach. Whereas previous inventories for global aviation assumed great-circle routings between departure and arrival airports, AERO2k uses routing and altitude information from ATC data. Besides, it provides information on particle emissions and the distance travelled per grid cell. A drawback in the AERO2k approach is the comparably high effort to create a movements database: flight plans and trajectories were gathered from two different sources and supplemented by flight schedules. Besides, the temporal resolution of the 4D data can be regarded as low (compared to the DLR-2 inventory). Inventories with a higher resolution could be produced for dedicated purposes from the unpublished raw data.

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[170] See http://www.cate.mmu.ac.uk/aero2k.asp

[171] See Eyers et al. (2004), p. 89

[172] See Eyers et al. (2004), Appendix

[173] See Eyers et al. (2004), p. 41

3.2.3 SAGE – APPROACH OF THE FUTURE?

3.2.3.1 GENERAL INFORMATION

The **S**ystem for Assessing **A**viation's **G**lobal **E**missions (SAGE) has been developed by the Federal Aviation Administration (FAA) in cooperation with the Volpe National Transportation Systems Center, Massachusetts Institute of Technology (MIT) and The Logistics Management Institute (LMI). Amongst the approaches presented in this thesis, SAGE offers the largest feature-set including delay modelling and track dispersion. At the current version 1.5 of the programme, SAGE is a research tool and not released to the general public. However, preliminary results of the model are made available to the aviation community.

SAGE aims to provide a tool for inventory production based on the best publicly available and non-proprietary methodologies. Four-dimensional data of global fuel burn and emissions of NO_x, CO and HC are calculated for commercial civil aviation, not including military and general aviation. Besides the global emissions data provided in a 1° latitude by 1° longitude by 1 km altitude grid, further output includes detailed raw data providing information on each flight and flight segments. A forecasting module is also part of SAGE, but will not be discussed in this thesis. Featuring a well-documented methodology in combination with the large scope of output data, SAGE is intended to be used as a comprehensive model for inventory production capable of evaluating policy, technology and operational scenarios.[174]

3.2.3.2 PROCESSING OF MOVEMENTS DATA

Flight movements data in SAGE include both Air Traffic Control (ATC) and scheduled information. Radar trajectories and flight plans – as the preferred source of information – are obtained via the FAA's Enhanced Traffic Management System (ETMS). While ETMS is estimated to cover around 50-60% of all commercial flights worldwide[175], movements data for the rest of the world are supplemented by schedules from the Official Airline Guide (OAG).

A schematic of the SAGE methodology is presented in Figure 27 on the following page. During *data processing*, both ETMS and OAG data are filtered and “cleaned” in order to produce viable data-sets. In the OAG schedules obtained from the FAA, starbust duplications are filtered out by default and need not be considered. Unlike in the NASA methodologies, codeshare-duplications are neglected. Helicopter flights and flights over less than 50 NM are filtered out and are not considered for the inventory[176].

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[174] See FAA[a] (2005), pp. 1-2

[175] See FAA[a] (2005), p. 11

[176] An analysis showed that codeshare duplications made up only 1% of all flights in recent years, see FAA[a] (2005), pp. 20-25

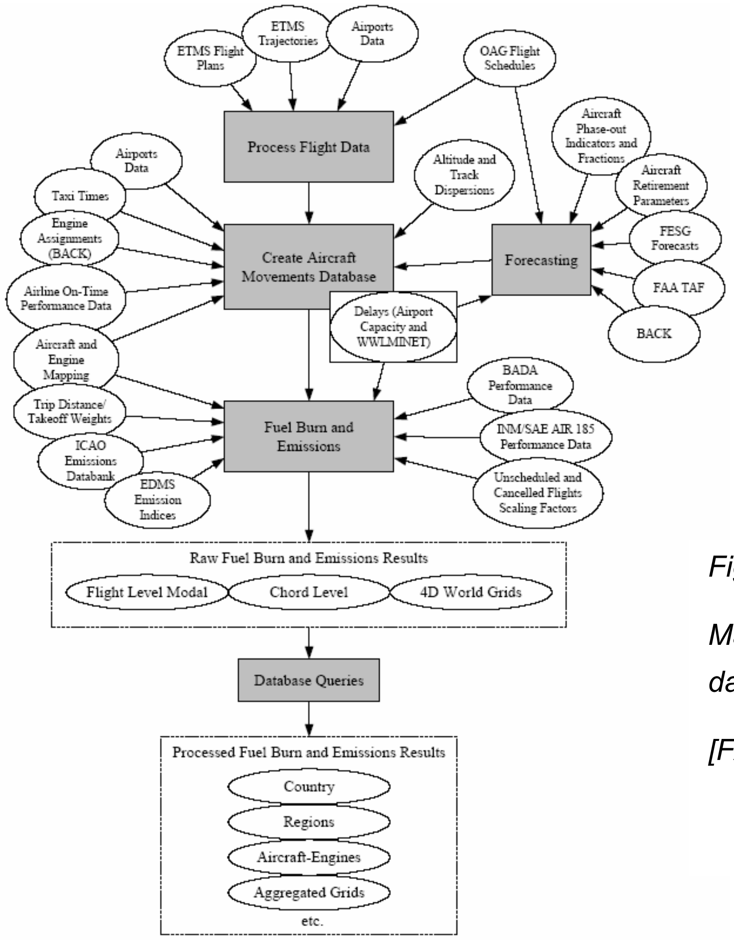


Figure 27:

Main modules and databases in SAGE

[FAA[a] (2005), p. 19]

The processing of ETMS flight plans includes the filtering of military and general aviation flights, the identification and flagging of duplications and the substitution of missing information from all data sources available. Non-viable data-sets, i.e. those flights where missing information could not be found, are not considered for the inventory. For the remaining flights, trajectory information from ETMS is checked for viability via several validation routines with a special emphasis placed on altitude information. Altitude spikes are analysed by rate-of-climb criteria and smoothed if appropriate. Waypoints which provide only redundant information are removed from the database. For flights with incomplete or non-viable trajectory information, this data is flagged as bad information and the flights are treated similar to OAG flights during inventory production[177].

Data from other sources are included when *creating the final aircraft movements database*. An *engine type* is assigned to each flight based on BACK's Fleet Database and the Airline On-Time Performance Database hosted by the US Department of Transportation's Bureau of Transportation Statistics (BTS). For this purpose, aircraft tail signs are determined from the BTS data and the respective engines are looked up in the Fleet Database. Since BTS data

[177] See FAA[a] (2005), pp. 20-25

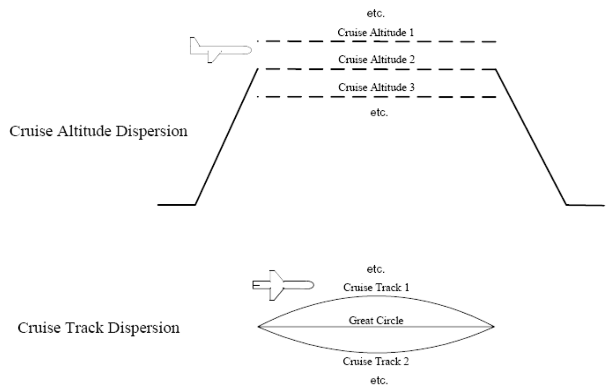
covers flights of the largest US carriers only, the majority of engine assignments (around 77%) are based on the statistical distribution of engine popularity amongst a given airline's fleet. For some 9% of flights either airline or aircraft information do not match the respective entries in BACK's Fleet Database. The most popular engine type on a given aircraft type is assigned to such flights[178]. During fuel burn and emission calculations, aircraft and engine mapping tables match all types from the movements database to their equivalents in the performance module.

Average *airport-specific taxi-in and taxi-out times* were calculated and included in the movements database. The BTS Airline On-Time Performance Database provides taxi times for flights of large US carriers. Since the original taxi times from BTS may include ground based delays (which are treated separately in SAGE), statistical distributions of taxi times were developed for all airports available. Taxi data for the 15th percentile were chosen to represent "pure" taxi-times without delays. For airports not covered by BTS data, the average times of all known airports were used[179].

Figure 28:

Cruise altitude and track dispersion in SAGE

[FAA[a] (2005), p. 28]



For flights without any trajectory information available, *cruise altitude and trajectories are assigned* via statistical distributions developed from ETMS data[180]. By this method, a dispersion effect for both altitudes and horizontal tracks is obtained (see Figure 28). The distributions are dependent on flight distance and categorized into jet and turboprop types. Besides the assigned cruise altitude the so-called track dispersion number is included in each flight's data. This number is linked to a set of perpendicular offsets from the Great Circle.

In the final movements database, OAG and ETMS data are stored in separate tables. OAG flights for which ETMS matching flights exist are excluded from being run during performance and emission calculations.

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178 See FAA[a] (2005), pp. 26-27

179 See FAA[a] (2005), p. 28

180 ETMS data for May and October 2000 and 2003 were analyzed to develop these distributions; see FAA[a] (2005), p. 27

3.2.3.3 FUEL BURN AND EMISSION CALCULATIONS

Aircraft movements are modelled from gate to gate including taxi phases as well as take-off/climb-out, cruise and approach/landing flight phases. All aircraft operations above 3000 ft altitude are modelled as cruise. A flight phase or mode consists of a series of chords which represent straight flight paths. Each flight is modelled via 30-40 chords which define this flight's trajectory. Aircraft weight is debited after each chord by the amount of fuel burned.

Performance calculations assume no winds and the ISA standard atmosphere. EUROCONTROL's BADA data and methodology are used to calculate fuel burn during cruise flight[181]. A constant altitude cruise is assumed for OAG flights while movements with an ETMS trajectory are modelled using three-dimensional waypoint coordinates from the movements database. Take-off weight is obtained from the FAA's Integrated Noise Model (INM) as a function of aircraft type and trip distance. Unlike in other inventories, take-off weight is overestimated systematically to account for fuel tankering. A combination of BADA and the Society of Automotive Engineer's AIR 1845 methodology (implemented in INM) is applied for performance calculations in the LTO flight phases[182]. Take-off and landing flight modes are represented by a number of chords between fixed altitudes (see Figure 29).

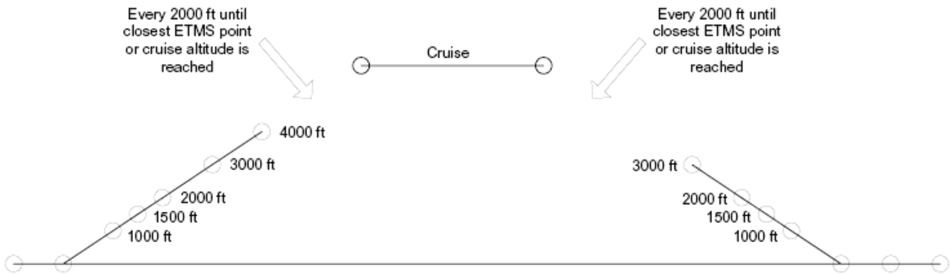

Figure 29: Take-off and approach trajectories in SAGE [FAA[a] (2005), p. 36]

Emissions are calculated using the Boeing-2 fuel flow method which determines emissions of CO, HC and NO_x from fuel flow and ambient atmospheric conditions. As far as jet engines are concerned, reference emission indices were taken from the ICAO emissions database. The respective indices for turboprop engines were gathered from a database in FAA's Emissions and Dispersion Modeling System (EDMS). Emissions of CO_2, H_2O and SO_x are assumed to be proportional to fuel consumption. The emission factors shown in Table 12 on page 63 are applied to calculate emissions of these species[183].

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181 Modifications were made to the BADA drag coefficients and the respective formulae to account for compressibility effects; see FAA[a], pp. 38-39

182 INM procedures as well as the INM engine thrust model are used for take-off and landing together with the BADA aerodynamic model, speed schedules and energy equations; see FAA[a] (2005), p. 197

183 See FAA[a] (2005), p. 46

3.2.3.4 SCALING FACTORS FOR UNSCHEDULED TRAFFIC

SAGE accounts for scheduled and unscheduled commercial aviation. While ETMS data includes all aircraft movements required for such an inventory, OAG data lacks unscheduled air traffic. *Scaling factors* are developed to account for unscheduled and cancelled flights in areas outside ETMS coverage.

Large sets of OAG and ETMS data were analysed and compared in order to determine statistic relations between the weekly number of unscheduled and cancelled flights on the one hand and the number of scheduled flights on the other hand. Two second-order regressions were fit to the data for unscheduled and cancelled flights respectively[184]:

(1) $$UF = 12.43653 + 0.09164 \cdot SF - 0.000003 \cdot SF^2$$

(2) $$CF = 0.1728847 + 0.024352 \cdot SF + 0.000001 \cdot SF^2$$

where: UF = Number of unscheduled flights in a week

CF = Number of cancelled flights in a week

SF = Number of scheduled (OAG) flights in a week

These equations are used to calculate the weekly number of flights for large airports. For this purpose, movements data of an average week are determine for each airport and plugged into the above equations[185]. Scaling factors for each airport are determined by the following formulae:

(3) $AF = SF + UF - CF$ and (4) $SCF = \frac{AF}{SF}$

where: AF = number of actual weekly flights at an airport

SCF = airport-specific scaling factor

The scaling factors are applied to all flights departing from an airport by multiplying calculations of fuel burned, emissions and distances travelled with the airport's scaling factor. In SAGE, this method is used for airports with more than 200 modelled OAG flights per week. Certain airports were identified as outliers from the above methodology, including major European hubs and airports with a high percentage of cargo traffic. Fixed airport-specific factors are applied in these cases, e.g. for Memphis and Cologne-Bonn[186].

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[184] See FAA[a] (2005), p. 34

[185] The number of flights for an average week is obtained by dividing the yearly number of flights by 52; see FAA[a] (2005), p. 34

[186] For a complete list of the 'outliers' and their respective scaling factors: see FAA[a] (2005), pp. 34-35

3.2.3.5 DELAY MODELLING

The WWLMINET ("**World Wide LMI Network**") delay model implemented in SAGE is a derivative from a network queuing model developed by the Logistics Management Institute (LMI). Whereas the original LMINET covers en-route and airport operations in the US, the "world wide" version is restricted to airports only. It covers 257 of the most frequented airports worldwide, which together represent 75% of scheduled air traffic[187].

Aircraft operations on runway and taxiway systems are modelled as linked queuing processes as shown in Figure 30. In principle, WWLMINET calculates hourly delays associated with a given demand. The mathematical model assumes a stochastic (e.g. Poisson distributed) demand of aircraft entering the arrival queue q_A at the average arrival rate λ_A. The runway system is modelled as a server which provides service to aircraft at a rate μ_A. Upon leaving the runway queue an aircraft enters a queue q_{ta} representing the taxiway system. Following a turnaround delay τ, the output of the taxiway queue enters a reservoir of ready-to-depart aircraft R. Departing aircraft enter a departure queue q_P, followed by taxiway (q_{td}) and runway (q_D) queues. Different distributions of demand and service rates can be modelled for the queues mentioned above.

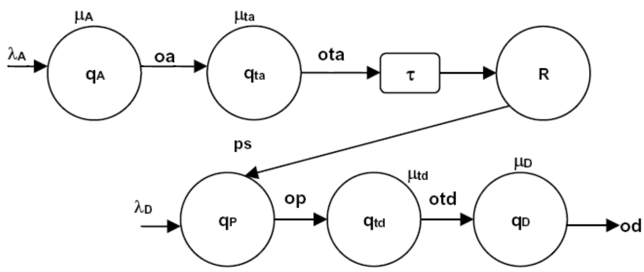

Figure 30:

Airport processes as modelled by the WWLMINET module

[FAA[a] (2005), p. 140]

The service rates of the airport components are calculated from various capacity parameters. Data for calibration were obtained from the FAA's runway capacity "benchmarking" reports for US airports while data for European airports were provided by EUROCONTROL. Average VMC weather conditions are assumed for the modelling.

Within SAGE, the demand fed into the model consists of a week's worth of OAG movements[188]. The model calculates average and airport-specific taxi delays as well as airborne arrival delays (e.g. due to holding). Ground-based delays are allocated to all flights of an inventory by creating nominal delay chords. The airborne arrival delay is assigned to OAG movements only, whereas flights with a validated radar trajectory are assumed to include such delays by default.

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[187] No delays are assumed for airports not covered by the model, see FAA[a] (2005), p. 29

[188] May 29th – June 4th was defined the representative week, see FAA[a] (2005), p. 29

3.2.3.6 SUMMARY OF RESULTS

The main calculation results of SAGE cover emissions of CO_2, H_2O, NO_x, CO, HC and SO_x (as SO_2) for civil aviation together with fuel burn. Inventories for the years 2000-2004 have been created so far and the respective results are analysed later in this chapter. Unlike in previous inventories, however, SAGE aims to provide a large scope of raw data contained in a relational (SQL) database, upon which user-defined queries and aggregations may be performed. This approach seems reasonable, since the processing capabilities of work-station computers have grown significantly in the last decades.

The raw inventories created by SAGE include[189]:

- *Modal results of each individual flight worldwide*, containing general information on the flight together with distance flown, fuel burned and emissions for each flight mode (i.e. taxi-out, take-off/climbout, cruise, approach/landing, taxi-in).
- *Chord-level results*, containing information on each individual flight chord modelled for all flights worldwide. Each chord is defined by its tail point and for each such point the four-dimensional coordinates in terms of longitude, latitude, altitude and time are stored together with the respective atmospheric conditions, aircraft aerodynamic and performance data, emission indices, absolute emissions and fuel burned.
- *Four-dimensional raw world grids* at a 1° latitude by 1° longitude by 1 km altitude resolution. This is a listing of flight segments corresponding to the portions of a flight path that traversed a grid cell. For each such record, the 3D-grid cell indices are given together with the time the aircraft entered the cell, the duration in the cell, as well as average speed, fuel burned and emissions.

The total raw data for a yearly inventory are in the order of 0.5 Terabyte[190]. It should be noted that the four-dimensional world grid contains around 900 million records, while modal and chord-level inventories contain around 30 million and 1 billion records per year respectively. Aggregations of results on global, regional and country level have also been compiled from the raw data mentioned, including monthly global inventories. Since the raw data include the time a flight entered a grid cell, four-dimensional inventories at any temporal resolution can be created. Whereas the gridded results may be used as inputs to models of the earth's atmosphere, the modal and chord-level results could be used for aircraft- or flight-specific comparisons or to assess the effects of policy, technological and operational changes[191].

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189 See FAA[b] (2005), pp. 4-8

190 See Fleming et al. (2003), p. 12

191 See FAA[b] (2005), p. 41

3.2.3.7 CONCLUSION

In summary, SAGE can be considered on a *similar technological level as AERO2k*. A major drawback, however, is the lack of estimates for particle emissions. Furthermore, military aviation is not accounted for. Regarding civil aviation, some fundamental differences exist between the overall methodologies of SAGE and AERO2k:

The movements database in SAGE consists of US Air Traffic Control (ATC) data supplemented by flight schedules for other regions of the world. Flight tracks are modelled via radar trajectories or by assuming dispersed great-circle routes. Compared to AERO2k, the SAGE approach is less complex but still a considerable improvement over “classical” inventories. In order to account for unscheduled traffic in regions without radar coverage, SAGE scales up results of fuel burn and emissions by means of statistically determined scaling factors. Fuel tankering is accounted for by systematically overestimating take-off weight. Moreover, a delay model based on queuing theory was implemented in order to approximate ground-based and airborne delays. The aforementioned innovative features may increase the precision of global total values of fuel burn and emissions, whereas the effects of fuel tankering and delays on single flights are not accurately accounted for. AERO2k, for comparison, does not model uncertain factors like fuel tankering and delays; instead, possible corrections by means of scaling factors are left to the user.

Unlike previous inventories, SAGE provides access to raw data results. Given the steadily increasing processing power of computers, this approach makes sense. User-specified inventories at almost any resolution can be produced from the raw data.

Table 13 on the following page summarizes the above paragraphs and provides an overview on the methodologies discussed in this thesis.

		NASA 1999 [Sutkus et al. (2001)]	AERO2k [Eyers et al. (2004)]	SAGE version 1.5 [FAA[a,b,c,d] (2005)]
General information	*Years*	1999, forecast for 2020	2002, forecast for 2025	2000 – 2004, forecasts in development
	Coverage	Scheduled aviation	Scheduled and unscheduled aviation, Military aviation*	Scheduled and unscheduled aviation**
Movements data	*Sources*	OAG flight schedules	ATC data from ETMS & AMOC, BACK flight schedules	ATC data from ETMS, OAG flight schedules
	Data collection period	Each month of 1999	6 representative weeks of 2002 (ATC), Each month of 2002 (schedules)	Each month of 2000 – 2004
	Contents of database	Scheduled information (no waypoints/trajectories)	4D trajectories from ATC data, Artificial routing for scheduled flights	4D trajectories from ATC data, Dispersed great-circles for scheduled flights
Performance	*Representative AC/Eng combinations*	120 (jets and generic turboprops)	40 (jets and turboprops)	91 (jets and turboprops)
	Performance data, Performance model	Boeing proprietary data, Boeing Mission Analysis Program (BMAP)	PIANO aircraft models, PIANO performance software	BADA & INM aircraft models, BADA & INM performance methodologies
	Selected mission assumptions	Great-circle routes, 70% passenger load factor, Empiric load factor for large freighters, Continuous climb cruise	Real routing, 60.9% load factor (by mass), Cruise with step climbs	Real routing for ETMS flights, Take-off weight estimated from INM, Cruise with step climbs, Delay modelling
Emissions	*Emission data, Emission model*	ICAO emission indices + industry data, Boeing-2 fuel flow method (NO_x, CO, HC)	ICAO emission indices + industry data, DLR fuel flow method (NO_x), DLR Omega method (CO, HC), DLR Soot method (particles)	ICAO emission indices + EDMS data, Boeing-2 fuel flow method (NO_x, CO, HC)
Results	*Allocation software*	Boeing GAEC	AERO2k data integration tool	SAGE fuel burn and emission module
	Species covered	Fuel burned, NO_x, CO, HC	Fuel burned, CO_2, H_2O, NO_x, CO, HC, soot + distance per grid cell	Fuel burned, CO_2, H_2O, NO_x, CO, HC, SO_x + distance per grid cell
	Resolution	3D data in a 1° x 1° x 1km world grid	3D data in a 1° x 1° x 500 ft world grid, 4D data in a 1° x 1° x 500 ft x 6h grid	3D data in a 1° x 1° x 1km world grid, 4D raw data at any resolution required
		** Estimated separately*	*** Scaling factors for unscheduled traffic in areas with no ETMS coverage*	

Table 13: Comparison of state-of-the-art inventory methodologies

3.3 COMPARISON OF RESULTS

3.3.1 GLOBAL DISTRIBUTION OF FUEL BURN AND EMISSIONS

A difficulty, which is encountered when discussing results from global emission inventories, is the lack of independent reference values. International statistics of aviation fuel sold may provide a rough guidance for fuel burn calculations. For the emissions of aviation, however, no such reference is available.

As a consequence, results from different inventories are to be compared and analysed on the basis of background knowledge on the methodologies that produced the results. While the methodologies of aviation emission inventories have been discussed in previous chapters, a comparison of selected results will be performed in this section. A discussion of results from aviation emission inventories may include the following aspects:

- Analysis of global total values of fuel burn and emissions,
- Analysis of the global distribution of fuel burn and emissions,
- Analysis of the altitude distribution of fuel burn and emissions,
- Analysis of the variation of fuel burn and emissions with time (seasonal and diurnal cycles)[192].

Trends may be evaluated if data for more than one year are available. Further analyses may be performed on various parameters of the global fleet of aircraft, most prominently the specific fuel consumption and average emission indices. However, results from different inventory methodologies may vary in each of the aforementioned aspects. Given the large number of influencing parameters, it is difficult to relate variations in fuel burn and emissions to differences in the methodologies. For an in-depth analysis of discrepancies between inventories, it is necessary to compare movements data as well as fuel burn and emissions for large samples of flights and flight segments[193]. Reference values for comparison purposes may be obtained from aircraft computer flight data recorders (CFDR).

The aforementioned level of detail cannot be reached in this thesis. In order to keep the amount of data manageable, the comparison has been restricted to global total values of aviation fuel burn and emissions. Global distribution as well as altitude distribution will be briefly discussed and will be exemplified on results of the SAGE inventory for the year 2000.

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[192] See Eyers et al. (2004), pp. 89-106 and Brunner et al. (1998), pp. 30-31

[193] Such a comparison is currently being performed between AERO2k and SAGE, see Locke et al. (2004), pp. 1-6

Figure 31 shows the global distribution of fuel burn from civil aviation as calculated by SAGE. All values given in the figure are integrated over altitude and time. As can be seen, the majority of fuel is burned over North America, Western Europe and Eastern Asia. More than 90% of aviation fuel burn and emissions are typically produced in the Northern Hemisphere, mostly between 30° North and 60° North latitude[194]. Emissions of carbon dioxide (CO_2), water vapour (H_2O) and sulphur oxides (SO_x) are proportional to fuel consumption (see chapter 2.2.4). Emissions of NO_x, which are mostly produced during cruise flight, can be assumed to follow the distribution of fuel burn[195]. Separate analyses would be required for the global distribution of CO and HC emissions, which are predominantly produced at low power settings of the engines.

The altitude distribution of fuel burn and emissions is given in Figure 32 on page 81. The majority of fuel is consumed at typical cruise flight levels between 10 and 12 kilometres of altitude. Emissions of NO_x tend to follow the trend in fuel consumption whereas CO and HC emissions peak both at cruise altitudes and – from descent and landing operations – near ground level.

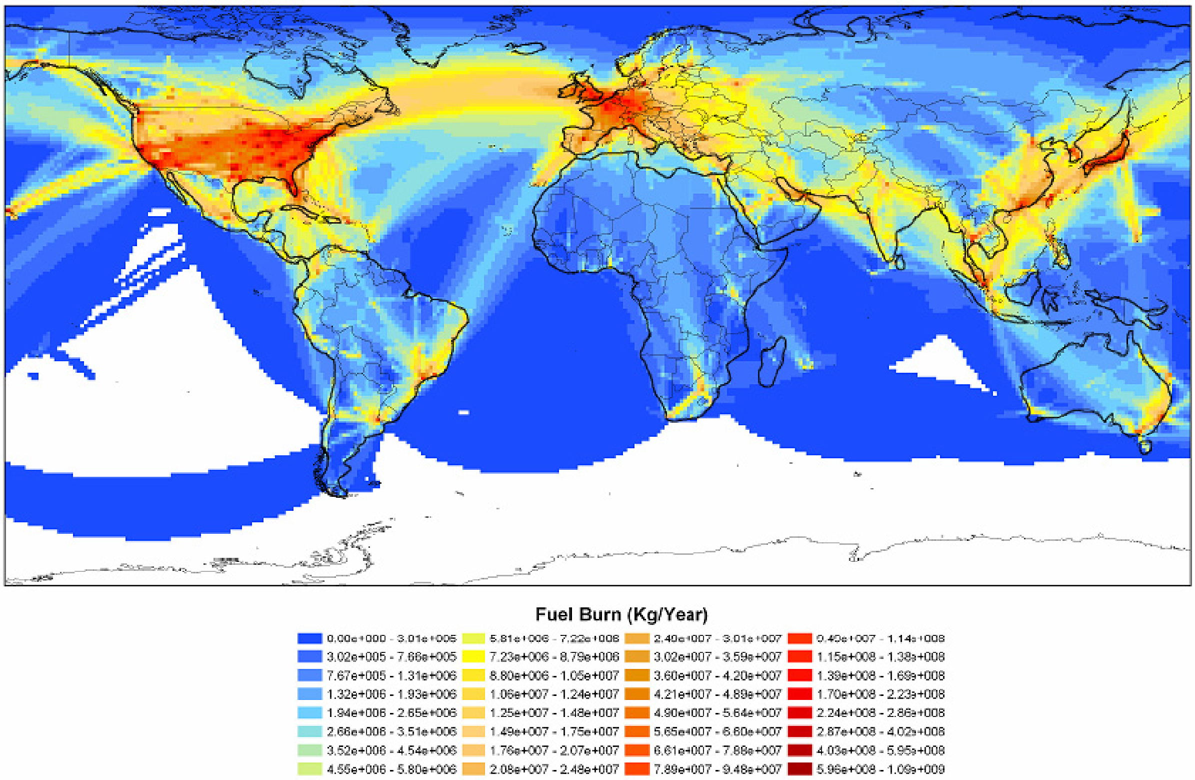

Figure 31: Global distribution of aviation fuel consumption in 2000 [FAA[b] (2005), p. 30]

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[194] See Sutkus et al. (2001), p. 31

[195] See FAA[b] (2005), p. 32

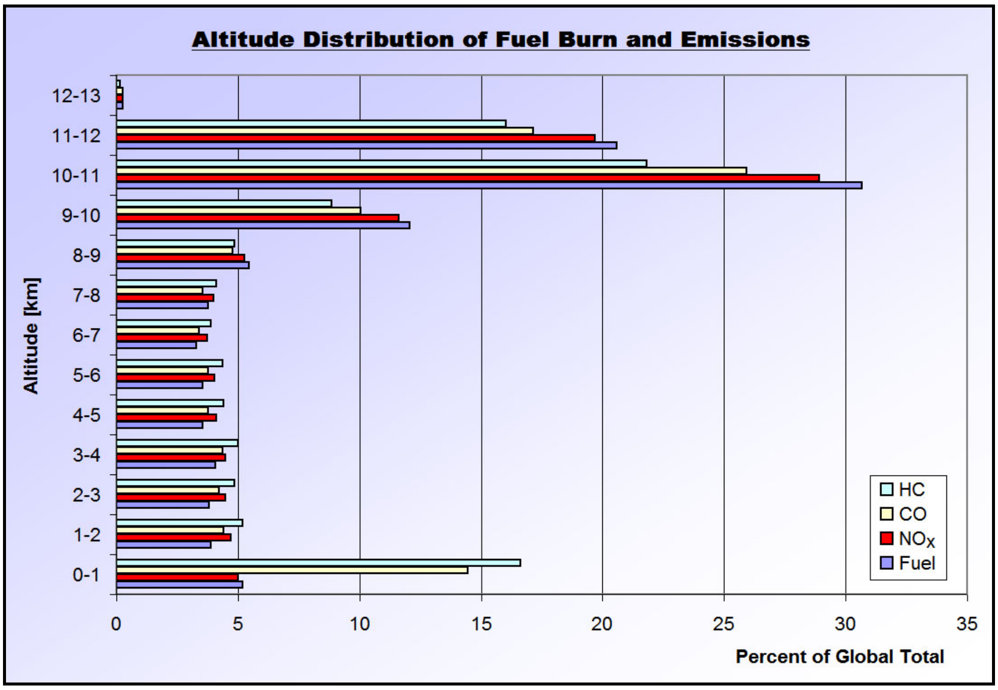

Figure 32: Altitude distribution of fuel burn and emissions in 2000 [FAA[b] (2005), p. 32]

3.3.2 COMPARISON OF FUEL BURN CALCULATIONS

Global total values of aviation fuel consumption are available from all inventories discussed in this thesis. Furthermore, fuel sold statistics of the International Energy Agency (IEA) may provide a rough guidance for the purpose of analysis and trend evaluation. Figure 33 shows the development of *aviation fuel sold compared to results from emission inventories*. The figure includes values of total fuel burn from civil and military aviation that were calculated in the NASA, DLR and ANCAT inventories as well as in AERO2k[196]. For 1992, the base year value of the AERO modelling system is shown for comparison purposes. Calculations for civil aviation are presented separately and are also available from the SAGE inventories.

As can be seen from Figure 33, the inventories find smaller values of aviation fuel consumption compared to IEA statistics. Care must be taken for a proper interpretation of this finding. For the inventories, an underestimation of fuel burn in the order of 15% can be expected (at least for the "classical generation") due to incomplete movements data and simplifying assumptions made for the purpose of calculation (see chapter 2.3). The IEA statistics, however, are not necessarily a better estimate of actual fuel consumption. These values are compilations of fuel production data collected from different sources and countries. The overall accuracy of such statistics is unknown[197].

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[196] The DLR-2 and ANCAT-2 results are nearly identical and presented as DLR/ANCAT in the diagram.

[197] See IPCC (1999), p. 308

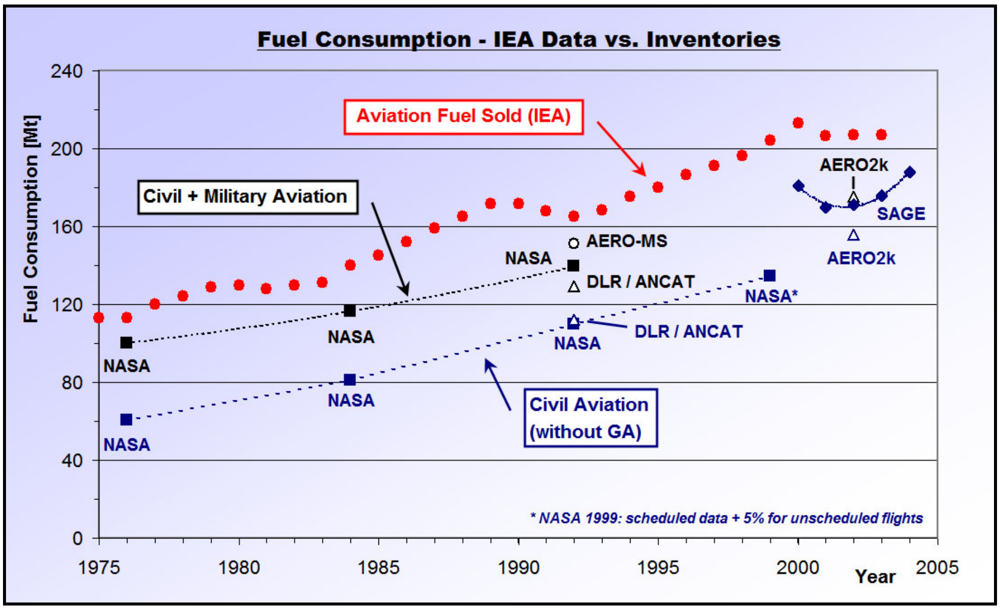

Figure 33: Comparison of aviation fuel sold and inventory fuel burn calculations [IEA, inventory data]

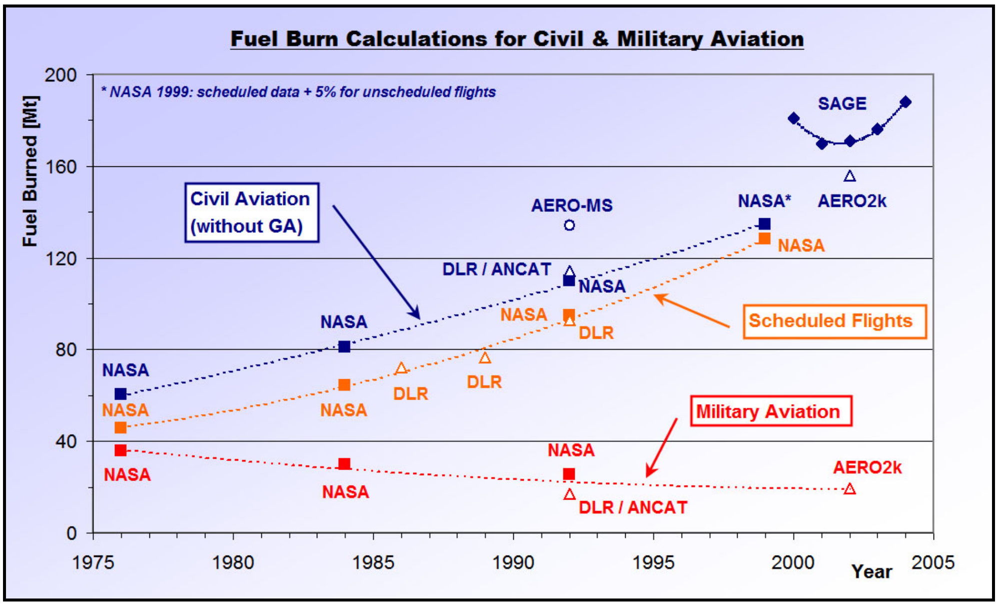

Figure 34: Comparison of fuel burn calculations [inventory data]

Furthermore, the fuel amount sold is not necessarily consumed in flight. Aviation fuel may be used for ground vehicles and engine testing or can be mixed with fuel oils or diesel fuel in order to lower the freezing point. Jet fuel may be reclassified and sold as kerosene, while other distillate fuels from refineries may satisfy jet fuel requirements[198]. Strictly speaking, the IEA statistics *are neither an upper nor lower boundary* for aviation fuel consumption. It seems reasonable, however, that the IEA values overestimate aviation fuel consumption while the inventories underestimate fuel burn. Reference values of higher quality could be gathered from internal airline data or fuel consumption reports by airlines to governments (e.g. in the United States). However, such data are not available on a global basis[199].

Figure 34 on page 82 presents separate results for scheduled and total civil aviation as well as for military aviation. Estimates for General Aviation (GA) are available for the NASA inventories only and were not included in the civil aviation totals shown in the figure. Besides, turboprop flights were not modelled in the DLR/ANCAT inventories. According to NASA calculations for 1992, General Aviation contributed around 2.6% to the global total fuel use of civil and military aviation while turboprop aircraft were responsible for some 2%[200].

As can be seen from Figure 34, the results of the scheduled aviation inventories from *NASA and DLR are within 3%* of each other, as are the results for total civil aviation. The AERO results for civil aviation in 1992 are comparably high, which is believed to be attributable to differences in the movements data rather than performance modelling or assumptions[201]. Since the AERO methodology has not been discussed in this thesis, the results are given as a reference only. The AERO2k results for 2002 are 12-15% above the fuel burn calculated by the DLR and NASA inventories, if the trend in aviation fuel consumption (e.g. from IEA statistics) is taken into account. This effect may largely be attributable to more complete movements data compared to inventories from the "classical generation" and the improved routing based on ATC trajectories.

The fuel burn calculated by the current version of *SAGE is approximately 10% higher than the AERO2k* value for civil aviation – a finding which is more difficult to analyse. AERO2k uses more complete movements information including ATC data for North America and Europe, while SAGE lacks such information for the greater part of Europe. In SAGE, however, unscheduled movements in areas without radar coverage are accounted for by the use of scaling factors. As can be seen from Table 14, the total distance travelled in AERO2k and SAGE is of comparable size. For SAGE, the distance includes the effects of scaling factors

[198] See Baughcum[b] et al. (1996), p. 64

[199] See Baughcum[b] et al. (1996), pp. 67-68

[200] See IPCC (1999), p. 303

[201] See Middel and de Witte (2001), p. 61

and delay modelling[202]. As a consequence, the higher fuel burn values in SAGE seem to be attributable to performance and trajectory modelling rather than movements data or scaling factors. Unlike the approach in AERO2k, the take-off weight in SAGE is systematically overestimated for all flights to account for fuel tankering. While this may contribute to higher fuel burn, an in-depth analysis of movements data and results for a large sample of flights is required to analyse such findings more thoroughly.

	Number of flights	Distance travelled [NM]
SAGE version 1.5 (2002)	28.48 Mio.	$1.76 \cdot 10^{10}$
AERO2k (2002)	n/a	$1.79 \cdot 10^{10}$

Table 14: Comparison of movements data between AERO2k and SAGE [Eyers et al. (2004) / FAA[b] (2005)]

A detailed study comparing AERO2k and SAGE is currently being performed by the developers of both inventories. Some preliminary findings have been published and there are indications that AERO2k models a greater number of flights in some regions of the world (e.g. Europe) while SAGE – on average – models longer trajectories. Furthermore, maximum cruise altitudes in SAGE were found to be higher than in AERO2k, which also contributes to higher fuel burn[203].

Estimates of *military fuel consumption* are available from NASA, ANCAT and AERO2k. Unlike civil aviation, military aviation shows decreasing fuel burn in past years. The AERO2k study confirms this trend. Given the limited availability of military movements data, however, the accuracy of results must be regarded as low.

3.3.3 COMPARISON OF NO_X EMISSIONS

Figure 35 on page 85 compares the global total emissions of NO_x according to the inventories which have been discussed in this thesis. The results for NO_x emissions show a similar pattern as observed for fuel consumption. *A trend towards higher NO_x output is visible.*

The DLR values for scheduled aviation are slightly above the NASA results, while the ANCAT and DLR calculations for civil aviation exceed the NASA value by 15%. Since the fuel burn determined in the "classical" inventories is nearly identical, the elevated NO_x output of the DLR and ANCAT inventories corresponds to a higher average emission index (EI). A comparison of average emission indices for the world fleet of aircraft is shown in Figure 36.

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[202] Nominal flight chords are created for airborne and ground-based delays.
Airborne delays are modelled for OAG flights only; see FAA[a] (2005), p. 29

[203] Locke et al. (2004), pp. 3-4

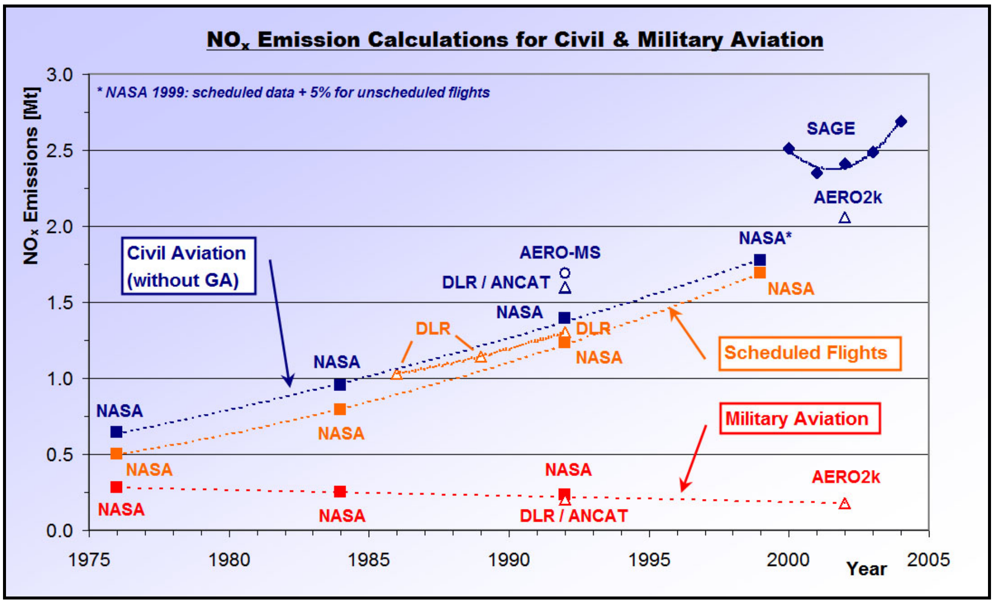

Figure 35: Comparison of NO_x emission calculations [inventory data]

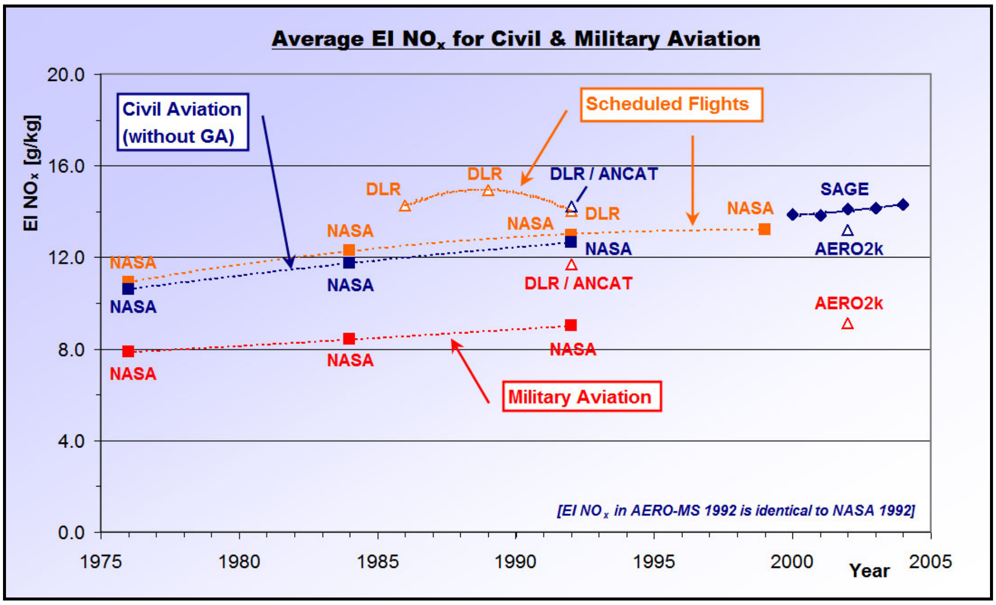

Figure 36: Comparison of EI NO_x in emission inventories [inventory data]

The comparably high emission indices of the DLR and ANCAT inventories are most likely due to a combination of different fleet representation and emission models[204]. As already mentioned in previous chapters, the NASA inventories use the Boeing-2 fuel flow method for NO_x calculations, whereas DLR and ANCAT inventories are based on the DLR fuel flow method. The absence of turboprop aircraft in the DLR inventories contributes to an elevated emission index, since turboprop aircraft typically have lower EI NO_x values than the world fleet on average[205]. On the other hand, the contribution of turboprops to the total emissions of NO_x is small. The result of the AERO modelling system for 1992 is well above the NASA and DLR estimates, this being attributable to higher fuel burn values. The NO_x emission index determined for AERO is nearly identical to the equivalent index from the NASA inventory[206].

It should be noted that an increase of the average NO_x emission index since the 1970s is visible in Figure 36, which corresponds to the introduction of high bypass engines in the 1970s and 80s. More recently, this tendency has slowed down, since progress has been made in the field of NO_x reduction technologies (see chapter 1.2.2). From the data available, no clear trend can be established for recent years. The AERO2k emission index for 2002 is very close to the NASA determined value for scheduled aviation in 1999. The emission indices in SAGE, however, are approximately 7% higher than in AERO2k and show a slight increase between 2000 and 2004. In combination with the higher fuel burn estimates in SAGE, this leads to a difference of *17% between the absolute NO_x outputs calculated in SAGE and AERO2k* respectively. Again, this may be attributable to a combination of differences in the emission models, aircraft representation and performance or trajectory modelling. This conclusion was drawn in a comparison by Locke et al. (2004), although the contributions of the influencing factors identified could not be determined[207].

NO_x emissions from *military aviation* were found to decrease in past years, whereas the emission indices – according to the NASA inventories – show a similar trend as their civil aviation counterparts. The AERO2k result for 2002 fits the NASA data. The comparably high uncertainty range for military emissions can be seen from the deviation in emission indices between the NASA and ANCAT studies. The average emission index determined by the ANCAT inventory for 1992 is almost 30% above the respective NASA value. This difference does not translate into a corresponding deviation of the absolute emissions, since lower fuel consumption was estimated by the ANCAT study (see Figure 34 on page 82).

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[204] See IPCC (1999), p. 304

[205] See Baughcum[a] et al. (1996), pp. M12-M13

[206] The AERO results shown in the figures are based on the Boeing-2 fuel flow method, see Middel and de Witte (2001), p. 61

[207] See Locke et al. (2004), pp. 3-4

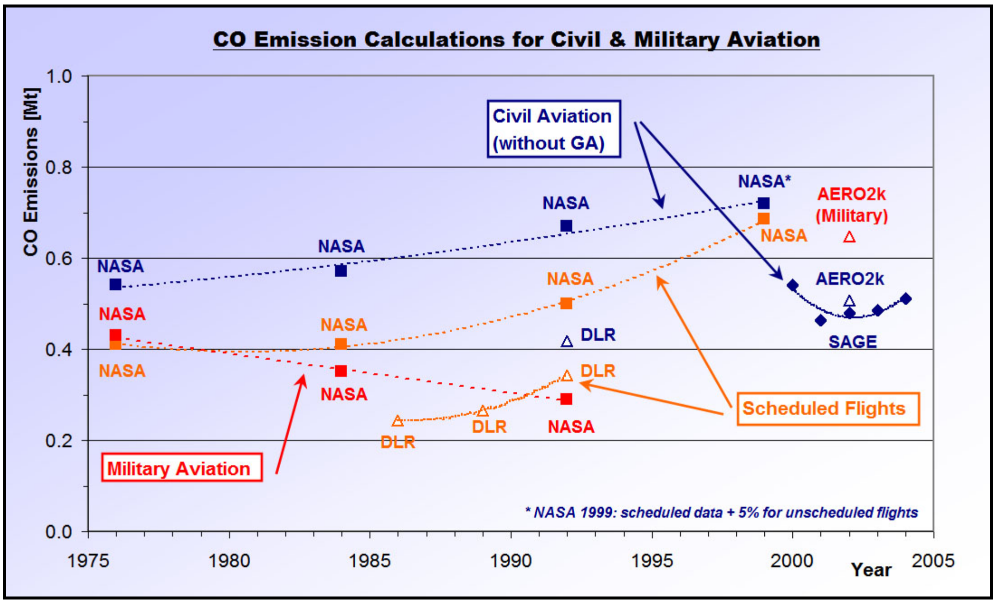

Figure 37: Comparison of CO emission calculations [inventory data]

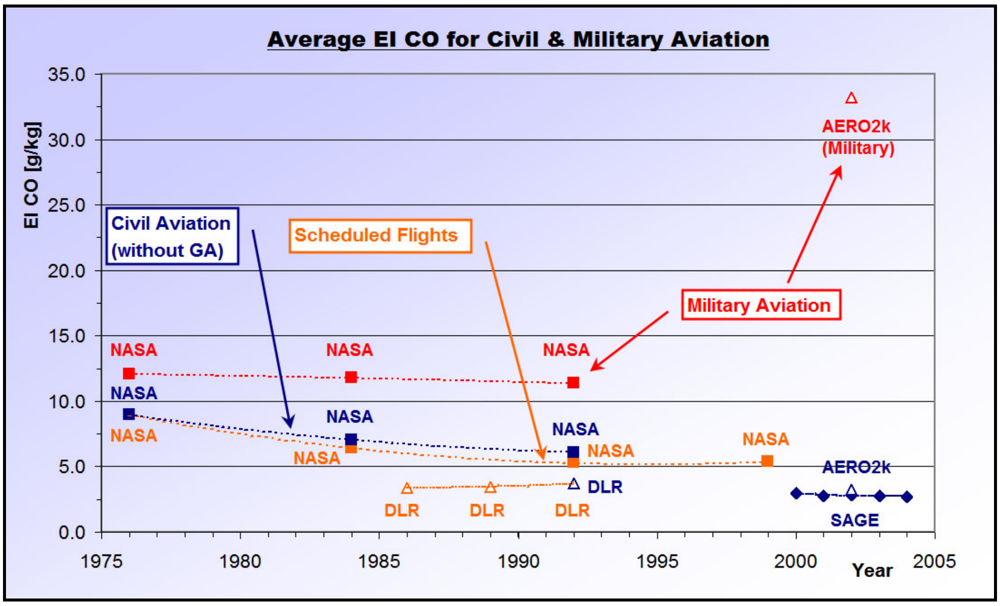

Figure 38: Comparison of EI CO in emission inventories [inventory data]

3.3.4 COMPARISON OF CO AND HC EMISSIONS

Whereas emissions of CO and HC may influence air quality in the surroundings of airports, their importance for the purpose of climate modelling is limited. As a consequence, no estimations of CO and HC emissions were given in early emission inventories. Even nowadays, the calculation of CO and HC emissions for global aviation does not offer the same accuracy as NO_x prediction. The graphs on page 87 give an overview on CO calculations for global aviation while the diagrams on page 89 cover HC emissions.

As can be seen from Figure 38, a trend towards lower *CO emission indices* is visible for civil aviation. This corresponds to improvements in the combustion efficiency of aircraft engines since the 1970s. However, this development is outpaced by the growth of civil aviation fuel consumption, which results in increasing values of total emissions (according to NASA and DLR data, see Figure 37). Differences in the order of 30-40% exist between the average CO emission indices of the NASA and DLR inventories. The emission indices from AERO2k and SAGE are nearly identical and on the level of the DLR values. *Emissions of HC* show a decrease over the years, if data calculated by the same methodology is compared (see Figure 39). The emission indices were reduced significantly following improvements in combustor designs (see Figure 40). Similarly to the pattern observed for CO emissions, DLR and NASA determined HC emissions for civil aviation differ almost by a factor of two. The AERO2k and SAGE results seem to confirm the DLR values.

The deviations observed cannot be explained by different emission models alone. Both NASA and SAGE inventories utilize a fuel flow correlation for CO and HC while DLR and AERO2k inventories use the Omega method. However, emissions of CO and HC are very sensible to small variations in fuel flow, which may explain the differences between the NASA and SAGE results[208]. Concerning emissions of military aviation, AERO2k found much higher emission indices for CO and HC than the NASA inventories. It is obvious that this development does not reflect a trend in real-world military aviation, but may largely be attributable to different assumptions on the use of reheat and afterburning operations[209].

Furthermore, the contribution of *General Aviation* towards CO and HC emissions should not be neglected. Estimates for General Aviation were made in the “classical” NASA inventories only. The piston engines used predominantly in General Aviation were found to contribute almost 40% to the total CO emissions in 1992 and 12% to the total HC production. However, emission indices for piston engines are not widely available and highly uncertain[210].

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[208] See FAA[b] (2005), p. 38

[209] See Eyers et al. (2004), pp. 90 and 105

[210] See FAA[a] (2005), p. 5

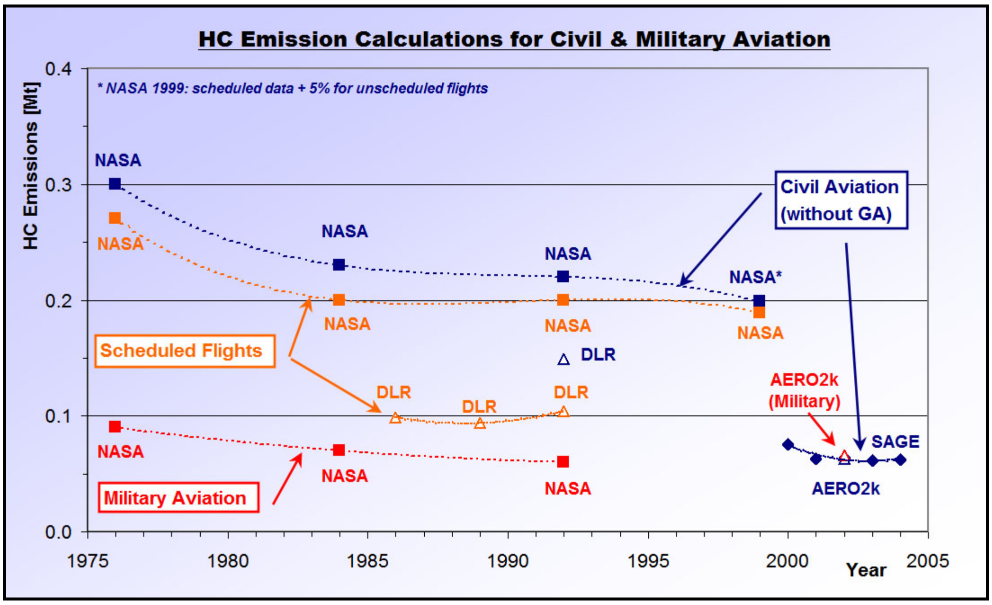

Figure 39: Comparison of HC emission calculations [inventory data]

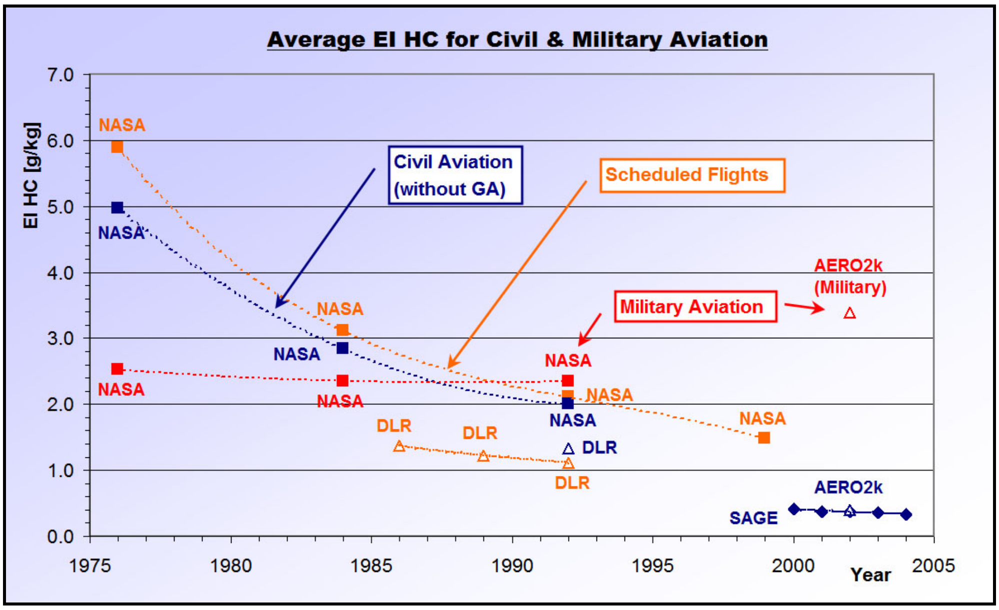

Figure 40: Comparison of EI HC in emission inventories [inventory data]

3.4 SUMMARY OF FINDINGS & CONCLUSION

Similar to other means of transportation, aviation creates social and economic benefits at the cost of adverse environmental impacts. Although technological progress has been made in the field of engine and airframe technology, the total emissions of the airline industry are still on the rise. Emission inventories enable an assessment of the global distribution of aircraft emissions. They are required for any research on the interrelation between aircraft emissions and climate change. Gridded results of fuel burn and emissions are calculated at three- or four-dimensional resolution and serve as input data for models of atmospheric chemistry. Consequently, the development of global emission inventories has mostly been driven by atmospheric scientists.

The first high quality inventories were produced in the 1990s by the U.S. National Aeronautics and Space Administration (NASA), the Abatement of Nuisances Caused by Air Transport (ANCAT) / European Community (EC) Working Group and the German Aerospace Center (DLR). Given the rapid growth of aviation in combination with changing air traffic rules, route systems and aircraft types in service, there is a constant need for up-to-date inventories. Following the introduction of advanced Air Traffic Management (ATM) systems in the USA and Europe, more complete data on global air traffic (including 4D flight trajectories) were made available to inventory creators. As a consequence, a new generation of emission inventories has been developed in the past 5 years, represented by:

- The NASA inventory for 1999,
- The EC initiated AERO2k inventory for 2002,
- The SAGE inventories of the FAA for 2000-2004.

These inventories define the current state-of-the-art for global aviation emission inventories. Their methodologies and results have been discussed in this thesis.

Comparison of Methodologies

Only minor and evolutionary improvements compared to the “classical” inventories were implemented into the methodology of the *NASA inventory for 1999 [Sutkus et al. (2001)].* More detailed modelling of cargo aircraft has improved the accuracy of performance calculations. The number of representative aircraft/engine combinations was increased and is larger than in any other inventory covered by this thesis. As in the methodologies from the “classical” generation, however, great-circle routes were assumed between city-pairs. Moreover, the movements data were based exclusively on flight schedules. Given the similarity with previous NASA inventories, the 1999 results are well suited for trend analyses.

A major drawback, however, is the *incomplete coverage of global aviation*. Whereas previous NASA inventories were supplemented by separate studies on charter, military and General Aviation, only scheduled air traffic was accounted for in the 1999 inventory. Besides, no estimates of particle emissions were given and the output data does not contain any four-dimensional results. In all the aforementioned aspects, the AERO2k and SAGE inventories must be regarded as superior. By contrast, the 1999 NASA inventory represents a comparably simple approach towards aviation emission inventories.

The *AERO2k inventory [Eyers et al. (2004)]* features a number of major improvements and largely defines the current state-of-the-art. Unlike the NASA inventories, it accounts for both scheduled and unscheduled traffic in a typical bottom-up approach. Civil and military aviation are assessed separately, while General Aviation was neglected due to lack of reliable data. Whereas previous inventories for global aviation assumed great-circle routes between city-pairs, AERO2k uses routing and altitude information from Air Traffic Control (ATC) wherever available. For the remaining flights, comparable trajectories were created artificially based on an analysis of radar-tracked flights. Unlike other inventories, AERO2k provides information on particle emissions and the distances travelled per grid cell. These features were requested by atmospheric scientists for the purpose of contrail assessment.

A drawback in the AERO2k approach is the comparably high effort required for the processing of movements data: flight plans and flight trajectories were gathered from European and North American Air Traffic Control (ATC) organizations and were supplemented by schedules where applicable. The filtering, harmonization and merging of such information requires a great share of the total workload for inventory production. In AERO2k, three-dimensional global inventories were created for 2002, supplemented by a four-dimensional inventory for the assessment of diurnal cycles. The six-hourly temporal resolution of the four-dimensional grid must be regarded as low, but inventories with a higher resolution could be produced from the raw output data.

The *SAGE inventories [FAA[a] (2005) and FAA[b] (2005)]* are being developed on behalf of the Federal Aviation Administration (FAA) and preliminary results have been published. In the current version, only civil aviation is considered. General Aviation is neglected due to lack of reliable data while military aviation may be accounted for in future versions. Regarding the modelling of civil flights, SAGE can be considered on a similar technological level as the AERO2k equivalent. A major drawback, however, is the lack of estimates for particle emissions. Furthermore, some fundamental differences exist between the overall methodologies of SAGE and AERO2k:

The movements database in SAGE consists of Air Traffic Control (ATC) data for North America supplemented by flight schedules for other regions of the world. Flight tracks are modelled via radar trajectories or by assuming dispersed great-circle routes. Compared to AERO2k, the SAGE approach is less complex but still a considerable improvement over "classical" inventories. In order to account for unscheduled traffic in regions without radar coverage, SAGE scales up results of fuel burn and emissions by means of statistically determined scaling factors. Fuel tankering is accounted for by systematically overestimating aircraft take-off weight. Moreover, a delay model based on queuing theory was implemented in order to approximate taxi and airborne delays. The aforementioned features may increase the precision of global total values of fuel burn and emissions, whereas the effects of fuel tankering and delays on single flights are not accurately accounted for. AERO2k, for comparison, does not model uncertain factors like fuel tankering and delays; instead, corrections by means of scaling factors are left to the user.

SAGE aims to provide four-dimensional raw data of the results, upon which used-defined queries can be run. Given the steadily increasing processing power of computers, this approach makes sense. User-specified inventories at almost any resolution can be produced from the raw data. Pre-processed inventories have been published at three-dimensional resolution covering civil aviation in the years 2000-2004.

Comparison of Results

All inventories assessed by this thesis underestimate actual fuel burn and emissions due to incomplete movements data and various simplifications. Moreover, no reliable reference exists for an assessment of global total results. From a comparison of inventory results with US airline data, Sutkus et al. (1999) and (2001) states systematic underestimation of aviation fuel burn in the order of 15-20%. In fact, a deviation of similar magnitude is found when comparing inventory results to fuel sold statistics from the International Energy Association (IEA). IEA data, however, do not accurately reflect the fuel amount burned by aircraft and are not necessarily better estimates of fuel consumption than inventory results.

The fuel consumption of military aviation has been found to decrease in the past 30 years, while civil aviation fuel use is increasing. The progress in terms of fuel efficiency of modern aircraft is currently outpaced by aviation growth. The NASA calculations for 1999 fit the results from previous inventories, if the trend in aviation fuel consumption is taken into account. Taking a similar approach for AERO2k, the fuel use calculated by this inventory has been found to be 12-15% above results from older methodologies – an effect which is largely attributable to more complete movements data and improved routing. The SAGE prediction of global fuel burn is 10% higher than the comparable AERO2k value. This deviation has been shown to result from differences in the performance models. The effects of delay modelling and scaling factors in SAGE have been found to be small: the total distances flown in SAGE and AERO2k are on a comparable level.

As to emissions of NO_x, a trend towards higher absolute NO_x output is visible from inventory data. Moreover, the deviations observed between results from different inventories are considerable: SAGE models a 7% higher fleet emission index than AERO2k, resulting in a 17% deviation in terms of absolute emissions. The scattering of average emission indices may be attributable to a combination of effects from different aircraft representation, performance and emission models. Even larger uncertainties exist regarding the average fleet emission indices of CO and HC, this being attributable to less accurate emission models for the aforementioned species.

Conclusion

As can be seen from the above paragraphs, the uncertainties regarding global total values of fuel burn and emissions are high. The absence of suitable reference data makes a "calibration" of inventory methodologies difficult. Future inventories will help to reduce the uncertainties, however at the cost of more complex calculations. Progress in the field of Air Traffic Management (ATM) systems will make more consistent movements data available to inventory creators. Flight planning software may be used for future inventories in order to account for wind effects; a comparable feature is planned for the next version of SAGE. Besides, more reliable results for particulate emissions are desirable for the purpose of research on contrail clouds. Only the most accurate methodologies may satisfy the requirements of atmospheric scientists, while comparably simple methodologies may be sufficient for trend analyses or forecast scenarios.

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APPENDICES

Glossary of Symbols & Units

Units:

°	Degree
°C	Degree centigrade
ft	Feet
g	Gram
K	Kelvin
kg	Kilogram
km	Kilometre
kN	Kilonewton
kt	Knot
m	Metre
Mt	Megaton
N	Newton
NM	Nautical miles
Pa	Pascal
Pkm	Passenger-kilometre
t	Ton
tkm	Ton-kilometre
W	Watt

Symbols:

a	Local speed of sound [m/s²]
AF	Number of actual flights per week in SAGE
C_D	Drag coefficient
C_L	Lift coefficient
CF	Number of cancelled flights per week in SAGE
D	Aerodynamic drag [N]
D_p	Total gross emission of a pollutant over the LTO cycle [g]
EI	Emission index [g/kg]
f	Fuel flow in BADA [kg/min]
F_{00}	Maximum rated trust of an engine [kN]
g	Gravitational acceleration [m/s²]
h	Altitude [m]

Symbols (continued):

H	Humidity correction factor in the Boeing-2 method
L	Aerodynamic lift [N]
m	Aircraft mass [kg]
M	Mach number
p	Pressure [Pa]
p_3	Combustor inlet pressure [Pa]
R	Universal gas constant [m²/Ks²]
REI	Emission index at reference conditions in the Boeing-2 method [g/kg]
RF	Radiative Forcing [W/m²]
RW_{ff}	Fuel flow from ICAO in the Boeing-2 method [kg/s]
S	Wing surface area [m²]
SCF	Airport-specific scaling factor in SAGE
SF	Number of scheduled flights per week in SAGE
T	Temperature [K or °C] <u>or</u> Thrust [kN]
T_3	Combustor inlet temperature [K]
UF	Number of unscheduled flights per week in SAGE
v	Velocity [m/s or kt]
V_C	Combustor volume [m³]
w_{air}	Air mass flow [kg/s]
w_{fuel}	Fuel flow [kg/s]
W_f	Actual fuel flow at altitude in the Boeing-2 method [kg/s]
W_{ff}	Actual fuel flow at reference conditions in the Boeing-2 method [kg/s]
ϕ	Bank angle [rad]
η	Thrust specific fuel consumption [kg/min/kN]
φ	Latitude [°]
λ	Longitude [°]
π_{00}	Pressure ratio of an engine
ρ	Air density [kg/m³]
Ω	Reciprocal value of the simplified combustor loading parameter Θ

Results of Emission Inventories *[Baughcum[a,b] et al. (1996), Sutkus et al. (2001), FAA[b] (2005)]*

	Year	Flights [Mio.]	Distance [NM]	Fuel Burn [Mt]	NO_x [Mt]	CO [Mt]	HC [Mt]	Soot [Mt]	Particle No. [-]
NASA 1976 ***(civil)***	1976			64.4	0.700	1.270	0.330		
- Scheduled	1976			45.8	0.500	0.410	0.270		
- Charter	1976			8.5	0.090	0.030	0.010		
- FSU / China	1976			6.1	0.040	0.100	0.020		
- General Aviation	1976			4.0	0.060	0.730	0.030		
NASA 1976 ***(military)***	1976			35.7	0.280	0.430	0.090		
NASA 1984 ***(civil)***	1984			86.6	1.020	1.320	0.280		
- Scheduled	1984			64.2	0.790	0.410	0.200		
- Charter	1984			9.3	0.110	0.040	0.010		
- FSU / China	1984			7.4	0.060	0.120	0.020		
- General Aviation	1984			5.6	0.070	0.750	0.050		
NASA 1984 ***(military)***	1984			29.8	0.250	0.350	0.070		
NASA 1992 ***(civil)***	1992			113.9	1.440	1.290	0.260		
- Scheduled	1992			94.8	1.230	0.500	0.200		
- Charter	1992			6.6	0.090	0.020	0.000		
- FSU / China	1992			8.8	0.060	0.150	0.030		
- General Aviation	1992			3.9	0.050	0.620	0.040		
NASA 1992 ***(military)***	1992			25.6	0.230	0.290	0.060		
NASA 1999 ***(scheduled only)***	1999		1.39E+10	128.0	1.690	0.685	0.189		
SAGE v1.5 ***(civil)***	2000	29.706	1.80E+10	181.0	2.510	0.541	0.076		
SAGE v1.5 ***(civil)***	2001	27.674	1.72E+10	170.0	2.350	0.464	0.063		
SAGE v1.5 ***(civil)***	2002	28.477	1.76E+10	171.0	2.410	0.480	0.064		
SAGE v1.5 ***(civil)***	2003	28.780	1.86E+10	176.0	2.490	0.486	0.062		
SAGE v1.5 ***(civil)***	2004	30.379	2.00E+10	188.0	2.690	0.511	0.063		

Results of Emission Inventories (continued) *[Brunner et al. (1998), IPCC (1999), Middel and de Witte (2001), Eyers et al. (2004)]*

	Year	Flights [Mio.]	Distance [NM]	Fuel Burn [Mt]	NO_x [Mt]	CO [Mt]	HC [Mt]	Soot [Mt]	Particle No. [-]
DLR ***(scheduled only)****	1986		5.68E+09	72.2	1.030	0.244	0.099		
	1989		6.09E+09	76.5	1.144	0.265	0.094		
	1992		8.46E+09	93.0	1.305	0.343	0.104		
DLR 1991/92 ***(civil)***	1992		9.74E+09	112.2	1.596	0.417	0.149		
DLR / ANCAT 1991/92 ***(military)***	1992			17.1	0.200				
ANCAT 1991/92 ***(civil)***	1992			114.2	1.600				
DLR / ANCAT 1991/92 ***(military)***	1992			17.1	0.200				
AERO-MS / BM2 ***(civil)***	1992			134.2	1.690				
AERO-MS / ANCAT ***(military)***	1992			17.1	0.200				
AERO2k ***(civil)***	2002		1.79E+10	156.0	2.060	0.507	0.063	0.0039	4.03E+25
AERO2k ***(military)***	2002			19.5	0.178	0.647	0.066		

** DLR data also available for international scheduled air traffic for every year from 1982 to 1992 [Brunner et al. (1998)]*

Results of Forecast Inventories *[IPCC (1999), Sutkus et al. (2003), Eyers et al. (2004)]*

	Year	Flights [Mio.]	Distance [NM]	Fuel Burn [Mt]	NO_x [Mt]	CO [Mt]	HC [Mt]	Soot [Mt]	Particle No. [-]
NASA 2015 ***(civil)***	2015			288.1	3.950	2.040	0.280		
- Scheduled	2015			252.7	3.570	1.120	0.170		
- Charter	2015			13.5	0.190	0.050	0.010		
- FSU / China	2015			15.8	0.120	0.260	0.050		
- General Aviation	2015			6.0	0.070	0.600	0.050		
NASA 2015 ***(military)***	2015			20.6	0.180	0.230	0.050		
DLR 2015 ***(civil)***	2015			270.5	3.414				
DLR / ANCAT 2015 ***(mil.)***	2015			14.5	0.156				
ANCAT 2015 ***(civil)***	2015			272.3	3.370				
ANCAT 2015 ***(military)***	2015			14.5	0.160				
AERO-MS 2015 ***(civil)***	2015		2.68E+10	278.0	3.860				
NASA 2020 ***(civil)***	2020		4.02E+10	347.4	4.890	1.390	0.230		
AERO2k 2025 ***(civil)***	2025		3.61E+10	327.0	3.308	1.150	0.145	0.0087	8.54E+25
AERO2k 2025 ***(military)****	2025			19.5	0.178	0.647	0.066		

** Values for 2002 are suggested to be used [Eyers et al. (2004)]*

Aviation Fuel Sold *[UBA (2003), IEA (1993-2005)]*

	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984
International Energy Agency [Mio. t]										
Umweltbundesamt [Mio. t]*	113.0	113.0	120.0	124.0	129.0	130.0	128.0	130.0	131.0	140.0

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
International Energy Agency [Mio. t]					171.8	171.8	168.1	165.1	168.2	175.4
Umweltbundesamt [Mio. t]*	145.0	152.0	159.0	165.0	171.0	171.0	168.0	167.0	171.0	174.0

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
International Energy Agency [Mio. t]	179.9	186.7	191.1	196.2	204.0	213.0	206.5	207.1	207.0	
Umweltbundesamt [Mio. t]*	179.0									

** Based on IEA statistics*

Zusammenfassung in Deutscher Sprache

Die vorliegende Diplomarbeit behandelt die Erstellung von Emissionskatastern, wie sie zur Ermittlung der Klimawirksamkeit des Luftverkehrs zum Einsatz kommen. Sie entstand in Zusammenarbeit der Technischen Universität Berlin, Fachgebiet Flugführung und Luftverkehr, mit dem Deutschen Zentrum für Luft- und Raumfahrt (DLR) in Köln, Abteilung Flughafenwesen und Luftverkehr.

Während in Kapitel 1 grundlegende Informationen zu den gasförmigen Emissionen des Luftverkehrs und deren Klimawirksamkeit vermittelt werden, betrachtet Kapitel 2 den aktuellen Stand des Wissens hinsichtlich der Erstellung von Emissionskatastern. Der Schwerpunkt liegt dabei auf einer überblicksartigen Darstellung der Berechnungsmethodik sowie der Diskussion möglicher Alternativen in der prinzipiellen Vorgehensweise.

Dargestellt werden im Einzelnen:

- Die Bearbeitung von Flugplan- und Radardaten zur Erstellung einer Datenbank globaler Flugbewegungen.
- Diverse Methoden der Flugleistungsberechnung zur Bestimmung des flugphasenabhängigen Treibstoffverbrauchs.
- Korrelationsmethoden zur Ermittlung der triebwerkspezifischen Emissionen sowie
- Die Integration vorstehender Methoden zur Erstellung eines globalen Emissionskatasters mit drei- oder vierdimensionaler Auflösung.

Mögliche Fehlerquellen und Vereinfachungen gegenüber der Realität werden qualitativ und quantitativ auf Basis der wissenschaftlichen Literatur bewertet.

Aufbauend auf den vorstehenden Zusammenhängen bietet Kapitel 3 einen Überblick über bislang durchgeführte Katasterberechnungen in Form eines Methodik- und Ergebnisvergleichs. Globale Emissionskataster der 1990er Jahre (NASA, DLR-2, ANCAT/EC-2) werden überblicksartig behandelt. Der Schwerpunkt liegt auf kürzlich abgeschlossenen (NASA 1999, AERO2k) oder noch in Entwicklung befindlichen (SAGE) Katasterprojekten. Ein Ergebnisvergleich behandelt Berechnungen des Treibstoffverbrauchs sowie der Emissionen von Stickstoffoxiden (NO_x), Kohlenstoffmonoxid (CO) sowie Kohlenwasserstoffen (HC).

Versicherung

Ich versichere hiermit, dass ich die vorliegende Arbeit selbständig und eigenhändig ohne Benutzung anderer als der angegeben Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten und nicht veröffentlichten Schriften entnommen sind, sind als solche kenntlich gemacht. Die Arbeit ist in gleicher oder ähnlicher Form noch nicht als Prüfungsarbeit eingereicht worden.

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