Hochschule für Angewandte Wissenschaften Hamburg
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Bachelor Thesis

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Developing an Ecolabel for Aircraft

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Abstract

The focus of this work is to analyse how an ecolabel could be defined for commercial, subsonic aircraft in a similar way to other products or modes of transport. This is done by determining the most relevant environmental impacts of aviation and the causative emissions of aircraft. The main impacts were found to be resource depletion, climate impact, air pollution and noise pollution. Further, the determination methods of emission species such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) are discussed, as well as their relative contribution to the overall environmental impact. Based on these results, methods are presented that allow the comparison of environmental performance for aircraft of different sizes and capability. This is achieved by using normalizing factors such as number of passengers, allowing a comparison of 'per-seat' performance. Since this is dependent on the cabin configuration defined by the airline, the label features also statements about the OEM-based aircraft, which shows how the seat layout of an airline alters relative performance. Additionally, a metric was developed that assigns impact factors based on travel class, as space-consuming seats would naturally have a proportionally larger impact.

All performance categories are then rated on a scale of A to G, indicating how good or poor they are compared to other aircraft. For this purpose, the emission data of various aircraft and engines was evaluated from publicly available databases such as the *Engine Emission Data Bank* or *Noise Data Bank*. It was made sure that preferably official, certified and public input data is used, allowing independent third parties to verify the results.

The analysis concludes with a usable scheme, but also indicates that some environmental factors still have large uncertainties, on the one hand due to indeterminate and complex atmospheric effects and on the other hand due to insufficient or not yet fully developed measurement methods. Moreover, the use of an ecolabel should be simple and can therefore not take into account all details. Nevertheless, an ecolabel could give a useful general indication of environmental performance.

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DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

Developing an Ecolabel for Aircraft

Background

The airline "flybe" introduced an ecolabel for their aircraft in 2007 and had hoped other airlines would follow. This was apparently not the case. The labeling scheme rates emissions such as of NOX, CO2 and noise of an aircraft in the style of ecolabels for fridges, microwaves and washing machines. The information is then broken down into "per seat" and distance-dependent categories, indicating the total amount of emissions alongside a rating from A to F. The result is then presented on a label, which the airline uses for advertising and displaying on board. The methodology used has potential shortcomings, which may inhibit further adaptation. Therefore, a more reliable and meaningful solution shall be investigated on a generally accepted and comprehensible basis.

Task

Task of this thesis is to develop an aircraft-related labeling methodology based on environmental impact. Existing emission determination methods and previous approaches such as flybe's shall be taken into account. Detailed tasks are:

- Describe the purpose of ecolabeling and how it is done
- Determine major environmental impacts of aviation
- How are emissions determined in aviation?
- Analyze existing labels or rating schemes and their potential shortcomings
- How could an ecolabel for aircraft best be defined?

The report should be written in English based on German or international standards on report writing.

Contents

List of Figures

List of Tables

List of Symbols

a	Altitude
B	Breguet factor
c	Specific fuel consumption
C_D	Drag co-efficient
C_L	Lift co-efficient
E	Lift to drag ratio
EI	Emission Index
$F(\dots)$	Function of ...
I	Sound intensity
m	Mass
p	Pressure
R	Range
s	Radiative forcing factor
SN	Smoke number
T	Temperature

Acronyms and Abbreviations

AEDT	Aviation Environmental Design Tool
ATM	Air Traffic Management
BPR	Bypass Ratio
CAEP	Committee on Aviation Environmental Protection
CF	Characterization Factor
EASA	European Aviation Safety Agency
EU	European Union
EPNL	Effective Perceived Noise Level
FAA	Federal Aviation Administration
GEN	Global Ecolabelling Network
GTP	Global Temperature Potential
GWP	Global Warming Potential
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LTO	Landing and Take-off cycle
OEM	Original Equipment Manufacturer
PAX	Passenger
PM	Particulate Matter
RF	Radiative Forcing
RFI	Radiative Forcing Index
SAR	Specific Air Range
SARPs	Standards And Recommended Practices
SFC	Specific Fuel Consumption
SGTP	Sustained Global Temperature Change Potential
SPL	Sound Pressure Level
TCDSN	Type-Certificate Data Sheet for Noise

Aircraft Masses

MTW	Maximum Taxi Weight
MTOW	Maximum Take-off Weight
MLW	Maximum Landing Weight
MZFW	Maximum Zero Fuel Weight
MFW	Minimum Flying Weight
OEW	Operating Empty Weight
P/L	Payload
MEW	Manufacturer's Empty Weight
SEW	Standard Empty Weight
BEW	Basic Empty Weight

1 Introduction

1.1 Motivation

Environment protection is one of the key issues and most ambigious challenges of the 21st century and is becoming increasingly important worldwide.

The transportation industry has its share in global environmental pollution. Therefore, the main objective in future development of transportation technologies is to reduce environmental burden through more efficient and sustainable methods, planning, regulations and new technology. The aviation sector is a growing market and is likely to expand even further in developing countries. This means that this area, too, has the obligation to take over responsibility.

However, not only environmental protection itself is an issue. Airline companies try to save fuel as it takes a major part in operating costs. Additionally, there is a lot of competition, which means every carrier tries to find a trade off in environmental impact, fuel consumption and passenger comfort while having to comply with regulations and high safety standards.

In many areas of our lives, so called ecolabels have been established for consumer goods and services. Ordinarily, these labels provide information about the impact on the environment and, where applicable, energy efficiency of a certain product. This gives consumers knowledge about how and to what extend the environment is affected through the fabrication and/or use of the product and allows easy comparison of similar offers due to simple labelling and comprehensible classification.

For the most part, labels classify consumer and household products that are examined for harmfulness to the environment, performance, water and resource consumption and energy efficiency. The transportation sector also has labels in different areas. One of the most common indicators are for example CO_2 efficiency classes for road vehicles.

In aviation, however, such labels are not yet common practice. There are attempts and methods to estimate emissions based on journey, which intend to give consumers an idea about their ecological footprint. These methods are usually based on empirical data based on specific routes.

By contrast, the aim of this thesis is to develop an *aircraft* based ecolabel. This means that ratings should be independent of a specific mission or route, but take into account the relative overall environmental performance and capability of the aircraft. The definite aim of this thesis is outlined more precisely in the following.

1.2 Aim of this Thesis

The aim of this thesis is to determine major environmental impacts of aviation and investigate how they can be assessed and rated using measured emission data from aircraft. Based on these results, it shall be examined how an ecolabel could be defined and what considerations are necessary and should be included.

Before addressing relevant environmental factors, a brief introduction to ecolabelling shall be given in order to determine what is important for their definition since it is not clearly evident from scratch how ecolabels are defined and what aspects are relevant, particularly with aircraft as a target in mind. These findings are then taken as a basis for the further work.

1.3 Structure of this Thesis

The thesis is structured as follows:

Chapter 2
Introduction to ecolabelling and its standards

Chapter 3
Determination of environmental issues that aviation has a considerable impact on and how they are indicated, as well as how they come into existence and impact the environment

Chapter 4
Assessment of methods to determine aircraft emissions and sources of certified data

Chapter 5
Analysis of existing ecolabels and potential shortcomings, in particular the approach for an ecolabelling scheme of the British airline "flybe".

Chapter 6
Evaluation of a new ecolabel scheme based on previous findings and development of a methodology which makes the environmental impacts of different aircraft comparable

Chapter 7
Conclusions and final remarks

2 Ecolabels in Practice

2.1 Purpose

Ecolabels are certification marks that give information about quality and property of products and hence make them comparable for the consumer or client. In particular, they are a special type of mark that emphasizes environmental issues.

Their purpose is to encourage more sustainable production and use or consumption of products and point out products that are qualitatively better through appropriate labelling. (GEN 2004)

Certification procedures may also play an important part for policy-makers by setting environmental standards which are based on them. In the English-speaking world, there is often made a distinction between ecolabels that are voluntary and green stickers, which are mandated by law. This work will be based on ecolabels on a voluntary basis.

The awarding is usually conducted by institutions and organizations as well as independent test laboratories, but manufacturer also develop labels on a voluntary basis. While the overall stimulant of voluntary ecolabels for environmentally friendly product innovations is not entirely clear, trustworthy and reliable ecolabels give important information for consumers and clients and can result in competitive advantages for a company. (Rennings et al. 2008)

The most important thing is that statements are reliable and contain no misleading information, e. g. through highlighting of one-sided positive aspects, in order to prevent so called greenwashing.

Greenwashing means that manufacturers praise merits without actual improvements in environmental friendliness. In order to make consumers have trust in ecolabels, misleading statements must be avoided in any case. Therefore, international standards exist through ISO, which ensure that manufacturer claims are valid and contain legitimate information. (ISO 2012)

2.2 Types

The International Organization for Standardization (ISO) issued an environmental standard called ISO 14000, which deals with topics of environmental management.

ISO 14020 is a series of standards which defines types and guidelines for environmental labelling. In particular, they describe three types of labelling, which are voluntary:

Type I: Ecolabelling schemes (ISO 14024:1999)

Type I describes voluntary, multiple-criteria labelling developed through third parties. The labels indicate overall environmental preferability of a product within a particular category, based on life cycle considerations.

This standard provides all requirements, guiding principles and procedures for the development and operation of Type I labelling schemes. It contains the method for selection of product categories, product environmental criteria and product function characteristics as well as means of compliance and certification processes.

Type II: Self-declared environmental claims (ISO 14021:1999)

Type II organizes self-declared claims that are voluntarily made by manufacturers. These claims do not necessarily have to be part of a product labelling (like on packaging), but deal with general statements that are being made, e. g. in advertising. This standard makes sure that information is accurate and not misleading while preventing unwarranted claims. If claims are made, they need to useful to the consumer. Therefore, ISO 14021 addresses use of symbols, requirements and verification of claims among other things.

Type III: Life-cycle data declarations (ISO 14025:2006)

Type III is targeted to a more business oriented audience as it presents quantified environmental information based on predefined categories from life cycle assessments (ISO 14040) and does not judge products, which is left to the consumer. Statements are therefore less amenable for the broad public and aimed at commercial purchasers.

Most labels are based on this classification and labelling organizations such as *Global Ecolabelling Network* (GEN) take it as a reference. The central statements are outlined in section 2.3 and used as a basis for the ecolabelling scheme in this work.

2.3 Findings

While all ISO ecolabel types share a common goal, they differ in what has to be considered and how extensive specifications are. As for the ecolabel considered in this work, Type I ecolabelling is probably most appropriate as multiple impact categories are regarded based on life cycle considerations and shall be rated relatively to other comparable aircraft. Type III may also be a possibility as it is based on life cycle assessment, but it requires strict adherence to the predefined categories whereas it was chosen in this work to allow some adjustments to be made, such as the inclusion of aircraft noise. As a consequence, a review of the respective standard suggested the following to be considered in this work:

Principles

- **Voluntariness**
  Labelling is voluntary
- **Life cycle consideration**
  In order to reduce environmental impact as a whole and not just partly, the entire product life cycle should be considered. This should include extraction of resources, manufacturing, distribution, use and disposal. In case there is a departure from this pattern, it shall be justified.
- **Criteria**
  Environmental Criteria shall be defined in a way that they highlight differences between products, presuming that there are significant distinctions.
  Criteria should be attainable and the levels of product performance taken into account.
  The selection of criteria shall be based on scientific and engineering principles.
- **Transparency**
  Development and operation of environmental labelling according to Type I should be transparent, meaning that information is available to interested parties in order to allow traceability.

Procedures

- **Selection of product categories**
  A study should be conducted to identify potential product categories and the market situation. This should include the analysis on environmental impact of products, availability of data, consultation with interested parties, market surveys, need for environmental improvement, a preselection of product categories etc.

- **Selection and development of product environmental criteria**
  ISO 14024 provides an environmental criteria selection matrix that combines stages of product life cycle with environmental input/output indicators.
  The development of criteria should take into account local, regional and global environmental issues, technology and economic aspects. Weighting factors may be applied to environmental requirements and shall be justified.
  After the criteria have been chosen, numerical values shall be defined in terms of minimum values, threshold levels, scale-point systems or other forms.

Certification and compliance

- **Basis**
  All environmental criteria shall be verifiable by the ecolabelling body. Means of compliance should follow international, national, regional or other comprehensible and reproducible scientific methods, in mentioned preference.
- **Documentation**
  The ecolabel applicant shall provide a documentation that proves compliance with the requirements.
- **Compliance monitoring**
  Any changes after the awarding of the ecolabel licence that may affect compliance shall be reported to the ecolabelling body.

3 Environmental Factors

3.1 Introduction

In order to further evaluate the effects of environmental pollution, it is sensible to determine what factors are considered to have an impact on the environment and how harmful they are.

It should first be noted that there are anthropogenic sources (caused by humans) and natural sources of environmental pollution. The human impact on the environment comprises many scopes of civilization, such as technology, agriculture, industry, energy production, mining and transportation.

This work deals with these human-made sources and delves into the impact of air traffic in particular. The actual extent of human-induced emissions is subject to extensive research and scientific debate. However, it can be determined what kind of pollutants and what amounts and concentrations of said substances are emitted. This data can be gathered objectively through measurements with accuracy depending on the considered substance and method. Evaluation and interpretation of this data on the other hand can lead to some dissent, but metrics have been developed to measure and quantify impact, although with more or less uncertainty.

This section describes different types of pollution and determines which are most relevant for aviation. These are then examined for their cause and environmental effects in detail. For this purpose, the relevant emissions of aircraft are identified and in particular the effects of emitted substances.

It should be noted that the aim of ecolabelling and this work is to provide general statements about environmental performance about an aircraft. Environmental impact may vary depending on location and local circumstances. In this case, specific assessments may be necessary, which determine the distinct outcome that is not predictable through general assumptions. If the intention is to realistically analyse the actual environmental impacts for a specific scenario, then there are sophisticated tools, which are improved continually and take into account as much influencing information as possible and are able to create complex simulation models. An example is the *Aviation Environmental Design Tool* (AEDT). (Koopmann et al. 2012)

The aim of this ecolabel, on the other hand, is to rate an aircraft itself and not the journey it undertakes, meaning that environmental impact should be based on the commonly intended mission profiles while mitigating case-, respectively journey-dependet factors.

3.2 Types of Pollution

Before analysing environmental impact of aviation in detail, the different forms of pollution should be mentioned. Pollution is regarded as the environmental contamination with substances that have an adverse effect on the environment. There are a variety of pollution types and contaminants.

Air Pollution
: Particles or gas that gets released into the atmosphere, mostly oxides such as of carbon. Main causes are vehicle exhaust, industry, burning such as fossil fuels, coals, gas but also forest fires, volcanic eruptions etc. Effects among others are: increase in smog, rain acidity, asthma and global warming through ozone holes, greenhouse effect

Land Pollution
: Litter and dumping, contamination of the soil through chemicals, pestizides, herbicides, hydrocarbons, heavy metals, oil and sewage spills as well as deforestation, unsustainable mining

Light Pollution
: Brightening of the night and over illumination, mainly through large cities affecting human health and animals in sleep cycles and astronomical observation

Noise Pollution
: High levels of noise, motor vehicles, aircraft, trains, manufacturing plants, construction, demolition, concerts effects are health issues, stress level, hearing isssues, animal wildlife

Thermal Pollution
: Increase of temperature in nature over a longer period of time, e. g. through power plants (water coolant), cities

Visual Pollution
: Subjective impairment of the environment, e. g. through buildings, structures, vandalism, litter, neglected areas, billboards etc.

Water Pollution

Contaminated water through waste disposal, chemicals, substances, sediment, bacteria effects are health issues due to contaminated drinking water, natural balance of plant grow and animals

Radioactive Pollution and Other

Radioactive Pollution - Nuclear power plant accidents or leakage, waster disposal, uranium mining, nuclear tests and deployment

The actual impact of a contaminant is dependent on concentration, chemical nature and persistence. Additionally, there are often complex interdependencies with the environment that determine its effect.

To systematically assess environmental impact, so called *life cycle assessments* (LCA) are performed. They define specific impact categories that are responsible for different types of pollution. These categories are defined in such a way that they are indicators of physically measurable quantities.

The following section will address life cycle assessment and determine how aviation affects the environment through pollution.

3.3 Impact of Aviation

3.3.1 Life Cycle Assessment and Impact Categories

Environmental burden starts with production and resource allocation. For instance, different materials require distinct amounts of energy for extraction, transportation and processing and cause respective emissions.

The consideration of environmental impact from design to end of life of a product is subject to life cycle assessment. The principles are described in international standards (ISO 14040:2006) and are widely used. Life cycle assessment has already been a significant and established discipline in many product groups.

Manufacturers of commercial large-scale production of aircraft show increasing environmental awareness by setting up environmental programmes and taking LCA into account.

There are several models for LCA which are characterized by their

- goal and scope definition
- inventory of relevant energy and material inputs and environmental releases (LCI)
- choice of environmental impact categories associated with these inputs and releases (LCIA)
- interpretation of the results. (SAIC 2006)

Since environmental impact is of particular interest in this context, a LCIA method called *ReCiPe* is referenced in this work. ReCiPe lists the following impact categories (Goedkoop et al. 2009):

- Climate change
- Ozone depletion
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication
- Human toxicity
- Photochemical oxidant formation
- Particulate matter formation
- Terrestrial ecotoxicity
- Freshwater ecotoxicity
- Marine ecotoxicity
- Ionising radiation
- Agricultural land occupation
- Urban land occupation
- Natural land transformation
- Water depletion
- Mineral resource depletion
- Fossil resource depletion

These categories are evaluated with regard to

- damage to human health
- damage to ecosystem diversity
- damage to resource availability.

When determining relevant environmental impact categories in aviation, an important point of consideration is that commercial aircraft are usually designed to be in operation for several decades with intensive use. Therefore, emissions during operation are likely to make up the major part of environmental impact. It was shown by Johanning 2014 that production and development have no significant effect on environmental impact during the lifetime of a common commercial aircraft, using the LCIA method (→ Fig. 3.1).

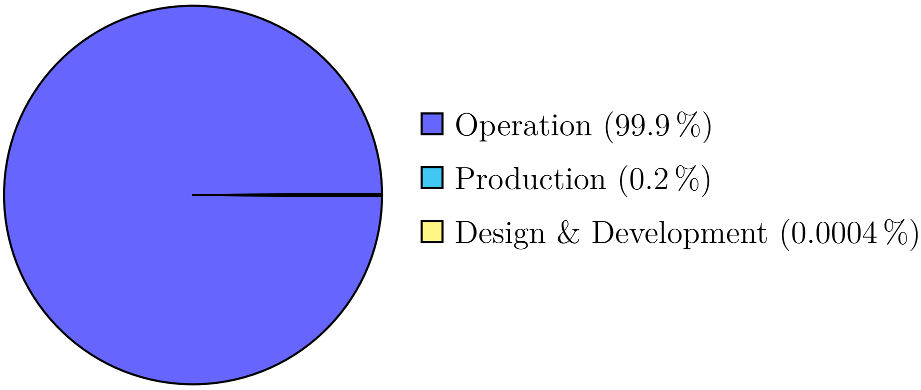


Figure 3.1 Environmental impact of life cycle phases of an Airbus A320-200 using LCIA (Johanning 2014)

When comparing the environmental impact of different means of transportation, additional influences like emissions of airport infrastructure might be taken into account as well. This includes for example ground vehicle operations, sealing of the soil surface etc, which are factors that are required for the operation of aviation, but not exactly aircraft-related. However, fig. 3.2 shows that these factors also have a negligible constribution to environmental impact.

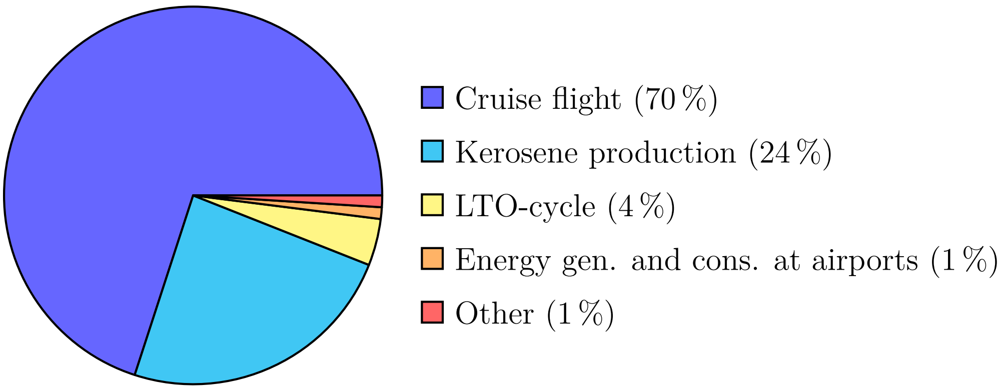


Figure 3.2 Environmental impact of processes of an Airbus A320-200 using LCIA (Johanning 2014)

The relatively large share of kerosene production is mostly due to fossil resource depletion, which was considered an impact category by ReCiPe. This can be seen in fig. 3.3, which also shows that the other important impact categories are climate change and particulate matter formation, which affects air quality.

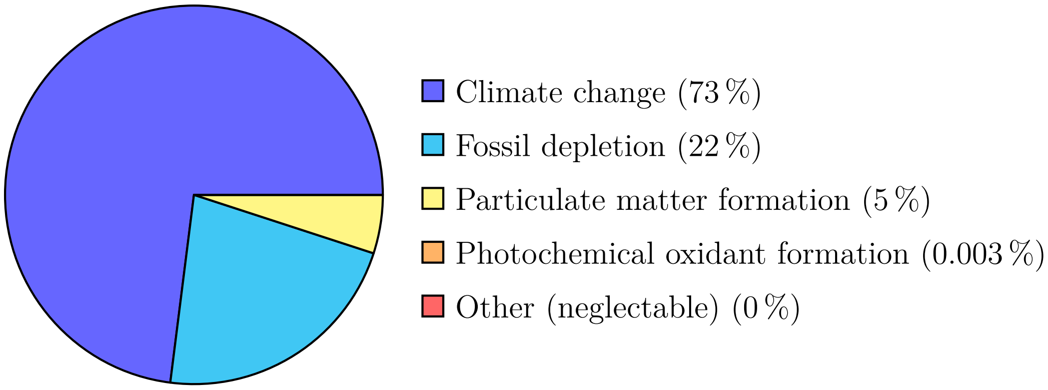


Figure 3.3 Environmental impact by impact category of an Airbus A320-200 using LCIA (Johanning 2014)

It should be noted that the depicted diagrams are based on an an adapted method of ReCiPe, that accounts for altitude-related effects of emissions which is not orginally considered by the LCIA. These effects will also be covered later in this work.

It is assumed that these impact categories are most relevant for all commercial aircraft. This is also encouraged by the publication of pertinent environmental reports and articles in the aviation sector.

However, noise pollution is one of the most frequently regarded environmental impacts as well that is not considered by ReCiPe. Due to its high importance, it is also assessed in this work and intended to be included in the ecolabel. Noise regulations from ICAO and airports are in effect and determine the political discourse in many places. Noise pollution may not have a significant overall environmental effect, respectively may affect only few people, but its relevance justifies further attention.

Accordingly, environmental impact factors to be examined in this work are the following:

- Resource depletion
- Climate impact
- Air quality
- Noise pollution

Before investigating the impact of aircraft emissions, it is sensible to identify emission species as they are the cause for environmental pollution.

3.3.2 Emission Species

Pollutants in aviation originate mostly from combustion processes from aircraft engines. During combustion of fossil fuels like kerosene, pollutants and greenhouses gases are being emitted as a consequence of chemical reactions.

The standard jet fuel type in commercial aviation is A-1 which ideally combusts to carbon dioxide (CO_2), water vapour (H_2O) and sulfur oxides (SO_x).

Fig. 3.4 depicts emission products of ideal and real combustion of aircraft fuel in a modern fan jet engine.

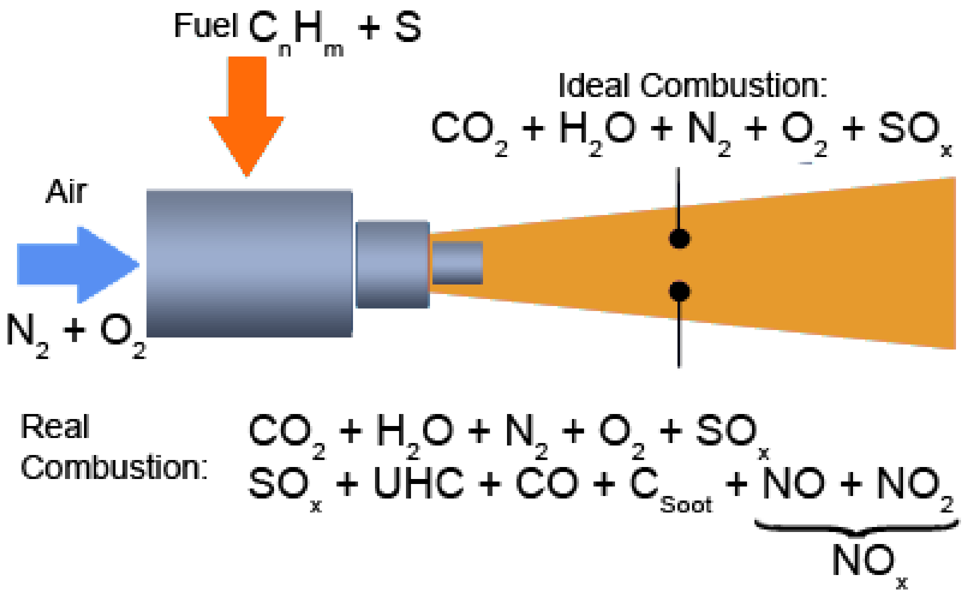


Figure 3.4 Combustion products of a jet engine (adapted from Norman et al. 2003)

Real combustion naturally produces nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC or HC) and soot. Fig. 3.5 shows the approximate distribution of emission species.

The largest share of engine exhaust emissions is composed of oxygen and nitrogen that are already part of the atmosphere (91.5% - 92.5%). Around 8% are products of combustion from which the major part consists of carbon dioxide (CO_2) and water vapour. Trace species only make up a small fraction of emissions, yet have an environmental impact. Nitrogen oxides (NO_x) are most significant which is why special focus is directed mainly at them. (Sarkar 2012)

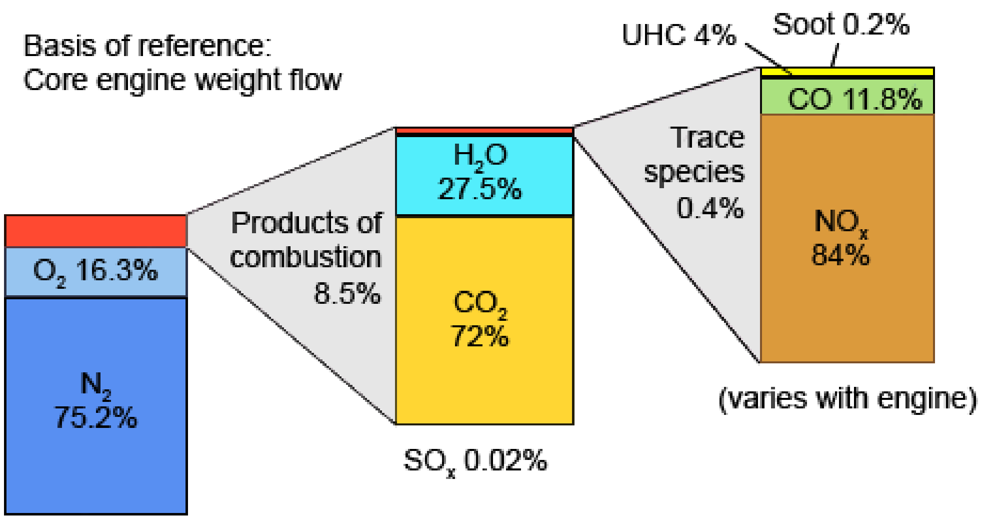


Figure 3.5 Distribution of combustion products (adapted from Norman et al. 2003)

A great reduction in unwanted trace species emissions has been achieved over the years through technology improvement and more efficient combustion processes, especially in case of smoke and fine particles, however, improved emission standards are continuously important not least because of increasing air traffic.

In order to be able to make assessments about engine emissions, it is important to differentiate between pollutants that are directly linked to mass of fuel and those that depend on ecological efficiency of the combustion process.

Masses of emitted CO_2, H_2O and SO_x are proportional to fuel consumption, meaning relative emission masses are fixed regardless of operating condition and depend solely on fuel composition. 1 kg of aircraft fuel produces the amounts of emissions shown in table 3.1. These coefficients are referred to as *Emission Index* (EI).

Table 3.1 Constant Emission Indices (IPCC 1999)

Species	**Emission Index (kg/kg fuel)**
CO_2	3.16
H_2O	1.23
SO_x	$2 \cdot 10^{-4}$
soot	$4 \cdot 10^{-5}$

Other species such as NO_x can not be assessed as easily because their production depends on many factors that determine how efficiently fuel is burned. This process heavily depends on engine design, which is why each engine type and generation has to be assessed individually. Moreover, operating condition and thrust setting play a crucial role in actual quantity of emissions. A good understanding of emissions is important for simulations and the determination of environmental effects. While the knowledge of absolute quantities of emission products resulting from flights is the key objective for environmental forecasts, an aircraft-related ecolabelling scheme could be based on the aircrafts relative emissions, but the environmental burden of particular species is still important for the purpose of determining their overall importance.

The most influential pollutions and their environmental impact are therefore described over the next sections. As mentioned in section 3.3.1, engine emissions have an impact on climate and air quality.

3.3.3 Share in Global Emissions

Aviation is one among many global emission sources that impose a burden on the environment. For better understanding of impacts through airborne activities, it is of interest to examine the share in global emissions, in other words determine the relevance of emissions in aviation compared to other anthropogenic sources.

The exact share in global emissions depends on considered pollutant, respectively greenhouse gas. Some emission products are well-understood while others have lower levels of understanding due to their complex nature or difficult verifiability and uncertain impact. It must also be noted that share of emission does not equal overall impact on the environment, because in aviation, most emissions are released into the lower stratospheres and upper troposphere where they have different effects than near the Earth's surface.

The *IPCC Special Report on Aviation* was published to address environmental issues with the best information available and also give forecasts for 2015 and scenarios for 2050 with 1992 as a base year (IPCC 1999). A few updates were added later on the basis of newer information. According to ICAO's environmental report 2010, it was estimated that the total volume of CO_2 emissions of aviation in 2006 is approximately 600 million tonnes which is about 2% of total global CO_2 emissions and accounts for 12% of emissions from the transportation sector. (ICAO 2010)

The IATA has set itself the objective to achieve an average improvement in fuel efficiency of 1.5% per year from 2009 to 2020 and a reduction of 50% in CO_2 emissions by 2050, relative to 2005 levels.

Since quantities alone do not give evidence about actual climate effects, the measure of radiative forcing has been introduced. It is defined as the energy change of the Earth-atmosphere system caused by certain gases and indicated in watts/square meter (→ section 3.5.4).

Aviation contributed about 5% of worldwide anthropogenic radiatve forcing in 2005. Studies expect advances in technology and improvements in air traffic management that could reduce fuel consumption and emissions, but an increase in air traffic would most likely cancel out any improvements in total global emissions. (IPCC 1999)

3.3.4 Environmental Protection in the Chicago Convention

The Convention on International Civil Aviation (*Chicago Convention*) was signed on December 7, 1944 in Chicago by 52 states in order to establish an international organisation of aviation. The International Civil Aviation Organization (ICAO) now is an agency of the United Nation and coordinates and regulates private international air travel.

The convention consists of articles containing rules about rights, obligations, safety, security etc and annexes containing standards and recommended practices and is amended every few years.

Annex 16 deals with environmental protection and is of particular importance for all aspects regarding environmental impacts. In 1983, a technical committee of the ICAO Council was established called *Committee on Aviation Environmental Protection* (CAEP). It has since been responsible for creating and adopting new standards and recommended practices (SARP) in terms of environmental issues such as noise and exhaust emissions.

As of 2015, Annex 16 is subdivided into these volumes:

Vol I – Aircraft Noise (ICAO 2011)

Due to growing awareness and concerns about aircraft noise in the vicinity of airports, members of ICAO have agreed on establishing standards and recommended practices on aircraft noise, resulting in the development and adoption of Annex 16 Volume I in 1971. This document contains certification requirements, measuring procedures and maximum allowed noise levels.

→ Section 4.2.3 and Appendix A.1

Vol II – Aircraft Engine Emissions (ICAO 2008)

Volume II deals with the certification of engine emissions regarding smoke and air pollutants. It contains specifications and measuring procedures. The document was proposed and adopted by the Committee on Aircraft Engine Emissions (CAEE) in 1980 after the establishment of the *ICAO Action Programme Regarding the Environment*.

→ Section 4.3.1 and Appendix A.2

Vol III – CO_2 Certification Requirement (draft) (ICAO 2011)

In order to further address the topic and reduce greenhouse gas emissions in aviation through incentives for technological advancement, the *ICAO Programme of Action on International Aviation and Climate Change* recommended an aircraft carbon dioxide emissions standard. In 2010, such a standard was requested at the 37th assembly. The CAEP has developed a standard since and endorsed a CO_2 metric system in 2012. It represents a CO_2 value by taking the efficiency of an aircraft into account which is dependent on fuel burn performance and aerodynamics.

As of 2015, Volume III is still in development and not officially part of the Annex 16 framework. Regulatory limits for emissions are still pending and to be determined. After completion, Volume III will be reviewed and put into the approval process by ICAO members. Technical work is expected to be finalized in late-2015. (Dickson 2013)

→ Section 4.4.1 and Appendix A.3

Regulations through ICAO are well-established and industry-wide environmental standards. Today, all aircraft and engines need to comply with emission standards for certification, which is implemented through aviation and certificating authorities. Emission data of certified records is publicly available and will be used as a basis for the definition of the ecolabelling scheme.

3.4 Resource Depletion

Resource depletion refers to extraction and consumption of natural resources at a faster rate than they can be replenished. This primarily relates to mining, consumption of fossil fuels, water usage, deforestation, fishing and farming. A distinction is made between renewable and non-renewable resources, the latter being defined by its insufficient rate of renewal for sustainable extraction, which for example takes millions of years in case of fossil fuels.

In terms of aviation, oil depletion is the main issue, which contributes to the cause of peak oil. This will result in an worldwide price increase of petroleum derived products and have broad consequences for economy and society. (Bezdek et al. 2005)

It could for example affect transportation, which currently mostly relies on fossil fuels, and agriculture, where fossil fuels are used for the production of ammonia as fertilizer.

A simple indicator of how much aircraft contribute to fuel depletion is their fuel consumption. There may be differences due to fuel type, but most commercial aircraft currently use type A-1 jet fuel. Potential alternative fuels could therefore have a smaller impact and reduce resource depletion.

3.5 Climate Impact

3.5.1 Introduction

Aviation has an impact on climate through the release of greenhouse gases and indirect climate-influencing pollutants. Greenhouse gases are gases in the atmosphere that absorb infrared radiation and radiate heat and hence are a major cause of the Earth's greenhouse effect.

The Earth's surface is warmed by solar radiation which passes the atmosphere. The ground then emits energy in the form of infrared radiation, which is absorbed by greenhouse gases and causes heat to be trapped in the atmosphere. A smaller amount of energy radiates back into space. (Baede et al. 2008)

Fig. 3.6 depicts energy exchanges resulting in the greenhouse effect:

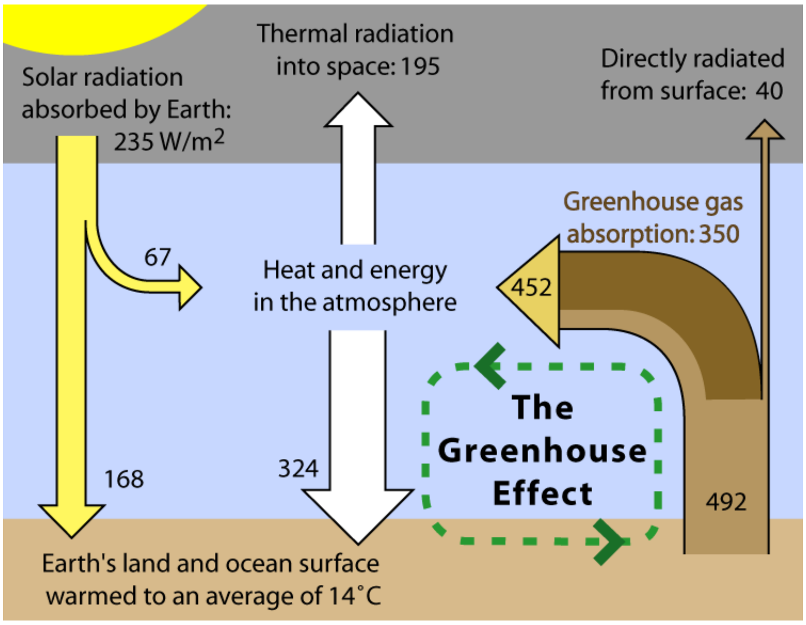


Figure 3.6 Energy exchanges and the greenhouse effect (Source: Robert A. Rohde/Global Warming Art)

Radiatively active gases have both natural and anthropogenic sources. Pertubation of its concencentration in the atmosphere causes a change in the equilibrium of incoming (insolation) and outgoing radiation called radiative forcing. According to the Kyoto Protocol, the following gases are considered to be greenhouse gases (UN 1997):

- Water vapor (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Ozone (O_3)
- Chlorofluorocarbons (CFCs)

The changes regarding the greenhouse effect contribute considerably to global warming and hence global climate. It is expected that this will have major long-term implications on human health and ecosystems. The overall effects of climate change and its relevance is not easy to quantify, which is why climate change metrics have been developed. This topic will be addressed in section 3.5.4.

The different gases have diverse levels of impact, depending on released mass into the atmosphere, dwelling time, environmental conditions and the nature of the gas itself. Additionally, there are species that are not greenhouse gases, but have an effect through alteration of these. They are called *indirect greenhouse gases*.

It is difficult to allocate certain percentages to specific gases in terms of how much they contribute to the greenhouse effect as it depends on many factors and varies with the considered case and its circumstances.

It can be said that carbon dioxide (CO_2) is the most important greenhouse gas for environmental considerations regarding anthropogenic sources. It is the primary and mostly quoted emission in environmental statements about products or activities.

3.5.2 Carbon Dioxide (CO_2)

Carbon dioxide can be found in very small quantaties in the Earth's atmosphere, approximately 400 ppm, yet plays an important role for life on Earth and atmospheric climate effects. It is part of the carbon cycle, where carbon exchanges with the biosphere, in other words with soil, oceans and living organisms. Plants and oceans absorb carbon dioxide which is eventually released again into the atmosphere through processes in the terrestrial biosphere and oceans, such as respiration and decomposition, resulting in a near equilibrium. Pertubations through antrophogenic sources have increased significantly since the industrial revolution with the result that there is a continuous rise in concentration in the atmosphere. Compared to pre-industrial times in the 19th century until today, the concentration increased from 280 ppm to almost 380 ppm. The Keeling Curve after Charles David Keeling depicts the concentration in the Earth's atmosphere and shows an increase with characteristic, annual fluctuating curve, as shown in fig. 3.7.(Houghton et al. 2001)

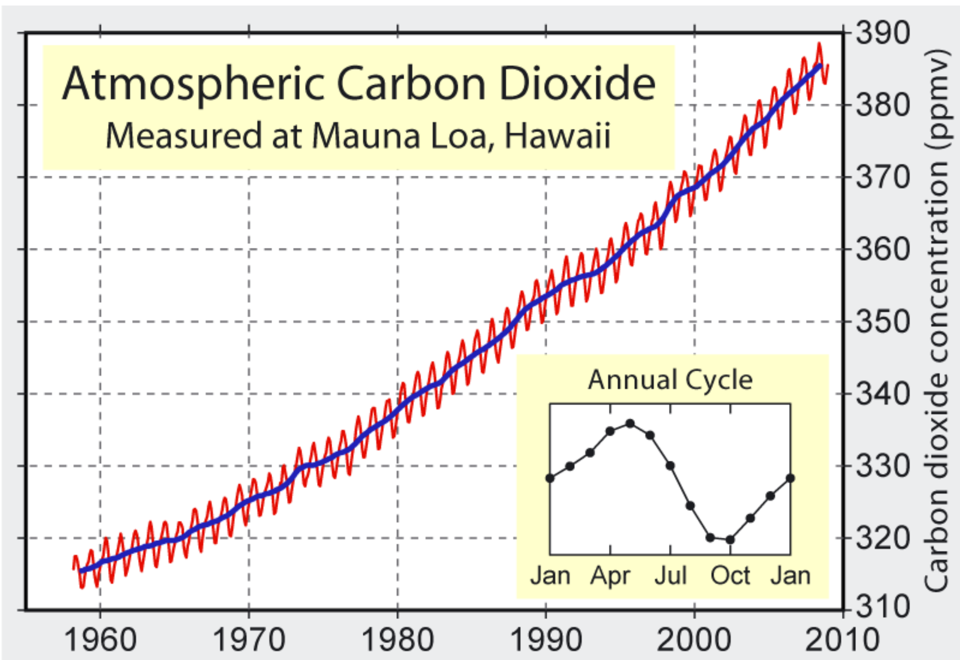


Figure 3.7 Keeling Curve (Source: Robert A. Rohde/Global Warming Art)

Since CO_2 as an infrared-active gas is capable of absorbing thermal radiation and emission, it is considered a direct greenhouse gas. It has a variable atmospheric lifetime, which cannot be specified precisely, but fractions remain in the atmosphere for a long period of time. The IPCC estimated that 50% remain in the atmosphere after 30 years and 30% after 200 years. Because of this, a large portion of radiative forcing caused by CO_2 is due to emissions many years ago (IPCC 2007). Its significant impact makes CO_2 the most important greenhouse gas under the influence of human activity. It has the best level of understanding and the amount of CO_2 in the atmosphere caused by human activity is well known due to the examination of carbon isotopes.

It is assumed that CO_2 emissions have mostly the same effect, regardless of the altitude they are emitted at. This is not the case for all gases.

3.5.3 Other Climate-Influencing Emissions

Besides carbon dioxide, other emission species have an impact on climate as well, but vary in significance.

Water vapour has the next highest share of emission mass after carbon dioxide in aircraft engine combustion. It is the largest contributor to the natural greenhouse effect, but is not significantly affected by human activity on a global scale. This is due to its very short atmospheric lifetime, which ranges from several days to a month, depending on altitude and temperature and about nine days on average. (Lee et al. 2010)

Nitrogen oxides are not a direct greenhouse gas, but contribute through indirect radiative effects caused by interference with other gases and chemical reactions. NO_x facilitates the formation of ozone (O_3) in the troposphere, which is a strong greenhouse gas, but also decreases concentrations of methane (CH_4), leading to a reduction in its radiative forcing and having a cooling effect. Its effect is highly dependent on altitude of emission.

Soot particles and sulfur oxides have a minor effect on climate. Soot absorbs some amount of heat which causes warming while sulfate particles reflect radiation and have a marginal opposite effect.

Another component affecting climate is aviation induced cloudiness (AIC). They comprise contrails and cirrus clouds that are caused by aircraft. The overall effect is assumed to have a positive radiative forcing on average, although there is a high uncertainty and it depends on local meteorological conditions. Contrails are produced when hot and moist air from the engine mixes with cold ambient air and only persist under certain circumstances. These circumstances are also altitude-dependent as conditions for contrail formation are only possible between altitudes of 20,000 to 45,000 ft. Contrails can lead to the formation of cirrus clouds, which is also dependent on the concentration of particles in the atmosphere. (Rädel and Shine 2008)

3.5.4 Quantification of Climate Impact

Climate-influencing gases and particles have different effects, depending on type and concentration, as well as altitude of emission and properties of the atmospheric layer.

In order to quantify their relative impacts, a climate change metric is required.

The causal chain of effects due to climate-influencing emissions is complex and has several stages that can be used as a measure of climate impact. These stages are shown in fig. 3.8 along with potential climate change metrics.

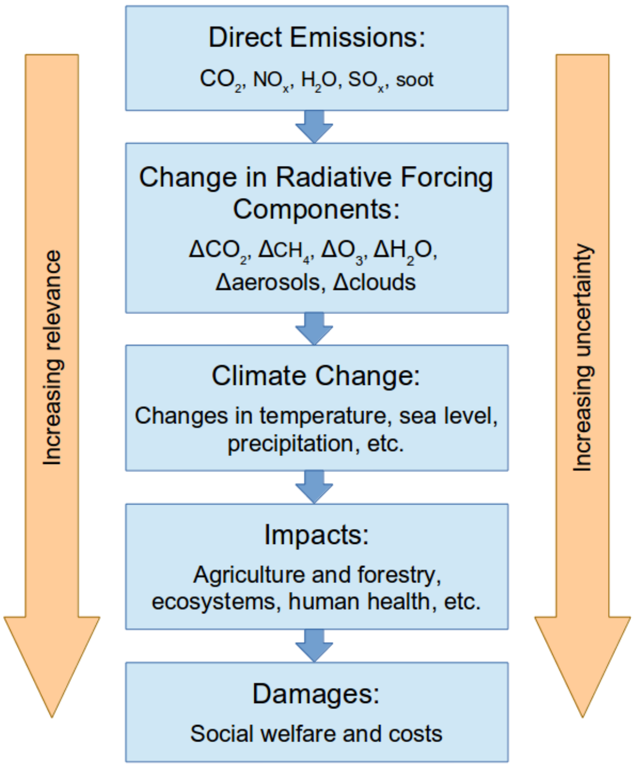


Figure 3.8 Effects of changes in climate (adapted from Schwartz 2011, based on Wuebbles et al. 2007)

Emissions of radiatively active gases affect the Earth's radiation balance which causes a rise in global temperature due to the greenhouse effect as depicted by fig. 3.6 as well as changes in weather, precipitation, sea level etc. in the long term.

This in turn impacts ecosystems, agriculture, human health etc. and causes damages in social welfare, for example in terms of financial strain. (Wuebbles et al. 2007)

While impacts directly affecting humans are most relevant for the general public, they are difficult to quantify as uncertainty rises sharply along the causal chain. The measurement of potential damages is also increasingly subjective and there is no consensus about a single, homogeneous unit that is scientifically utilizable. Life cycle impact assessment methods like ReCiPe have defined such measurements in order to compare environmental effects of different impact categories. However, they make use of metrics that are defined for a specific domain such as climate change. These metrics are therefore one of the following well-defined physical quantities, which also come into consideration for assessing climate impact of aviation:

- Mass of Emissions
- Radiative Forcing
- Global Warming Potential
- Global Temperature Potential

Mass of emissions is a simple measure and can be used to rate environmental performance of its emitter relatively to others, if ambient conditions allow comparison. It is common practice to express CO_2 emissions by mass since the gas and its impact are well understood. The advantage of this metric is that it is a physical quantity which retains immediate values with relatively little uncertainty. However, in order to assess and weight the impact of multiple emission species among themselves and compare net climate impact, another metric is required.

A comparison can be made through radiative forcing which describes the change of energy in the Earth's radiation balance. It determines how much energy is absorbed in the Earth's system through insolation and radiated back into space. The system is warmed when this value is positive and cooled when it is negative. Radiative forcing is expressed by watts per square meter and can be determined for certain gases, which either have an increasing or decreasing effect on total radiative forcing.

Fig. 3.9 depicts radiative forcing components of emissions due to aviation in the year 2005, including emissions from aviation since the 1940s when jet aviation began (*Jet Age*).

Radiative forcing (RF) can be linked to global temperature change ΔT_s on the Earth's surface by climate sensitivity (λ) linearly, but the exact value is not certain:

$$\Delta T_s = \lambda \, \Delta RF \tag{3.1}$$

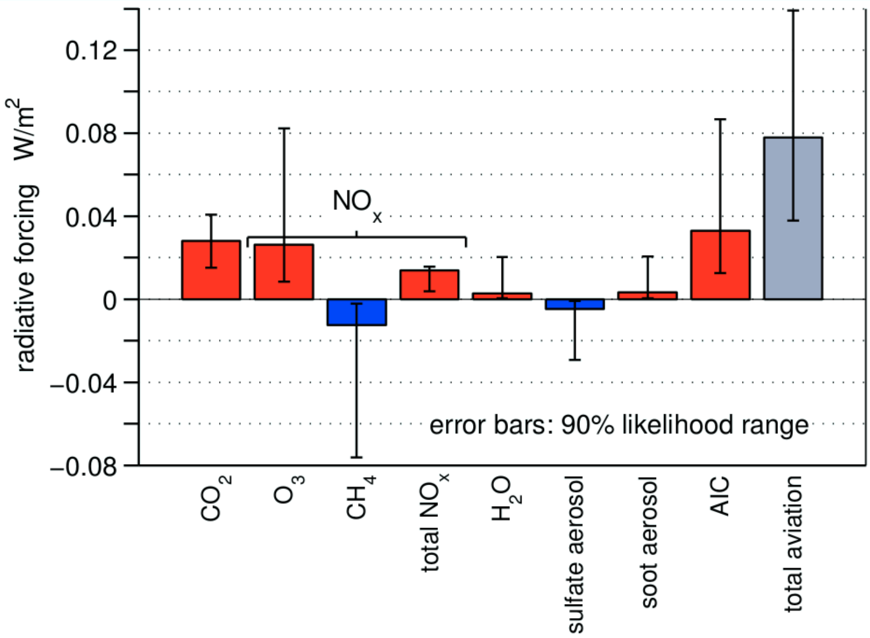


Figure 3.9 Radiative forcing components of aviation emissions (Schwartz 2011, based on Lee et al. 2009)

The change in energy balance due to pertubations described through radiative forcing is a snapshot in time and may change over years. RF can be integrated over time, assuming pulse or sustained emissions. This is used in order to derive global warming potential (GWP), which normalizes the time-integrated RF by time-integrated RF of CO_2 emissions over the same period of time. In other words, GWP measures how much a climate influencing agent contributes to climate change compared to CO_2 over a specific time interval, commonly 100 years, which is why it is also referred to as *carbon dioxide equivalent*.

Table 3.2 Radiative Forcing through Aviation (2005) (Lee et al. 2009)

Species	Radiative Forcing (mW/m2)	Low	High
CO_2	28.0	15.2	40.8
O_3	26.3	8.4	82.3
CH_4	-12.5	-2.1	-76.2
H_2O	2.8	0.39	20.3
SO_4	-4.8	-0.79	29.3
Soot	3.4	0.56	20.7
AIC	33	12.5	86.7

GWP is the metric ReCiPe uses for its environmental impact analysis. An alternative is so called global temperature potential (GTP). GTP describes global mean temperature changes at the end of a time horizon. This metric was proposed by Shine et al. 2005 and is used by Schwartz 2011 for considerations of climate impact in aviation.

3.6 Air Quality

3.6.1 Introduction

Air pollutants are substances in the air that, when in high enough concentration, have adverse effects on the environment and potentially harm humans, animals and vegetation. Substances that contribute to air pollution may be gases, liquid droplets or solid particles. They can be of natural or anthropogenic origin and be a result of complex interactions between different substances in the air.

There is a wide range of pollutants which may cause harmful effects. Some examples are:

- Nitrogen oxides (NO_x)
- Ammonia (NH_3)
- Sulfur oxides (SO_x)
- Carbon monoxide (CO)
- Particulates
- Volatile organic compounds (VOC) such as HC
- Chlorofluorocarbons (CFCs)
- Persistent free radicals
- Toxic metals
- Radioactive pollutants
- Odors

Emission products of jet engines were pointed out in section 3.3.2. Observed emissions of aviation are nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC/HC), sulfur oxides (SO_x) and other particles such as soot, and smoke.

Nitrogen oxide as a collective name refers to all oxides of nitrogen, which are binary compounds of nitrogen and oxygen or mixtures of those compounds. Examples are nitric oxide (NO), nitrogen dioxide (NO_2), Nitrous oxide (N_2O) and several others. NO_x is used for NO and NO_2, which are produced during combustion such as in a jet engine, mostly at high temperatures.

NO_x emissions are regarded as the most important in terms of aviation as they have the highest share of emission and impact. Consequently, they have been the focus within standards and regulations.

CO and UHC are primarily produced during inefficient combustion conditions. It was possible to reduce their emission greatly over the years through more efficient engine designs, which is why they have a minor impact nowadays.

Sulfur oxide refers to compounds of sulfur and oxygen the same way as nitrogen oxides. Its formation depends on fuel type as they are inherent to its composition and can not be influenced seperately (cf. table 3.1) and has a relatively small impact.

Smoke refers to remaining fine particles that derive from combustion. They are currently taken into account a "Smoke Number" in the environmental standard.

3.6.2 Implications and Quantification

The effects of air pollutants on air quality are mostly considered and monitored at near ground level, especially in the vicinity of airports.

Air quality is important for human health and also affects the natural environment such as vegation and animals.

Health implications derive mostly from inhalation of particles and ozone. Particles in the air can enter the respiratory system of humans and cause medical conditions such as respiratory infections, cancer, heart and lung diseases. The smaller they are the more severe effects can occur, especially if they are transferred into the bloodstream. Ozone is a result of reactions of NO_x and can inflame airways and damage lungs. The WHO estimated 7 million premature deaths in 2014 due to air pollution. (WHO 2014)

Particulate matter is usually defined as PM_{10} or $PM_{2.5}$, where the number indicates the maximum size of considered particles in μm. The measure therefore considers particles that are inhalable.

If they are emitted directly into the air, they are called primary PM. Secondary PM are formed through chemical reactions of gaseous pollutants such as NO_x. (WHO 2013)

Aircraft emissions are not determined as a measure of particulate matter, however a PM_{10}

standard is being developed by the CAEP as it is considered as one of the remaining gaps in environmental assessement of aviation (ICAO 2013). Since this development includes the introduction of a new standard sampling procedure for the measurement of PM, this will likely take some time for completion.

Nevertheless, a methodology was developed to estimate particulate matter emissions based on available engine emission data, which will be discussed in section 4.3.4.

3.7 Noise Pollution

3.7.1 Introduction

Noise pollution is excessive amount of noise or unpleasant sound that causes disruption to people or nature and can have adverse effects on health. Although there is no singular definition of noise pollution and completely objective way of measuring it, volume, duration, frequency and repetitiveness are frequently referred to as generic factors that can be salient. The perception of noise pollution varies on individuals though and is also based on age, gender, general medical condition and psychological aspects as well as time of day and mood.

Aircraft noise is often considered as a significant noise pollution and is especially an issue near airports and densely populated areas around them. In addition to subjective annoyance, there are long term health effects that can arise such as cardiovascular diseases like hypertension or even strokes, heart attacks and hearing loss. It is not easy to find direct causal coherence, but long term studies show that residents exposed to aircraft noise over time have increased risk of said health issues. The significance of the subject mostly derives from widespread concern of residents in the vicinity of airports and high importance in society.

3.7.2 Quantification

Sound waves carry energy, which causes changes in air pressure. The greater these changes are, the louder is the sound. The transferred energy by a sound wave through an area is defined as sound intensity (I).

However, the human ear does not respond proportional to sound intensity, but approximately ten times to its logarithm. A common measure is therefore sound intensity level, or related, sound pressure level in decibel:

$$SPL = 10 \lg \left(\frac{I}{I_{ref}} \right) \text{ dB} \tag{3.2}$$

with $I_{ref} = 10^{-12} W/m^2$.

This measure is used in many regulations, however, in aviation, another scale was developed called *Perceived Noise Level* (PNL) and derived *Effective Perceived Noise Level*, expressed in units of *EPNdB*. (Kroo 2010)

This scale specifically tries to measure the perceived noiseness of aircraft by observers on the ground. It takes into account human annoyance factors of aircraft noise by spectral shape, intensity, tonal content and duration.

The measurement methodology is specified by ICAO in Annex 16, Vol I.

3.7.3 Sources of Aircraft Noise

The sources of aircraft noise are various and depend on flight phase. Most of the noise emissions however are ascribed to the engines and stream of air around the airplane, resulting in aerodynamic noise. Noise from engines is most prominent during take off, when thrust is typically set to 100%, whereas the airframe has a clearly increased impact during approach. Air molecules are put into strong motion, which leads to pressure waves being generated that are audible as noise in respective frequencies. In a jet engine, the noisiest parts are the jet stream when it encounters the surrounding slower air during high thrust modes and the fan. Fig 3.10 illustrates the components of engine noise sources in a logarithmical way. There has been a lot of improvement in modern jet engines through higher bypass ratios which reduce jet stream velocity.

During approach, thrust is reduced and aerodynamical noise has a high proportion on emissions. The effects of aeroacoustic noise occur mainly on flaps, slats and extended landing gear. Aerodynamical noise increases with aircraft speed and air density. Propeller-driven planes also have this kind of noise through their engine, whose impact is mainly determined by the rotor speed.

Over the years, noise mitigation has achieved considerable successes through regulations, new methods and technological progress, however the amount of flight movement has steadily increased.

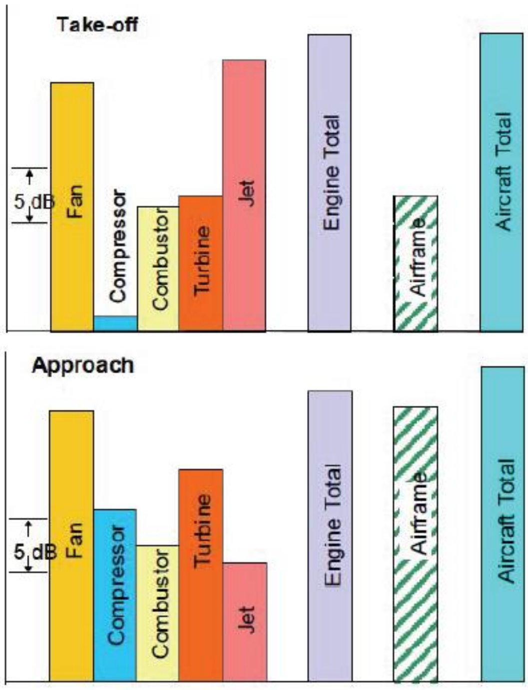


Figure 3.10 Aircraft noise sources (Batard 2005)

4 Determination of Aircraft Emissions

4.1 Introduction

In order to investigate aircraft emissions and their impact, the released amount of critical agents needs to be determined. Section 3.3.2 concluded that there are emissions that are directly proportional to fuel consumption. Both CO_2 and H_2O emissions can be derived from the amount of burned fuel with emission indices shown in table 3.1. They are also responsible for the largest share of climate impact. For non-proportional emissions, more sophisticated procedures are necessary as they have to be determined individually.

4.2 Fuel-Proportional Emissions

4.2.1 Fuel Metric

The relationship between fuel and emissions makes it easy to determine the amount of pollutants since fuel consumption can be monitored without any difficulty as opposed to measuring the concentration of released gases and particles.

However, in order to derive emissions from fuel, a fuel metric is required that reliably describes fuel consumption of aircraft.

In principle, the amount of fuel consumed after a certain flight could be taken as a basis, which is precisely known by airlines. This will determine the amount of emissions from which environmental impact could be derived specifically for one flight. However, this may not be representative for the aircraft's average performance as these informations only apply to a specific flight and route from a predefined origin to destination. This is due to the high number of parameters that individually depend on conditions on each flight and may differ drastically. Some parameters that are unique to a specific flight and affect fuel consumption are:

- Wind and weather conditions
- Load, occupancy rate
- Rerouting
- Flight profile
- Holding

- Taxiing time

In order to assess fuel performance for a variety of different aircraft, a standardized model with comparable parameters is required.

Such a metric is currently under development by ICAO with *Annex 16, Vol III* as noted in section 3.3.4. It is referred to as a CO_2 metric, but in fact assesses aircraft fuel performance which is equivalent as previously mentioned. ICAO makes use of a parameter called *Specific Air Range* (SAR), which is an immediate indicator of fuel consumption and overall aircraft fuel efficiency. Since there are principally two ways how fuel consumption can be determined, they shall be described in the following.

4.2.2 Block Fuel vs Specific Air Range

The first method is mission-based and the second is point-based, which both have their advantages and disadvantages. (Bonnefoy et al. 2010)

Block fuel method

Measurements are carried out over a full mission of aircraft operation, giving total amounts of emissions or burned fuel. Theoretically, these measurements could also be carried out over a predefined segment of flight which then represent certain modes of operation, but a mission is usually defined as from departure gate to arrival gate. After the flight, the exact amount of fuel used is known, which is commonly referred to as block fuel. This allows easy computation of emitted CO_2 by multiplying the amount of fuel by its emission index (→ table 3.1).

The good knowledge of airlines from experience about burned fuel on different routes could be used for this calculation, but is not suitable for making comprehensive comparisons between aircraft due to route specific factors. One useful way of using this route-specific data is to average values over long periods of time and link it to the specific type of aircraft. This is done by the *ICAO Carbon Calculator Methodology* (ICAO 2014) in order to make predictions about emitted CO_2 for a specific route, for which destination and arrival is needed to be entered through the flight passenger.

However, in order to compare aircraft on a route-independent basis, a a standardized mission profile has to be defined, which appropriately addresses several aircraft types and represents the de facto use in normal operating conditions. This is difficult to implement in real conditions as all environmental parameters have to be controlled over the entire mission and potentially adjusted in a complex way.

SAR method

Another method is to derive aircraft fuel performance by determining certain parameters at a single point in flight. Specific Air Range (SAR) describes the distance travelled over the next incremental amount of fuel burned, or, using a different expression, the ratio of true air speed and gross fuel consumption. The reciprocal therefore makes an equal statement in terms of units as block fuel correlated with distance.

By choosing points and conditions that are representative of the flight, a good appraisal of the aircraft's performance can be made. Their definition should take into account applicability for the entire range of aircraft types that are considered in the comparison group.

4.2.3 Determination and Certification

Both block fuel and SAR can be calculated for preliminary aircraft design using the Breguet range equation. However, knowledge of design flight parameters is required such as lift to drag ratio, which is not accessible and verifiable by outsiders (→ section 4.2.5).

It is important for any metric to be verifiable through measurements that produces certifiable values. Table 4.1 shows how the values are determined through measurement and calculation.

Table 4.1 Fuel Metric Overview

Determination method	**Block fuel**	**SAR**
Measured	directly measured	$\text{SAR} = -\frac{dR}{dm} = \frac{V}{Q}$
Calculated	$m_f = (exp(\frac{c}{VE}R) - 1)m_A$	$\text{SAR} = -\frac{dR}{dm} = \frac{VE}{cg}\frac{1}{m}$

A problem arises as block fuel captures the net performance of flights, which are not predictable in terms of influentual pertubations from the environment. In order to achieve comparable results, flight conditions must be the same for all aircraft over the entire mission which is hardly possible and therefore not a viable solution for certification.

SAR on the other hand is a value that is relatively easy to determine, particularily compared to the required effort of alternative methods in order to obtain a similar outcome.

SAR is a direct indicator of overall aircraft performance, which includes all relevant parameters like aerodynamics, weight and propulsion.

The metric can be easily determined by measuring true air speed and gross fuel flow at one point in time and hence ensuring similar conditions. The measurement can be implemented in common test flights, which are performed by manufacturers during certification procedure. This is in fact common practice for many aircraft.

In summary, it can be stated that single point measurements such as SAR require far less parameters to be taken into consideration than mission measurements and are therefore much easier to certify. It does not rely on a specific mission, which is why it is favoured for flight performance comparison of different aircraft.

SAR does not give exact information about fuel consumed during entire flights, but can be used as a reliable and standardized indicator about average performance.

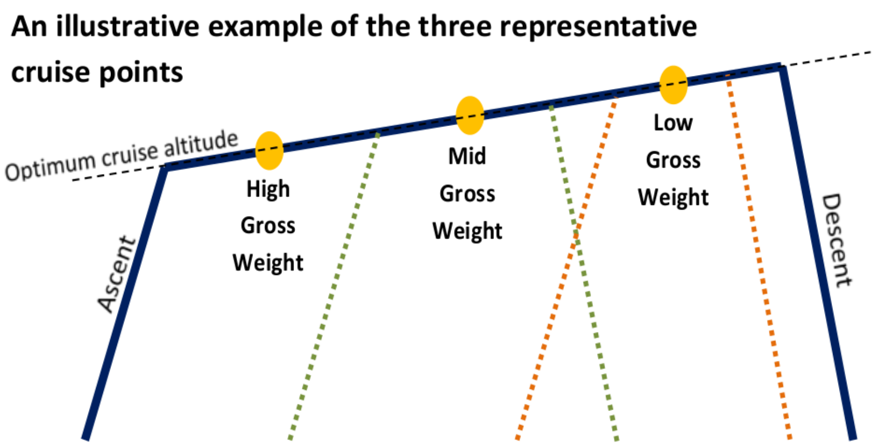


Figure 4.1 Operational points (ICAO 2012)

A measurement of SAR could be performed in different points in flight, which is why a representative point should be chosen. There are customary definitions of points in the flight plan such as Top of Climb (TOC) and Top of Descent (TOD), however the CAEP found that that three measurement points of SAR during mid-flight are a good indicator of fuel burn performance. These points represent high, middle and low MTOW by definition (→ Appendix A.3) and are a relatively easy to determine while being reliable and sufficiently accurate. Fig. 4.1 shows the concept of these representative cruise points according to Annex 16, Vol III .

→ Appendix A.3

4.2.4 Documents for Airport Planning

Since the ICAO CO_2 (or fuel) metric is still in development as of 2015, there is no consistent CO_2, respectively fuel emission data bank based on aircraft type. It is expected that this will be the case eventually like it is the case for engine emission and noise data (→ section 4.3.2, 4.4.2).

As long as this data is not available, a surrogate should be found for assessment.

Required information about aircraft should preferably originate from publicly accessible sources, making it easier for external surveyors to be able to comprehend procedures and results.

A lot of data can be derived from so called *Documents for Airport Planning.* These documents are publicly provided from aircraft manufacturers and are essential for airport and maintenance planners in order to correctly dimension airport infrastructure.

These documents, which are issued for each type of aircraft, provide a large amount of information about aircraft characteristics and are broadly obtainable.

Following data is usually included, but not limited to, in these documents:

Aircraft description: general characteristics, dimensions, clearances, interior arrangements, position of doors, cargo compartments
Airplane performance: payload/range diagrams, take-off and landing conditions, runway length and requirements
Ground maneuvering: turning radii, visibility from cockpit, runway and taxiway paths
Terminal servicing: servicing arrangements, ground servicing connections, turnaround times, grounding, towing, airflow requirements, de-icing, aircraft systems: electrical, hydraulic, pneumatic, fuel, oxygen, water, waste
Operating conditions: jet engine exhaust velocities and temperatures and contours, noise data
Pavement data: landing gear footprint and loads, maximum pavement loads, pavement requirements

In order to derive fuel data and conceivably SAR, payload/range diagrams are of particular interest. Other official data might be of interest as well for later consideration:

- Aircraft weight / Maximum take-off weight (MTOW)
- Standard seating capacity / standard seating class layout
- Max structural payload

- Max cargo volume
- Cross section width
- Fuselage length
- Number of floors
- Number of aisles
- Payload/range diagrams

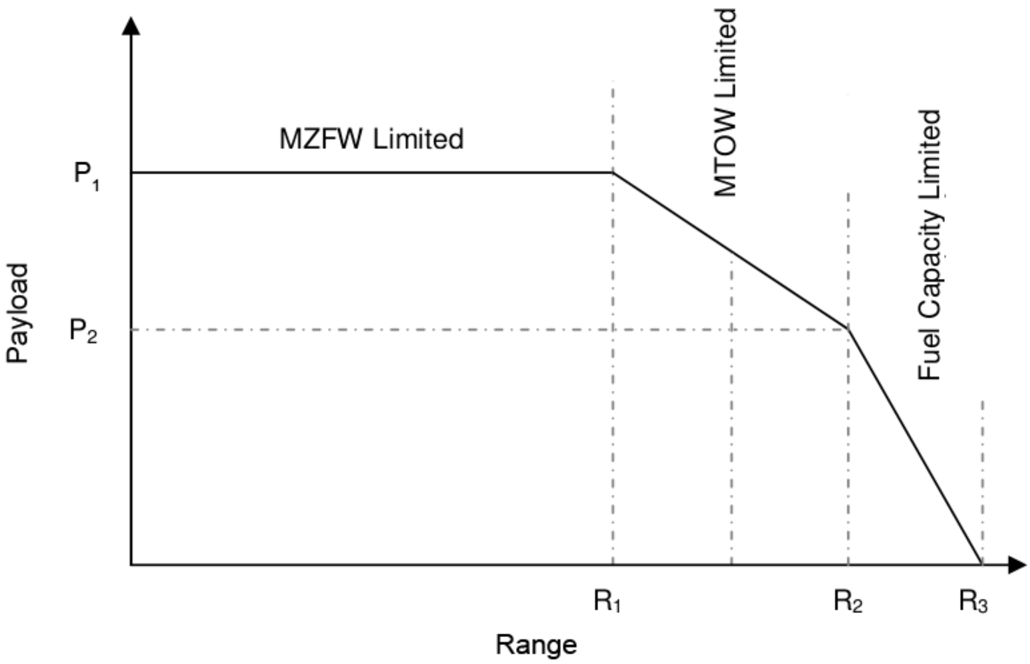


Figure 4.2 Schematic payload/range diagram

An illustrative payload/range diagram is shown in fig. 4.2.

R_1, R_2 and R_3 are referred to as *range at maximum payload*, *maximum range* and *ferry range* respectively. The diagram usually shows three flight sections, ranging from 0 to R_1, from R_1 to R_2 and from R_2 to R_3. They are limited by payload (MZFW), MTOW and maximum fuel capacity. Table 4.2 provides values for flights at the extreme of each flight section with m_1 being the take-off weight and m_2 landing weight. (MacDonald 2012)

4.2.5 Estimating SAR for Selected Aircraft

As there is no certified sample base data for fuel consumption yet, the SAR value should be estimated for a number of different aircraft.

Annex 16, Vol III has definite conditions about how SAR has to be determined. The

Table 4.2 Limiting Parameters of Flight phases

Flight Range	**Limiting Parameter**	m_1	m_2	**R**
1	MZFW	m_{MTO}	m_{MZF}	R_1
2	MTOW	m_{MTO}	$m_{MTO} - m_{F,max}$	R_2
3	Fuel Capacity	$m_{OE} + m_{F,max}$	m_{OE}	R_3

specification states that 1/SAR shall be determined at these three points in flight:

- high gross mass ($0.92 \cdot \text{MTOW}$)
- mid gross mass (average of high gross mass and low gross mass)
- low gross mass ($0.45 \cdot \text{MTOW} + 0.63 \cdot \text{MTOW}^{0.924}$)

This is difficult to accomplish with only payload/range diagrams at hand. For preliminary aircraft design, SAR can be calculated exactly using the method shown in 4.1, but only if the Breguet factor is known:

$$B = \frac{VE}{cg} \tag{4.1}$$

In order to calculate this factor, knowledge of the lift to drag ratio (E) and specific fuel consumption (c) is required. The corresponding equations for C_L, respectively C_D (Eq. 4.2), and the Hermann equation (Eq. 4.3) indicate that much data is required that is not freely available and relies for example on internal engine data.

$$C_L = -\frac{2W}{\rho V^2 S} \tag{4.2}$$

$$c = -\frac{0.697\sqrt{\frac{t}{t_0}}\left(\phi - \vartheta - \frac{\chi}{\eta_{comp}}\right)}{\sqrt{5 \cdot \eta_{diffuser} \cdot (1 + \eta_{BT} \cdot \text{BPR})(G + 0.2 \cdot Ma^2 \text{BPR}\frac{\eta_{comp}}{\eta_{BT}}) - Ma \cdot (1 + \text{BPR})}} \tag{4.3}$$

To circumvent this problem, an alternative is developed, using mass and range data solely derived from payload/range diagrams, which indicates an SAR value according to Eq. 4.4.

$$\text{SAR} = -\frac{dR}{dm} \tag{4.4}$$

This gives a value for SAR, but the detriment is that it is unclear, which aircraft mass and flight it represents. Therefore, an "average" mass and flight is assumed as depicted by 4.3.

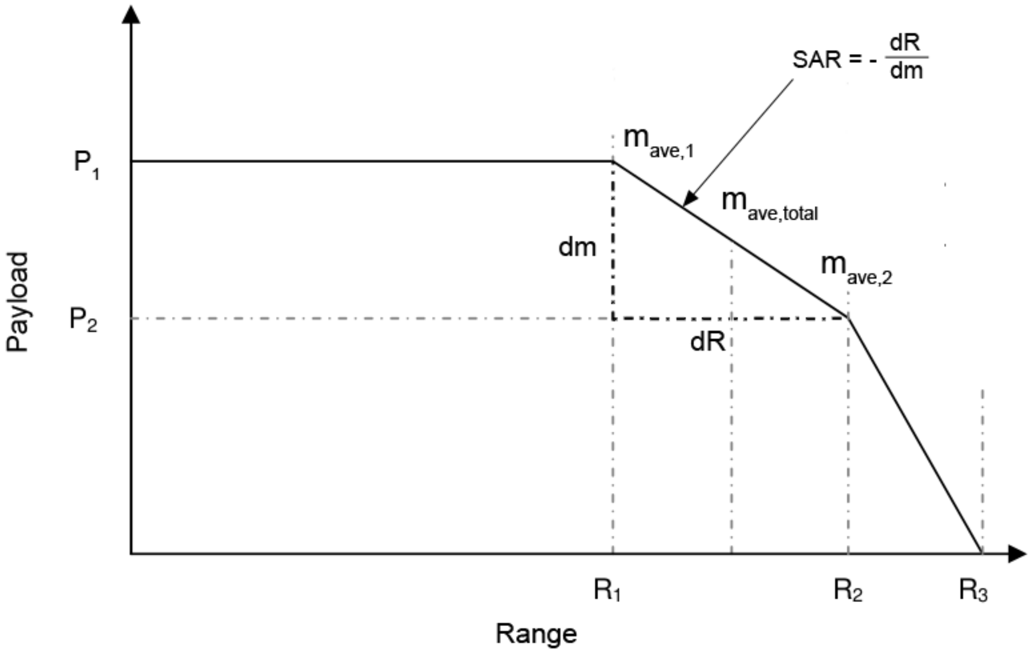


Figure 4.3 Payload/range diagram with SAR

The average mass is calculated in reference to table 4.2 by:

$$m_{ave,1} = \frac{m_{MTO} + m_{MZF}}{2} \tag{4.5}$$

$$m_{ave,2} = \frac{m_{MTO} + (m_{MTO} - m_{F,max})}{2} = m_{MTO} - \frac{m_{F,max}}{2} \tag{4.6}$$

$$m_{ave,total} = \frac{m_{ave,1} + m_{ave,2}}{2} \tag{4.7}$$

The calculated mass is then compared to the average value defined by ICAO and the derivation is determined.

$$m_{ICAO,ave} = m_{ICAO,mid} = \frac{m_{ICAO,high} + m_{ICAO,low}}{2} \tag{4.8}$$

$$m_{ICAO,high} = 0.92 \cdot m_{MTO} \tag{4.9}$$

$$m_{ICAO,low} = 0.45 \cdot m_{MTO} + 0.63 \cdot {m_{MTO}}^{0.924} \tag{4.10}$$

The error is determined by:

$$\text{error} = \frac{m_{ave,total} - m_{ICAO,ave}}{m_{ICAO,ave}} \tag{4.11}$$

SAR and respective masses have been calculated for a range of different aircraft in Appendix B. Data was taken from Roux 2007 as values could be extracted more easily than from Airport Planning Documents, but they could be used as a source and verification as well. For now, they are relatively small sample size, which could be extended eventually, although it is expected that some certified data will be available after the introduction of new corresponding ICAO procedures.

4.3 Non-Proportional Emissions

4.3.1 Determination and Certification

The amount of emissions of pollutants that are non-proportional to fuel can be calculated by determining their emission index first and then multiplying by mass of fuel consumed.

The only feasible way to determine emissions of these pollutants (and hence their emission index) is to perform ground based measurements. In these tests, the concentration of certain particles is detected through filtering methods in the jet stream at the rear of the engine. Substances and compounds that are currently considered by means of ICAO certified standards are NO_x, HC, CO and smoke.

Since they can not be derived from fuel directly using a method like SAR, a reference measurement procedure has to be defined in order to ensure consistent conditions for all aircraft. This is why ICAO defined a test procedure in Annex 16, Vol II where conditions of a landing and take off cycle are simulated (LTO). This makes it possible to use this data as a basis for comparative analyses.

While it is possible in individual cases to determine emissions of respective pollutants in mid-air, it is not feasible to be a standard certification procedure for all aircraft due to complexity and financial expense. Therefore, all estimates, predictions and simulation models of flight missions are based solely on data available from sea level tests according to Annex 16, Vol II.

→ Appendix A.2

4.3.2 Engine Exhaust Emissions Data Bank

The ICAO Engine Exhaust Emissions Data Bank (Doc 9646) is hosted by the EASA on behalf of ICAO (ICAO 2005). It contains all information collected from engine exhaust tests in the LTO cycle according to Annex 16, Volume II. The Data Bank is updated regularly in the wake of submitted data from engine manufacturers. Manufacturers are required to submit their data to the certification authority for approval, the submission to the Engine Exhaust Emission Data Bank afterwards is voluntary.

The following essential data is included in an *ICAO Engine Exhaust Emissions Data Bank Sheet*:

- Engine ID/type
- Engine characteristics: bypass ratio, pressure ratio, rated output
- Percentage of HC, CO, NO_x, smoke emission referred to certification limits
- Fuel flow at each operation mode and LTO Total
- Emissions of HC, CO, NO_x, smoke at each operation mode and LTO total
- Number of engines/tests
- Atmospheric conditions
- Fuel type
- Test location, date, organization

4.3.3 NO_x Adjustments

The emission index of NO_x can be determined through test procedures as described previously. However, the emission index varies significantly with operating and engine condition and is dependent on several complex physical and chemical processes. While the measured value gives a good average estimate across different operating conditions, procedures have been developed in order to compute a more accurate EI_{NO_x} for specific conditions. Since NO_x has a significant environmental impact, detailed understanding of its emission was desired.

So called P3-T3 methods predict emissions of NO_x based on reference emission data and combustor inlet pressure and temperature. This method is for example used by engine manufacturers to determine fairly accurate results. The required data however is not available publicly, which is why other methodologies have been developed such as the fuel flow methods by Boeing and the German Aerospace Center (DLR). These methods calculate NO_x emissions based on reference data, ambient atmospheric conditions and fuel flow. The principle of these methods is to use a ratio of predicted and reference emission index and conditions as follows (Norman et al. 2003, Schaefer 2006):

$$\frac{EI_{NO_x}}{EI_{NO_{x,ref}}} = f\left(\frac{p}{p_{ref}}, \frac{T}{T_{ref}}, \frac{c_{fuel}}{c_{fuel,ref}}\right) \cdot F(H) \tag{4.12}$$

with p = ambient static or total pressure, c_fuel = engine fuel flow, $F(H)$ = humidity correction factor.

The Boeing and CLR method use the same principle, but differ in the way corrections are made. These methods are less accurate than T3-P3, but give a decent estimate.

Equation 4.12 suggests that the variation of EI_{NO_x} is essentially dependent on ambient conditions, meaning that it scales similarly across all aircraft. An aircraft-related relative rating of its NO_x emission could therefore be assumed to be valid for all conditions.

4.3.4 Particulate Matter

As stated before, PM is not determined through certified test procedures. However, a method is presented by Wayson et al. 2009 to estimate PM using data from the ICAO Engine Exhaust Emissions Data Bank.

It was found that non-volatile PM correlates with smoke number (SN) and volatile PM can be derived from sulfur and organic fuel components. The emission index for volatile PM can be calculated by:

$$EI_{vols} = EI_{sulfur} \cdot \epsilon + \delta(EI_{HC}) \tag{4.13}$$

with $\epsilon = 0.033$ and $\delta(EI_{HC})$ depending on operating mode.

The emission index for non-volatile PM is:

$$EI_{nvols} = Q(AFR) \cdot CI(SN) \tag{4.14}$$

with Q depending on air-to-fuel ratio (AFR) of the engine. Since this data is proprietary and not publicly available, representative average values are used from table 4.3. Concentration index (CI) is a function of smoke number and for SN $\leq$ 30: $CI = 0.0694(SN)^{1.24}$.

Table 4.3 Representative engine volumetric flow rates by mode (Wayson et al. 2009)

Mode	AFR	Predicted volumetric core flow rate (Q)
Idle	106	83.1
Approach	83	65.3
Climb Out	51	40.5
Take off	45	35.8

Instead of using $\delta(EI_{HC})$ in equation 4.13, volatile PM emissions of fuel organics can be derived by:

$$PM_{volFuelOrganics} = 0.0085 \cdot (\mathrm{HC})_{LTO} \tag{4.15}$$

with HC being the mass of emitted HC during the LTO cycle.

The overall PM is then given by:

$$\text{Total PM} = EI_{vols} + EI_{nvols} \tag{4.16}$$

PM can be calculated for the respective mode of operation or total LTO by multiplying with mass of fuel.

4.4 Noise Measurement

4.4.1 Determination and Certification

Sound levels can be measured easily using a standardized procedure. Noise prediction models for conceptual aircraft designs are under investigation by research groups, but for now, measurements of existing aircraft are required.

New Aircraft are required to be assessed for noise emissions according to Annex 16, Volume I. These requirements are as for instance requested by EU regulations such as *Comission Regulation (EU) No 6/2013*.

The certification requirements are then enforced through aviation authorities such as the EASA and FAA. The FAA however has its own certification procedure by means of *Document 36-4C: Noise Standards: Aircraft Type and Airworthiness Certification* (FAA 2003), but is in compliance with Annex 16, Vol I from ICAO.

→ Appendix A.1

4.4.2 Noise Data Bank

In Europe, *Type-Certificate Data Sheets for Noise* (TCDSN) are issued by the authorities which record EASA approved noise levels. The documents are publicly accessible through a database provided by the EASA. The database not only contains type certificates issued by EASA but also approved noise levels of so called "transferred" products. (EASA 2015)

Another database called NoisedB is maintained by the French DGAC (Direction générale de l'aviation civile) under the aegis of the ICAO. It combines certified noise level data from certifications made under Annex 16, Chapter 3 and 4 and FAR standards for each airplane type.

TCDSN or NoisdB sheets primarily contain the following important data:

- Type Certificate Holder
- Aircraft Type Designation and Variant
- Engine Manufacturer and Type Designation
- Noise Certification Standard
- Modifications regarding noise levels
- MTOW
- MLM
- Lateral EPNL
- Flyover EPNL
- Approach EPNL

5 Existing Ecolabels

5.1 Introduction

Before evaluating new potential rating methods based on available data, existing systems may give important insights about procedures and approaches, but possibly exhibit shortcomings as well. A review suggested that there is only one airline that has implemented a comprehensive aircraft-based ecolabelling scheme. This scheme was own-developed by the airline flybe and made publicly available in order to encourage other airlines to adapt the label. As this was apparently not the case, the approach will be analysed in the following to determine potential shortcomings.

5.2 Flybe's Ecolabelling Scheme

Flybe (Flybe Group plc) is a British regional airline based in Exeter. As of May 2015, its fleet consists of 68 aircraft (+31 orders).

Table 5.1 flybe fleet (Source: Civil Aviation Authority)

Aircraft type	Total	Orders
ATR 72-600	–	5
Bombardier Dash 8 Q400	48	22
Embraer E-175	11	4
Embraer E-195	9	0

In 2007, the airline introduced an ecolabel for their aircraft which was modelled after established labels from other product categories such as refrigerators, washing machines and other electronic devices. The label is shown on flybe's aircraft, onboard literature, advertising and in on-line booking. Other airlines are encouraged to adopt this labelling scheme and for this purpose flybe provides a guide on how to create one (flybe 2007). However, no other carrier seems to have adopted it yet.

The label provides information on noise, CO_2 emissions, seat pitch (leg room) and makes use of a rating system where emissions are related to parameters such as the number of seats in an airplane. The values are then given a score based on self defined rating tables.

The design of the label is shown in fig. 5.1

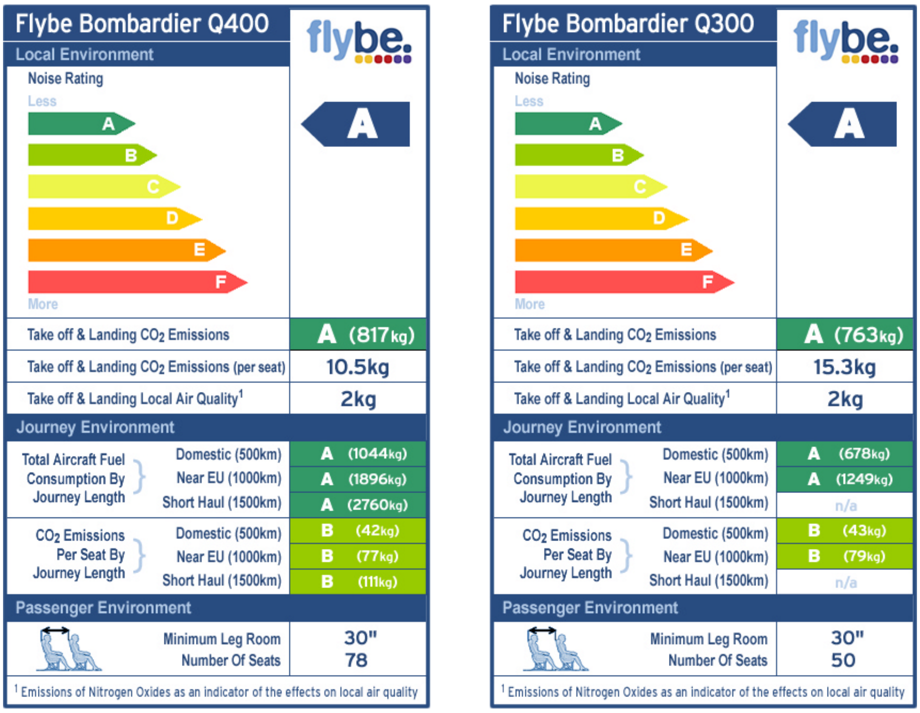


Figure 5.1 Flybe label design (flybe 2007)

The procedure has been subjected to assurance company Deloitte & Touche LLP. In their assurance statement it is mentioned that the following aspects were subject to a review of collation, aggregation, validation and reporting (Deloitte 2007):

- Journey fuel consumption (kg) for domestic, near EU and short haul flights
- CO_2 emissions during the landing and take off cycle (LTO) and per seat during the LTO. CO_2 emissions kg/seat for domestic, near EU and short haul flights
- NO_x emissions during the LTO cycle (kg)
- Noise rating produced by aircraft
- Seat pitch (inches) and number of seats onboard the aircraft

Deloitte confirmes the correctness of methodology, albeit it does not assess the overall reasonableness of applied procedures:

> *Based on the assurance work we performed, nothing has come to our attention that causes us to believe that the environmental performance data within Flybe's Environment Labels is materially misstated.*

The following will give an overview of flybe's methodology on how to create an ecolabel according to their guideline (flybe 2007). It is suggested to use an independent label for each aircraft/configuration combination, as they may vary through seating layout and engine type. The label is subdivided in three categories: local environment, journey environment and passenger environment.

The local environment section depicts exhaust emissions and noise around airports in contrast to differing effects of high altitude cruising flight.

The noise rating is based on a system called *Quota Count*, which is used to regulate noise at airports in London and elsewhere. Flybe uses an average of the two Quota Count values for departure and arrival, which is rated according to table C.1. The Quota Count system is described in Appendix D.

Contemplated emissions are carbon dioxide and nitrogen oxides that emerge during landing, take off and taxiing for which the standardized LTO cycle is used. The information on engine emissions during LTO derives from the ICAO Engine Exhaust Emissions Data Bank (→ section 4.3.2).

The value of used fuel per engine is multiplied by the number of engines i in order to calculate the total fuel per aircraft:

$$(\text{Total Fuel per Aircraft})_{LTO} = (\text{Total Fuel per Engine})_{LTO} \cdot i \tag{5.1}$$

To obtain the amount of emitted CO_2, the total fuel mass is multiplied by 3.15, the factor of produced CO_2 per unit of fuel burned:

$$(\text{Emitted CO}_2)_{LTO} = (\text{Total Fuel per Aircraft})_{LTO} \cdot 3.15 \tag{5.2}$$

The result is rated according to table C.2. The label also shows CO_2 emissions per seat. The number of seats n is taken instead of number of passengers, because the occupancy depends on each flight and is not an inherent factor of the aircraft.

$$(\text{Emitted CO}_2 \text{ per Seat})_{LTO} = \frac{(\text{Total Fuel per Aircraft})_{LTO}}{n} \tag{5.3}$$

The amount of emitted NO_x during LTO can be read directly from the sheet and is also multiplied by the number of engines. The emissions of nitrogen oxides are taken as an indicator of the effects on local air quality.

In the journey environment section, the whole journey of an aircraft is considered in terms of CO_2 emissions. Due to the fact that aircraft have different amounts of fuel consumption based on their intended range, several stage lengths are defined in table C.3 by selecting example routes. There is no simple standard model for the journey environment, which is why flybe takes the actual amount of fuel used by the aircraft from experience on different routes for its Label. The amount is then rated according to table C.5, regarding the respective stage length. The same applies for the amount of CO_2 per seat, where the fuel mass is again multiplied by 3.15 and divided by number of seats.

The last section about the passenger environment simply takes the minimum seat pitch as a key indicator of passenger comfort. The customer is encouraged to value the balance between comfort and CO_2 emissions, as more space per seat naturally increases emissions per seat.

5.3 Potential Shortcomings

The method presented by flybe has some potential shortcomings:

Use of Quota Count

The Quota Count system does not differentiate between different sizes of aircraft and hence is not an appropriate rating of noise when it comes to rate an aircraft itself.

By nature, larger and heavier aircraft with more capacity are much louder due to more powerful engines or multiple engines which are required to produce the required thrust. Their increased capability should be acknowledged some way, which is not the case with Quota Count, where the ambition is to limit the maximum noise level at night and not give aircraft appropriate ratings based on their characteristics. Therefore absolute instead of relative values are important.

Flybe's rating scheme simply adapts Quota Count by taking the mean values and thus discriminates specific aircraft by not taking size and capability into account.

Duplicative Rating

Quota Count already carries out a valuation based on certified noise levels by assigning a score to different noise level bands. There is no need to apply a second layer of criteria on Quota Count scores.

By doing so, inaccuracy increases as actual values from source are reduced to tiered values which are then classified again according to flybe's rating tables (→ Appendix C).

LTO CO_2 Emissions

A CO_2 amount is calculated based on emissions on ground by means of the ICAO LTO cycle. This method is insufficient as it takes the engine's fuel flow as a basis and does not consider the aircraft or engine characteristics at all. It therefore discriminates larger and heavier airplanes with higher capability as they require more fuel to perform the specified LTO settings.

Absolute Emission Values

The contemplated value of NO_x is an absolute value, meaning that no correlation is made to capability and performance of the engine and hence is of little meaningfulness.

Route-based Emissions

All statements about cruise CO_2 emissions, respectively fuel consumption, are based on empirical data from different routes. The valuation is made only with regard to journey length. This might lead to inconsistencies as fuel consumption is case-dependent to a certain extent. Two different routes may require different amounts of fuel despite having the same distance due to external factors. In fact, it is possible that even the same route has different outcomes, depending on whether outward or inward flight is considered over several cycles. For example, the north atlantic jet stream wind has significant impact on aviation. It is a strong and relatively reliable natural phenomenon that affects flight routes between Europe and North America. The direct linear distance is therefore departed in favor of more efficient routes in order to benefit from tailwinds or avoid headwinds. Under these premises, the metric used is not suited for generalizations of mission profiles.

Additionally, the metric once again does not take into account the aircraft and its characteristics. A 'per-seat' statement is made afterwards, but only as a secondary supplement.

Use of non-official data

The underlying amount of fuel consumption is derived as an empirical value without further explanation and specification. Since these statements would have to be made by airlines, the method lacks traceability and transparency. It is a non-certified value as no repeatable procedure is defined for the determination of fuel usage. This circumstance contradicts the requirement of ecolabel schemes having to be transparent and verifiable according to the previously suggested ISO standard (→

section 2.3).

Definition of Rating classes

Flybe defined several rating scales (Appendix C) with classifications from A to G with certain criteria. The criteria covers certain ranges, e. g. of emissions, but it remains unclear on how they were defined. Since the ecolabel was only applied to aircraft in flybe's fleet, it is not apparent how those of other carriers would perform and whether the classification is appropriate for a wide range of different aircraft or only geared to flybe's needs.

Selection of Parameters

A variety of parameters was chosen to be displayed on the label, including absolute emissions of CO_2, Fuel and NO_x and per-seat statements. Besides absolute values that have questionable meaningfulness, certain information is redundant because there is no added value. In virtually all given examples, there is no signficant variation among different journey length, thus indicating no additional value.

Label Design

Further, the design of the ecolabel as a whole is suboptimal. The prominent element is noise rating, which takes up nearly half of the label space and therefore could easily be mistaken for some kind of overall evaluation.

As a matter of fact, it is only one of several parameters and should be presented in a way that is appropriate to its importance.

6 Evaluation of an Ecolabel Scheme

6.1 Introduction

The previous sections dealt with the design of ecolabels, the identification of environmental issues, in particular the determination of emissions in aviation and certification procedures. Section 3 identified main environmental polluters by their type of impact on nature. The ecolabel shall therefore assess the following categories:

- Ressource depletion
- Climate impact
- Air quality
- Noise pollution

It was found that some emission products are linked to fuel directly and their emission mass is solely dependent on fuel usage while others are also dependent on the combustion process of the engine (→ 3.3.2).

Table 6.1 depicts all previously considered emissions along with their dependencies.

Table 6.1 Emission Dependencies

Group	Emissions	Depends on	Determination Method
1	CO_2, H_2O, SO_x	Fuel Usage (+ Fuel Type)	Fuel Flow/ Total Fuel Amount
2	NO_x, CO, HC, Smoke	Engine Combustion Process + Fuel Usage	Particle Filter
3	Noise	Aircraft Components (Aerodynamic surfaces, Engine..)	Noise Measurement

This indicates that aircraft manufacturers and operators have certain determining factors that may influence several emission parameters. For example, a reduction in fuel consumption entails a reduction in CO_2 and H_2O equally on a proportional basis as they are inherent to mass of fuel (group 1). Therefore, fuel consumption can be seen as an absolute, self-contained factor, which means that pollutants are implied. All emissions that are solely derived from fuel consumption thus have the same relative performance as overall fuel consumption. This can be used to assign the same rating to all of these emissions, without needing to be considered seperately. However, if they are assessed together with emissions that are non-proportional to fuel in order to derive environmental impact, the emitted mass may be of relevance for the purpose of weighting their share of impact. Whether this is needed will be discussed in section 6.6.

On the other hand, emissions from group 2 are not directly dependent on each other and thus require separate consideration . They are determined through test facilities in accordance with ICAO procedures (cf. section 4.3). Each component is assessed for its performance and can then be rated seperately or used for the determination of environmental impact.

The ecolabel aims at using official and ICAO certified emission data as an input. While it is possible to derive simulation models based on this data for single airplanes, it requires additional effort to make it comparable across different types and classes. The acquired data is useless as a comparison parameter unless put into context. This is done by normalizing input parameters, which then allows performance to be rated by the ecolabel.

These, however may vary based on the cabin configuration a specific airline has made in contrast to the default OEM aircraft. Therefore, the label will rate the aircraft based on a standard configuration defined by the manufacturer and additionally based on airline specific configurations, thus allowing a comparison to be made.

6.2 Correlating Parameters and Performance Measurement

In order to gain meaningfulness and basic comparability, emissions or fuel data, respectively their measure of environmental impact needs to be put into perspective. For example, the statement about an amount of fuel consumed by a car is only useful, when the distance travelled is also known. Other factors may be weight and type of the car or number of carried passengers. However, these factors do not vary as much as with airplanes, which is why they are usually neglected or classified into several subordinate groups such as weight classes, whereas the selection of appropriate parameters in aviation is a crucial factor. Hence, a normalizing, or correlating parameter is needed. In the car industry, fuel consumption *per 100km* is common. CO_2 emissions are referred to in grams per kilometer.

The relevant key data for aviation was derived previously and shall be used in the following to determine comparable measures for all considered aircraft.

The correlating parameter is used to minimize the effects of size and thus to obtain a measure of relative performance. Therefore, the term is expressed as a fraction with the key value or input parameter as the numerator and the correlating parameter as the denominator. It can also be visualized as a diagram with the value plotted on the y-axis and the correlating parameter plotted on the x-axis.

In general, performance could hence be expressed as follows:

$$\text{Performance} = \frac{\text{Input parameter}}{\text{Correlating parameter}} \tag{6.1}$$

The correlating parameter should be some direct or indirect indicator of output, or achieved benefit, whereas the key data value is the input. Referring to previous examples, output in this context could be for example: distance travelled, mass transported, passengers carried etc. The input parameter would be emissions produced or fuel burned, which is desired to be as low as possible. For this application, the metric can hence be specified further, resulting in an emission parameter:

$$\text{Performance parameter} = \frac{\text{Emissions produced or fuel burned}}{\text{Benefit obtained}} \tag{6.2}$$

Similar notations are used in relevant literature such as Norman et al. 2003 and Bonnefoy et al. 2010.

In case of aviation, "benefit obtained" (or *air transportation output*) is determined through productivity or capability of the aircraft.

However, a definition of capability is not as evident compared to other forms of transportation, because several interdependencies come into effect. For example, range, altitude, weight, fuel consumption and profile of the mission have influence among one another.

Additionally, there is a large disparity in size, purpose and capability of different aircraft and performance also varies between operations.

It may be useful to subdivide into classes or find correlating parameters that scale for a wide range of aircraft types to allow comparisons. Potential candidates for aircraft efficiency and productivity are investigated in the following.

6.3 Aircraft Efficiency and Productivity

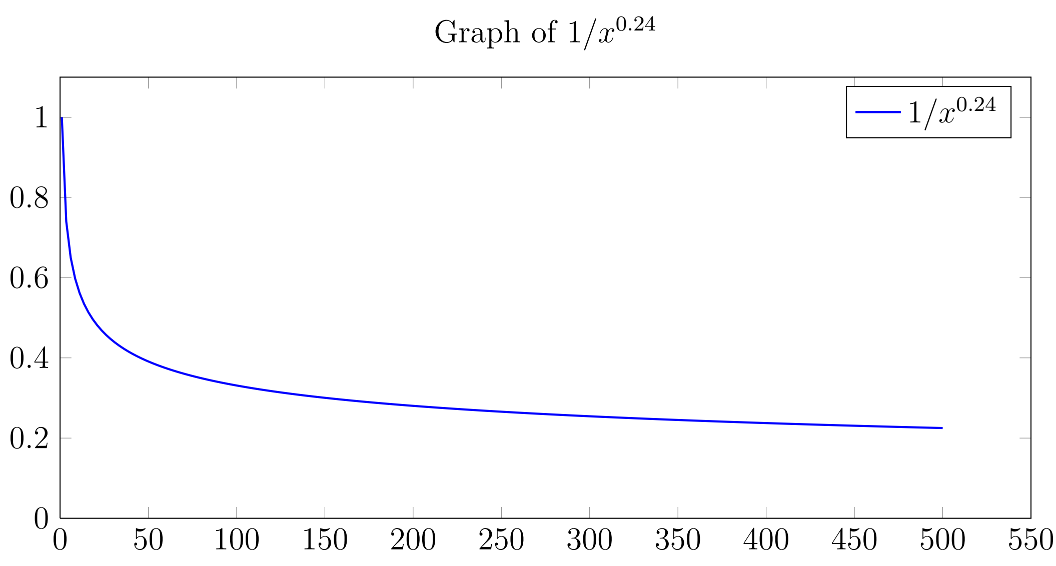
As stated before, the correlating parameter for overall aircraft performance should include a parameter representing productivity of aircraft. Several pertinent parameters come into consideration for this purpose:

- Range
- Payload or useful load
- Maximum take-off weight
- Floor area or number of seats
- Speed or travel time

An increase in any of these also implies an increase in productivity and hence aircraft efficiency for a certain parameter. This way, specific efficiency can be compared among aircraft of different sizes and capability and promote technological advances that lead to its improvement.

It has been noted that Annex 16, Vol III will introduce a fuel metric using SAR. This methodology also introduces a parameter called *Reference Geometric Factor* (RGF), which is a measure of fuselage size and uses a specially defined area that is similar to floor area in the pressurized zone (→ Appendix A.3).

According to this metric, 1/SAR is then normalized with $RFG^{0.24}$. An explanation about the occurrence of this exponent was not given by ICAO. This parameter suggests that large values of RFG, i.e. large aircraft, are advantaged as illustrated by the following graph:



Apart from that, the exponent leads to unwieldy units, which is why some of the alternatives mentioned above are examined in the following.

It is possible to include multiple parameters with the ambition of obtaining more precise performance metrics. A great number of metrics with combinations of correlating parameters was investigated by Bonnefoy et al. 2010.

Single-, two- and three parameter metrics were considered for both block fuel missions (full mission metrics) and SAR (instantaneous performance metrics). The evaluated metrics of the study are shown in fig. 6.1.

	Full Mission Metrics				
Single parameter metric	Block Fuel ---------------- Range				
Two-parameter metric	Block Fuel ---------------- **Payload** * Range	Block Fuel ---------------- **Useful Load** * R	Block Fuel ---------------- **MTOW** * Range	Block Fuel ---------------- **Floor Area** * R	Block Fuel ---------------- **Av. Seats** * R
Three-parameter metric	Block Fuel ---------------- **Payload** * R.*Speed	Block Fuel ---------------- **Useful Load** * R.*Speed	Block Fuel ---------------- **MTOW** * R. *Speed	Block Fuel ---------------- **Floor Area***R.*Speed	Block Fuel ---------------- **Av. Seats** * R. *Speed
	Block Fuel ---------------- **Payload** * R./Time	Block Fuel ---------------- **Useful Load***R./Time	Block Fuel ---------------- **MTOW** * R./Time	Block Fuel ---------------- **Floor Area***R./Time	Block Fuel ---------------- **Av. Seats** * R./Time
	Instantaneous Performance Metrics				
Single parameter metric	1 ---------------- **Specific Air Range** = 1 ----- **SAR**				
Two-parameter metric	1 ---------------- SAR * **Payload**	1 ---------------- SAR * **Useful Load**	1 ---------------- SAR * **MTOW**	1 ---------------- SAR * **Floor Area**	1 ---------------- SAR * **Av. Seats**
Three-parameter metric	1 ---------------- SAR * **Payload** * Speed	1 ---------------- SAR * **Useful Load** * Speed	1 ---------------- SAR * **MTOW** *Speed	1 ---------------- SAR * **Floor Area*** Speed	1 ---------------- SAR * **Av. Seats** * Speed

Note: R = Range

Figure 6.1 Block fuel (full mission) vs. SAR (instantaneous performance) metrics (Bonnefoy et al. 2010)

It is stated that a metric in transportation has to include at least a parameter of distance like it is common for automobiles. This is taken into account by using range for block fuel. SAR naturally relates to travel distance.

In aviation, some measure of capability (in terms of transport capacity or weight) should be taken into account as well, because of its significant effect due to the large disparity and different sizes of airplanes.

Since not all aircraft parameters are publicly available, officially certified parameters should be preferred.

6.4 Certifiability and Availability of Data

Another significant aspect in the determination of emission metrics is the availability and reliability of data. It is not always feasable to introduce complex new procedures like entire test flights for single certification parameters.

Moreover, some parameters are not possible or at least very difficult to certificate. However, some sort of certification of relevant data is an essential requirement in order for it to be of any use for valuation. This might be difficult for some characteristics because they vary to a large extend, are not accurately defined or are difficult to measure.

This is why it is favorable for any definition of emission metric for ecolabelling to be based on already certified parameters that are determined in common practice.

As noted previously, the idea of this ecolabelling scheme is to rate the base aircraft seperately from specific airline cabin configurations. A distinction should therefore be made between the standard airframe and default configuration that is based on the aircraft type produced by the manufacturer on one hand and the specific cabin layout set by the airline on the other hand.

The pursued approach in this work is to firstly identify metrics that are based on aircraft parameters which are certified by the manufacturer and then include airline specific modifications at a later point in time.

However, this limits possible measures of overall aircraft capability. For example, payload is generally not a certified parameter from the manufacturer, although it is a key influence factor as it determines capability and productivity of the aircraft.

Since maximum take-off weight is a fixed parameter by the aircraft type specification, all additional weight through installation of equipment and interior decoration is a reduction of payload. Thus, there is a trade-off in equipment weight and residual payload for airlines.

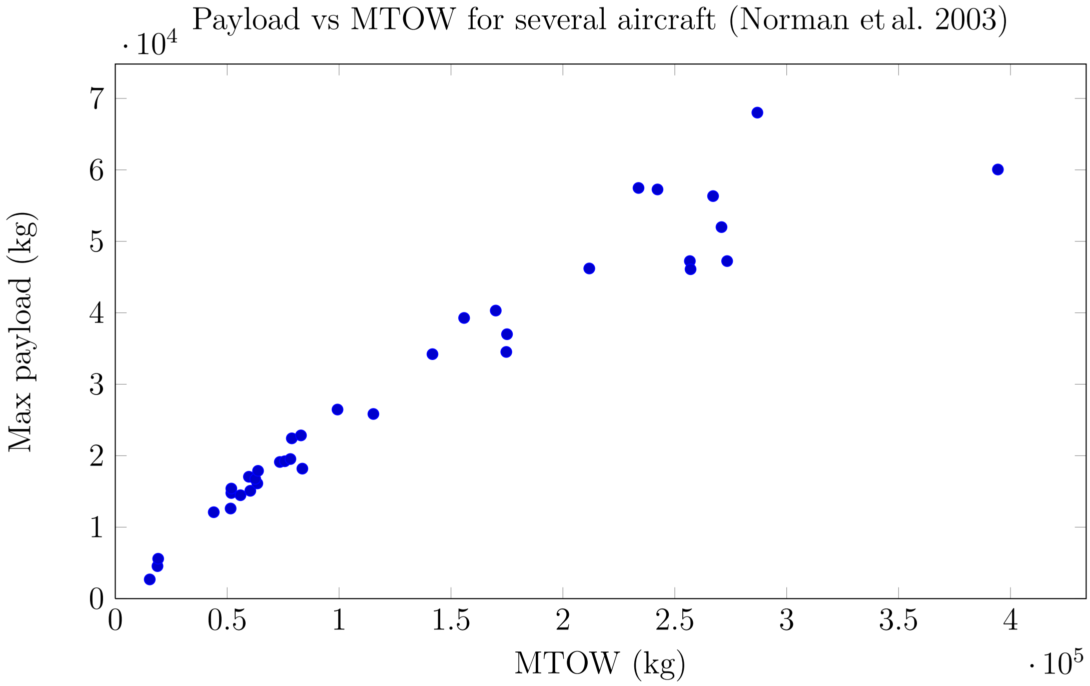
Fig. 6.2 lists all manufacturer certified weights that could be used to derive a weight based correlating parameter as opposed to operator certified weights.

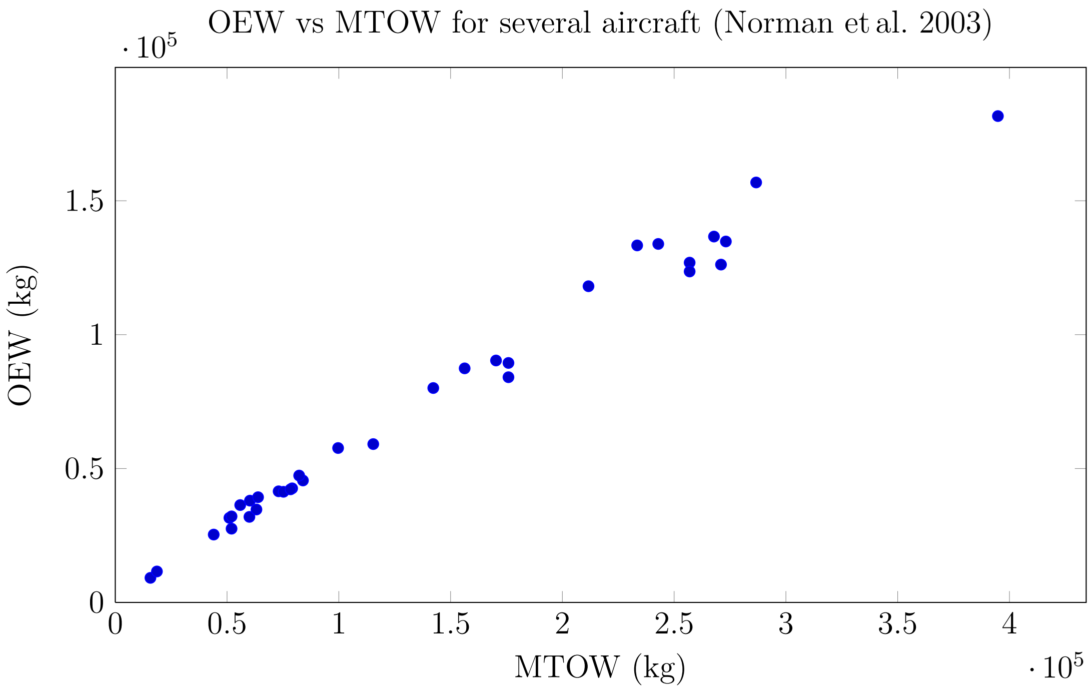
Table 6.2 Certified and non-certified metrics

Acronym	**Metric**	**Aircraft Manufacturer**	**Operator**
MTW	Maximum Taxi Weight	Certified	N/A
MTOW	Maximum Take-off Weight	Certified	N/A
MLW	Maximum Landing Weight	Certified	N/A
MZFW	Maximum Zero Fuel Weight	Certified	N/A
MFW	Minimum Flying Weight	Certified	N/A
OEW	Operating Empty Weight	Not Certified	Certified*
Max. Payload	Maximum Payload	Not Certified	Certified*
MEW	Manufacturer's Empty Weight	Not Certified	N/A
SEW	Standard Empty Weight	Not Certified	Certified*
BEW	Basic Empty Weight	Not Certified	Certified*

*in Airplane Flight Manual

It was found that MTOW is a sufficient surrogate as a correlating parameter by Bonnefoy et al. 2010, respectively Norman et al. 2003, as MTOW generally correlates with maximum payload and OEW, shown by the following graphs, which use data from the *PIANO* software.





Noise regulation limits of aircraft usually use MTOW as a correlating parameter (cf. 6.10.1). However, as for fuel efficiency, MTOW should not be a representative of aircraft capability, because it does not award an increase in actual useful load, when overall aircraft weight stays the same.

Out of the considered parameters in section 6.3, weight parameters were identified to be most suitable for capability measures in general, but an alternative that remains is number of seats.

Documents for Airport Planning (→ section 4.2.4) include standard cabin layouts and number of seats that can be utilized for this purpose. This has the advantage, that a direct comparison of standard cabin layout from manufacturer and operator cabin layout is possible and demonstrates how use of space affects relative performance.

Number of seats is a suitable indicator for aircraft capability, but it has the disadvantage that it is only applicable to passenger aircraft, whereas payload or useful load in general could be used for all types of aircraft. This does not need to be considered in this case as the ecolabel is targeted for commercial passenger aircraft.

6.5 Rating Scale

In order to establish a rating system, a scale with different classes has to be defined. This allows performance values to be categorized into groups which are eventually given marks from A to G. These marks will show how a specific aircraft performs relatively compared to others in the comparison group. The classification from A to G was chosen following common ecolabels, e. g. energy efficiency labels and CO_2 labels in the automotive sector.

In this approach, the boundaries and criteria for rating scales will be defined by actual performance of aircraft based on publicly available emission data. For this purpose, the frequency distribution of performance data (respectively their indices) will be analysed. It is expected that performance values for every category will show approximately a normal distribution, if large numbers of sample data are considered, in the fashion of the following:

Expected distribution and histogram

Since the set of considered elements is finite, the actual frequency distribution is discrete. Due to the high number of values, statistical data binning is necessary in order to obtain an expected histogram.

The number of bins is a trade-off of resolution versus error. A large number of input values allows smaller bin intervals, but becomes more difficult to handle and may eventually become unrepresentative of the distribution. The same applies if too few bins are defined with wide bin intervals.

As the proposed final rating scale consists of 6 thresholds, respectively 7 classes (A-G), the same number of bins would be theoretically sufficient if each of them is assigned to a certain interval. However, the sample data was found to contain some outliers, some of which are even above certification limits due to remnants from old sample data that should be excluded. Further, each emission type has its own set of sample data which has unique characteristics in terms of variance and expected value. Therefore, a situation-specific number of bins may be used to analyse the distribution, assuring an adequate level of accuracy.

To be able to conflate different emission components into an overall rating, their individual distribution needs to be normalized by assigning a continual value from 0-1 to the emission index, which is referred to as *normalized index value* in the following. This is done by finding an interval on the index axis that represents the majority of sample data, which was, as previously mentioned, expected to be normally distributed.

Consequently, different statistical variability and expected values are neutralized, making it possible to compare their relative representation of performance.

In order to find an appropriate interval, the maximum and minimum boundary has to be determined which define the top and bottom of the scale. All values above or below are consequently assigned the best, respectively worst normalized index value (0 or 1) and values in between proportional to the scale from 0 to 1. Assuming a symmetrical distribution, the expected value should be in the center and hence correspond to approximately 0.5.

The exact boundaries are undetermined to a certain degree due to irregular values in the actual distribution and thus require case-specific consideration. It was first considered to assign a certain percentage of entries to each category, e. g. that around 5% fall into the top and bottom category, so that 5% would receive an "A" and a "G" rating, but it became apparent that some values may be too far off the center of the distribution and would distort an appropriate grading of the scale.

6.6 Rating Categories and Weighting

The ecolabel scheme intends to rate emissions and then deduce an overall score that represents environmental impact of all considered categories. This, however, requires a weighting of different types of emissions, which should be based on the severity of environmental impact caused by a certain amount of substances emitted. This could be done by rating the individual emission parameters of each aircraft that are monitored relatively to to each other, i.e. comparing the emission index of a substance with its comparison group. Consequently, emissions of the same type are judged relatively and with low uncertainty. This approach was taken at first (→ Appendix E), but it turned out that determining appropriate weighting factors for the overall score is difficult as the exact share of the total environmental impact of each species is not known. Some species may have a large specific impact, but are emitted in such small quantities that the overall effect is small or negligible.

In order to estimate the share of environmental impact, it is therefore advantageous to assess a superordinated impact category, such as those described for climate change in section 3.5.4. As noted before, the measure of impact instead of direct emissions allows better comparison but to the detriment of certainty.

A useful property of several impact categories is that they are mostly dependent on one characteristic from table 6.1.

As determined in the evaluation of environmental factors (→ section 3), fossil depletion is solely dependent on fuel consumption and climate impact is largely dependent on emission that derive from fuel-proportional emissions. NO_x represents most of the emissions that affect air quality as it contributes to the creation of ground based ozone and secondary particulate matter. Noise emissions stand for themselves and are easily definable.

The following sections will derive a metric based on emission data and provide a method to rate environmental cateogories.

For climate impact it will be investigated whether it is useful and feasible to include NO_x as a climate influencing parameter. As for air quality, a measure of particulate matter creation is examined and analysed together with the impact of NO_x.

The evaluation of the respective impact categories is therefore guided by the life cycle impact assessment method ReCiPe, which determines so called midpoints that are then combined and weighted. In order to combine several emissions and impacts, characterization factors are used to weight them according to their significance. (Goedkoop et al. 2009)

For the definition of an ecolabel, it was chosen to use a fixed weighting for impact categories itself, which contribute to an overall aircraft score. This was considered to be sufficient, as the application of an ecolabel should be kept simple without its users needing to perform a full life cycle assessment, and also due to the many uncertainties. Nevertheless, weighting factors should be representative, which is why LCIA results are used as a reference. The composition of the overall aircraft score is therefore determined after the individual impact categories.

6.7 Fuel Consumption and Resource Depletion

6.7.1 Metric and Correlating Parameter

SAR was found to be an appropriate metric for measuring fuel consumption and overall aircraft efficiency. The reciprocal, 1/SAR, yields fuel burned over distance travelled and is therefore comparable to block fuel measurements over distance and fuel consumption statements in other modes of transportation.

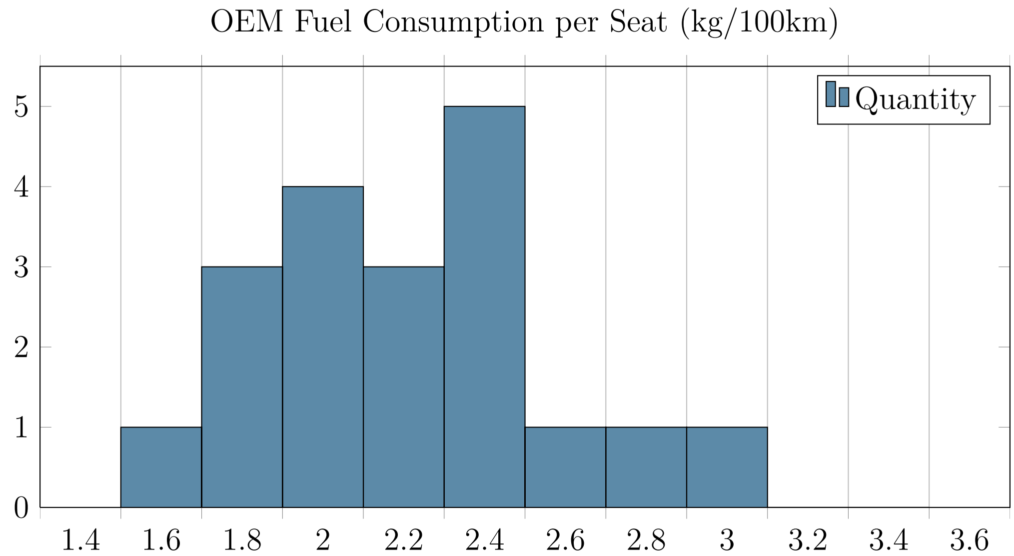
Since SAR includes distance, it is already a specific measurement and does not need assumptions about a particular journey or travel distance. In this work, 1/SAR is derived from payload/range diagrams and expressed in kg/km.

6.7.2 OEM and Airline Rating

The idea of this ecolabel scheme was to seperate the base aircraft from operator-specific configurations and modifications. Hence, the aircraft shall be rated using the default configuration of the original equipment manufacturer (OEM). Fuel consumption is therefore normalized with number of passengers in a standard seat layout, which can be for example obtained through Documents for Airport Planning (→ sections 4.2.4, 6.4):

$$\text{OEM-based Fuel Consumption} = \frac{1}{SAR \cdot n_{PAX,OEM}} \tag{6.3}$$

The derivation of a rating scale for this specific fuel consumption is difficult, because there is no official or certified data of SAR yet that can be used for this purpose. Therefore, values of SAR were estimated for selected aircraft in section 4.2.5. After normalizing with $n_{PAX,OEM}$, the distribution of values can be seen in the following histogram:



Due to the very small sample size and uncertainties in the estimation of SAR, this may not give very accurate results, but gives an overview of the scale and some tendencies. While the error margin is relatively big with reference to certified measurement, this distribution is used as a first orientation that may need to be corrected, once better data is available.

As for now, the upper and lower boundary for the rating scale could be defined as 1.5 and 3.1 kg/100km, giving the rating table 6.3.

Next, average fuel consumption for a specific seat configuration that is determined by the

Table 6.3 Rating Table: Fuel Consumption

Rating	Range	Normalized to 0-1
A	x ≤ 1.73	x ≤ 0.143
B	1.73 < x ≤ 1.96	0.143 < x ≤ 0.286
C	1.96 < x ≤ 2.19	0.286 < x ≤ 0.429
D	2.19 < x ≤ 2.41	0.429 < x ≤ 0.571
E	2.41 < x ≤ 2.64	0.571 < x ≤ 0.714
F	2.64 < x ≤ 2.87	0.714 < x ≤ 0.857
G	2.87 < x	0.857 < x

airline can be calculated in the same manner, using the number of seats of the layout:

$$\text{Airline-based Fuel Consumption} = \frac{1}{SAR \cdot n_{PAX,Airline}} \tag{6.4}$$

The result is then rated using the same scale as OEM-based fuel consumption.

6.7.3 Travel Class Rating

The seperation of base aircraft and airline layout-specific rating of fuel consumption shows how the deviation changes relative 'per seat' performance. Another focus of interest is how travel class influences relative performance.

Since first and business class proportionally have a much higher stake on fuel consumption and emission of the aircraft per passenger than the economy class due to increased use of space and heavier equipment, the label should demonstrate how the choice of class affects relative impact by passenger.

Using total number of passenger seats as a normalizing parameter ($1/n_{PAX,Airline}$) only results in average 'per seat' statements that give no information about specific influence of travel class, which is why an additional class-dependent factor is needed.

This can be achieved by introducing impact factors that are specified individually for travel class and correlate with their proportion of environmental impact. A weighting factor of 1 therefore equals average aircraft emissions and the overall aircraft rating from section 6.11. In this case, there is only one travel class and each seat is weighted equally.

By contrast, if there are first class seats and economy class seats, the former would receive a weighting factor of >1 and the latter <1 according to the division in the seating plan. To determine a rating per travel class, the overall aircraft emission performance is taken as a basis and then broken down into class specific performance by applying the factor.

The definition of class-specific factors should include a measurement of the class' proportional use of total aircraft capability. A simple indicator that is dependably ascertainable is area per seat. It correlates with seat class, allows comparison and is easy to determine.

Seat area S_{Class} is determined as seat pitch mutliplied with width, which have a clear definition.

$$S_{class} = (\text{Seat pitch})_{class} \cdot (\text{Seat width})_{class} \tag{6.5}$$

Usually, two or three classes are common which are labelled in the following as First Class (FC), Business Class (BC) and Economy Class (EC).

The total area S_{total} used by seats is therefore:

$$S_{total} = n_{FC} \cdot S_{FC} + n_{BC} \cdot S_{BC} + n_{EC} \cdot S_{EC} \tag{6.6}$$

with n_{class} being number of seats of the respective class and thus giving total number of seats n_{total}:

$$n_{total} = n_{FC} + n_{BC} + n_{EC} \tag{6.7}$$

The class-specific seat ratio is:

$$\frac{S_{class} \cdot n_{class}}{S_{total}} = \frac{S_{Class} \cdot n_{Class}}{n_{FC} \cdot S_{FC} + n_{BC} \cdot S_{BC} + n_{EC} \cdot S_{EC}} \tag{6.8}$$

From this, the class-specific weighting factor K_{FC} can be determined by dividing Eq. 6.8 by ratio of numbers of seats n_{FC}/n_{total} ($\rightarrow$ Eq. 6.9).

$$K_{FC} = \frac{S_{FC} \cdot n_{FC}}{n_{FC} \cdot S_{FC} + n_{BC} \cdot S_{BC} + n_{EC} \cdot S_{EC}} \div \frac{n_{FC}}{n_{FC} + n_{YC} + n_{EC}} \tag{6.9}$$

$$= \frac{n_{FC}}{n_{FC} + n_{BC} \cdot \frac{S_{BC}}{S_{FC}} + n_{EC} \cdot \frac{S_{EC}}{S_{FC}}} \cdot \frac{n_{FC} + n_{BC} + n_{EC}}{n_{FC}} \tag{6.10}$$

$$= \frac{n_{FC} + n_{BC} + n_{EC}}{n_{FC} + n_{BC} \cdot \frac{S_{BC}}{S_{FC}} + n_{EC} \cdot \frac{S_{EC}}{S_{FC}}} \tag{6.11}$$

The weighting factor K_{class} is multiplied with average aircraft performance, which then results in class-specific emission values that can be rated on a scale of A to G by analogy with previous ratings.

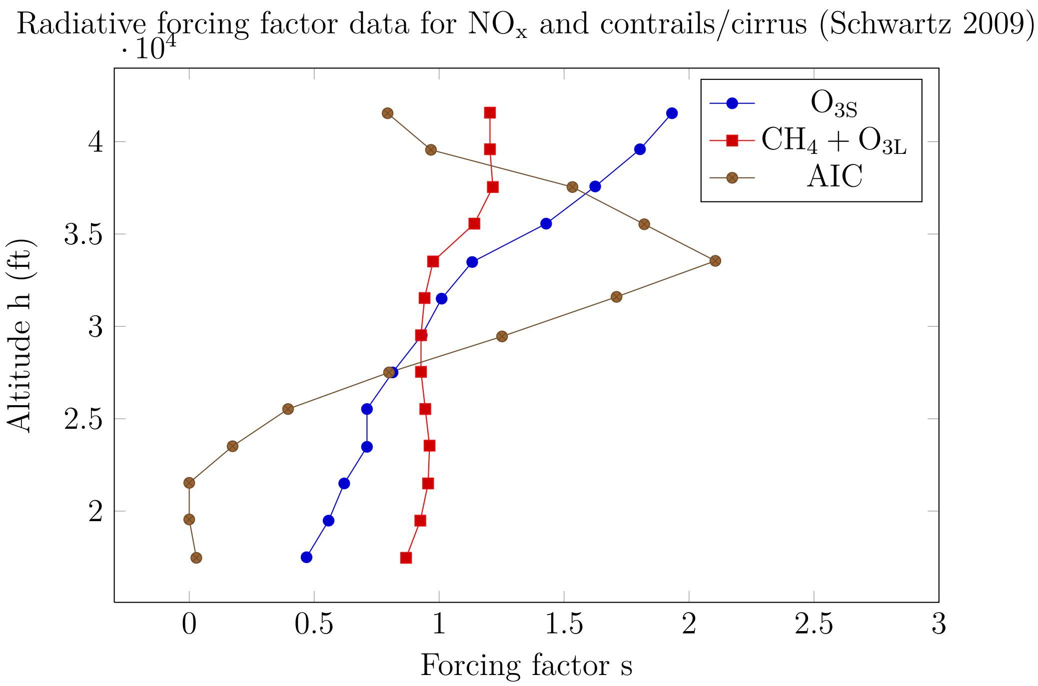
As previously suggested, average fuel consumption can be expressed by division by number of seats, giving *per seat* fuel consumption. In combination with weighting factor K_{class}, class-specific fuel consumption is derived:

$$\text{Travel Class-based Fuel Consumption} = \frac{1}{SAR \cdot n_{PAX,Airline}} \cdot K_{class} \tag{6.12}$$

6.8 Climate

Section 3.5 identified climate-affecting emissions. In order to determine a metric for climate impact of aircraft, the importance of each species has to be known. Their particular impact depends on the amount of radiative forcing (RF) they cause. A common metric which is used to compare the impact of different substances is *Global Warming Potential* (GWP) (cf. 3.5.4), which describes RF over a certain time. The values of GWP for different species are reported by IPCC.

However, it was found that the impact of certain emissions is altitude-dependent. For example, the effects of NO_x and contrails/cirrus vary greatly with altitude of emission. There have been attempts to quantify this dependency, and Schwartz 2009 presented a graph showing forcing factors depending on altitude for aviation induced cloudiness (AIC) and the combination of NO_x-induced methane (CH_4) and long-lived ozone (O_{3L}) as well as short-lived ozone (O_{3S}), based on Köhler et al. 2008 and Rädel and Shine 2008:



The ReCiPe method uses GWP as a characterization factor, which then weights each emission species, but other impact assessment methods will likely use a similar procedure. Schwartz 2009, however, does not use GWP, but sustained global temperature potentials (SGTP, cf. section 3.5.4).

$$\Delta T_{s,100} = \sum_{i=1}^{N_i} SGTP_{i,100} \cdot E_i \cdot s_i + \sum_{j=1}^{N_j} SGTP_{j,100} \cdot L \cdot s_j \tag{6.13}$$

with $i = \mathrm{CO_2, H_2O, CH_4, O_{3S}, O_{3L}, soot, sulfate}$ and $j = \mathrm{contrails, cirrus}$.

Values for SGTP are provided in table 6.4 by Schwartz 2009. If a full mission is considered, an average s can be calculated depending on flight profile. E_i is determined by Eq. 6.14 and the share of AIC is calculated using stage length L.

$$E_i = EI_i \cdot m_{fuel} \tag{6.14}$$

Johanning 2014 showed that this method can be used alternatively to calculate altitude-dependent characterization factors, or CO_2 equivalents, refering to a time horizon of 100 years. The characterization factor can be determined by:

$$CF_{midpoint,i}(a) = \sum \frac{SGTP_{i,100} \cdot s_i(a)}{SGTP_{CO_2,100}} \tag{6.15}$$

Table 6.4 Sustained global temperature change potential (Schwartz 2009)

i	$\mathbf{SGTP}_{i,100}$
CO_2 (K/kg CO_2)	3.58E-14
Short O_3 (K/kg NO_x)	7.97E-12
Long O_3 (K/kg NO_x)	-9.14E-13
CH_4 (K/kg NO_x)	-3.90E-12
Contrails (K/NM)	2.54E-13
Contrails (K/km)	1.37E-13
Cirrus (K/NM)	7.63E-13
Cirrus (K/km)	4.12E-13

For NO_x, it is therefore calculated by:

$$CF_{midpoint,NO_x}(a) = \sum \frac{SGTP_{i,100} \cdot s_i(a)}{SGTP_{CO_2,100}} \tag{6.16}$$

with $i = \mathrm{CH_4}, \mathrm{O}_{3S}, \mathrm{O}_{3L}$, and for AIC:

$$CF_{midpoint,CC}(a) = \sum \frac{SGTP_{i,100} \cdot s_i(a)}{SGTP_{CO_2,100}} \tag{6.17}$$

with $i =$ contrails, cirrus.

The total CO_2 equivalent is then determined by:

$$(\text{Total CO}_2\text{ eq}) = \sum_{i=1}^{N_i} x_i \cdot CF_{midpoint,i} \tag{6.18}$$

with $i = E_i$, respectively $i = L$ for contrails, cirrus.

This can also be done for normalized values by using specific fuel consumption. In this case, the fuel metric from section 4.2, $1/(SAR \cdot n)$, is used for m_{fuel} and $L/(L \cdot n) = 1/n$ for x, which will then give total CO_2-equivalents per seat-kilometer.

Since all input parameters except EI_{NO_x} are fuel-proportional and L is basically independent from a specific aircraft in this calculation, the overall climate-affecting emissions are largely dependent on fuel consumption rate. It takes some effort and assumptions to calculate the share of the overall effect of NO_x. First, an altitude has to be assumed for the calculation and second, the exact EI of NO_x is unknown and has to be estimated, which requires further assumptions about the environmental conditions. Additionally, in order to determine the share of NO_x, the overall impact has to be calculated, which is highly uncertain due to the complex nature of atmospheric interdependencies.

In order to provide a simple ecolabel that does not require the input of altitude information for specific aircraft, a standardized altitude could be assumed for all. However, the impact of contrails and clouds in particular remains uncertain and so does overall impact, which is needed to derive of relative impact of NO_x.

Because of all the necessary assumptions, heterogeneity and uncertainty, Azar 2012 and Forster et al. 2006 (Forster et al. 2007) argue that they should not be included in emission schemes, but are still useful for the understanding of overall aircraft impact. Moreover, the emission of NO_x itself is mostly determined by amount of fuel burned (→ Eq. 6.14), which is why the actual specific emission rate of NO_x only accounts for a fraction of the total impact. Therefore, climate impact is considered to be proportional to fuel consumption as specified in section 6.7. Nevertheless, the inclusion of further parameters in the future is conceivable. A similar approach is used by many other climate schemes and calculators such as atmosfair, which uses the *Radiative Forcing Index* (RFI). (atmosfair 2008)

The RFI describes the historical overall climate impact of aviation in terms of radiative forcing in relation to the sole impact of CO_2 (Fuglestvedt et al. 2003):

$$\text{RFI} = \frac{RF_{\text{Total Emissions}}}{RF_{\text{Share of CO}_2}} \tag{6.19}$$

The overall RFI has been determined by accumulating data since 1950 and found to be in the range of 2-4 in 1992 (IPCC 1999). The best estimation was considered to be 2.7, but in 2007 the IPCC reconsidered it to be in the range of 1.9-4.7 due to uncertainties .

6.9 Air Quality

6.9.1 Metric and Correlating Parameter

As noted in section 3.6, air quality is determined by the creation of ground level ozone and the formation of particulate matter. Ground level ozone, however, only plays a minor role and can thus be neglected, but will be briefly considered since it can be easily calculated using LTO data.

PM is mostly created as secondary PM through NO_x. Primary PM is not measured directly and must therefore be estimated from the other measurements. This can be done using the method described in section 4.3.4, which is used as a surrogate until certified PM data is available.

It turned out that primary PM also has only a minor share of overall air quality impact, since the mass of emitted NO_x (cf. fig. 3.5) and its effects are significantly greater in comparison.

The metric for air quality is calculated using predefined characterization factors from ReCiPe, which are listed in table 6.5. Basically, emissions from relevant species are converted into NMVOC-equivalents (ozone formation potential) and PM-equivalents (particulate matter formation potential).

Table 6.5 Characterization factors from ReCiPe (ReCiPe 2012)

Midpoint category	**NO_x**	**SO_2**	**PM**	**CO**	**HC**
Photocemical oxidant formation (ozone)	1	0.081	-	0.046	0.476
Particulate matter formation	0.22	0.20	1	-	-

All emissions are calculated for an entire LTO cycle, as defined by Annex 16, Vol II (→ Appendix A.2). Total masses are consequently the sum of emitted amounts during respective operating modes from table A.1.

Total ozone potential is therefore obtained by:

$$\text{NMVOC}_{LTO} = 1 \cdot (\text{NO}_x)_{LTO} + 0.081 \cdot (\text{SO}_2)_{LTO} + 0.046 \cdot (\text{CO})_{LTO} + 0.476 \cdot (\text{HC})_{LTO} \tag{6.20}$$

and particulate matter potential:

$$(\text{PM eq})_{LTO} = 0.22 \cdot (\text{NO}_x)_{LTO} + 0.20 \cdot (\text{SO}_2)_{LTO} + 1 \cdot (\text{PM})_{LTO} \tag{6.21}$$

$(\text{PM})_{LTO}$ is calculated using the method of Wayson et al. 2009 (cf. Eq. 4.16):

$$(\text{PM})_{LTO} = (\text{PM}_{vols})_{LTO} + (\text{PM}_{nvols})_{LTO} \tag{6.22}$$

with

$$PM_{nvols} = 0.033 \cdot (\mathrm{SO_2})_{LTO} + 0.0085 \cdot (\mathrm{HC})_{LTO} \tag{6.23}$$

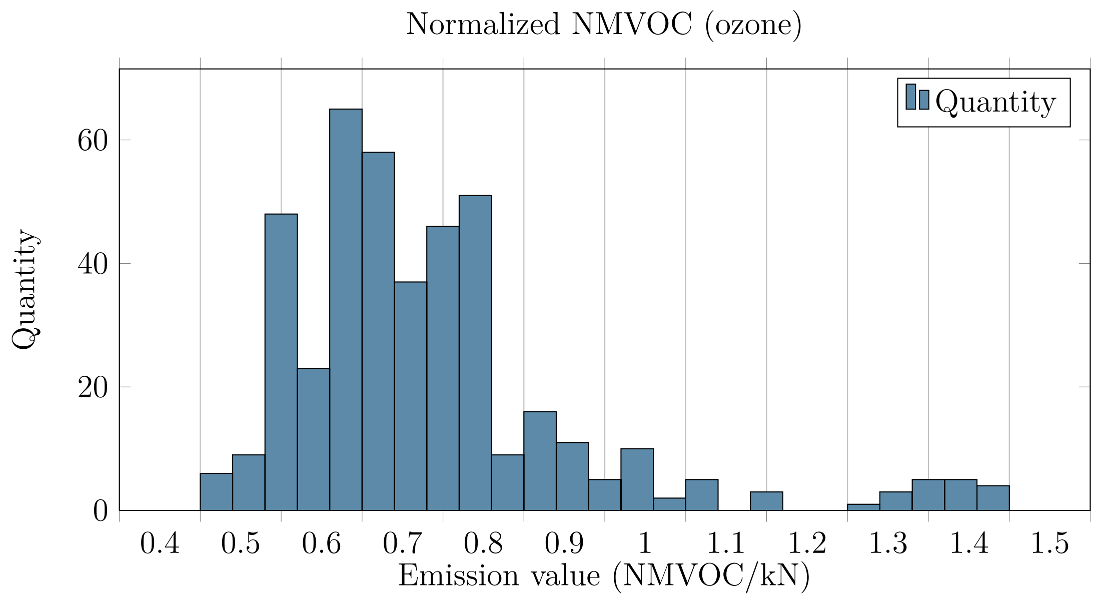
according to Eq. 4.13 and 4.15 and

$$(\mathrm{PM}_{vols})_{LTO} = \sum Q_i \cdot 0.0694 \cdot (\mathrm{SN})_i^{1.24} \cdot (\mathrm{Fuel\ flow})_i \tag{6.24}$$

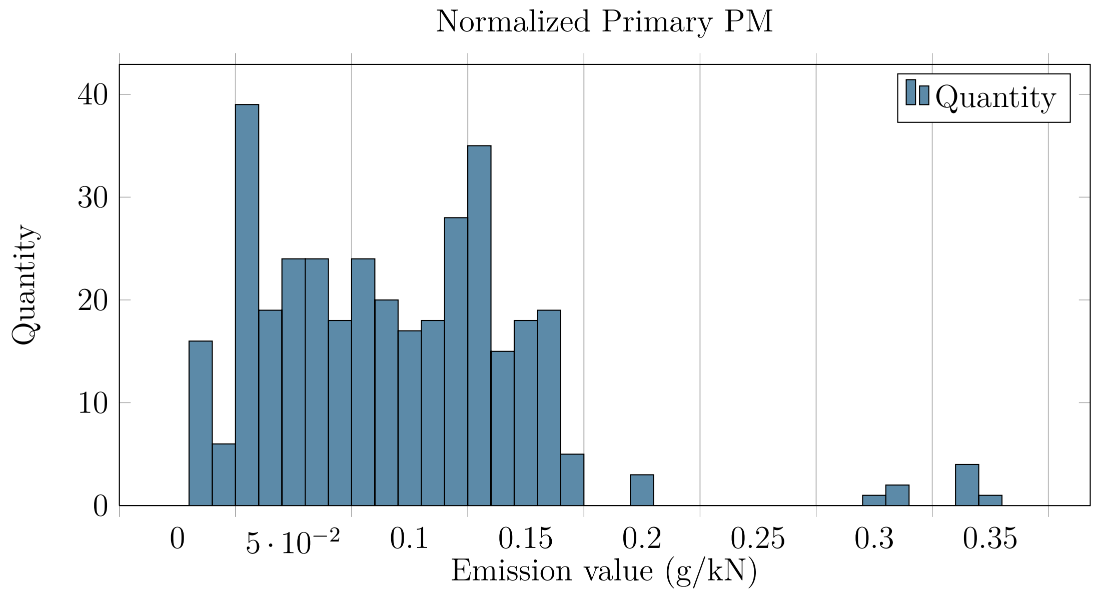
using Eq. 4.14 and i = approach, take-off, idle, climb out, as well as Q from table 4.3.

Since all data is engine-related, a normalizing factor which describes engine capability is used. As more powerful engines have a larger fuel consumption rate, they emit larger amounts of pollutants in the LTO, but provide a benefit on the other hand. This is why emissions are normalized with maximum rated thrust at sea-level of the engine in the certification procedure (D_p/F_{oo}).

This will be done in a similar matter for the results of ozone and PM potentials. Hence, the distribution of calculated values for ozone based on the Engine Exhaust Emission Data Bank is as follows:



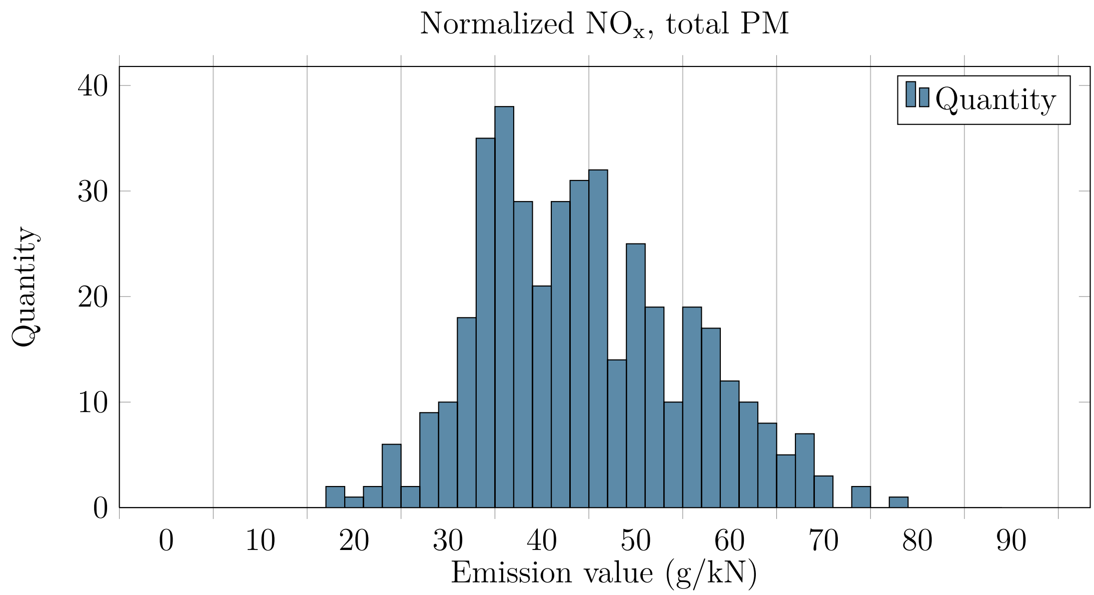
For primary particulate matter:



6.9.2 Air Quality Rating

Due to the generally low emissions of primary PM and ozone-causing substances and a small characterization factor, NO_x represents the bulk of air impact. This also becomes evident by considering that the mass of emitted NO_x is significantly larger.

As for an air quality metric, the effects of non-NO_x substances can be included, but don't effectively change the outcome. Therefore, the overall distribution of air impact is as follows:



The boundaries for the rating scale range from 22 to 82, resulting in the following rating table:

Table 6.6 Rating Table: Air Quality

Rating	Range	Normalized to 0-1
A	$x \leq 30.57$	$x \leq 0.143$
B	$30.57 < x \leq 39.14$	$0.143 < x \leq 0.286$
C	$39.14 < x \leq 47.71$	$0.286 < x \leq 0.429$
D	$47.71 < x \leq 56.29$	$0.429 < x \leq 0.571$
E	$56.29 < x \leq 64.86$	$0.571 < x \leq 0.714$
F	$64.86 < x \leq 73.43$	$0.714 < x \leq 0.857$
G	$73.43 < x$	$0.857 < x$

6.10 Noise

6.10.1 Metric and Correlating Parameter

As noted in sections 3.7 and 4.4, noise of aircraft is measured in EPNdB using a standard procedure, where noise levels are recorded at three reference points according to Annex 16, Vol I. Since noise is a relatively independent parameter unlike other emissions, the definition of a metric is easier in principle.

A metric can be defined by taking the certified values measured for take-off, approach and lateral side and determine the average:

$$\text{Average Noise Level} = \frac{\text{EPNdB Take-off} + \text{EPNdB Approach} + \text{EPNdB Lateral}}{3} \tag{6.25}$$

Aircraft noise is usually correlated with MTOW, like it is the case with the regulatory limits. Since aircraft noise does not increase proportionally with aircraft size, the maximum allowed limit is a function of MTOW, which is calculated according to Annex 16, Vol I.

A logarithmical function links MTOW and noise level as larger aircraft have overproportional noise levels. This is due to the fact that high masses require larger amounts of thrust and engine power, which inherently account for the major part of noise.

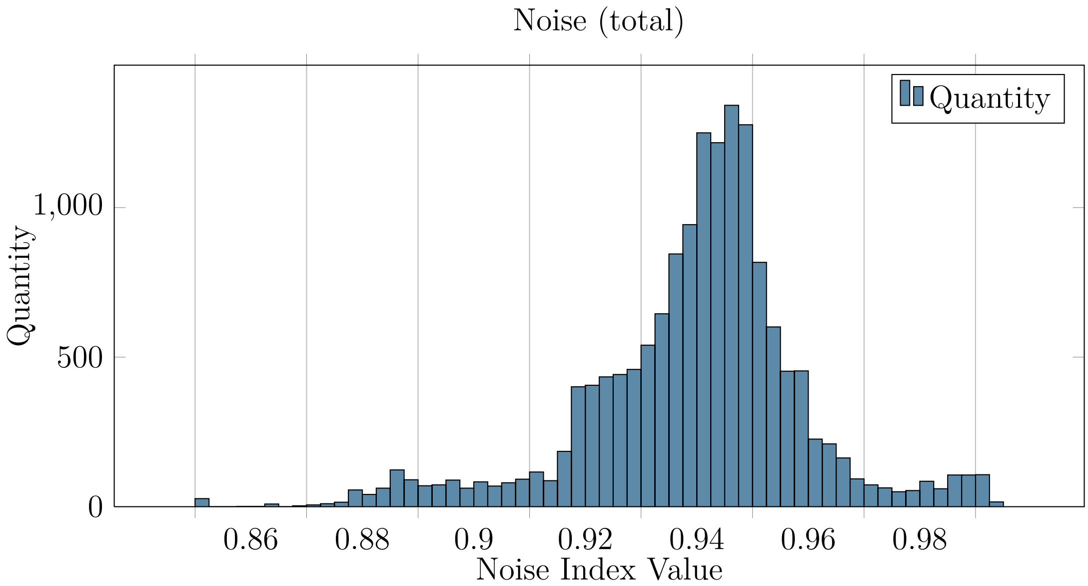
Aircraft weight therefore naturally limits the possible amount of noise mitigation that can be achieved through new technology. By correlating noise with a function of mass, the level of actual noise can be put into perspective to what is achievable in the respective weight class.

The noise rating is hence expressed by an index, which is calculated as follows:

$$\text{Noise Index Value} = \frac{\text{Average Noise Level}}{\text{Noise Limit}} \tag{6.26}$$

6.10.2 Noise Rating

The derivation of a rating scale can be done by evaluating the index value for a set of aircraft using data from the TCDSN database from EASA (cf. section 4.4.2). The following histogram shows the distribution of the sample data.



Due to the large number of input values (15538), the core area of the distribution is clearly visible. This also allowed to use a smaller bin size, giving a more precise picture.

As the rating scale should encapsulate the larger part of the distribution, the lower end of the boundary is defined at 0.91 and the upper boundary at 0.97.

This accordingly results in the following rating table:

Table 6.7 Rating Table: Noise

Rating	Range	Normalized to 0-1
A	x $\leq$ 0.919	x $\leq$ 0.143
B	0.919 < x $\leq$ 0.927	0.143 < x $\leq$ 0.286
C	0.927 < x $\leq$ 0.936	0.286 < x $\leq$ 0.429
D	0.936 < x $\leq$ 0.944	0.429 < x $\leq$ 0.571
E	0.944 < x $\leq$ 0.953	0.571 < x $\leq$ 0.714
F	0.953 < x $\leq$ 0.961	0.714 < x $\leq$ 0.857
G	0.961 < x	0.857 < x

6.11 Final Outcome

6.11.1 Overall Aircraft Rating

The ecolabel is meant to present an easy to understand indication of environmental performance, relative to the capability of the aircaft. To achieve this, several categories were rated on a scale from A to G. However, the label should also include an overall rating, which summarizes all categories in a single rating. While it is difficult to weigh different environmental categories such as climate change and air pollution according to their severity of impact, impact assessment methods like ReCiPe try to do this by assigning quantified damages to human health, ecosystem diversity and resource availability (cf. section 3.3.1). This, however, adds another layer of uncertainty and complexity. Since the use of an ecolabel should be simple and comprehensible in a transparent way, a full life cycle assessment should not be necessary for its validation, which is why a simplified method is preferred that takes the methods of environmental impact assessments as a reference. This is why the focus has been set on impact categories itself, which make use of established methods to represent them. The overall rating then again is subjective to a certain degree, e. g. when it comes to noise impact. Therefore, it was chosen to use a fixed and standardized weighting of impact categories, which conflates the individual ratings. For this purpose, the findings of Johanning 2013 and Johanning 2014, where a full life cycle assessment was performed, are taken as a loose indication of the relative importance.

In section 3.3.1, fig. 3.2 that the vast majority of impact is due to fossil depletion and climate change. As these are almost entirely determined by fuel consumption, its performance rating takes up the largest share. Particulate matter only has a small proportion of the total impact. Since a very bad performance in this area would not significantly affect the overall score, which is eventually expressed in only six grades (A-G), the share should be increased so far that it is at least noticeable in the overall rating, which otherwise would be just equivalent to fuel rating. It was therefore chosen to include air quality and noise rating with 20%.

As a result, the overall aircraft rating is determined as follows:

$$\text{Overall Rating} = 0.6 \cdot (\text{Normalized OEM-based fuel consumption rating}) \tag{6.27}$$

$$+0.2 \cdot (\text{Normalized air quality rating}) + 0.2 \cdot (\text{Normalized noise rating}) \tag{6.28}$$

The normalized values refer to the continous scale of 0 to 1, which is determined by the metric of each impact category as defined previously.

Table 6.8 Rating Table: Overall aircraft

Rating	Range
A	x ≤ 0.143
B	0.143 < x ≤ 0.286
C	0.286 < x ≤ 0.429
D	0.429 < x ≤ 0.571
E	0.571 < x ≤ 0.714
F	0.714 < x ≤ 0.857
G	0.857 < x

6.11.2 Ecolabel Design

A possible design for this ecolabel is shown in fig. 6.2. The label should prominently feature the overall aircraft rating and additionally the ratings for each category. The score alongside the rating from A to G should show the achieved value, e. g. kg fuel per passenger or the index value for noise according to the respective metric. The label is divided into a general aircraft statements and airline-specific statements, which are expressed through travel classes.

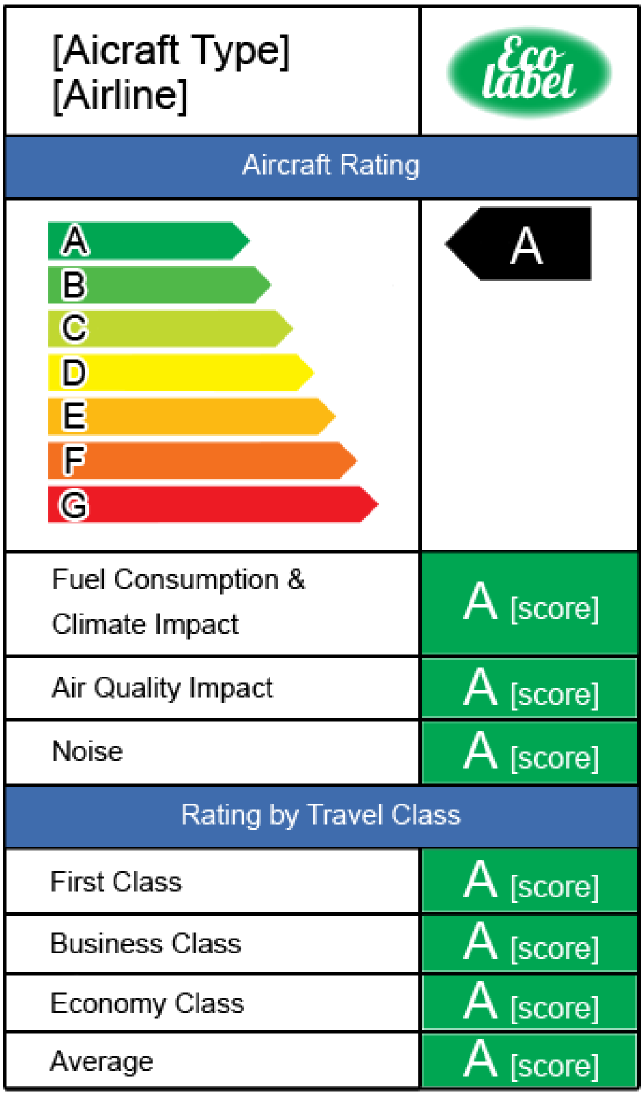


Figure 6.2 Draft for an ecolabel design

7 Conclusions and Future Work

7.1 Conclusions

This work identified the most relevant environmental factors of commercial aviation and how the measurable emissions are linked to quantified indicators of impact. In order to compare aircraft of different sizes and capability, metrics were developed that indicate the relative performance for different impact categories. Subsequently, the performance is rated using existing performance data as a reference.

It turned out that some indicators are subject to high uncertainty as environmental effects are a result of complicated mechanisms that are not yet fully understood or predictable, which is partly due to the large disparity in duration and manner of efficacy.

Additionally, not all relevant emission data is available or directly ascertainable. Certified data for aircraft fuel performance and particulate matter is not yet obtainable, as the corresponding methodologies are still in development, which is why estimates had to be made.

While large uncertainties exist in the determination of net environmental impact of aviation and aircraft, the uncertainty is less when considering relative performance, as most environmental impacts are mostly determined by a single parameter such as fuel consumption. Nevertheless, in order to give a more precise picture, assumptions have to be made that are specific to certain aircraft, their flight and mission profile. Such a fundemental assessment, however, is only sensible when the objective is to understand the net impact resulting from specific and known framework conditions. Since net impact scales with aircraft emissions, a comparison of these emissions can be used to derive relative performance for an ecolabel without knowing the overall net impact precisely due to the many uncertainties.

This scheme for an ecolabel consequently tried to provide a simple way of assessing emissions and weigh their importance of impact where needed. Moreover, requirements and a methodology was given about how input data can be used for this purpose, which can also be used as a basis for further adjustments.

7.2 Future Work

Possible adjustments that can be made are for example to include altitude-dependent information. This would give a little more accurate results for specific aircraft, but on the other hand make it more complicated and also it requires a standardized and verifiable statement of the assumed altitude.

Something that should be done in the future is to include official certified emission data, which could not be used yet as it is still in development and had to be estimated. These include the pending ICAO certified SAR measurements and the announced particulate matter standard. As a result, the rating tables used in this work may need to be adjusted to better fit the performance of today's aircraft. Especially the SAR data should be revaluated as a very small sample size was used with high uncertainty.

Further work could be done by altering weighting factors. They could be based on a different way of damage quantification, depending on impact assessment model. While impacts of a certain category such as climate change have established methods of quantification, the overall environmental burden does not have a standardized measure. Consequently, different systems may be taken into account and compared.

Another area of interest might be the possibility of calculating the potential ecolabel rating of newly designed conceptual aircraft. A method was provided to calculate SAR based on aircraft design parameters. Engine emission data can be obtained from existing engines, but noise data will be difficult to predict, although respective methods are under investigation. This work was also done with conventional fuels and aircraft configurations in mind. Future considerations might therefore also investigate whether the used performance models are appropriate for unconventional designs.

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A Certification According to ICAO Annex 16

A.1 Volume I – Aircraft Noise

Volume I of the Annex 16 to the Convention on International Civil Aviation contains reference conditions and initial demonstration procedures for aircraft noise certification (ICAO 2011). The related ICAO Document 9501-AN/929 *Environmental Technical Manual on the Use of Procedures in the Noise Certification of Aircraft* provides guidance in the application of equivalent procedures.

Measurement points and limits are specified for different types of aircraft. The reference noise measurement points are defined as follows:

- lateral point on a line parallel to runway at 450 m distance, where noise level is at maximum during take-off
- flyover point at take-off on the extended center line of the runway at 6500 m distance (from break release point/start of roll)
- flyover point at approach on the extended center line of the runway at 2000 m from runway threshold

The reference points are depicted by fig. A.1.

Noise limits are defined as a function of MTOW. A distinction is made between aircraft with 2 or less, 3 and 4 or more engines. The applicable limit is either set by a predefined minimum or maximum value or a logarithmic function, depending on MTOW.

Noise levels are indicated in *Effective perceived noise level* (EPNL). Values for EPNL are not directly measured but have to be calculated according to the specification, using the following steps:

1. Conversion of sound pressure level (SPL) to perceived noise level (PNL) by means of a noy table

2. Calculation of a tone correction factor (C)

3. Summation of tone correction factor and perceived noise level to obtain tone corrected perceived noise level (PNLT) and determination of the maximum value (PNLTM)

4. Calculation of a duration correction factor (D)

5. Determination of effective perceived noise level by adding the maximum tone corrected perceived noise level and the duration correction factor
(EPNL = PNLTM + D)

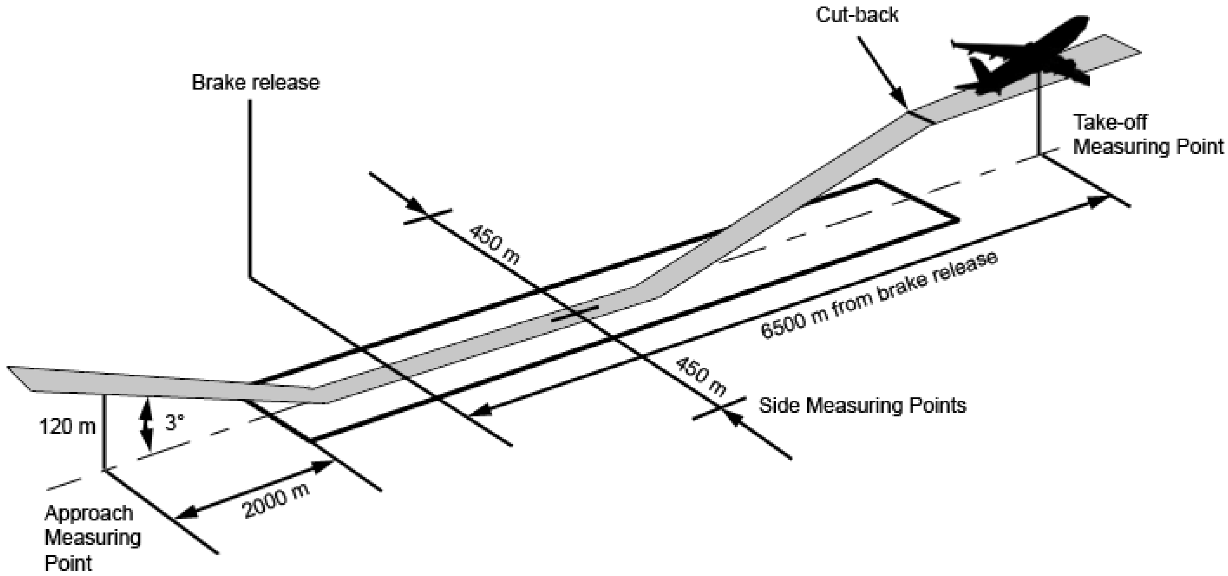


Figure A.1 Reference points for noise measurement (based on specifications by ICAO Annex 16, Vol I)

A.2 Volume II – Aircraft Engine Emissions

Volume II contains standards relating to emissions certification and is targeted at measurements of nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (HC) and smoke (SN) (ICAO 2008).

In order to provide standardized and comparable measurements, a reference procedure was defined, simulating a landing and take-off cycle (LTO) according to fig. A.2.

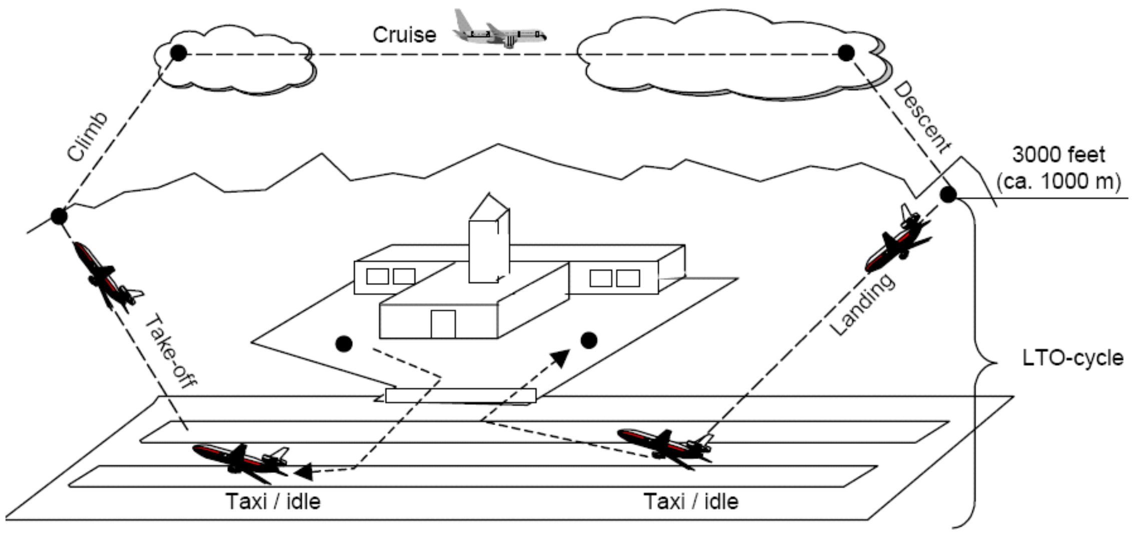


Figure A.2 LTO cycle (EMEP 2006)

During this procedure, the engine is tested at different thrust settings, representing several modes of operation, for a specified time as shown in table A.1.

Table A.1 LTO Operations

Operation mode	Engine Thrust (%)	Operating Time (min)
Approach	30	4
Taxi-in	7	19
Taxi-out	7	7
Take-off	100	0.7
Climb-out	85	2.2

The mode of taxi-in and taxi-out combined is also referred to as "Idle".

During this test, the concentrations of the defined species is measured at different probe sampling positions. From this, emission indices can be calculated by dividing mass of the emitted species by mass of fuel consumped.

Volume II further specifies detailed procedures, conditions and requirements, e. g. for agent analysers.

Regulatory limits for emissions are provided as well, which are defined for mass of pollutant over static maximum rated thrust at sea level (D_p/F_{oo}) as a function of pressure ratio of the engine, respectively of F_{oo} in case of smoke number.

A.3 Volume III – CO_2 Certification Requirement

Volume III is currently in development and not yet officially part of Annex 16, but is expected to be approved soon (ICAO 201x). This document establishes a CO_2 metric system based on fuel efficiency of the aircraft by making use of Specific Air Range (SAR). This indicates overall performance by taking into account structure, aerodynamics and propulsion. Three parameters have to be considered for the metric:

- Specific Air Range (measured during test flight)
- Aircraft size (factor representing fuselage width and length)
- Aircraft weight (MTOW)

Specific Air Range is defined for jet aircraft by (using the *Brueget factor*):

$$SAR = \frac{VE}{cgm} \tag{A.1}$$

It can also be determined by change of range over change of (fuel) mass, respectively velocity over fuel flow:

$$SAR = -\frac{dR}{dm} = \frac{V}{Q} \tag{A.2}$$

Volume III specifies the determination of SAR by measuring true air speed (TAS) and fuel flow at certain flight conditions:

$$SAR = \frac{TAS}{W_f} \tag{A.3}$$

The measurement shall be made at these three reference points in flight:

- High gross mass ($0.92 \cdot$ MTOW)
- Mid gross mass (Average of high gross mass and low gross mass)
- Low gross mass ($0.45 \cdot \text{MTOW} + 0.63 \cdot \text{MTOW}^{0.924}$)

Since gross mass can not be determined at any time during flight, it shall be determined by subtracting the fuel used from the mass of the aircraft at the start of the test flight.

The result of the CO_2 metric is calculated as follows:

$$\text{Value of the CO}_2\text{ emissions evaluation metric} = \frac{\left(\frac{1}{SAR}\right)_{AVG}}{RGF^{0.24}} \tag{A.4}$$

$\left(\frac{1}{SAR}\right)_{AVG}$ is the average of the three determined values of 1/SAR.

The Reference Geometric Factor (RFG) is a measure of fuselage size and is determined by a specifically defined area, which is defined by the pressurized area and a fuselage outer mould line (OML).

B Estimated SAR for Several Aircraft

Table B.1 Estimated 1/SAR for different aircraft, based on data from Roux 2007

Aircraft type	$m_{ave,total}$ (kg)	$m_{ICAO,ave}$ (kg)	Estimated 1/SAR (kg/100km)	error
A300 B2-100	123273	111409	685.79	0.106484
A300-600	143804	133882	607.20	0.074101
A310-200	115133	107391	477.80	0.072086
A318	52728	48479	209.35	0.087640
A319-100	57478	52534	229.27	0.094115
A320	62621	55774	257.86	0.122744
A321-200	78799	72755	484.56	0.083057
A330-300	196488	185899	575.83	0.056956
A340-300	209869	207456	619.66	0.011629
A380-800	446555	448111	1190.65	-0.003474
B707-120	93493	95326	439.99	-0.019239
B717-200	45289	41085	241.72	0.102318
B720	81527	84855	390.57	-0.039228
B727-100	62010	59499	351.15	0.042198
B737-200	41030	37396	203.37	0.097145
B747-400	291811	291772	935.33	0.000129
B757-300	106935	99728	434.41	0.072263
B767-400	172221	165251	569.92	0.042176
B777-200LR	276753	279797	702.28	-0.010881
B787-300	151808	132877	454.09	0.142462
B787-900	201777	197830	502.61	0.019948

C Flybe Rating Tables

C.1 Local Environment

Table C.1 flybe Rating Table: Noise (flybe 2007)

Rating	Average QC
A	0 – 0.177
B	0.177 – 0.354
C	0.354 – 0.707
D	0.707 – 1.414
E	1.414 – 2.828
F	> 2.828

Table C.2 flybe Rating Table: Take off & Landing CO_2 Emissions (flybe 2007)

Rating	LTO CO_2 Emissions (kg)
A	< 1000
B	1000 – 1999
C	2000 – 2999
D	3000 – 3999
E	4000 – 4999
F	> 5000

C.2 Journey Environment

Table C.3 flybe Table: Stage Length (flybe 2007)

Type	Distance (km)	Route	
Domestic	500	BRUBHX	Brussels to Birmingham
Near EU	1000	STNEBU	Stansted to St Etienne Boutheon
Short-Haul	1,500	LGWPMI	London Gatwick to Palma de Majorca
Medium Haul	3,000	BHXHER	Birmingham to Heraklion (Crete)
Long Haul	5,000	AMSYHZ	Schipol, Amsterdam to Halifax, Canada
Ultra Long Haul	10,000	FRALAX	Frankfurt to Los Angeles

Table C.4 flybe Rating Table: CO_2 Emissions (kg) Per Seat By Journey Length (flybe 2007)

Stage Length	A	B	C	D	E	F
Domestic	<35	36-45	46-54	55-63	64-73	>74
Near EU	<63	64-80	81-97	98-113	114-130	>131
Short Haul	<90	91-114	115-139	140-164	165-188	>189
Medium Haul	<173	174-211	212-250	251-289	290-327	>328
Long Haul	<278	279-346	347-414	415-482	483-550	>551
Ultra Long Haul	<871	872-928	929-985	986-1041	1042-1098	>1099

Table C.5 flybe Rating Table: Total Aircraft Fuel Consumption By Journey Length (flybe 2007)

Stage Length	A	B	C	D
Domestic	<1097	1098 – 2852	2853 – 4607	4608 – 6363
Near EU	<1948	1949 – 4837	4838 – 7726	7727 – 10616
Short Haul	<2802	2803 – 6832	6833 – 10862	10863 – 14891
Medium Haul	<9127	9128 – 15856	15857 – 22585	22586 – 29314
Long Haul	<13973	13974 – 25598	25599 – 37223	37224 – 48847
Ultra Long Haul	<104515	104516 – 109120	109121 – 113726	113727 – 118331

Stage Length	E	F
Domestic	6364 – 8118	>8119
Near EU	10617 – 13505	>13506
Short Haul	14892 – 18921	>18922
Medium Haul	29315 – 36044	>36045
Long Haul	48848 – 60472	>60473
Ultra Long Haul	118332 – 122936	>122937

D Quota Count

Quota Count is a simple system used in several airports such as Heathrow, Gatwick and Stansted in London as well as Madrid and Brussels. It classifies aircraft into seven categories based on certified noise levels. It is used as a system to control the noise level at night. The categories are defined in bands of EPNdB as defined in Annex 16 Vol I, each having a range of 3 EPNdB. The categories are then given a QC rating value from 0.25 to 16 that doubles to the next higher group according to table D.1.

Table D.1 Quota Count (Ollerhead 2002)

Noise Classification*	**Quota Count**
Below 84 EPNdB	Exempt
84 - 86.9 EPNdB	0.25
87 - 89.9 EPNdB	0.5
90 - 92.9 EPNdB	1
93 - 95.9 EPNdB	2
96 - 98.9 EPNdB	4
99 - 101.9 EPNdB	8
Greater than 101.9 EPNdB	16

*Effective Perceived Noise in decibels (EPNdB)

A separate Quota Count value is assigned to take-off and landing. For take-off, it is based on averaged certified flyover and sideline noise level and for landing, it is based on certified approach noise level, always with MTOW, respectively MLW. Some examples are given in table D.2.

Table D.2 Some QC examples (Source: Quota Count system/Wikipedia)

Aircraft type	**QC Departure**	**QC Arrival**
Airbus A320 family	0.5 - 1	0.25 - 0.5
Airbus A380	2	0.5
Boeing 737 Classic	0.25 - 0.5	1
Boeing 747-400	4	2
Boeing 747-8	2	1
Boeing 757-200	0.5	0.25
Boeing 767-300	1 - 2	1
Boeing 777-200ER	2	1
Embraer 145	0.25	0.25

E Individual Emissions Metric

E.1 Remarks

The following approach follows the concept of rating emissions individually. Hence, different emissions can be compared directly and overall uncertainty is low. However, it does not give information about the relative importance and interaction of emission agents with respect to environmental impact. Therefore, it was decided to conflate individual emissions by determining their overall particulate matter potential for the scheme of the label, which is then rated rather than vice versa (→ Section 6.9). The proposed metric for individual rating of emissions is provided for reference in the following.

E.2 Metric and Correlating Parameter

Emission measurements according to Annex 16, Vol II include statements of D_p/F_{oo}, meaning mass of pollutant divided by static maximum rated thrust at sea level of the engine. The smoke number is a dimensionless quantity determined by a formula based on reflectance of filter material.

The denominator links and normalizes emissions to capability of the engine. In case of smoke number, F_{oo} is part of a function for the regulatory limit.

Dividing the metric by its regulatory limit gives a normalized index that shows a percentage of the regulatory limit. For Dp/Foo, the regulatory limits are defined as a function of pressure ratio. This was done in order to allow engine manufacturers to comply with the standard, but not impose a certain way or design philosophy on how this is achieved.

As NO_x is a key indicator in engine emissions and advancement was achieved over time, new regulatory limits have been issued through amendments from time to time, the latest being CAEP/8. These are used as a basis for the sake of making NOx data comparable, although not all engines from the Engine Emission Data Bank comply with these. ICAO Emission Sheets generally provide data with respect to all previous limits.

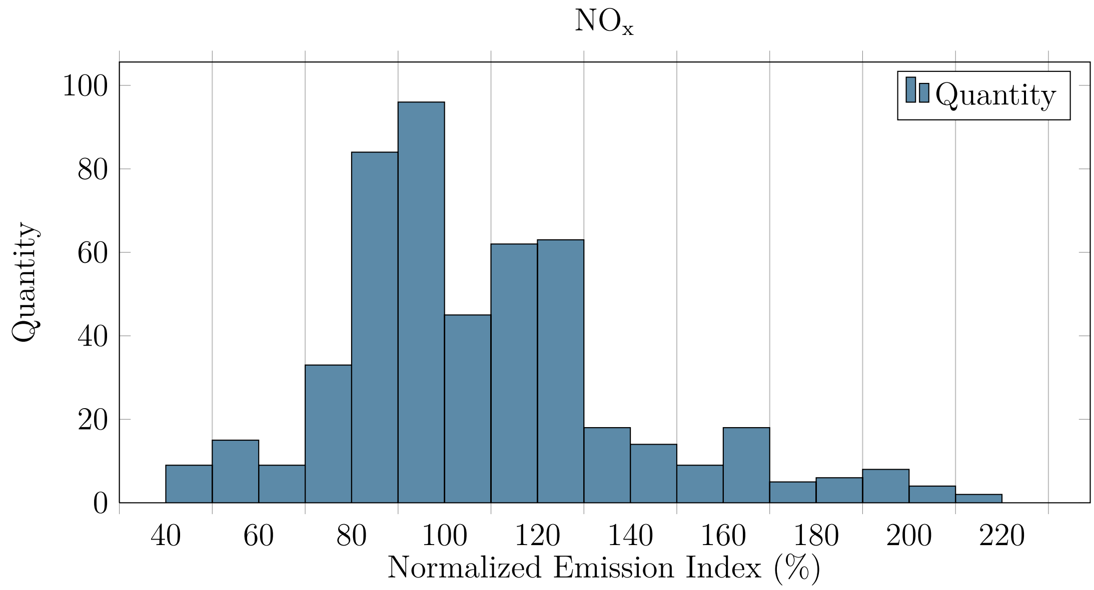
Emissions of HC, CO, NO_x and smoke number are issued as percentage of its regulatory limit as follows:

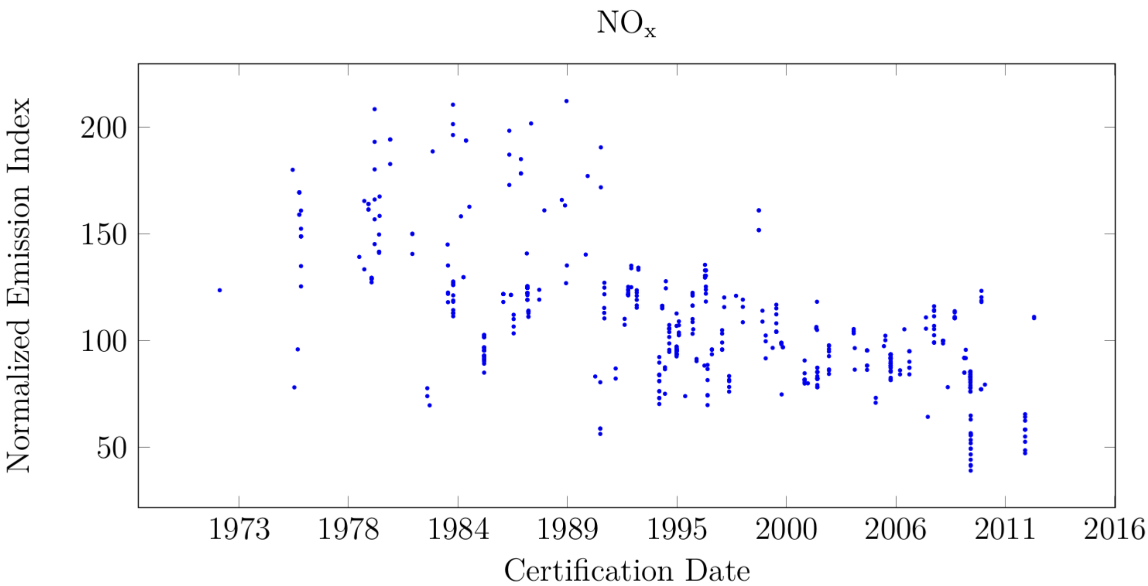
$$\text{Normalized Emission Index} = \frac{D_p/F_{oo} \text{ or Smoke Number}}{\text{Emission Limit}} \tag{E.1}$$

All data originates from the ICAO Engine Exhaust Emissions Data Bank hosted by EASA, last updated on March 7, 2014.

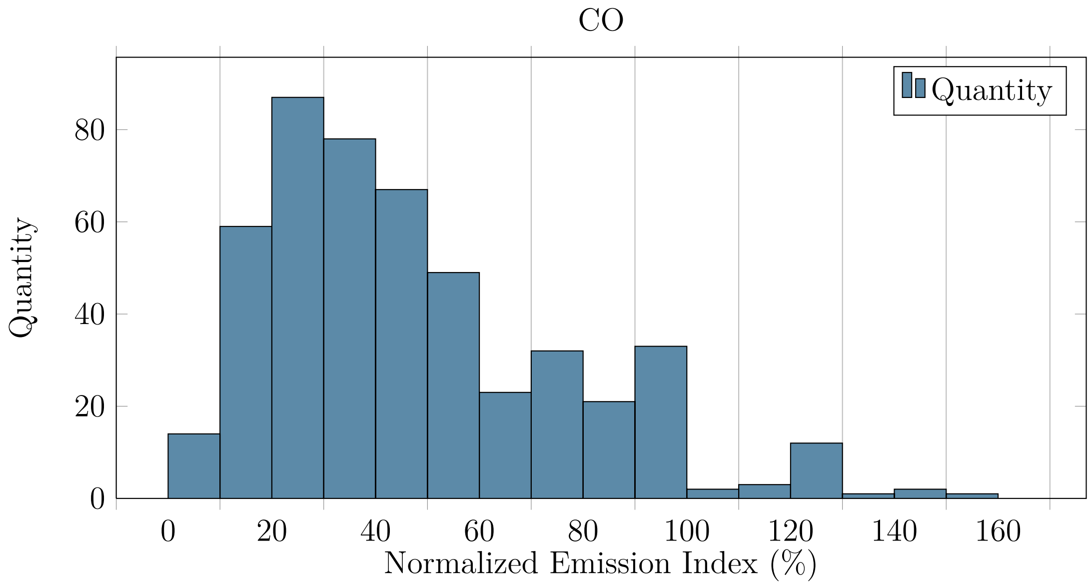
The following graphs depict the distributions of D_p/F_{oo}, respectively smoke number, over their regulatory limit (in percent) for NOx, CO, HC and smoke. The bin size has been adapted individually to show a characteristic picture of the distribution. Additionally, the distribution of values is shown over their certification date, showing how relative performance has changed over time.

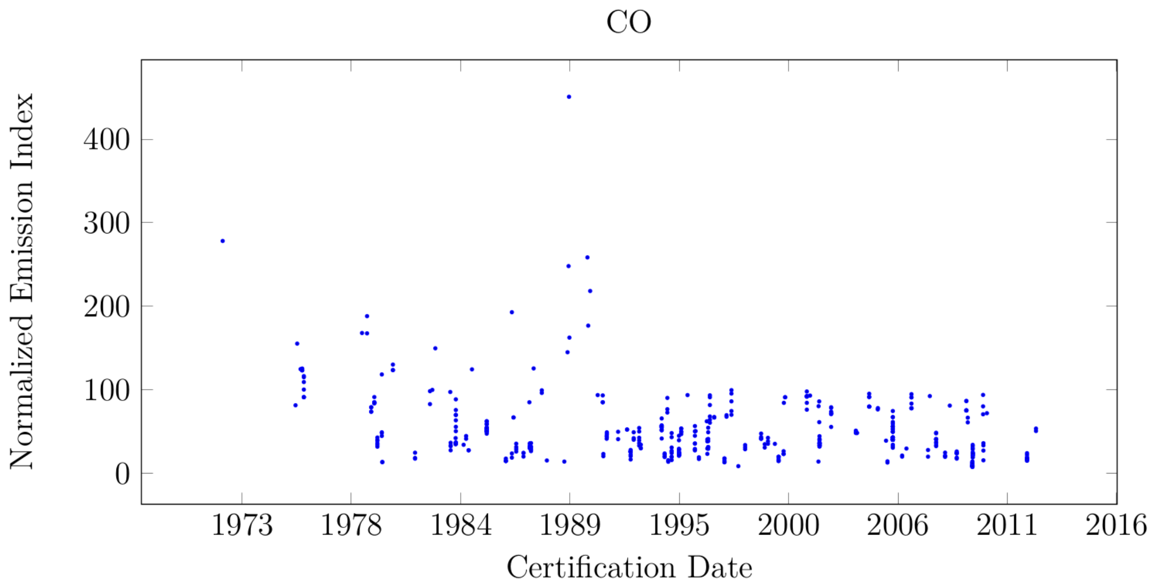
E.3 Nitrogen Oxides (NO_x)



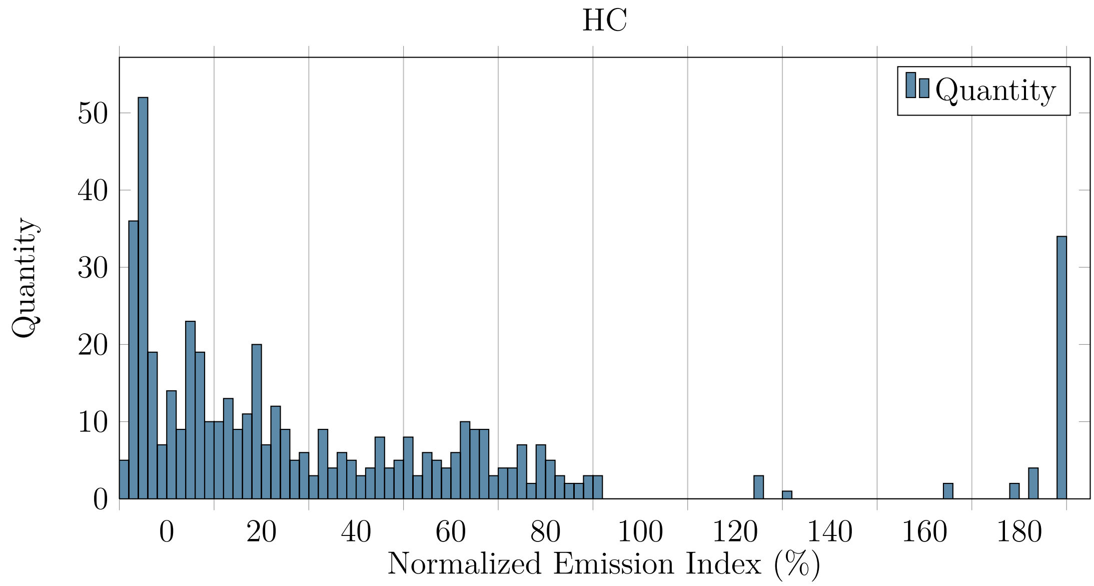


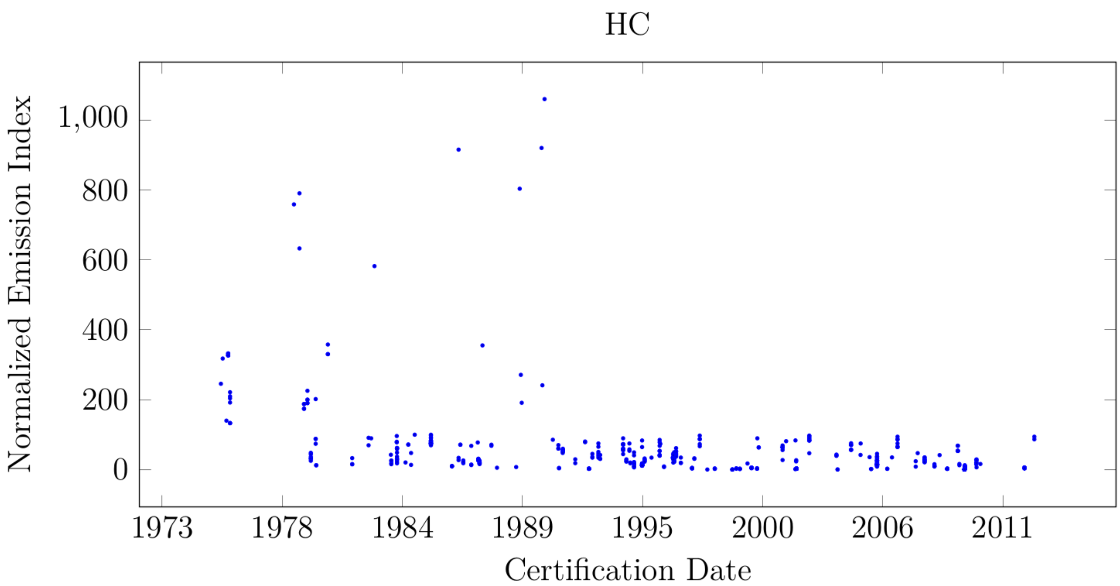
E.4 Carbon Monoxide (CO)



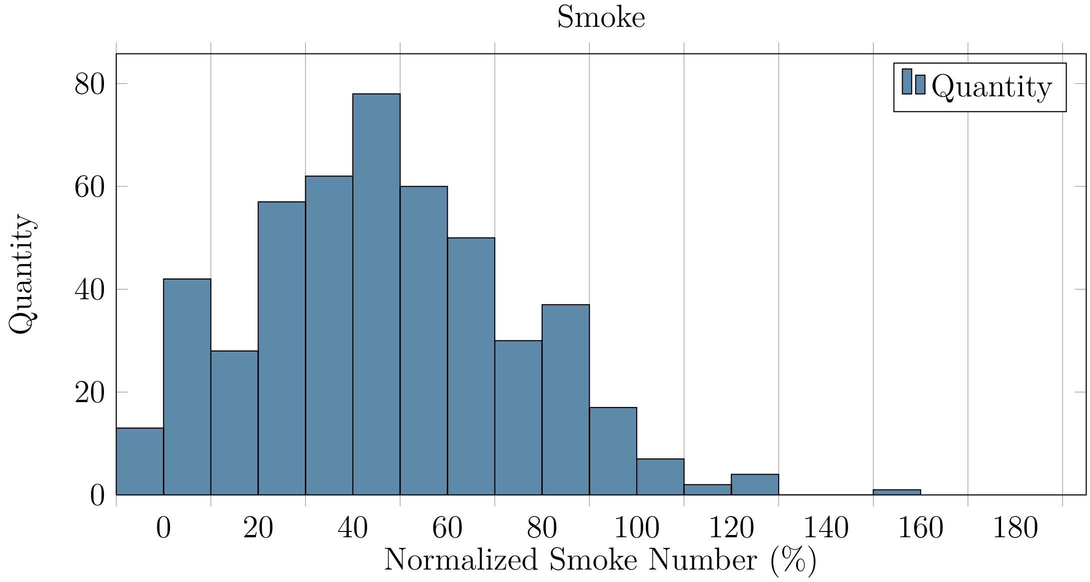


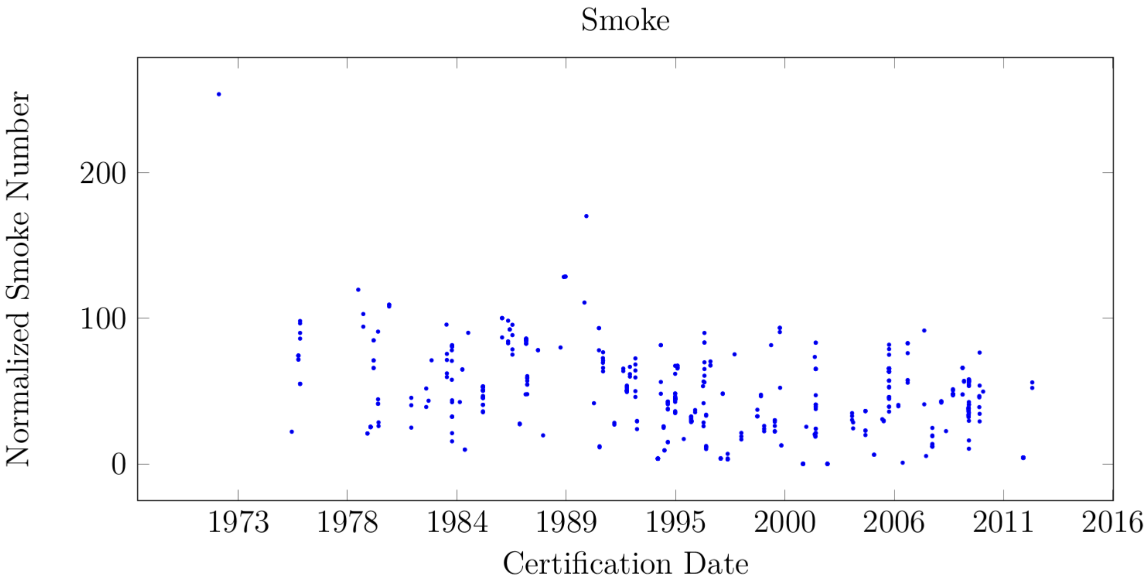
E.5 Hydrocarbons (HC)





E.6 Smoke


Smoke
Quantity
0
20
40
60
80
0
20
40
60
80
100
120
140
160
180
Normalized Smoke Number (%)
Quantity


Smoke
Normalized Smoke Number
0
100
200
1973
1978
1984
1989
1995
2000
2006
2011
2016
Certification Date

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