**Master Thesis**

# Definition of an Ecolabel for Aircraft

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# Abstract

In attempting to increase the environmental awareness in the aviation sector and to eliminate the green washing phenomenon, an investigation was done into the development and definition of an ecolabel for aircraft. Based on life cycle assessment it was found that aviation affects the environment most with the impact categories resource depletion and global warming (both due to fuel consumption), local air pollution (due to the nitrogen oxide emissions in the vicinity of airports) and noise pollution. For each impact category a calculation method was developed based solely on official, certified and publicly available data to meet the stated requirements of the ISO standards about environmental labeling. To ensure that every parameter is evaluated independent on aircraft size, which allows comparison between different aircraft, normalizing factors such as number of seats, rated thrust and noise level limits are used. Additionally, a travel class weighting factor is derived in order to account for the space occupied per seat in first class, business class and economy class. To finalize the ecolabel, the overall environmental impact is determined by weighting the contribution of each impact category. For each category a rating scale from A to G is developed to compare the performance of the aircraft with that of others. The harmonization of the scientific and environmental information, presented in an easy understandable label, enables the traveling customers to make a well informed and educated choice when booking a flight, selecting among airline offers with different types of aircraft and seating arrangements.

**DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING**

# Definition of an Ecolabel for Aircraft

Task for a *Master thesis* according to university regulations

## Background

It can be observed that new passenger aircraft are advertised with many claims about their environmental advantages compared to a reference model and compared to the competition. These advertisement claims are often not verifiable, not based on any reporting standards (due to a lack of such standards), and generally not backed up by reviewed scientific publications. Published PR information does not help the traveling public. The goal should be to inform the travelling passengers in a way that they can choose a service (an airline with a specific transport option and seating arrangement) and a product (an aircraft type) such that this selection is the least damaging to the environment. An "Ecolabel for Aircraft" should be defined to allow passengers to make this educated choice. A meaningful ecolabel should quantify energy consumption and pollution by way of index scores or units of measurement.

## Task

The task of this thesis is to define an Ecolabel for Aircraft in accordance with ISO 14025 (2006): Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures. A Type III environmental declaration can be described as "quantified environmental data for a product [or service] with pre-set categories of parameters based on the ISO 14040 (2006) series of standards [Environmental management – Life cycle assessment]." The Ecolabel for Aircraft can only be a simplified version of a full life cycle assessment, but should include the categories resource depletion, climate impact, local air quality, and noise pollution. It should be considered that some emission products ($CO_2$, $H_2O$, $SO_x$) are linked to the fuel and hence their emission mass is solely dependent on fuel usage while others ($NO_x$, CO, HC, Smoke) are also dependent on the combustion process of the engine. All categories should be rated on a scale from A to G. Initially an aircraft related rating should be calculated based on the standard cabin layout and its number of seats. If the airline uses a different cabin layout with a different number of seats, the overall rating changes. For each travel class – First Class (FC), Business Class (BC) and Economy Class (EC) – a separate weighting factor should be calculated based on the cabin floor area (seat pitch times seat width) occupied by the respective seat. All input data for the calculations should be taken from open sources on the Internet and from known aircraft parameters.

The detailed tasks are:

- Discuss the ISO standards for environmental labeling and how they are applied to the "Ecolabel for Aircraft".
- Perform a literature study about existing labeling schemes and evaluate them.
- Define a method to calculate the environmental impact for each category (resource depletion, climate impact, ...).
- Develop a tool that calculates all parameters of the "Ecolabel for Aircraft" and automatically generates the label itself as designed with the most important parameters embedded. Develop a tool for the travelling public to adapt existing labels to a certain seat layout of a certain aircraft operated by a certain airline.
- Calculate ecolabels for some selected aircraft and discuss the results.
- Discuss the overall benefits of the defined "Ecolabel for Aircraft" and propose work on issues that are still open or would warrant improvement.

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

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# List of Symbols

| | |
|---|---|
| $c$ | Specific fuel consumption |
| $C$ | Fuel consumption |
| $C_L$ | Lift coefficient |
| $C_{L,max,landing}$ | Maximum lift coefficient in landing configuration |
| $E$ | Glide ratio |
| $E_i$ | Amount of emitted specie |
| $F_{oo}$ | Thrust |
| $g$ | Gravitational acceleration |
| $H$ | Humidity correction factor |
| $h$ | Altitude |
| $h_{cr}$ | Cruise altitude |
| $k$ | Class weighting factor |
| $k_L$ | Landing coefficient |
| $L$ | Stage length |
| $m$ | mass |
| $m_{MTOW}$ | Maximum take-off mass |
| $m_{ML}$ | Maximum landing mass |
| $M_{cr}$ | Cruise Mach number |
| $n$ | Number of seats |
| $n_E$ | Number of engines |
| $p_0$ | Pressure at sea level/standard conditions |
| $p(h)$ | Ambient pressure |
| $Q$ | Volumetric core fuel rate |
| $R$ | Range |
| $r$ | Correction factor of Boeing |

| | |
|---|---|
| $S$ | Seat area |
| $S_w$ | Wing area |
| $s$ | Radiative forcing factor |
| $s_{LFL}$ | Landing field length |
| $SN$ | Smoke number |
| $T_0$ | Temperature at sea level/standard conditions |
| $V$ | Speed |
| $V_{TAS}$ | True airspeed |
| $W_f$ | Fuel flow |

# Greek Symbols

| | |
|---|---|
| $\gamma$ | Ratio of specific heats |
| $\delta_{amb}$ | Ratio of the ambient pressure and the pressure at sea level |
| $\theta$ | Ratio of the ambient temperature and the temperature at sea level |
| $\sigma$ | Ratio of the ambient pressure and the pressure at sea level |

# List of Abbrevations

| | |
|---|---|
| AFR | Air-to-Fuel Ratio |
| BC | Business Class |
| BFFM2 | Boeing Fuel Flow Method 2 |
| CAEP | Committee on Aviation Environmental Protection |
| Ceo | Classical engine option |
| CI | Concentration Index |
| DGAC | Direction Générale de l'Aviation Civile |
| EASA | European Aviation Safety Agency |
| EC | Economy Class |
| EEA | European Environment Agency |
| EI | Emission Index |
| EPNdB | Effective Perceived Noise Levels in dB |
| FC | First Class |
| GWP | Global Warming Potential |
| IATA | International Air Transport Association |
| ICAO | International Civil Aviation Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISA | International Standard Atmosphere |
| ISO | International Organization for Standardization |
| LTO | Landing and Take-off Cycle |
| MTOW | Maximum Take-Off Weight |
| MV | Metric Value |
| Neo | New engine option |
| NMVOC | Non-Methane Volatile Organic Compound |
| OEM | Original Equipment Manufacturer |

| | |
|---|---|
| PCR | Product Category Rules |
| PDCA | Plan-Do-Check-Act |
| PEC | Premium Economy Class |
| PM | Particular Matter |
| RF | Radiative Forcing |
| RFI | Radiative Forcing Index |
| RGF | Reference Geometric Factor |
| SAR | Specific Air Range |
| SGTP | Sustainable Global Temperature Potential |
| SI-units | Standard International units |
| TCDSN | Type-Certificate Data Sheet for Noise |

# 1 Introduction

## 1.1 Motivation

It can be observed, that the environmental awareness is a central growing topic of mankind. Almost every product or service on the market is provided with a certain ecolabel and/or an energy label. These labels tend to inform customers about the environmental impact of the product that they are interested in or that they want to purchase. In this manner, the costumer is able to make a well-considered decision about a certain service and/or product. The labels have two main purposes: first of all, the goal of the labels is to influence purchasing decisions by customers in favour of products with the least disadvantaged impact on the environment. The second purpose of the labels is to encourage manufactures to optimise each parameter of their product.

At this point this tendency of growing environmental awareness is not followed by the aviation industry. New passenger aircraft are advertised with claims about their environmental advantages, but most of the time these claims cannot be verified due to a lack of standards or scientific backup. This phenomenon is called ‘green washing’. Therefore, the idea of an ecolabel for aircraft rose. The purpose is to create objective and standardized information, which is harmonized in one document also called ‘ecolabel’.

This thesis focuses on the development of the ecolabel according to the ISO standards. The label includes parameters as resource depletion, climate impact, local air quality and noise pollution. With these four parameters, the travelling public should be properly informed about the environmental impact their journey would create.

## 1.2 Terms and Definitions

**Definition** Wikipedia based its definition of a definition on Bickenbach 1996 and ‘Semantics, vol. I’ of Lyons 1977:

> *“A definition is a summary description of the characteristics of an understanding so that it cannot be confused with another. Definitions can be classified into two large categories, intensional definitions (which try to give the essence of a term) and extensional definitions (which proceed by listing the objects that a term describes).”*

**Ecolabel** The online dictionary of the University of Cambridge that an ecolabel can be defined as:

> *"An official symbol that shows that a product has been designed to do less harm to the environment than similar products." (**Cambridge University Press 2017**)*

**Aircraft** An Aircraft can be defined as a vehicle or machine that is capable of flying such as an aeroplane or a helicopter. The definition of an aircraft provided by ICAO is as follows:

> *"Aircraft: Any machine that can derive support in the atmosphere from the reaction of the air." (**ICAO 1990**)*

## 1.3 Objectives

This thesis presents the metric systems developed for each parameter included in the label. Indicators that are included in the label are fuel consumption, climate impact in terms of CO2-equivalents, air quality in terms of emitted NOx and noise pollution. With these metric systems the rating scales are derived and used in the ecolabel. Furthermore, calculation tools as well as tools to generate the label are created and explained in this work. Finally some examples of ecolabels are calculated and compared with each other.

## 1.4 Structure of the Thesis

This work consists of 8 chapters. The structure of the thesis is as follow:

| | |
|---|---|
| **Chapter 2** | In this chapter the ISO standards for environmental labels will be discussed. It will clarify the requirements of the ecolabel which have to be met. |
| **Chapter 3** | A brief literature study about already existing ecolabels in the aviation industry as well as in the car sector. |
| **Chapter 4** | The development of the metric systems, formulas and definitions as well as the rating scales of each parameter are presented in this chapter. |

| | |
|---|---|
| **Chapter 5** | The developed tools to calculate and generate the ecolabel are explained on the basis of an example. |
| **Chapter 6** | The calculated ecolabels are discussed and compared with each other in this chapter. |
| **Chapter 7** | This chapter provides the conclusion of the thesis. |
| **Chapter 8** | Recommendations and future work is explained in this chapter. |

# 2 ISO Standards for Environmental Labels

## 2.1 General Information

The International Organization for Standardization, also called ISO, created the ISO 14000 standard family. These standards are focussed on the environment and environmental related management. The ISO 14000 standards can be divided into specific and more detailed standards which can be placed in a Plan-Do-Check-Act (PDCA) circle. In the context of this research, the use of the ISO 14020 standard is appropriate.

The ISO 14020 standard defines various approaches to use environmental labels and declarations. Also they say something about the kind of communication that is necessary in the different cases. This means that the standard can be placed in the acting phase of the PDCA circle (**ISO 2009**). More specifically ISO 14020 describes three types of labeling. All of them are located on voluntary base.

> *"Type I is a multiple-criteria-based labeling method which is authorized by a third party. The labels on products indicate overall environmental preferability of a product within a particular product category based on life cycle considerations". (**ISO 14024:1999**)*

This standard states all the necessary procedures like for example the selection and development of product environmental criteria, selection of product categories and certification processes. (**ISO 14024:1999**)

The type II-labeling method consists of self-declared environmental claims. For this reason they do not need a third party to provide the authorization to make an environmental statement.

> *"The claim can be made by manufacturers, distributors or anyone else likely to benefit from such claims". (**ISO 14021:1999**)*

The top priority of a type II label is its trustworthiness. It has to be avoided that the market will be negatively affected due to misleading environmental claims. A self-declared claim about a product can be presented in several manners such as a package label, an official statement, a symbol, as advertising or on electronic media. (**ISO 14021:1999**)

The type III-method exists out of environmental declarations that are aimed for a business-to-business communication. They describe "Quantified environmental data using predetermined parameters which are based on a life cycle assessment of a product (**ISO 14040:2006**) and, where relevant, additional environmental information". This makes it possible to compare products which have the same function. The administration of the environmental declaration has to be subjected to a programme operator which should be preferably a scientific organization. (**ISO 14025:2006**)

## 2.2 The Ecolabel for Aircraft

Generally the ecolabel for aircraft is defined according to ISO 14025 (2006): Environmental labels and declarations-Type III environmental declarations-principles and procedures. This standard contains several principles and requirements which have to be fulfilled by this label. These principles and requirements are listed below.

- The label has to be voluntary
- The label has to be life cycle based
- The label has to be verifiable
- The label has to be open for interested parties
- The label has to be transparent
- The label has to be flexible
- The label allows comparing different offers
- The label can be calculated by anyone

Also a third party should be found to operate as programme operator. Preferable this should be a scientific organization, but it can also be a public authority or a group of companies. The programme operator is responsible for the administration of the ecolabel. Therein one of its tasks is to develop a document with the product category rules (PCR). "The PCR is a set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories" (**ISO 14025:2006**). In the case of the ecolabel the PCR defines the service as the flight of the aircraft and the product as the aircraft itself. These PCR making it easy to obtain transparency and, verification and comparison.

The ecolabel for aircraft provides information which is intended for two types of audience: a business orientated group of people (called experts) and the travelling public. To make sure both target groups understand the offered information, two different ISO standards are used. An environmental declaration is used to provide the information to the experts. The travelling public obtains the information in a compressed form as an environmental label according to ISO 14021 Type II standard. This label is based on the well-known energy labels with a scale from A to G for every performance category. This scale is chosen because recently the EU Commission proposed to go back to this original scale for simplicity (**EU Commission 2015**).

To fulfil the requirements of transparency, verification, the possibility to compare different offers and the possibility that everyone can calculated the label, all input data used for the calculations in Chapter 4 are taken from open sources and available database on the internet such as the Engine Emission Data Bank or the Noise Data Bank.

# 3 Examples of Existing Ecolabels

Introductory a literature study has to be executed about existing ecolabels. This shall provide a good insight in already available procedures in calculating an environmental label and can help in the development of new rating methods. It could also be possible that the study reveals flaws or deficiencies in these existing schemes. Research disclosed that there is only one ecolabel elaborated in the aviation sector. The airline that launched it on the market is called Flybe. They made it public available with the intention that other airlines afterwards would be encouraged to use their ecolabel scheme as well. Their label will be discussed in the following paragraphs. Out of the reason that there exists so little available information and procedures in the aviation sector, also an environmental label of another product category will be discussed.

## 3.1 Flybe's Ecolabel

The airline that first came up with an ecolabel scheme for their fleet is called Flybe. Flybe is a British airline based in Exeter which is a city in the shire Devon. They are also the largest independent airline of Europe which focused its business activities on regional flights. Therefore they feel responsible to reduce the contribution of their fleet to global climate change. In the past few years they invested in new aircraft to improve the fuel burn efficiency and to reduce the noise pollution and carbon dioxide emissions of their fleet. Flybe's current fleet is stated in Table 3.1.

**Table 3. 1** Aircraft of Flybe which are in service (**CAA 2017**)

| Aircraft | In service |
|---|---|
| ATR 72-200 | 5 |
| Bombardier Dash 8 Q400 | 58 |
| Embraer ERJ 170-200 | 11 |
| Embraer ERJ 190-200 | 9 |
| **Total** | **83** |

Flybe presented the ecolabel for their fleet in 2007. The development of the labeling scheme was based on the energy labels used on household appliances like refrigerators, microwaves and other electronic devices. They displayed the label on their aircraft, in the onboard literature, in the company's advertising campaigns and on the online ticket booking process. To encourage other air carriers to adopt the labeling scheme, Flybe created a public available guide that explains how the ecolabel can be produced (**Flybe 2007**). Afterwards no other airline used the suggested labeling scheme.

Generally the label includes the environmental effects on the local environment near airports, the global environment of the total journey and the passenger environment inside of the aircraft.

These mentioned effects are noise, air pollution due to NOx-emissions and climate change due to carbon dioxide emissions. Information about the legroom of the passengers also called seat pitch is provided as well. These four indicators will be rated in a self-defined scale from A to G. In this manner the travelling public should be able to make a decision about the trade-off between passenger comfort, price and environmental impact.

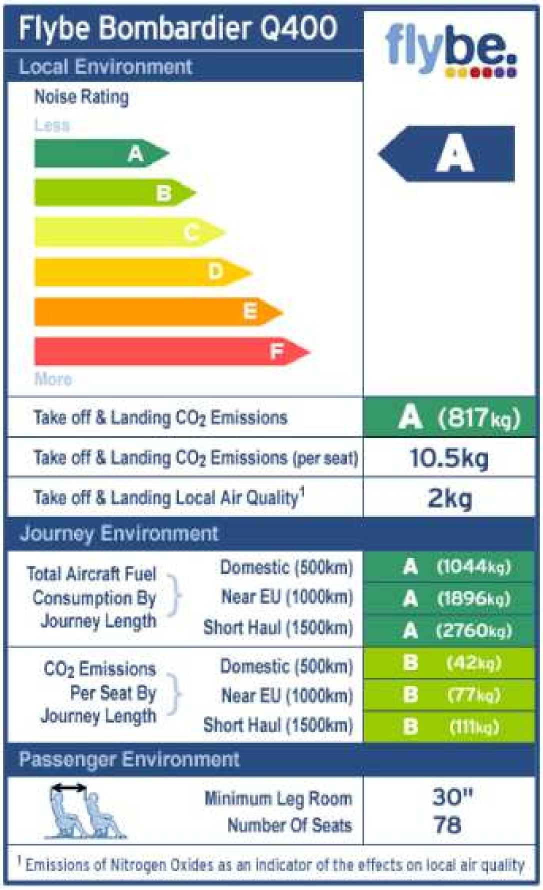
The environment data included in the ecolabels is evaluated by the independent assurance company Deloitte & Touche LLP. In their assurance statement it is mentioned that a review and a sample test was executed of the collation, aggregation, validation and reporting of (**Deloitte 2007**):

- Journey fuel consumption (kg) for domestic, near EU and short haul flights
- $CO_2$-emissions during the landing and take-off cycle (LTO) and also per seat during 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 seat onboard the aircraft

Deloitte assures the correctness of the environment data:

> *"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." (**Deloitte 2007**)*

An example of a Flybe's ecolabel is given in Figure 3.1:



Flybe Bombardier Q400

flybe.

Local Environment

Noise Rating

Less

A

B

C

D

E

F

More

A

| | |
|---|---|
| Take off & Landing $CO_2$ Emissions | A (817kg) |
| Take off & Landing $CO_2$ Emissions (per seat) | 10.5kg |
| Take off & Landing Local Air Quality[1] | 2kg |

Journey Environment

| | | |
|---|---|---|
| Total Aircraft Fuel Consumption By Journey Length | Domestic (500km) | A (1044kg) |
| | Near EU (1000km) | A (1896kg) |
| | Short Haul (1500km) | A (2760kg) |
| $CO_2$ Emissions Per Seat By Journey Length | Domestic (500km) | B (42kg) |
| | Near EU (1000km) | B (77kg) |
| | Short Haul (1500km) | B (111kg) |

Passenger Environment

| | |
|---|---|
| Minimum Leg Room | 30" |
| Number Of Seats | 78 |

[1] Emissions of Nitrogen Oxides as an indicator of the effects on local air quality

**Figure 3. 1** Example of an ecolabel of Flybe (**Flybe 2007**)

In the upcoming paragraphs the calculations of all the aspects included in the Flybe's ecolabel will be reviewed. Also the potentials deficiencies will be discussed. Due to the many possibilities of aircraft/engine configuration as well as seat layout, it is recommended to produce an ecolabel for each aircraft separately (**Flybe 2007**).

### 3.1.1 Local Environment

As stated before, the local environment describes the environmental impact of the airplane near airports. This includes the noise pollution during the landing and take-off cycle (LTO), the $CO_2$-emissions during LTO and the local air pollution near the airport due to $NO_x$-emissions during LTO. The LTO cycle is defined by ICAO Annex 16 Volume II, given in Appendix A.

## Noise during LTO

To rate the noise pollution the Quota Count system is used. This is a method used at several airports such as Heathrow and Gatwick. The method is created to limit the noise caused by aircraft movements during night time (22:00-06:00 hour). The method is rated into 7 categories which are based on the certified noise data of aircraft. Because an increase of three EPNdB (Effective Perceived Noise level in decibel) results in a noise energy that doubles, the categories are sized into a range of three EPNdB. This results in a Quota Count value that doubles with each category. The rating scale is given in Table 3.2, which is taken from ACL 2013:

**Table 3. 2** Rating scale of Quota Count system (**ACL 2013**)

| Noise level in EPNdB | Quota Count value |
|---|---|
| Smaller than 84,0 | 0 or Exempt |
| 84,0 – 86,9 | 0,25 |
| 87,0 – 89,9 | 0,50 |
| 90,0 – 92,9 | 1,0 |
| 93,0 – 95,9 | 2,0 |
| 96,0 – 98,9 | 4,0 |
| 99,0 – 101,9 | 8,0 |
| Greater than 101,9 | 16 |

The Quota Count value for take-off and landing are calculated separately according to the following formulas (**ACL 2013**):

$$Quota\ Count\ value_{take-off} = \frac{EPNL(lateral) + EPNL\ (flyover)}{2} \tag{3.1}$$

$$Quota\ Count\ value_{landing} = EPNL(approach) - 9\ EPNdB \tag{3.2}$$

With EPNL(lateral, flyover, approach): The effective perceived noise levels at the different reference points according to ICAO Annex 16 Volume I which is further explained in Appendix B.

In the ecolabel the noise effect is rated according to the average of the Quota Count values for take-off and landing. The rating scale of Flybe for the average Quota Count is given in Table C.1 in Appendix C.

## $CO_2$-emissions during LTO

The $CO_2$-emissions can be calculated with the fuel burn during the LTO cycle up to an altitude of 3000 feet, the number of engines and the emission index of $CO_2$. The emission index of $CO_2$ shows the produced $CO_2$ per kilogram of burned fuel. In the case of carbon dioxide this is a constant factor namely 3,15 kg/kg fuel. The number of engines and the fuel burn are obtained from the ICAO Engine Emissions Databank.

The ICAO Engine Emissions Databank is a voluntary database for engine manufactures. They provide information about the exhaust emissions tests of their engines in the LTO cycle which are measured according to Annex 16 volume II. This information is collected in one database which is hosted by the European Aviation Safety Agency (EASA) on behalf of ICAO. The databank is frequently updated which depends on the availability of new data. The following parameters are included in the ICAO Engine Emissions Databank (**EASA 2017a**):

- Unique identification number and engine identification
- Engine type
- Engine characteristics: bypass ratio, pressure ratio, rated output
- Number of engines and tests
- Emission indices for HC,CO and $NO_x$ at each operation mode
- Total amount of emissions of HC, CO and $NO_x$ during LTO
- Smoke number of the engine at each operation mode
- Fuel flow of the engine at each operation mode
- Total amount of fuel burned during LTO
- Fuel type
- Atmospheric conditions
- Test location, date and organization

To award the label the following calculations were performed. First the fuel burn for the total aircraft is calculated by multiplying the total used fuel during LTO with the number of engines.

$$(Total\ fuel\ burn)_{aircraft,LTO} = (Total\ fuel\ burn)_{engine,LTO} \cdot n_E \tag{3.3}$$

To obtain the amount of emitted $CO_2$, the total fuel burn of the aircraft is multiplied with emission index of $CO_2$.

$$(Emitted\ CO_2)_{LTO} = (Total\ fuel\ burn)_{aircraft,LTO} \cdot 3{,}15 \tag{3.4}$$

This result is rated according to the scale given in Table C.2 of Appendix C. Also the emitted $CO_2$ per seat is included in the label. The number of seats is chosen because it is an inherent parameter of the aircraft. The number of passengers differs each flight and would be meaningless to use for the calculation.

$$(Emitted\ CO_2\ per\ seat)_{LTO} = \frac{(Emitted\ CO_2)_{LTO}}{n} \tag{3.5}$$

**$NO_x$-emissions during LTO**

The air quality in the surrounded areas close to the airport can be affected by the nitrogen oxides in these air zones. Therefore the $NO_x$-emissions during the LTO cycle represent the effects of aircraft movement on the local air quality in the ecolabel. The amount of emitted $NO_x$ for the engine can be directly obtained from the ICAO Engine Emission Databank, but still has to be multiplied with the number of engines. In this manner the amount of emitted $NO_x$ for the total aircraft can be achieved.

### 3.1.2 Journey Environment

This section of the label takes into account how the global environment is affected by the complete flight through $CO_2$-emissions. Again the fuel burn of the aircraft as well as the number of seats and the emission index of $CO_2$ are necessary to calculate the environmental impact. Flybe claims that it is well known how much fuel each aircraft consumes on certain routes. Therefore the flight plan will be used to obtain the fuel burn of the aircraft. Due to the fact that the used fuel varies with range of the flight, 6 standard stage lengths are defined in Table 3.3 based on a specific route. This makes it possible to compare fuel consumption data and $CO_2$-emissions of different aircraft.

**Table 3. 3** The standard stage lengths for the ecolabel scheme of Flybe (**Flybe 2007**)

| Journey type | Distance (km) | Route | |
|---|---|---|---|
| Domestic | 500 | BRUBHX | Brussels to Birmingham |
| Near EU | 1000 | STNEBU | Stansted to St. Etienne Boutheon |
| Short-haul | 1500 | LGWPMI | London Gatwick to Palma de Majorca |
| Medium haul | 3000 | BHXHER | Birmingham to Heraklion (Crete) |
| Long haul | 5000 | AMSYHZ | Schiphol, Amsterdam to Halifax, Canada |
| Ultra-long haul | 10000 | FRALAX | Frankfurt to Los Angeles |

Once the amount of fuel burn is determined from the flight plan, this can be rated according to the rating scale given in Table C.3 in Appendix C. To calculate the $CO_2$-emissions the same formulas can be used as in subchapter 3.1.1.2. This result can again be rated to the scale given in Table C.4 in Appendix C.

### 3.1.3 Passenger Environment

In this section the key parameter is the minimum seat pitch, also called legroom. The seat pitch is connected to the amount of seats as well as to the passenger comfort. So the more seats in the aircraft, the smaller the seat pitch will be. The smaller the seat pitch, the less legroom the passenger will have which results in a lower passenger comfort. This information is included in the ecolabel to sensitize the consumer for the trade-off he/she has to make between comfort and environmental impact because more space and thus more comfort per seat results in an increase of the $CO_2$-emissions per seat.

### 3.1.4 Deficiencies of the Ecolabel

The methods developed by Flybe for the ecolabel show some deficiencies in their reasoning.

First of all the use of the Quota Count method for the noise rating does not take the size of the aircraft in consideration. Physically it is logic that a larger aircraft which can carry more payload will be heavier. Therefore the airplane has to be equipped with more powerful engines to achieve the extra required thrust and will be eventually louder. This means that larger aircraft are misappreciated with the current rating method. This should not be case. Every airplane should be rated equally. There is even a second shortcoming in the noise rating. The Quota Count method already performs an appraisal based on certified noise data by giving a score to various noise level bands. By taking the average of the Quota Count scores for take-off and landing to determine the value for the noise rating and rate it according the scale developed by Flybe, the accuracy of the actual values decreases. Thus the procedure leads to a double rating which is totally not necessary.

Furthermore the calculation of the $CO_2$-emissions during the LTO cycle does not value the capability of the aircraft. The amount of carbon dioxide is determined only with the fuel burn characteristics of the engine. Memento: the heavier and larger aircraft are disadvantaged because they need more fuel to carry out the LTO settings. Furthermore the environmental effects on the local air quality are rated with an absolute value for the amount of $NO_x$-emissions in the vicinity of the airport. Memento: this results in a rating which does not acknowledge the performance of the engines. Therefore the value for the amount of nitrogen oxides is rather meaningfulness.

In the section of the journey environment the climate change effect on the global environment is determined by the amount of $CO_2$ produced during the total journey. The amount of fuel that will be used during the whole flight is provided by the flight plan. This is an empirical value without a clear explanation and specification. This leads to a lack of traceability and transparency of necessary data. The use of this non-official value for the fuel burn results in a procedure that cannot be repeated. This conflicts with the ISO 10425 standard which stated that a repeatable method should be developed to guarantee the transparency and verifiability of the ecolabel scheme (**ISO 10425:2006**).

The rating scales themselves are a doubtful part of the ecolabel. They are defined with a classification system from A to G which is based on a certain criteria. This criteria covers certain ranges, for example average Quota Count values, but it stays unclear how these ranges are determined. It is also uncertain if the rating scales are suitable for different aircraft of other airlines as the ecolabel is applied to the fleet of Flybe. It could be possible that the scales are only defined to fulfill the needs of Flybe (**Hass 2015**).

At last a remark can be made about the label design itself. Almost half of the label is covered by the noise rating which is not very clearly stated on the label. Therefore this rating could be easily misinterpreted as a sort of overall rating. It is only one indicator of the label and should be presented equally with respect to the other indicators.

## 3.2 Environmental Label of Tire Fuel Efficiency

The purpose of the label for tires of passenger cars and light-commercial vehicles is to inform the purchaser about the characterization factors of a tire. In this manner the purchaser is encouraged to buy tires that are safer, quieter and more fuel-efficient. The label exists out of three parameters that are rated on a scale from A to G. These parameters are defined as the rolling resistance coefficient which determines the fuel efficiency of the tire, the wet grip of the tire and the rolling noise of the tire (**EUR-LEX 2012**).

The calculation methods and the measure procedures as well as the rating scales of each indicator are given in the regulation (EC) No 1222/2009 ‘Labelling of tyres with respect to fuel efficiency and other essential parameters’. This document also provides specifications about the design of the label and the technical promotional material as well as the responsibilities of each party and verification procedures. In illustrative example of a label is given in Figure 3.2.

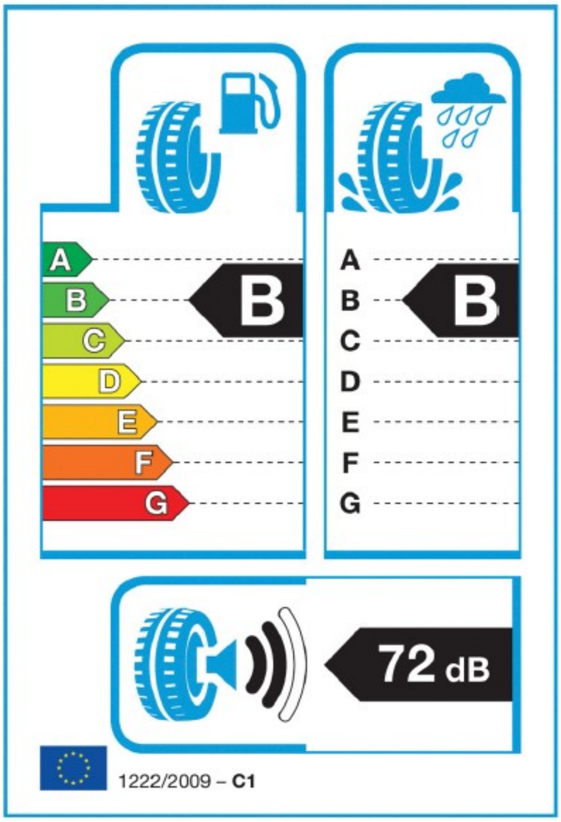


**Figure 3. 2** Illustrative example of environmental label for tires (**EUR-LEX 2015**)

The solely usage of pictograms could lead to ignorance of the parameters. Therefore, the suppliers of tires are obligated to provide a description of each pictogram on their webpage. It can be argued that this is a disadvantage of the label. Furthermore the absence of a value for the wet grip performance as well as the fuel efficiency is discussable.

On the other hand it can be stated that the pictogram of the noise rating, as well as the rating scales of the two other parameters, are easy to read and comprehend. It is for everybody logical that a B-rating is better than an F-rating. The same applies for the rating of the noise. It is logical that a tire with a full black-colored pictogram produces more noise than a tire with a pictogram that has only one or two bars colored black.

It can be concluded that the label of the tire fuel efficiency is a good example. Therefore, the design of the ecolabel for aircraft will be based on this example.

# 4 Calculations for an Ecolabel for Aircraft

Based on the previous work of Tim Hass 2015 and the PhD of Andreas Johanning 2016 about life cycle assessment in aircraft design, the ecolabel will assess the environmental impact of aircraft through rating the following categories:

- Resource depletion
- Climate impact
- Local air quality
- Noise pollution

More specific the fuel consumption of the aircraft will be analyzed as well as the produced emissions and noise pollution during the LTO cycle. Also the severity level of nitrogen oxide emissions, contrails and cirrus clouds produced during the cruise flight will be examined. Finally each category will be provided with a weighting factor which makes it possible to include an overall rating of the aircraft in the ecolabel.

## 4.1 Resource Depletion and Fuel Consumption

The resource depletion can be defined by the fuel consumption of the airplane. To make comparison of fuel performance of different aircraft possible, a standardized metric should be developed. ICAO has recently defined such a metric, called the $CO_2$ metric which is determined according to ICAO Annex 16 Volume III. It uses the specific air range (SAR). This is a parameter which directly indicates the fuel consumption of the aircraft. However these developed procedures of ICAO are ready to be applied, there is still no official certified data for the SAR available. This $CO_2$ metric system will be further discussed in section 4.1.5. An own standard will be developed to assess the fuel performance of aircraft for the ecolabel for aircraft. This metric is also based on the SAR and will be explained in the following.

### 4.1.1 Determination of SAR

The specific air range is defined as the ratio between the true airspeed and the gross fuel consumption. These parameters could be determined by doing a measurement during test flights. Unfortunately this data is not publicly available. Also it is possible to calculate the specific air range with the so-called Breguet factor. Table 4.1 shows the parameters necessary to determine SAR through measurement and calculation.

**Table 4. 1** Determination of SAR for different methods

| **Method** | **Specific Air Range** |
|---|---|
| Measurement | $SAR = -\frac{dR}{dm} = \frac{V_{TAS}}{C_{gross}}$ |
| Calculation | $SAR = -\frac{dR}{dm} = \frac{V \cdot E}{c \cdot g}$ |

As shown in Table 4.1, the calculation of the Breguet factor requires the lift-to-drag ratio (E) and the specific fuel consumption (c). Both parameters are very difficult to determine. To avoid these difficulties, the specific air range will be determined only by using payload-range diagrams according to the definition and formula of SAR:

$$SAR = -\frac{dR}{dm} \tag{4.1}$$

A theoretical example of a payload-range diagram is given in Figure 4.1. $R_1$ is referred to as the range at maximum payload and $m_1$ is then the maximum payload. $R_2$ is the maximum range and $m_2$ is the payload at maximum range. Thus the specific air range can be calculated as:

$$SAR = \frac{R_2 - R_1}{m_1 - m_2} \tag{4.2}$$

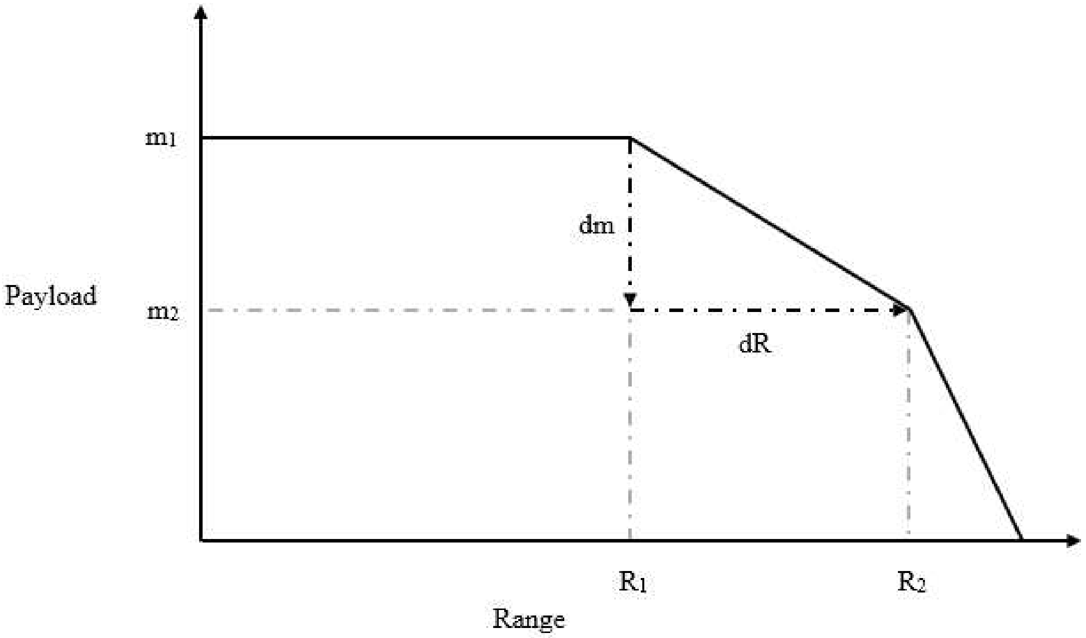


**Figure 4. 1** Illustrative example of a payload-range diagram

### 4.1.2 Documents for Airport Planning

Manufactures develop publicly available documents which provide a lot of useful information about the aircraft characteristics. These papers are called ‘documents for airport planning’. They make it possible, for the airport and maintenance planners, to plan the airport properly. The following data is mostly provided:

- **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
- **Operating conditions**: jet engine exhaust velocities and temperatures and contours, noise data
- **Pavement data**: landing gear footprint and loads, maximum pavement loads, pavement requirements

The payload-range diagrams, which are necessary to calculate the specific air range, are obtained from these documents. Other interesting data included in these documents can be used in the fuel consumption determination as well as in the other rating calculations:

- Maximum take-off weight
- Maximum landing weight
- Maximum and standard seat layout
- Runway length

### 4.1.3 Fuel Consumption Rating

**Determination of the Reference Group**

In order to rate the fuel consumption of the aircraft properly a representative rating scale should be conducted. Therefore the fuel consumption has to be calculated for a reference group of airplanes which should represent and appeal to all airplanes worldwide. It should be chosen wisely and with a scientific point of view. Therefore the Word Airliner Census of 2016 is used. This is a document which contains all the commercial transport aircraft that were in service in the year 2016. It means that both jet and turboprop powered airplanes are included. Only aircraft with a seating capacity less than 14 passengers or an equivalent cargo is excluded from this list. It is also stated in this census that

> *"The tables have been compiled using the Flight Fleets Analyzer database. The information is correct up to July 2016 and excludes non-airline operators, such as leasing companies and the military."* (***Flight Global 2016***).

All passenger airplanes in this census are listed starting with the type that has the largest amount in service. This list, which is given in Appendix D, counts 147 aircraft and is too large to use the reference group. Therefore it is mathematical derived how many airplanes should be included in the reference group.

$$\left(\frac{i}{i_{max}}\right)_{in\ service} = 1 - 0{,}748088 \cdot e^{-0{,}047978 \cdot \left(\frac{i}{i_{max}}\right)_{type}} \tag{4.3}$$

Where: $(i/i_{max})_{in\_service}$ is referred to the percentage of passenger aircraft in service and $(i/i_{max})_{type}$ is the number of passenger aircraft type. This formula can be compared with the statistics included in Appendix D to make sure it is appropriate to use for the determination of the reference group. This refers to the graph shown in Figure 4.2. The graph proves that it is allowed to use the given formula to determine the size of the reference group.

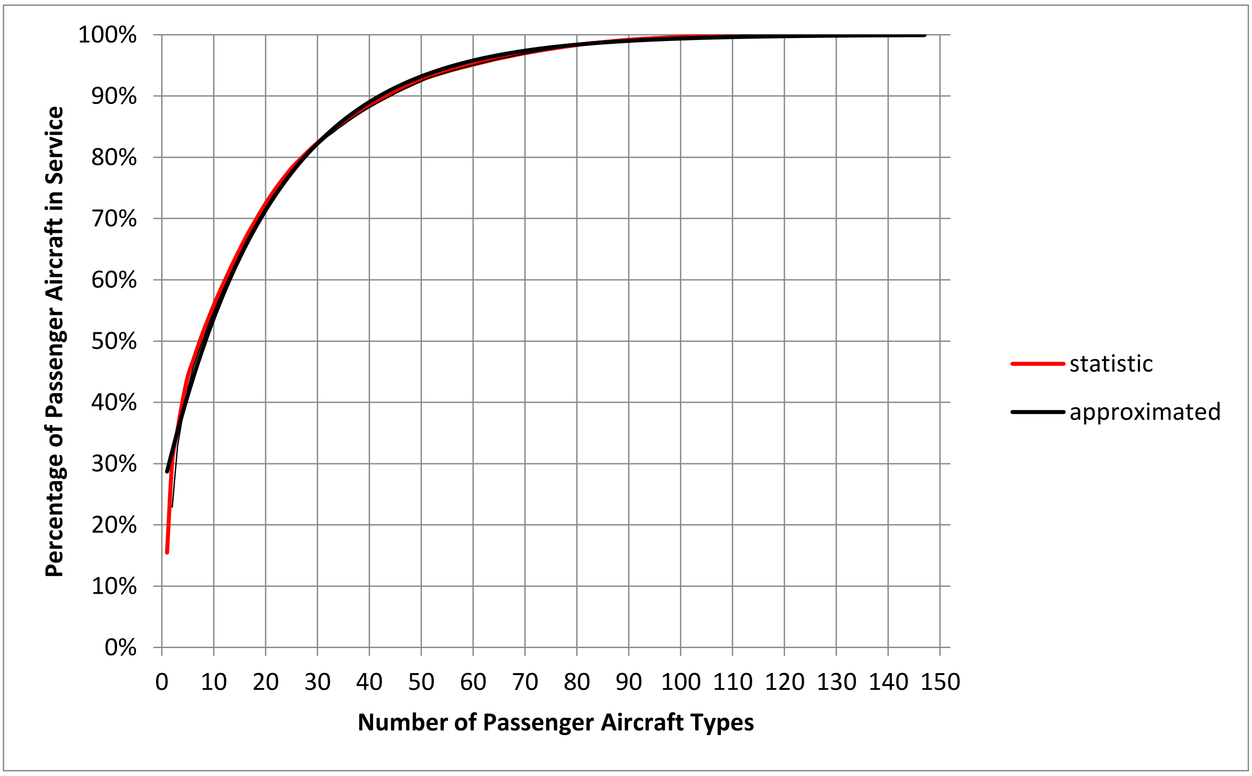


**Figure 4.2** Comparison of mathematics with statistics

Based on the graph and the results in Appendix D, the first 40 types of airplanes with the largest amount of aircraft in service according to Flight Global 2016 could act as the reference group that represents 90% of all commercial transport aircraft in service. Taking into account that necessary data for the calculation of the fuel consumption cannot be found for each aircraft, a reference group of 49 airplanes is chosen which is given in Appendix E.

### Determination of the Fuel Consumption and Rating Scale

In subchapter 4.1.1 the specific air range was already determined. As stated before, this parameter is a direct indicator of the fuel consumption. However, it is expressed in units of kilometer divided by kilogram. This is not common in Europe. Therefore, the inverse of the specific air range is taken. This results in kilograms divided by kilometers which is a frequently used unit in the transport sector.

$$\mathrm{C} = \frac{1}{SAR} \left[\frac{\mathrm{kg}}{\mathrm{km}}\right] \tag{4.4}$$

This results in an absolute value which cannot be used to compare different aircraft as well not in the ecolabel status. To secure the rating of the fuel consumption, it is necessary to include the capacity of the airplane in the calculation. This will result in an appreciation without disadvantaging larger and heavier aircraft which is desired and intended with the ecolabel. Also the rating scale should be based on comparison of aircraft without influences of operator-specific modifications. Therefore the fuel consumption will be normalized with the default configuration of the original equipment manufacturer (OEM) which means the standard seating capacity.

$$C_{OEM} = \frac{1}{SAR \cdot n_{seat,OEM}} \tag{4.5}$$

Sometimes the standard number of passengers can be obtained through the Documents of Airport Planning but this is not guaranteed. The maximum seating capacity allowed in the aircraft is always included in this document. The use of this number would result in a rating scale that is too severe. Therefore, a statistic is performed with the reference group which can be used to predict the standard number of seats. The result of this statistic is given in Figure 4.3.

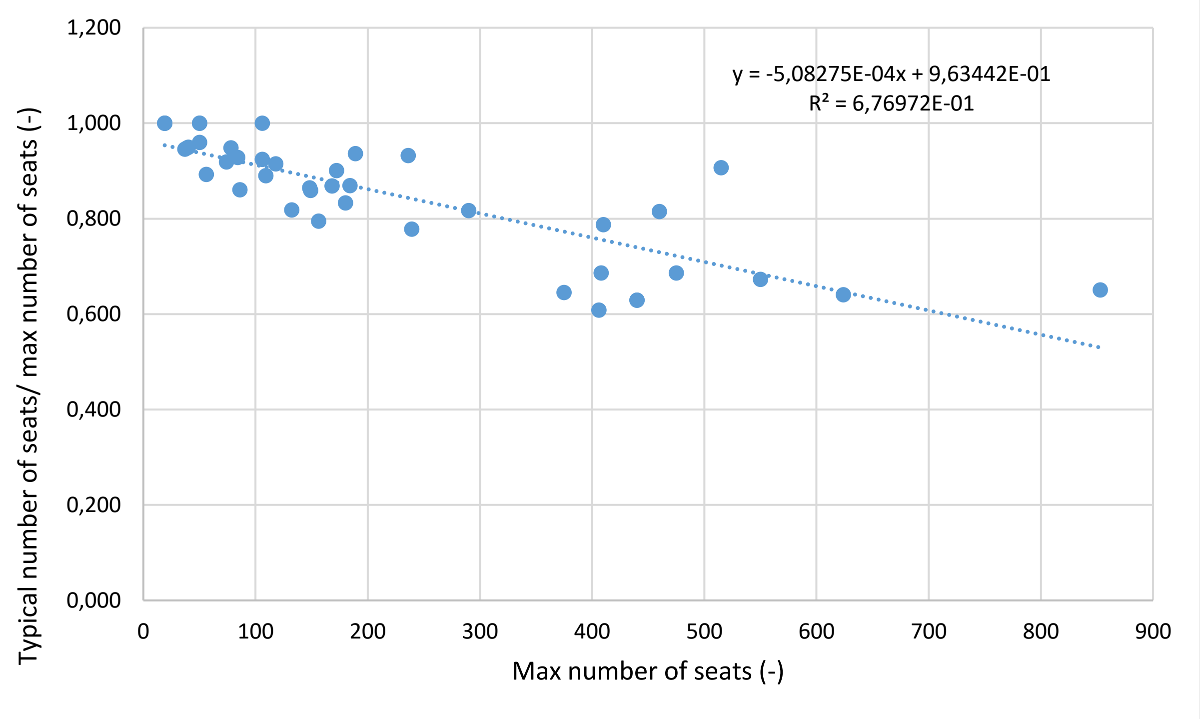


**Figure 4. 3** Statistic to predict the typical number of seats

This makes it possible to predict the typical amount of seats for the aircraft of which this data is not included in their document for airport planning. The formula produced in the graph should be multiplied with the maximum number of seats. The result is the predicted standard number of seats with a correctness of approximated 70%.

$$n_{seat,OEM} = -5{,}08275 \cdot 10^{-4} \cdot {n_{seat,max}}^2 + 9{,}63442 \cdot 10^{-1} \cdot n_{seat,max} \tag{4.6}$$

After this establishment the rating scale for the fuel consumption can be easily derived by applying formula 4.5 to all the aircraft included in the reference group. The results are given in Appendix F. The distribution of the calculated values is shown in Figure 4.4.

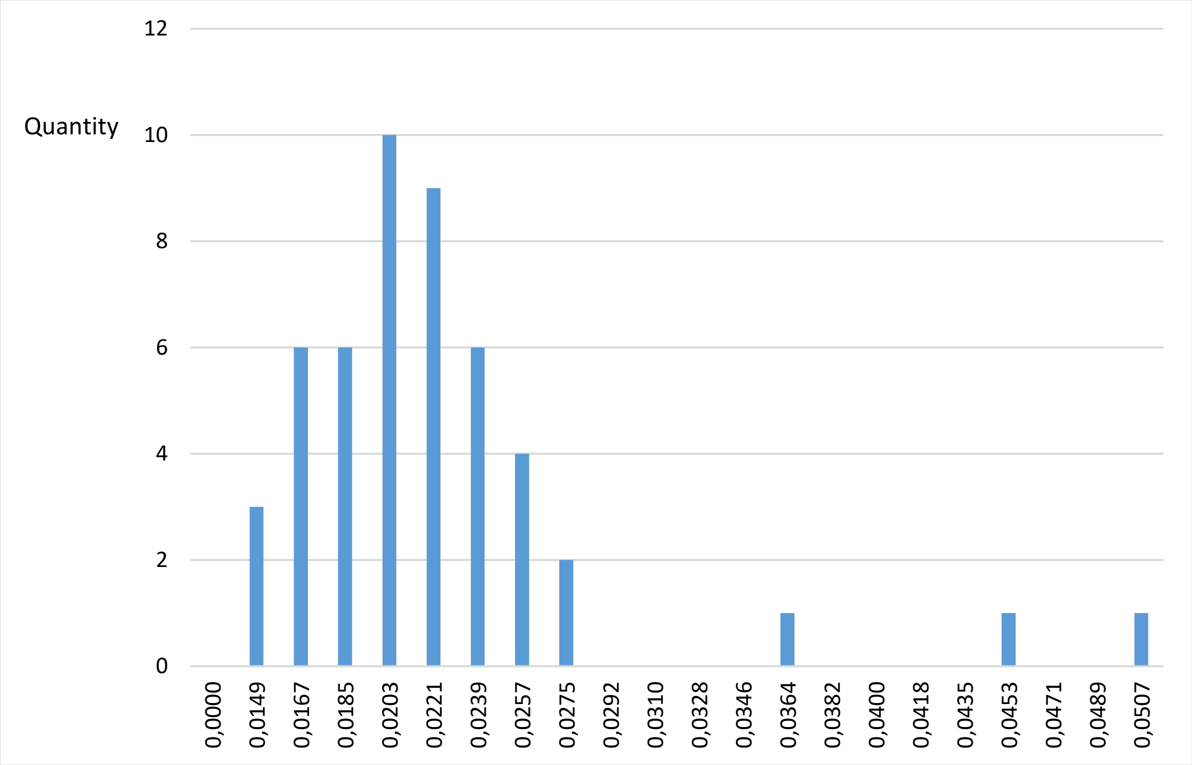


**Figure 4. 4** Normalized OEM based fuel consumption per seat (kg/km)

At last the rating table has to be generated. This scale will be defined with 7 classifications from A to G. The range of every category should be based on the histogram given in Figure 4.4. From this graph it can be concluded that the outer classifications should have a larger range than the middle ones, because airplanes with a fuel consumption located at one of the boundaries are rather rarely. To obtain a rating scale like this, the total amount of calculated values, in this case 49, should be divided by the amount of classifications.

$$\text{Number of values per classification} = \frac{\text{Total amount of calculated values}}{7} \tag{4.7}$$

The calculated fuel consumption values of the reference group are sorted from minimum to maximum, this is already done in Appendix F. Then the ranges for every classification of the rating table are defined starting by taking the minimum value as the lower boundary and the value that corresponds with next multiple of 7 (the number determined in formula 4.7) as the upper boundary. Moving on with this method, the total rating table is generated and shown in Table 4.2.

**Table 4. 2** Rating scale for the fuel consumption per seat (kg/km)

| Rating | Range | | Normalized to 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| A | 0,01493 | 0,01772 | 0 | 0,0781 |
| B | 0,01772 | 0,01983 | 0,0781 | 0,1370 |
| C | 0,01983 | 0,02131 | 0,1370 | 0,1783 |
| D | 0,02131 | 0,02246 | 0,1783 | 0,2106 |
| E | 0,02246 | 0,02392 | 0,2106 | 0,2514 |
| F | 0,02392 | 0,02602 | 0,2514 | 0,3099 |
| G | 0,02602 | 0,05070 | 0,3099 | 1,000 |

To verify that the used method for normalizing the fuel consumption fulfills its purpose to rate every airplane equally, a graph is produced where the relation between the standard number of seats and the normalized fuel consumption is visualized. This graph is shown in Figure 4.5. Although there is much scatter, it can be seen that the fuel consumption per sear is only a very week function of the number of seats. This means that, independent of the number of seats, the often used fuel consumption in kilogram fuel per kilometer per seat seems to be a good metric to compare aircraft independent of their size. The average fuel consumtpion determined here is 0,0231 kg/km and the standard deviation is only 0,006618 kg/km.

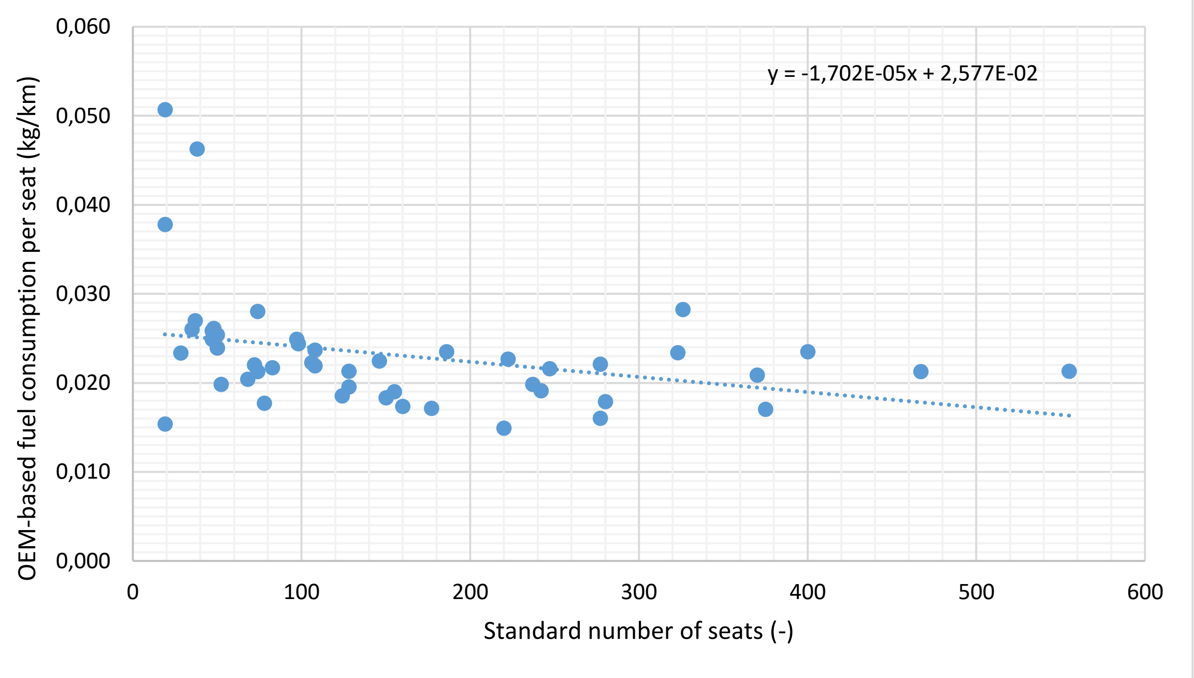


**Figure 4. 5** Fuel consumption per seat in function of standard number of seats

When the ecolabel is calculated for an aircraft of a specific operator, the seat layout probably differs from the original equipment manufacturer layout. Because of that, the fuel consumption should be calculated with the number of seats used in the seat layout of this specific airline. In this case the specific aircraft of this airline will be rated and not the base aircraft itself.

$$C_{airline} = \frac{1}{SAR \cdot n_{seat,airline}} \tag{4.8}$$

The result is rated according to the rating scale shown in Table 4.2.

### 4.1.4 Travel Class Rating

The calculated and normalized fuel consumption in the previous subchapter is only an average value for the seats which does not give specific information about the travel classes. As stated in section 3.1.3 the more comfort and therefore the more space per seat is desired, the larger fuel consumption per seat will be. The ecolabel should reveal that the choice of class influences the relative impact by the passenger.

To rate each travel class separately a weighting factor should be derived for each of them. To make this possible a certain factor specific for the class should be determined. This factor should measure the proportional use of the class with respect to the total capability of the aircraft. An easy parameter to use is the seat area.

Seat area $S_{class}$ is defined as the multiplication of the seat pitch with the seat width, which both have an unambiguously definition.

$$S_{class} = (Seat\ pitch)_{class} \cdot (Seat\ width)_{class} \tag{4.9}$$

Commonly aircraft have a seat layout with two or three classes. In the following derivation of the weighting factor for the travel class rating the classes are labelled as Economy Class (EC), Business Class (BC) and First Class (FC).

Hence the total area $S_{total}$ of the seat layout:

$$S_{total} = n_{EC} \cdot S_{EC} + n_{BC} \cdot S_{BC} + n_{FC} \cdot S_{FC} \tag{4.10}$$

With $n_{class}$ being the number of seats of the respective class and this gives the total number of seats $n_{total}$:

$$n_{total} = n_{EC} + n_{BC} + n_{FC} \tag{4.11}$$

The class-specific seat ratio is:

$$\frac{S_{class} \cdot n_{class}}{S_{total}} = \frac{S_{class} \cdot n_{class}}{n_{EC} \cdot S_{EC} + n_{BC} \cdot S_{BC} + n_{FC} \cdot S_{FC}} \tag{4.12}$$

Afterwards the class-specific weighting factor $k_{class}$ can be derived by dividing the class-specific seat ratio by the ratio of the number of seats $n_{class}/n_{total}$.

$$k_{class} = \frac{n_{class} \cdot S_{class}}{n_{EC} \cdot S_{EC} + n_{BC} \cdot S_{BC} + n_{FC} \cdot S_{FC}} \div \frac{n_{class}}{n_{EC} + n_{BC} + n_{FC}} \qquad (4.13)$$

$$k_{class} = \frac{n_{class} \cdot S_{class}}{n_{EC} \cdot S_{EC} + n_{BC} \cdot S_{BC} + n_{FC} \cdot S_{FC}} * \frac{n_{EC} + n_{BC} + n_{FC}}{n_{class}} \qquad (4.14)$$

$$k_{class} = n_{total} \cdot \frac{S_{class}}{S_{total}} \qquad (4.15)$$

This derived weighting factor is multiplied with the average fuel consumption per seat. This results in a class-specific value which will be rated again according to the rating scale defined in the Table 4.2.

$$C_{Travel\ Class} = k_{class} \cdot \frac{1}{SAR \cdot n_{seat,airline}} \qquad (4.16)$$

### 4.1.5 Discussion of the $CO_2$ Standard of ICAO

Recently the development of Annex 16 Volume III '$CO_2$ Certification Requirement' of ICAO is finished. This volume includes a new $CO_2$ emissions standard.

> *"However, this important standard has so far (July 2017) not been released by ICAO to the public for futher open discussion. Therefore, it seems important to make this standard available in a form easy to read, to foster such a discussion in the wider aviation and scientific communities." (**Scholz 2017**)*

Therefore, Prof. Dr.-Ing. Dieter Scholz has published a public available document about the $CO_2$ standard converted from: European Aviation Safety Agency, NPA 2017-01, 6. Appendices, '6.3.2 Proposed 1st Edition of ICAO Annex 16, VOL III'.

In this document the $CO_2$ standard of ICAO is explained. This standard is derived based on three parameters:

- Specific air range
- Aircraft size
- Aircraft weight

There are several definitions of SAR as mentioned in Table 4.1, but Volume III defines the specific air range by measuring the true airspeed and fuel flow at certain reference points during a test flight.

$$SAR = \frac{V_{TAS}}{W_f} \tag{4.17}$$

These reference points are shown in Figure 4.6 and are defined as follows:

- High gross mass = 0,92 · MTOW
- Mid gross mass = average of high gross mass and low gross mass
- Low gross mass= 0,45 · MTOW+0,63 · MTOW$^{0,924}$

With MTOW expressed in kilograms.

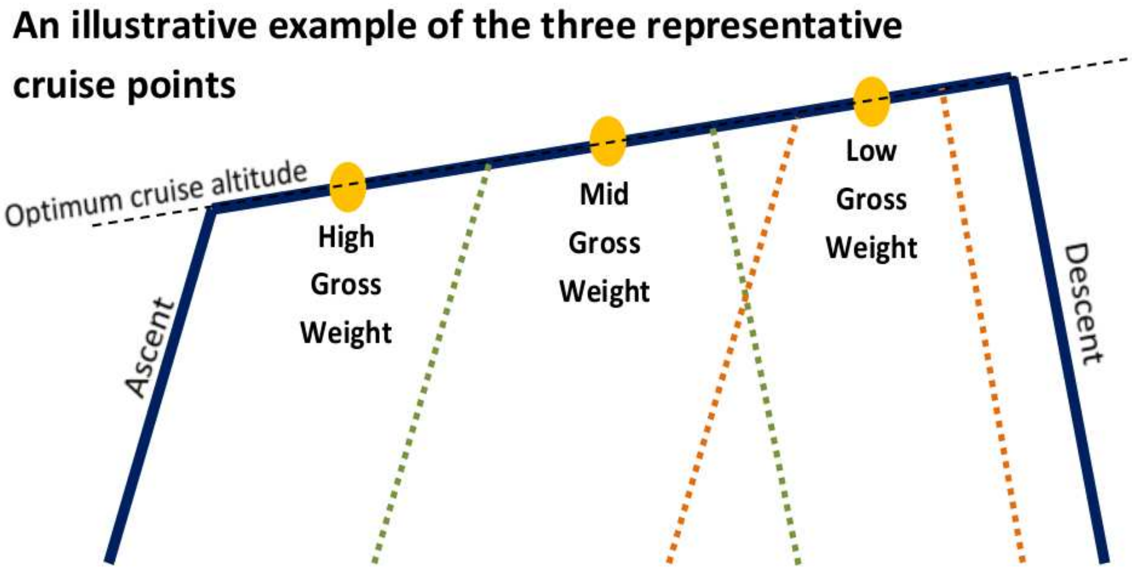


**Figure 4. 6** Reference points for determination of SAR (**ICAO 2012**)

The gross mass is calculated by subtracting the mass of the burned fuel from the mass of the airplane at the start of the test flight.

The Metric Value (MV) of $CO_2$ is determined according to the following formula 4.18 with $\left(\frac{1}{SAR}\right)_{AVG}$ the average value for the specific air range for the three reference points and RGF the Reference Geometric Factor which is related to the size of the aircraft.

$$(MV)_{CO_2} = \frac{\left(\frac{1}{SAR}\right)_{AVG}}{RGF^{0,24}} \tag{4.18}$$

The reference geometric factor is a parameter to take into account the size of the fuselage. It is the area defined by the pressurized area and a fuselage outer mould line.

However, the calculation of the metric value receives some critics. As an example:

> *"Our main criticism of the circular in its current form is that it does not address the ICAO goal of reducing fuel used per revenue tonne-kilometre performed and makes no reference to payload. This defect could be eliminated simply by omission of the exponent 0.24 of the Reference Geometric Factor (RGF) in the formula for the metric given in Chapter 2 (paragraph 2.2) of the circular. Retaining the RGF to the power unity in the metric and multiplying it by an appropriate value of the effective floor loading would convert it to what the 37th Assembly of ICAO called for – a statement of fuel used per revenue tonne-kilometre performed." (**Green 2016**)*

Therefore, it was chosen to define a metric for the fuel consumption which is normalized with the amount of seats. As shown in Figure 4.5 this manner of normalizing attends to assess every aircraft equally and is thus correct.

## 4.2 Local Air Quality

### 4.2.1 Emission Species

In commercial aviation a standard fuel type is used which is called A-1. This type produces carbon dioxide ($CO_2$), water vapor ($H_2O$) and sulfur oxides ($SO_x$) when an ideal combustion would occur. Physics shows that it is impossible to create an ideal process. Therefore, due to the non-ideal combustion processes of aircraft engines, pollutants are formed in the air. Real combustion of the fuel generates besides the products stated above also nitrogen oxides ($NO_x$), carbon monoxide (CO), unburned hydrocarbons (HC) and soot. This is shown for a fan jet engine in Figure 4.7.

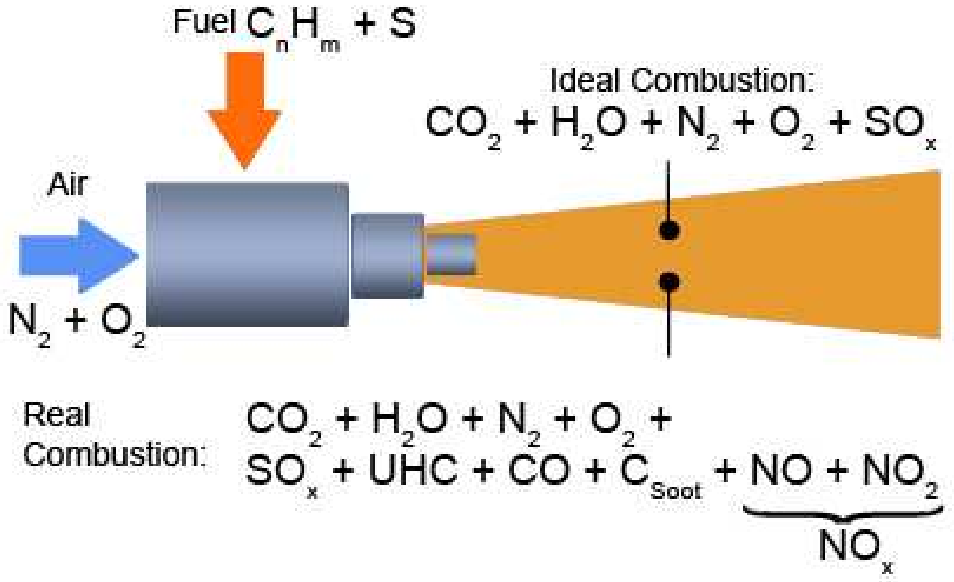


**Figure 4. 7** Emission products of combustion of a jet (adapted from **Hass 2015**)

91,5% to 92,5% of the emission products are consisting of oxygen and nitrogen which are already part of the atmosphere. Of the approximated remaining 8% carbon dioxide and water vapor are the largest components. So only a small fraction of the emission products are pollutants, but still they effect the environment. Nitrogen oxides are the most severe and that is why a special focus is directed at them. (**Sarkar 2012**)

The emission products $CO_2$, $H_2O$ and $SO_x$ can easily be appraised as they are directly connected to the fuel consumption. This means that their emitted masses are proportional to the used fuel resulting in a constant value regardless of the operation mode of the engine. In Table 4.3 the emission indices, EI, for these products are given. The emission index is defined as the amount of emitted species produced by one kilogram of fuel.

**Table 4. 3** Emission indices of emission products (**IPCC 1999**)

| Species | Emission Index (kg/kg fuel) |
|---|---|
| $CO_2$ | 3,16 |
| $H_2O$ | 1,23 |
| $SO_2$ | $2{,}00 \cdot 10^{-4}$ |
| Soot | $4{,}00 \cdot 10^{-5}$ |

The other emission products are more difficult to be assessed because they depend on the efficiency of the combustion process of the engine. This means that the engine type, the operation mode and the thrust setting are necessary parameters to determine the amount of emissions.

### 4.2.2 Effects on Air Quality

The air quality in the vicinity of airports is affected by the emission products generated by the aircraft engines. They can harm the well-being of humans as well as the balance of fauna and flora.

Health problems are mostly caused by inhaling particles and ozone. Once the particles enter the human body through the respiratory system, diseases such as cancer and respiratory infections can be developed. Two types of particular matter (PM) are distinguished. Primary particular matter is defined as the particles that are directly emitted into the air. When the particles are formed through a chemical reaction of gaseous pollutants such as $NO_x$, it is defined as secondary particular matter (**WHO 2014**). Reactions of $NO_x$ can form ozone which can cause inflammation of the airways and damage to the lungs.

To determine a metric for the local air quality predefined characterization factors from ReCiPe are employed. They are listed in Table 4.4.

> *"ReCiPe is a method for the impact assessment (LCIA) in a LCA. Life cycle impact assessment (LCIA) translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterisation factors." **(RIVM 2011)***

The ReCiPe-method assess the environmental problems by dividing them into midpoint categories such as climate change, terrestrial ecotoxicity, ozone formation, human toxicity, fossil depletion and so on (there are 18 midpoint categories in total). These midpoint categories are then converted into endpoint categories. The endpoint categories indicate the environmental impact on three higher aggregation levels which are: the human health, the ecosystems and the resources (**RIVM 2011**).

The local air quality focuses on the human health in the vicinity of the airport. Therefore, only the midpoint categories with impact on human health have to be taking into account. There are 5 of them: climate change, photochemical oxidant formation (also called ozone formation potential), particular matter formation, human toxicity and ionizing radiation. The climate change will be discussed and evaluated separately. Of the four remaining categories only two of them are caused by aviation: particular matter formation and photochemical oxidant formation. Therefore, the metric of the evaluation of the local air quality will consist of NMVOC-equivalents (Non-Methane Volatile Organic Compound or ozone formation potential) and PM-equivalents (particulate matter formation potential) which are calculated by converting relevant emission products and by the $NO_x$-emissions.

**Table 4. 4** Characterization factors of ReCiPe

| **Midpoint category** | **$NO_x$** | **$SO_2$** | **PM** | **CO** | **HC** |
|---|---|---|---|---|---|
| Photochemical oxidant formation (ozone) | 1 | 0,081 | - | 0,046 | 0,476 |
| Particulate matter formation | 0,22 | 0,20 | 1 | - | - |

If these midpoint categories are converted to the endpoint category 'Human health', it can be observed in ReCiPe 2012 that environmental impact of the ozone formation potential is very low compared to the impact of the particular matter. Further, if the amount particular matter is compared with the amount of emitted $NO_x$, it can be observed that remarkable more $NO_x$ is produced. Therefore, it can be concluded that the impact of the $NO_x$ is more significant than the impact of particular matter. This makes the emitted $NO_x$ the key indicator in the evaluation of the local air quality. Due to their smaller impact on the environment, the ozone formation and the particular matter formation are included in the ecolabel as additional information, but they will not influence the rating of the local air quality.

All the emissions in the following sections are calculated for an entire LTO cycle as defined by Annex 16, Volume II (Appendix A). Therefore, all the necessary data can be found in the Engine Emissions Databank.

## Ozone

The total amount of ozone equivalents can be calculated by multiplying the total emitted mass of the relevant emission products by their corresponding factor given in Table 4.4.

$$NMVOC_{LTO} = 1 \cdot (NO_x)_{LTO} + 0{,}081 \cdot (SO_2)_{LTO} + 0{,}046 \cdot (CO)_{LTO} + 0{,}476 \cdot (HC)_{LTO} \qquad (4.19)$$

To allow comparison, which is intended with the ecolabel, the results should be normalized with a factor that represents the engine capability. Therefore the amount NMVOC-equivalents are divided by the maximum rated thrust, also called rated output in the Engine Emission Databank, of the engine at sea-level. Applying this calculation to all available engines included in this database yields to the distribution of values for ozone that is given in Figure 4.8.

$$(Normalized\ NMVOC)_{LTO} = \frac{NMVOC_{LTO}}{\text{rated output}} \qquad (4.20)$$

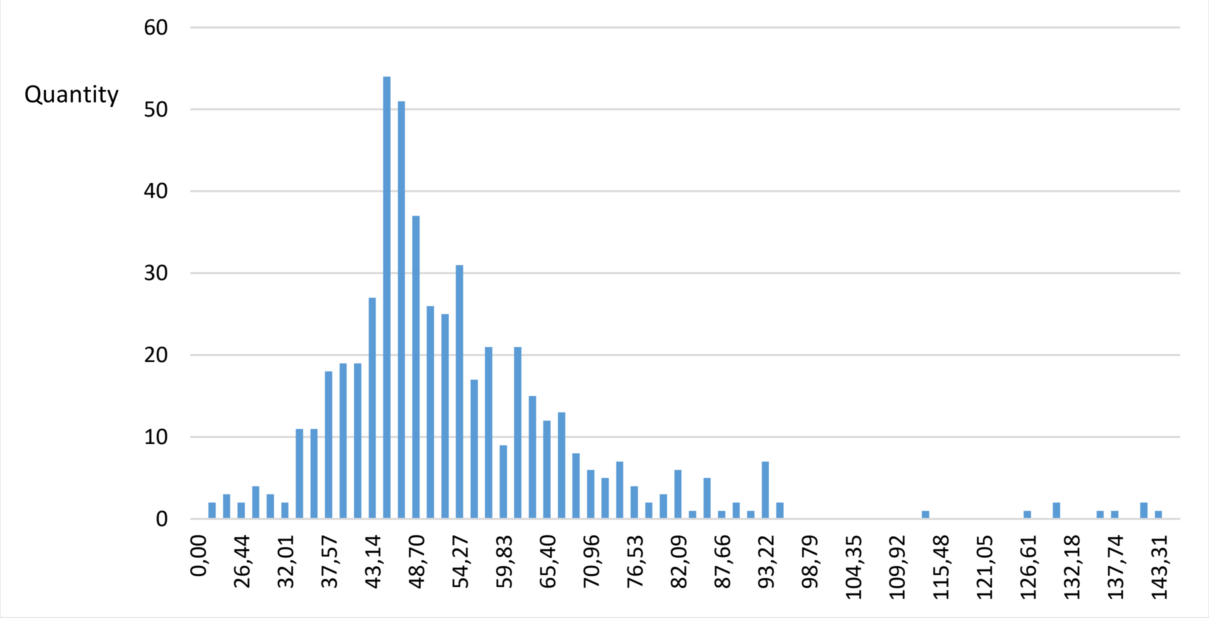


**Figure 4. 8** Normalized NMVOC equivalents (g/kN)

## Particular Matter

There are no certified test procedures to determine the particular matter yet. The CAEP (Committee on Aviation Environmental Protection) recommended in their 10th formal meeting an amendment to ICAO Annex 16 Volume II ‘Aircraft Engine Emissions’ by including a new standard and a standard test procedure for non-volatile particular matter.

A draft of the new standard for non-volatile particular matter is given in EASA 2017b. This draft contains calculation methods for the emission indices for the mass and the number of non-volatile particular matter as well as measurement procedures, test procedures and a regulatory limit for the concentration of non-volatile particular matter. This limit is given by the following formula:

$$\text{Regulatory limit concentration of nvPM}_{\text{mass}} = 10^{\left(3+2{,}9\cdot F_{oo}{}^{-0.274}\right)} \tag{4.21}$$

With $F_{oo}$ defined as the thrust.

As this standard is not yet official, it cannot be used in the determination of the particular matter in this thesis. Nevertheless a method is used that is derived by Wayson 2009 to estimate PM using data from the Engine Emission Databank.

First of all the emission index of the particular matter has to be determined, which consists of volatile and non-volatile PM.

$$EI_{PM,total} = EI_{PM,vols} + EI_{PM,nvols} \tag{4.22}$$

It was discovered that volatile particular matter is mainly composed of sulfates and organics from unburned fuel. Therefore the emission index is defined as:

$$EI_{PM,vols} = EI_{SO_2} \cdot \epsilon + \delta(EI_{HC}) \tag{4.23}$$

With $\varepsilon = 0.033$ and $\delta$ $(EI_{HC})$ depending on the operating mode. As there is little data available to calculate $\delta$ $(EI_{HC})$, the contribution of the fuel organics can be calculated in a different manner based on LTO cycle data.

$$PM_{vol-FuelOrganics} = 0{,}0085 \cdot (HC)_{LTO} \tag{4.24}$$

With $(HC)_{LTO}$ the total mass of emitted HC during the LTO cycle.

The non-volatile particular matter, also called soot, is linked at the smoke number. Therefore the emission index of non-volatile PM is defined as:

$$EI_{PM,nvols} = Q \cdot CI(SN) \tag{4.25}$$

With CI defined as the concentration index which is the mass per standard volume of exhaust in which standard conditions are zero degrees of Celsius and one atmosphere of pressure. CI is a function of smoke number. For smoke numbers less than or equal to 30, the concentration index can be defined as:

$$CI = 0{,}0694 \cdot (SN)^{1{,}24} \tag{4.26}$$

Also with Q defined as the exhaust volumetric flow rate which can be calculated with the mass air-to-fuel ratio (AFR). As the exact data is proprietary, at least average values for each power setting are given in Table 4.5.

**Table 4. 5** Air-to-Fuel ratio for each operating mode (**Wayson 2009**)

| Mode | AFR (-) |
|---|---|
| Idle | 106 |
| Approach | 83 |
| Climb out | 51 |
| Take-off | 45 |

In the calculation of the exhaust volumetric flow rate a distinction is made between two engine types: a turbofan and an internally mixed turbofan. Only the core flow is considered by a turbo fan. Therefore the exhaust volumetric flow can be derived as:

$$Q_{core} = 0{,}776 \cdot AFR + 0{,}877 \tag{4.27}$$

Using the average values for the AFR for the different operating mode of the LTO cycle the following results for the core flow rate can be found, which are given in Table 4.6:

**Table 4. 6** Prediction of the volumetric core flow rate for each operating mode (**Wayson 2009**)

| Mode | Predicted volumetric core flow rate (m³/kg fuel) |
|---|---|
| Idle | 83,1 |
| Approach | 65,3 |
| Climb out | 40,5 |
| Take-off | 35,8 |

If an internally mixed turbofan is used, not only the core flow rate but also the bypass flow was included in the measurement of the smoke numbers. Therefore the flow has to be adjusted. The necessary data of the bypass ratio, as well as the engine type, is given in the Engine Emissions Databank. Again, the average values for the AFR are used for the various operation modes.

$$Q_{mixed} = 0{,}776 \cdot AFR \cdot (1 + \mu) + 0{,}877 \tag{4.28}$$

Now the emission indices are determined, the amount of emitted particular matter during the LTO cycle can be calculated.

$$(PM)_{LTO} = (PM_{vols})_{LTO} + (PM_{nvols})_{LTO} \tag{4.29}$$

With both terms determined as:

$$(PM_{vols})_{LTO} = 0{,}033 \cdot (SO_2)_{LTO} + 0{,}0085 \cdot (HC)_{LTO} \tag{4.30}$$

And

$$(PM_{nvols})_{LTO} = \sum Q_i \cdot 0{,}0694 \cdot (SN)_i^{1{,}24} \cdot \left(w_f\right)_i \cdot t_i \qquad (4.31)$$

Whereby i = operating mode, Q = the exhaust volumetric flow rate, $w_f$ = the fuel flow in kilograms per second and $t_i$ is the operating time of each operation mode in seconds.

Applying these calculations for each available engine in the Engine Emission Databank and normalizing the results with the same method used for ozone, leads to the following distribution for the particular matter given in Figure 4.9.

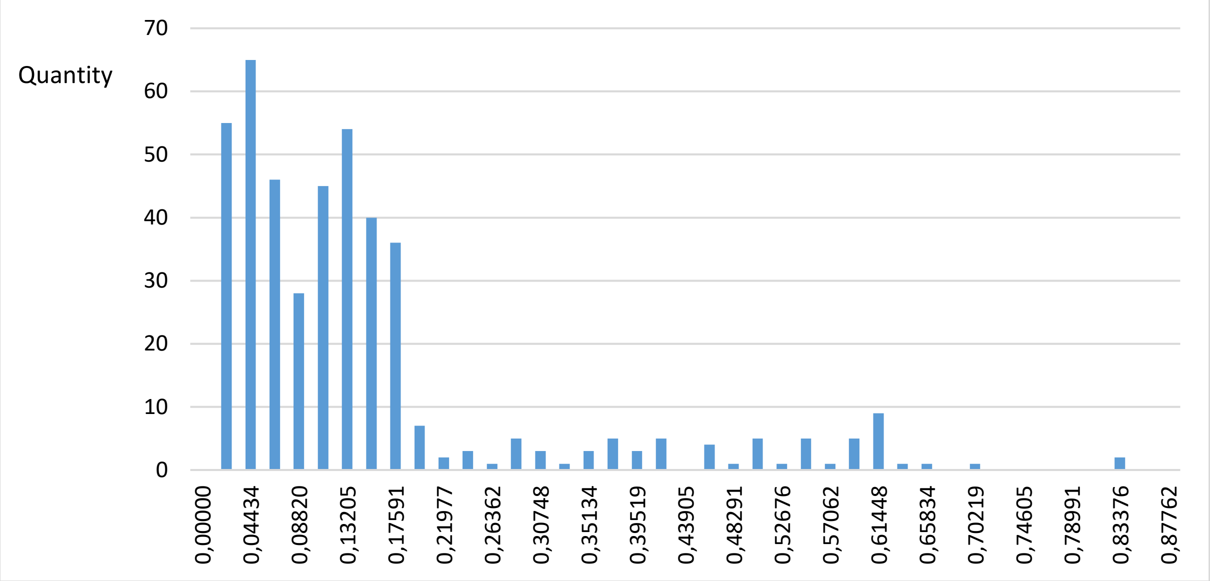


**Figure 4. 9** Normalized $PM_{LTO}$ (g/kN)

The particular matter potential is calculated according to the characterization factors from ReCiPe as mentioned before:

$$(PM_{equivalents})_{LTO} = 0{,}22 \cdot (NO_x)_{LTO} + 0{,}20 \cdot (SO_2)_{LTO} + 1 \cdot (PM)_{LTO} \qquad (4.32)$$

Again, applying this calculation for each available engine in the Engine Emission Databank and normalizing the results with the same method used for ozone and PM, gives the following distribution for the particular matter potential shown in Figure 4.10.

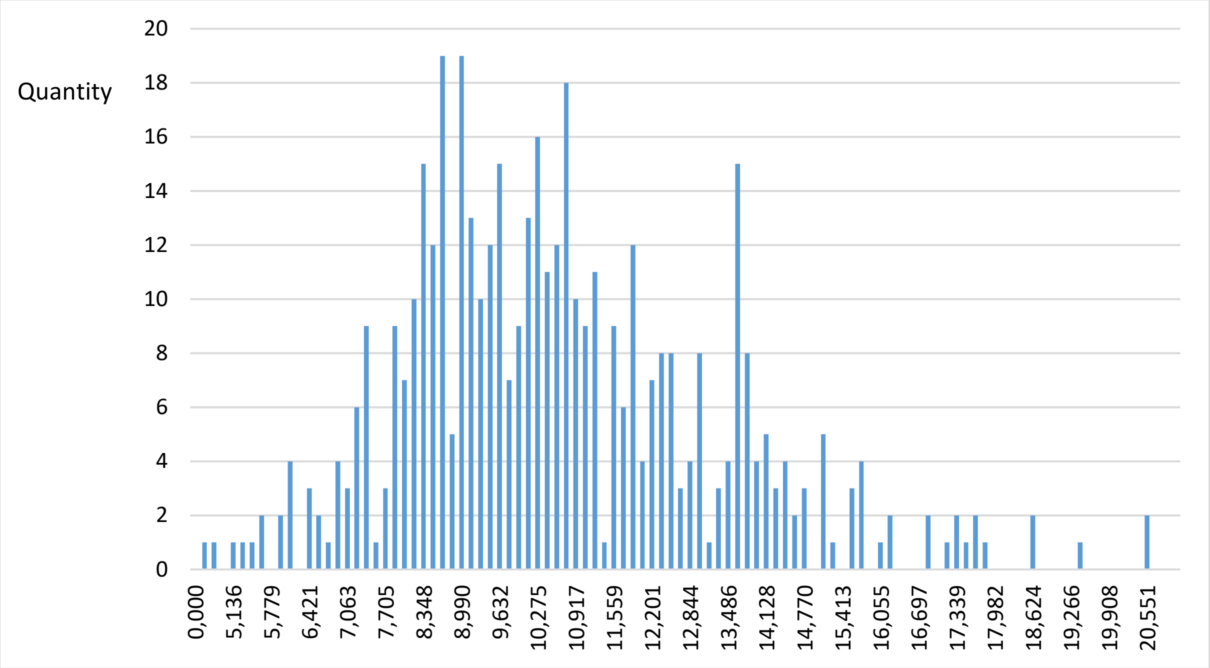


**Figure 4. 10** Normalized $(PM_{equivalents})_{LTO}$ (g/kN)

### NO$_x$-Emissions

As stated before, the amount of emitted nitrogen oxides is defined as the key indicator to rate the air quality in the vicinity of the airport. Since the data of the emitted NO$_x$ during the LTO cycle is available in the Engine Emissions Databank, the calculation of the NO$_x$-emissions is very straightforward as the given data only has to be normalized. This is done in the same manner as with the ozone and the particular matter.

$$\text{Normalized amount of emitted } NO_x = \frac{(NO_x)_{LTO}}{\text{Rated thrust}} \tag{4.33}$$

This results in the distribution of values for NO$_x$-emissions given in Figure 4.11.

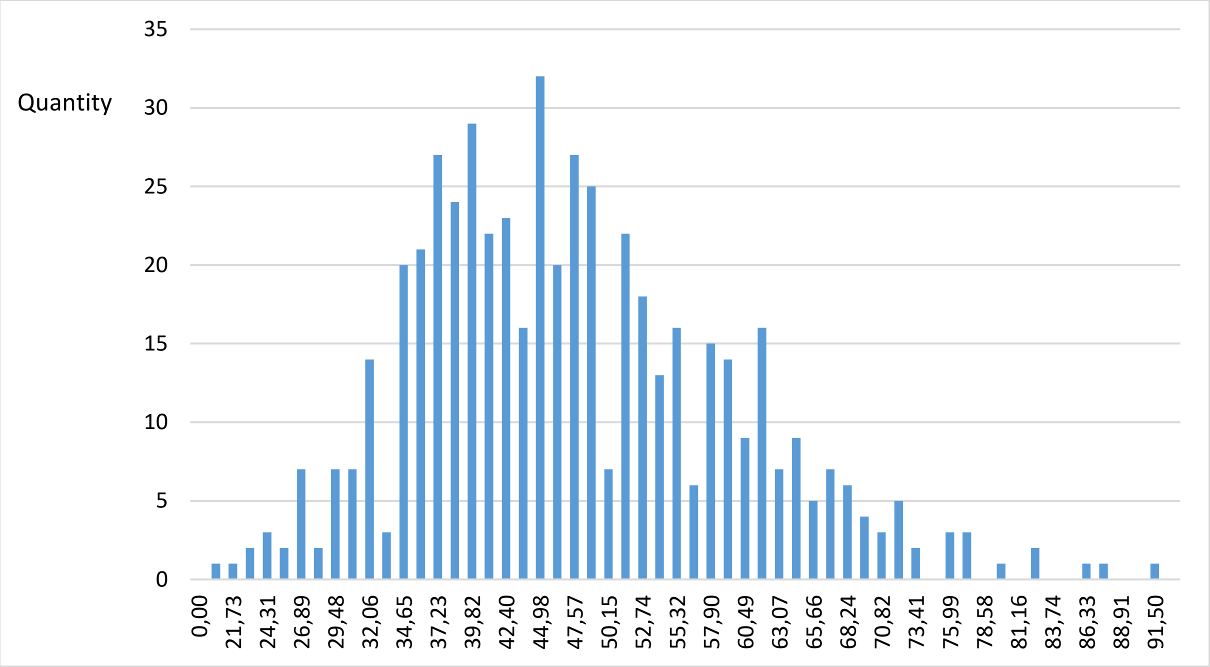


**Figure 4. 11** Normalized (emitted $NO_x$)$_{LTO}$ (g/kN)

The rating scale is defined with the same method as the one for the fuel consumption in section 4.1.3.2. The total amount of calculated values is divided by the amount of classifications which is 7. The list of calculated values, sorted from minimum to maximum, determines the range boundaries of each category by taking the value corresponding with the multiple of the number calculated in formula 4.7. This results in the rating scale given in Table 4.7.

**Table 4. 7** Rating scale for emitted $NO_x$ (g/kN)

| Rating | Range | | Normalized to 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| A | 20,435 | 36,641 | 0 | 0,0836 |
| B | 36,641 | 40,028 | 0,0836 | 0,1011 |
| C | 40,028 | 44,887 | 0,1011 | 0,1262 |
| D | 44,887 | 48,399 | 0,1262 | 0,1443 |
| E | 48,399 | 53,746 | 0,1443 | 0,1719 |
| F | 53,746 | 61,836 | 0,1719 | 0,2136 |
| G | 61,836 | 214,239 | 0,2136 | 1,000 |

There has to be made one remark about the rating of the local air quality. As all the calculations are based on data given in the Engine Emissions Databank, which only includes jet engines, and there no similar publicly databases about turboprops are available, the local air quality cannot be determined for turboprops.

## 4.3 Noise Pollution

In the aviation sector, the metric to measure noise is called ‘Effective Perceived Noise Level’ (EPNL) expressed in units of EPNdB. This metric is derived from the scale ‘Perceived Noise Level’ (PNL). This metric intends to measure the perceived noisiness of aircraft by observers on the ground. It takes into account the duration and the presence of discrete frequency tones. The method is defined in Annex 16 volume I by ICAO which is given in Appendix B.

### 4.3.1 Noise Data Bank

The Type-Certificate Data Sheets for Noise (TCDSN) documents contain the EASA approved noise levels for aircraft. They are bundled together in a database developed by EASA which is public available (**EASA 2017c**).

There is a second database named ‘NoisedB’ which is developed by the French DGAC (Direction générale de l’aviation civile) under the aegis of ICAO. It contains certificated data of noise levels for each aircraft type that are certificated under Annex 16, Chapter three and four and FAR standards. The purpose of this database is to function as a general source of information for the public (**DGAC 2017**).

Both databases provide the following information:

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

### 4.3.2 Determination of Noise Metric

Due to the independency of noise as a parameter, the rating method can easily be determined by calculating the normalized noise level by dividing the noise level with the noise limit. The larger and heavier the aircraft are, the more engine power they need and as a result of this the more noise they will produce. Therefore, the maximum permitted limit is a function of the maximum take-off weight, which is determined in Annex 16 Volume I. Normalizing the noise level with this calculated limit, it becomes possible to compare different aircraft with each other. This normalized noise level is called the 'Noise Index Value'.

The calculation method is defined according to the reference points defined by Annex 16 Volume I of ICAO, which is explained in Appendix B. Therefore, the noise level index has to be calculated for each of these reference points.

$$(Noise\ index\ value)_{Lateral} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{Lateral} \tag{4.34}$$

$$(Noise\ index\ value)_{Flyover} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{Flyover} \tag{4.35}$$

$$(Noise\ index\ value)_{Approach} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{Approach} \tag{4.36}$$

Subsequently the average noise index value is calculated by summing the determined index values and dividing them by three as there are three reference points.

$$(Noise\ index\ value)_{Average} = \frac{(NIV)_{Lateral} + (NIV)_{Flyover} + (NIV)_{Approach}}{3} \tag{4.37}$$

### 4.3.3 Noise Rating Scale

Calculating the average noise index value for the airplanes that are included in the TCDSN database from EASA, makes it possible to determine a rating scale for noise. EASA has two different databases for jets and turboprops. Therefore a distinction is made between the rating scale of jets and turboprops. For jets the distribution for the noise index values is given in Figure 4.12.

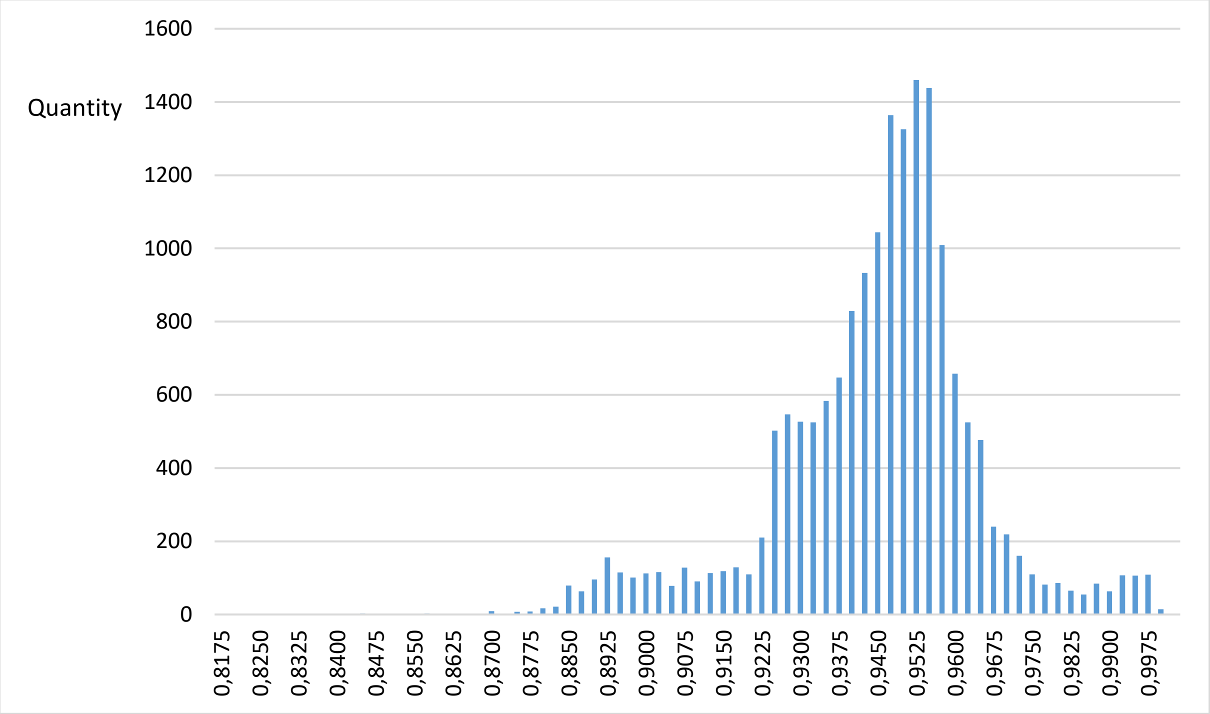


**Figure 4. 12** Noise index value for jets

Out of the reason that the reference group is so large, the distribution and the rating scale can be determined very precisely. The rating table is defined according to the same method as mentioned before in section 4.1.3.2 and formula 4.7. The result is given in Table 4.8.

**Table 4. 8** Rating scale for the noise pollution of jets (-)

| Rating | Range | | Normalized to 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| A | 0,8175 | 0,9283 | 0 | 0,6055 |
| B | 0,9283 | 0,9396 | 0,6055 | 0,6676 |
| C | 0,9396 | 0,9466 | 0,6676 | 0,7055 |
| D | 0,9466 | 0,9515 | 0,7055 | 0,7327 |
| E | 0,9515 | 0,9558 | 0,7327 | 0,7562 |
| F | 0,9558 | 0,9624 | 0,7562 | 0,7923 |
| G | 0,9624 | 1,0004 | 0,7923 | 1,000 |

The same can be done for turboprops. This leads to the distribution given in Figure 4.13.

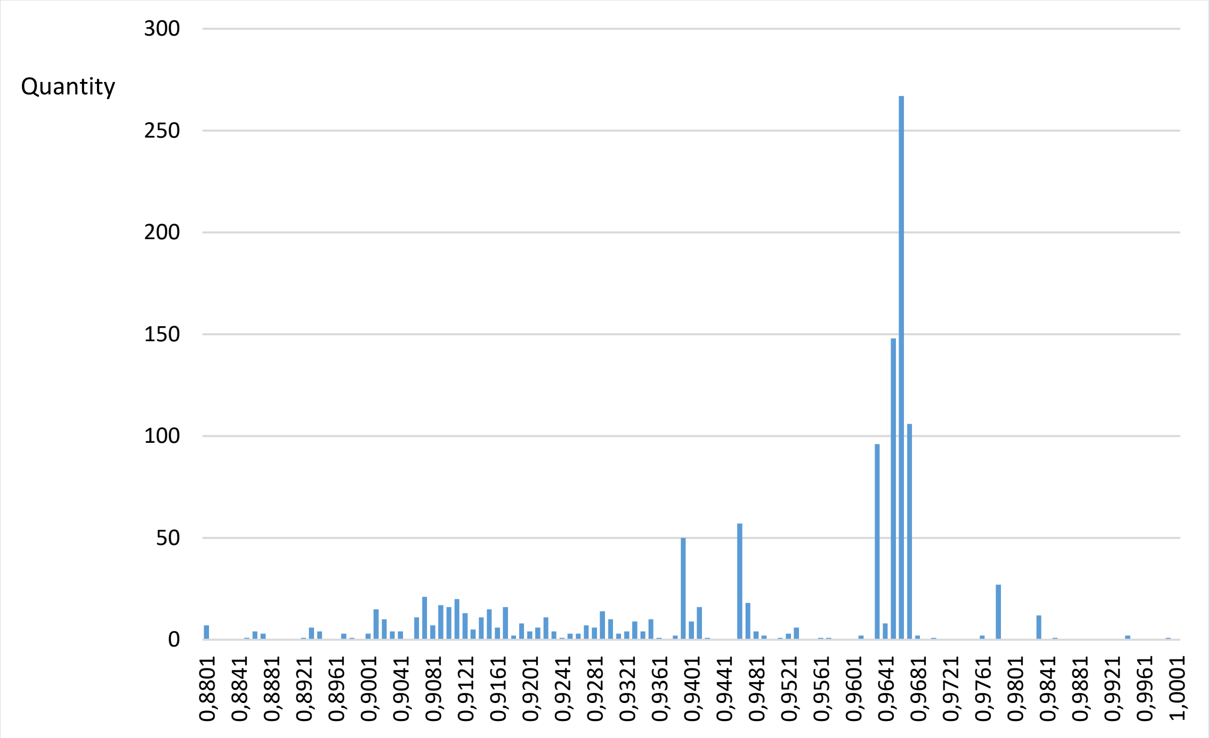


**Figure 4. 13** Noise index value for turboprops

Also the rating scale can be determined in the same manner as said before and is given in Table 4.9.

**Table 4. 9** Rating scale for the noise pollution of turboprops (-)

| Rating | Range | | Normalized to 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| A | 0,8801 | 0,9127 | 0 | 0,2720 |
| B | 0,9127 | 0,9399 | 0,2720 | 0,4990 |
| C | 0,9399 | 0,9621 | 0,4990 | 0,6835 |
| D | 0,9621 | 0,9658 | 0,6835 | 0,7152 |
| E | 0,9658 | 0,9664 | 0,7152 | 0,7200 |
| F | 0,9664 | 0,9669 | 0,7200 | 0,7241 |
| G | 0,9669 | 1,000 | 0,7241 | 1,0000 |

## 4.4 Climate Impact

The last indicator of the ecolabel is the climate impact. This will be rated according to the produced $CO_2$-equivalent during a cruise flight. What these equivalents are and how they are calculated is explained in the following paragraphs.

### 4.4.1 Radiative Forcing Index

The radiative forcing index (RFI) is used by a lot of calculators such Atmosfair. It is a numerical multiplier which indicates the non-$CO_2$ climate impact of aviation. It means that the total climate impact of all the emission products is approximated by multiplying the amount of emitted $CO_2$ with the radiative forcing index.

$$RFI = \frac{RF_{total\ of\ all\ emissions}}{RF_{CO_2}} \tag{4.38}$$

In 1992, the RFI was approximated in a range of two to four with a best estimate of 2,7 (**IPCC 1999**). In 2007 this RFI was revised and adapted to a new range of 1,9 to 4,7 due to insecurities (**Atmosfair 2008**).

> *"Yet RFI is an inappropriate metric to use for personal air travel emissions calculators because RFI calculations are based on RF values for aviation emissions from the last 50 years. RFI therefore includes warming responses from past air travel emissions. Furthermore, future warming due to long-lived greenhouse gases is not included in these calculations. RFI was never intended to be used to calculate the total effect of current aviation ..." **(SEI 2011)***

Therefore, it is necessary to determine another metric system to evaluate the climate impact during cruise flight.

### 4.4.2 Determination of Metric for $CO_2$-Equivalent

A typical metric to assess the climate impact of the emitted pollutants is the radiative forcing (RF). This parameter represents how the radiation balance of the earth is affected by a specific gas or particles by defining the amount of absorbed energy in the earths system as well as the energy that is radiated back into space. This causes a change in the global temperature. An augmentation in the temperature occurs by a positive radiative forcing value and a reduction by a negative value. The radiative forcing value is expressed in units of Watts per square meter. Figure 4.14 shows the radiative forcing of pollutants caused by aviation in 2005 since the beginning of the jet age.

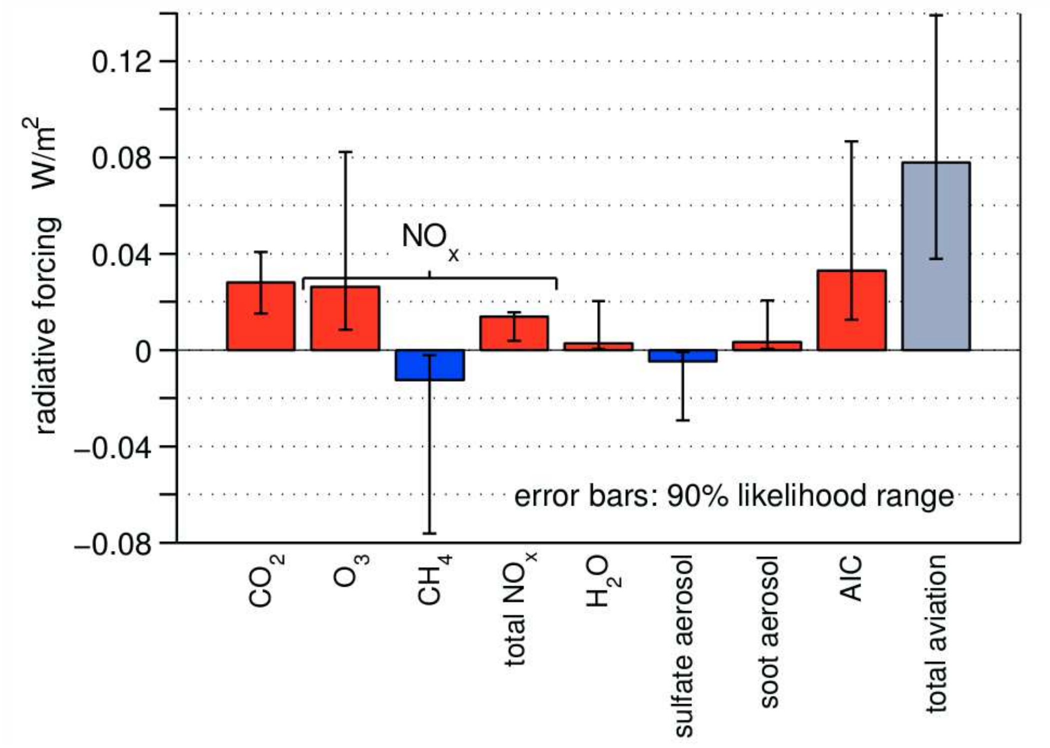


**Figure 4. 14** Radiative forcing components of aviaton emissions (**Schwartz 2011**, based on **Lee 2009**)

It can be concluded from Figure 4.14 that the total radiative forcing of aviation is mostly determined by $CO_2$-emissions, $NO_x$-emissions, contrails and cirrus clouds. Therefore those three types of emissions will be used in the calculations for the rating scale of the climate impact in the ecolabel.

The disruption of the radiation balance, defined by the radiative forcing, is only a moment in time and may change over years. It can be integrated by assuming maintained emissions or pulse. To be able to compare the influences of different emission products, another metric is used, called ‘The Global Warming Potential’ (GWP). This method determines the severity of the influence of certain emission products on climate impact compared to $CO_2$ over a certain time interval, mostly 100 years also referred as carbon dioxide equivalent. Therefore, the time-integrated RF of the non-$CO_2$ species is normalized by the time-integrated RF of $CO_2$ over the same time interval. The values of GWP for the various emission products are recorded by IPCC.

The ReCiPe method normally uses the GWP as the characterization factor to determine the midpoint categories. In this case only the midpoint category ‘climate change’ has to be calculated. However, it was discovered that the impact of the $NO_x$-emissions as well as the impact of the contrails and the cirrus clouds are very dependent of the flight altitude of the aircraft. Therefore, the method should be adapted to include this altitude dependency in the midpoint calculation of the climate change (**Johanning 2016**). This can be determined on the procedure given in Schwartz 2009 based on Shine 2005 and Egelhofer 2007. They used the global temperature change after 100 years of maintained emissions, $\Delta T_{s,100}$, to compare the climate influence of aircraft. To calculate $\Delta T_{s,100}$, sustained global temperature potentials (SGTP) are used as well as the amount of emitted species, $E_i$, and the stage length L. Also an altitude-averaged forcing factor, $\overline{s_i}$, is used for the desired mission profile.

$$\Delta T_{s,100} = \sum_{i=1}^{N_i} SGTP_{i,100} \cdot E_i \cdot \overline{s_i} + \sum_{j=1}^{N_j} SGTP_{j,100} \cdot L \cdot \overline{s_j} \tag{4.39}$$

With i = $CO_2$, $H_2O$, $CH_4$, $O_{3,S}$, $O_{3,L}$, soot, sulfate and j = contrails, cirrus clouds

Johanning 2016 determined that it is possible to use the SGTP of species for calculating the $CO_2$-equivalent, or altitude-dependent characterization factors, instead of using GWP of that species, as both of them results in more or less the same outcome (**Shine 2005**).

$$CF_{midpoint,i}(h) = \sum \frac{SGTP_{i,100} \cdot s_i(h)}{SGTP_{CO_2,100}} \tag{4.40}$$

Values for the SGTP of the different species are provided in Schwartz 2009 and are given in Table 4.10.

**Table 4. 10** Sustainable global temperature potential (**Schwarz 2009**)

| Species | $SGTP_{i,100}$ |
|---|---|
| $CO_2$ (K/kg $CO_2$) | $3{,}58 \cdot 10^{-14}$ |
| Short $O_3$ (K/kg $NO_x$) | $7{,}79 \cdot 10^{-12}$ |
| Long $O_3$ (K/$NO_x$) | $-9{,}14 \cdot 10^{-13}$ |
| $CH_4$ (K/kg $NO_x$) | $-3{,}90 \cdot 10^{-12}$ |
| Contrails (K/NM) | $2{,}54 \cdot 10^{-13}$ |
| Contrails (K/km) | $1{,}37 \cdot 10^{-13}$ |
| Cirrus (K/NM) | $7{,}63 \cdot 10^{-13}$ |
| Cirrus (K/km) | $4{,}12 \cdot 10^{-13}$ |

So for $NO_x$-emissions it is calculated as:

$$CF_{midpoint,NOx}(h) = \frac{SGTP_{O_{3S},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,S}(h) + \frac{SGTP_{O_{3L},100}}{SGTP_{CO_2,100}} \cdot s_{O_3,L}(h) + \frac{SGTP_{CH_4,100}}{SGTP_{CO_2,100}} \cdot s_{CH_4}(h) \tag{4.41}$$

And for the induced cloudiness:

$$CF_{midpoint,cloudiness}(h) = \frac{SGTP_{contrails,100}}{SGTP_{CO_2,100}} \cdot s_{contrails}(h) + \frac{SGTP_{cirrus,100}}{SGTP_{CO_2,100}} \cdot s_{cirrus}(h) \qquad (4.42)$$

Schwartz 2009 presents a graph that gives the relation between the altitude and the forcing factor of induced cloudiness (AIC), the methane ($CH_4$) and long-lived ozone ($O_3$) as well as the short-lived ozone which are all three induced by $NO_x$-emissions. This data is based on information of Köhler 2008 and Rädel 2008. The graph is given in Figure 4.15. This shows that the forcing factor of methane and long-lived ozone are the same as well as those for contrails and cirrus clouds.

$$s_{O_3,L}(h) = s_{CH_4}(h) \qquad (4.43)$$

And

$$s_{contrails}(h) = s_{cirrus}(h) = s_{AIC}(h) \qquad (4.44)$$

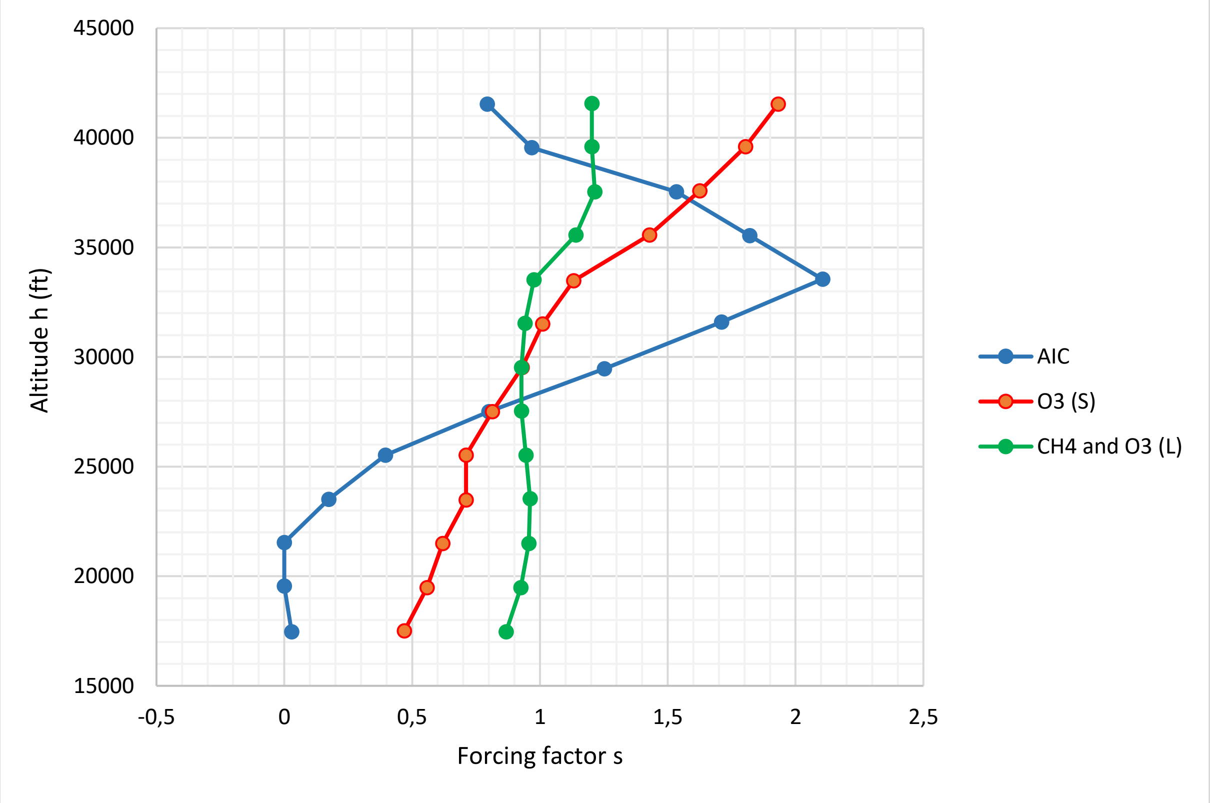


**Figure 4. 15** Forcing factors for different greenhouse gases depending on the altitude (adapted from **Schwartz 2009**)

The total amount of $CO_2$-equivalent can be determined using these characterization factors. In case of $NO_x$-emissions and $CO_2$-emissions $x_i$ is defined as $E_i$, the amount of emitted species, and respectively as the stage length L for contrails and cirrus clouds. As $CO_2$ is used as the reference, its emitted mass has to be multiplied by one.

$$(CO_2 - equivalent)_{Total} = \sum_{i=1}^{N_i} x_i \cdot CF_{midpoint,i} \tag{4.45}$$

Or more detailed:

$$(CO_2 - \mathrm{eq})_{Total} = E_{i,CO_2} \cdot 1 + E_{i,NOx} \cdot CF_{midpoint,NOx} + L \cdot CF_{midpoint,clouds} \tag{4.46}$$

To calculate the mass of emitted pollutants, the emission index of that specie has to be multiplied with the mass of the used fuel. As the emission index of carbon dioxide is a constant, 3,16 kg $CO_2$/kg fuel, it is very straight forward to calculate its emitted mass:

$$E_{i,CO_2} = EI_{CO_2} \cdot m_{used\,f\mathrm{uel}} \tag{4.47}$$

$$E_{i,CO_2} = 3{,}16 \cdot m_{used\,fuel} \tag{4.48}$$

Although the same formula can be applied for $NO_x$-emissions, it is not that easy to determine the amount of emitted $NO_x$. As stated before the emission index for $CO_2$ is a constant, that of $NO_x$ not. This factor is heavily dependent of the combustion efficiency of the engine. Also the flight altitude will have an influence and has to be taken into account.

$$E_{i,NOx} = EI_{NOx} \cdot m_{used\,fuel} \tag{4.49}$$

There are several methods developed to calculate the emission index of nitrogen oxides. Most accurate procedure is called P3-T3. It uses the inlet pressure and temperature of the combustor as well as reference data of emissions to forecast the emissions of $NO_x$. Unfortunately this method cannot be used in the ecolabel as the necessary data is not public available. Another method was developed by Boeing which is less accurate. It will be explained in section 5.2 as this is not the main method that is used to determine the emission index of $NO_x$. It was found that Eurocontrol an up-to-date database, called BALADA, possess that contains information of specific aircraft such as fuel burn, amount of emitted $NO_x$, $CO_2$, $SO_2$, PM, etcetera during cruise as well as during the LTO cycle. Again this database is not public available and cannot be used, but it was discovered that the European Environment Agency (EEA) has a similar database with the same information which is public available (**EEA 2016**). As the information is so recent in the database it is allowable to determine the emission index of $NO_x$ of a certain airplane by dividing the emitted amount of $NO_x$ by the amount of fuel burn. The proper use of the database of EEA is explained in Chapter 5.

To obtain a meaningful value for the $CO_2$-equivalent, which allows comparison between different airplanes, normalization is again required. This is realized by using the specific fuel consumption which is determined in section 4.1.3.2 instead of the mass of the used fuel for the emissions of nitrogen oxides and carbon oxides. The share of the contrails and cirrus clouds can be normalized by dividing the stage length by the stage length multiplied with the typical amount of seats which are determined in section 4.1.3.2. Finally the total amount of $CO_2$-equivalent is expressed in units of kg $CO_2$/km per seat.

$$\left(CO_{2,eq}\right)_{Total} = \frac{E_{i,CO_2}}{SAR \cdot n} \cdot 1 + \frac{E_{i,NOx}}{SAR \cdot n} \cdot CF_{midpoint,NOx} + \frac{L}{L \cdot n} \cdot CF_{midpoint,clouds} \tag{4.50}$$

To determine the rating scale for the climate impact, the same reference group is used as in section 4.1.3.1 excluding 7 aircraft. The Bombardier CR100/200, the Bombardier Q series, the Dornier 228 and the Saab 340 are not included in the reference group because they were not included in the database of EEA. Therefore, the data to determine the emission index of $NO_x$ is missing. As a representative rating scale is desired, no simplifications or other methods were used to determine the emission index of the missing airplanes. Applying the calculations to the reference group leads to a distribution of values for $CO_2$-equivalents given in Figure 4.16.

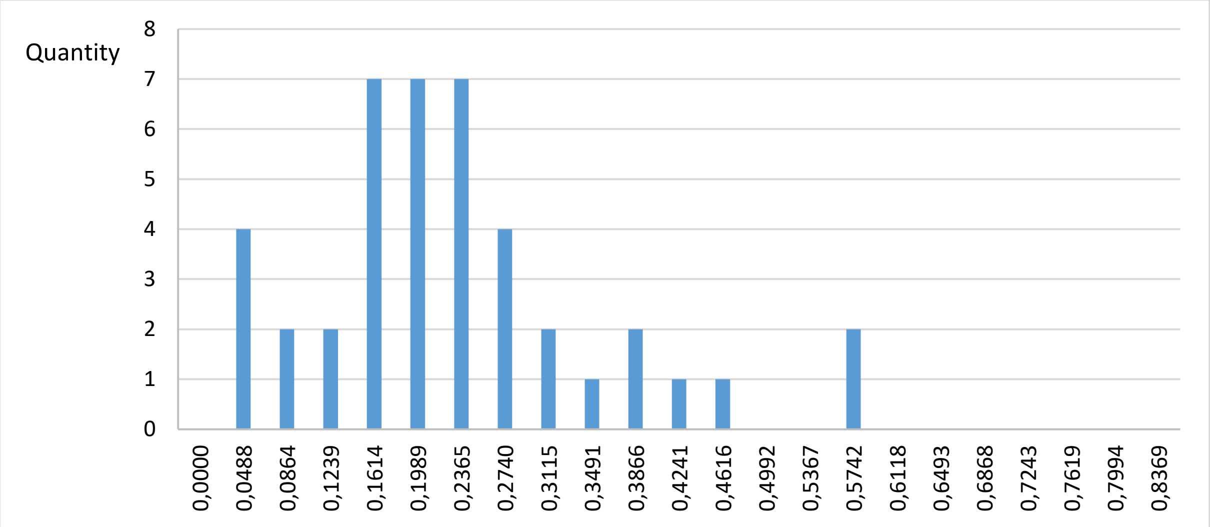


**Figure 4. 16** Normalized $CO_2$ equivalent

The rating scale is determined according to the same method as used for the other rating tables. The results are sorted from minimum to maximum and according to formula 4.7 (section 4.1.3.2) every value that corresponds with a multiple of 6 determine the boundaries of each classification.

$$\text{Number of values per classification} = \frac{\text{Total amount of calculated values}}{7} \tag{4.7}$$

This result in the rating scale given in Table 4.11:

**Table 4. 11** Rating scale for the climate impact per seat (kg $CO_2$/km)

| Rating | Range | | Normalized to 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| A | 0,04882 | 0,09487 | 0 | 0,0818 |
| B | 0,09487 | 0,18706 | 0,0818 | 0,2456 |
| C | 0,18706 | 0,21106 | 0,2456 | 0,2882 |
| D | 0,21106 | 0,24062 | 0,2882 | 0,3407 |
| E | 0,24062 | 0,27891 | 0,3407 | 0,4087 |
| F | 0,27891 | 0,36805 | 0,4087 | 0,5671 |
| G | 0,36805 | 0,61175 | 0,5671 | 1,0000 |

## 4.5 Overall Rating

So far, the key indicators of the ecolabel are established which are rated according to a rating scale from A to G. However, the label should contain an overall score for the airplane. Therefore weighting factors for each indicator should be derived. It is chosen to use a fixed factor for each category based on the results of the life cycle assessment derived in the PhD of Johanning 2016.

It was discovered in Johanning 2016 that the resource depletion and the climate change have the largest share in the impact on the environment. This is shown in Figure 4.17. Both of them are determined by the fuel consumption of the aircraft. Therefore the weighting factor of the fuel consumption is 60%. This percentage should be split into two parts, one for the resource depletion and one for the climate change. According to Figure 4.17 the ratio between both categories is 2,6.

$$\text{Ratio} = \frac{\text{Climate change}}{\text{resource depletion}} = \frac{68\%}{26\%} \approx 2{,}6 \tag{4.51}$$

It is chosen to round this factor down to two. Therefore, the climate change or impact is accounted for twothirds of the 60%. This means the climate impact gets a weighting factor of 40% and the resource depletion respectively 20%.

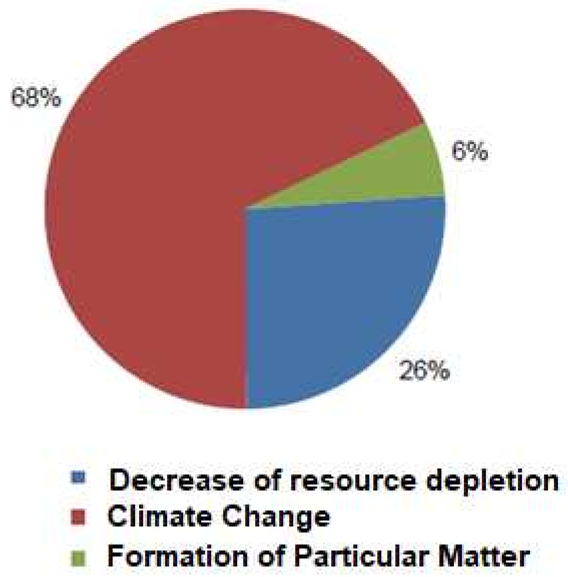


**Figure 4. 17** Distribution of the influence of each parameter on the overall environmental impact (adapted from **Johanning 2016**)

The remaining 40% will be equally divided for the rating of the local air quality and the noise pollution. In this manner the share to the overall rating of these parameters will be noticable. Therefore the overall rating is defined by:

$$\text{Overall rating} = 0{,}6 \cdot \text{Fuel consumption} + 0{,}2 \cdot \text{Noise} + 0{,}2 \cdot \text{Local air quality} \tag{4.52}$$

Or more detailed:

$$\begin{aligned}\text{Overall rating} = {} & 0{,}4 \cdot (\text{norm.}\, CO_2 \text{ equivalent}) + 0{,}2 \\ & \cdot (\text{norm. fuel consumption}_{\text{OEM}}) + 0{,}2 \cdot (\text{norm. local air quality}) \\ & + 0{,}2 \cdot (\text{norm. noise})\end{aligned} \tag{4.53}$$

As there was made a difference for the rating of the noise of jets and turboprops, there will be also two different rating scales for the overall rating of the aircraft. In Table 4.12 respectively in Table 4.13 the rating scales for the overall rating of jets and turboprops are shown.

**Table 4. 12** Rating scale of the overall impact by jets (-)

| Rating | Range | |
|---|---|---|
| | min | max |
| A | 0 | 0,1861 |
| B | 0,1861 | 0,2794 |
| C | 0,2794 | 0,3173 |
| D | 0,3173 | 0,3538 |
| E | 0,3538 | 0,3994 |
| F | 0,3994 | 0,4900 |
| G | 0,4900 | 1,0000 |

**Table 4. 13** Rating scale of the overall impact by turboprops(-)

| Rating | Range | |
|---|---|---|
| | min | max |
| A | 0 | 0,1194 |
| B | 0,1194 | 0,2456 |
| C | 0,2456 | 0,3129 |
| D | 0,3129 | 0,3503 |
| E | 0,3503 | 0,3921 |
| F | 0,3921 | 0,4763 |
| G | 0,4763 | 1,0000 |

As stated in section 4.2, the local air quality can only be calculated for aircraft with jet engines for now. Therefore the overall rating for a turboprop will be determined by:

$$\text{Overall rating} = \frac{0{,}4 \cdot (\text{norm. } CO_2 \text{ eq}) + 0{,}2 \cdot (\text{norm. fuel consumption}_{\text{OEM}}) + 0{,}2 \cdot (\text{norm. noise})}{0{,}8} \quad (4.54)$$

## 4.6 Design of the Ecolabel

A proposed design is given in Figure 4.18. In the label some general information will be provided such as the airline, the type of aircraft and the type of the installed engine and the number of seats available in this specific airplane (so not the OEM seat layout). The overall rating is the most important and will be the most prominent factor of the label. The rating class, as well as the calculated value of all indicators separately, are also shown in the label.

A use of symbols is chosen, so that everybody could understand the key indicators even if they are not familiar with the language used in the label. It is advised to use English as main language on the label. English as language is commonly used in aviation and as well very known all over the world.

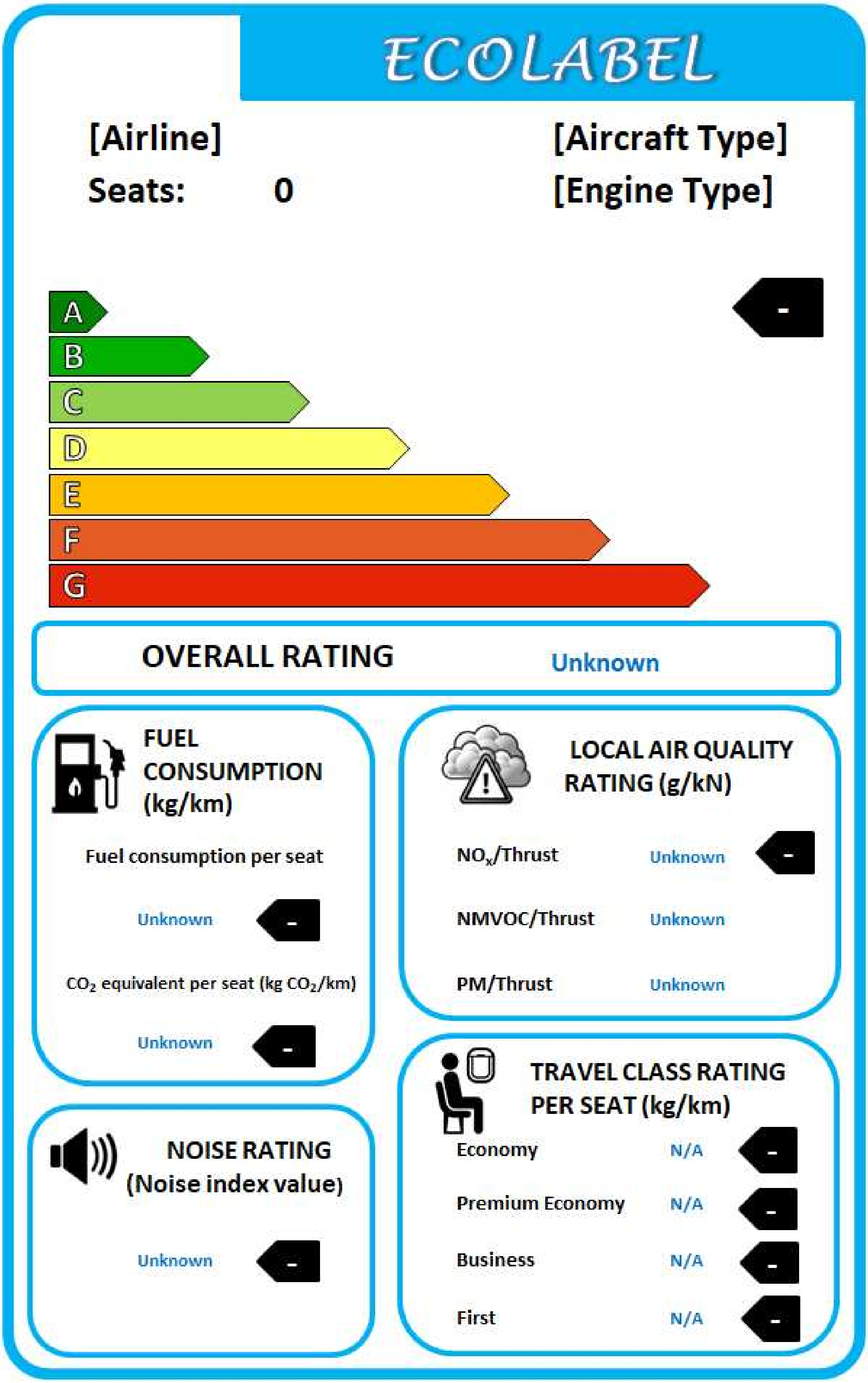


**Figure 4. 18** Proposed design for the ecolabel for aircraft

# 5 Explanation of the Tools

This chapter is meant to be a guideline on how to use the programs to generate a desired ecolabel for a specific airplane. First of all the operation of the main procedures will be explained. In some cases not all data can be found to apply the given methods. Therefore some extra procedures and calculations are provided. These extras will also be described. Finally a small calculator is provided for the costumers, in case the seat-layout of the airplane of their trip differs from an already existing ecolabel of the airplane. In this manner they can calculate the label themselves for the aircraft they will use. This makes it possible for them to make a well-considered choice about their travel.

The usage of all the tools given in this chapter will be explained on the basis of an example. The A320, A320neo and the bombardier CRJ100 are used in these examples.

## 5.1 The Main Program to Generate the Ecolabel

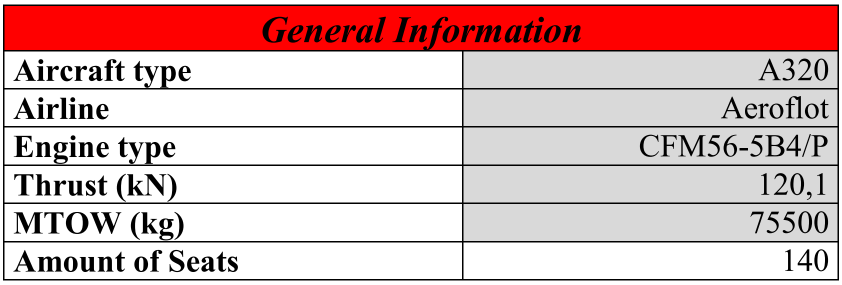
If all the necessary data can be found and all the explained methods in chapter 4 can be applied, the ecolabel can be generated quick and simple with the main Excel file which is called 'Production of an Ecolabel' in the tab page 'ECOLABEL'. First of all general information about the program itself should be provided. If a cell is grey colored it means that data should be inputted by the user, if it is white then the parameter is automatically calculated. The orange cells are the results which will be rated according to the rating scales. The green ones are the normalized results and are used to calculate the overall rating. The blue cells are results of parameters which will be given on the ecolabel as extra information but they are not included in the overall rating and are not rated. The aircraft used in this example is the Airbus A320 of the airline Aeroflot.

### 5.1.1 General Information of Aircraft

The label will be provided with some general information such as the aircraft type, the airline which owns the aircraft, the engine type because it is common that one type of aircraft can be equipped with different versions of engines and as last the number of seats in the aircraft as this can differ for each airline. Other information that is important for the calculations but do not have an added value to put them on the label, are the maximum thrust the engine can deliver and the maximum take-off mass of the airplane.

This information can be easily found on the internet on websites like seatguru.com or planespotters.net. Also the webpage of the airline itself as well as that of the manufacturer can contain some basic information about the airplane. Finally certification documents, like the noise certification in the noise databank ‘NoisedB’, will provide the same information as well as. The results for the example of the A320 are given in Figure 5.1. This figure as well as the other figures presented in this chapter are screen shots of the tool.

A remark should be made about Figure 5.1. As mentioned before, white cells are automatically calculated. This means that the amount of seats has not to be inputted. The total amount of seats will be calculated in the block of the travel class raring. The reason for this is that the data of the number of seats mostly is taken from seatguru.com. They give the number of seats for each class. This will be done also in the program and the total amount of seats will be automatically calculated. In this manner the probability of making a mistake is limited.



| ***General Information*** | |
|---|---|
| **Aircraft type** | A320 |
| **Airline** | Aeroflot |
| **Engine type** | CFM56-5B4/P |
| **Thrust (kN)** | 120,1 |
| **MTOW (kg)** | 75500 |
| **Amount of Seats** | 140 |

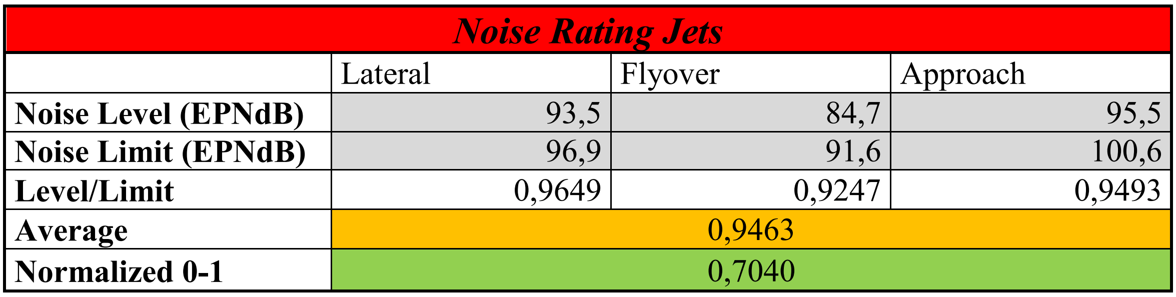
**Figure 5. 1** Example of A320 of the general information block in the tool

### 5.1.2 Noise Rating

The certification data of noise of the aircraft are given in the database ‘NoisedB’ or the ‘TCDSN’ documents provided by EASA. The use of NoisedB is preferred as this database is specially developed to function as a general source. This database can be found on the webpage ‘http://noisedb.stac.aviation-civile.gouv.fr’. If an aircraft is not included, the TCDSN documents can be consulted. These documents are provided in the main Excel file ‘Production of an Ecolabel’ under the tabs ‘TCDSN_Jets’ and ‘TCDSN_Props’. Both databases contain the certified noise levels and limits for the three different reference points determined in Appendix B, also called lateral point, flyover point and approach point.

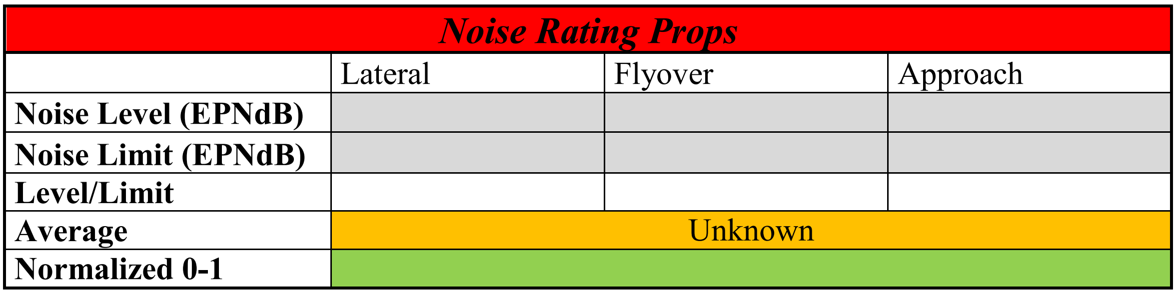
As shown in Figure 5.2 and in Figure 5.3 only the data given in the certification documents have to be inputted for a jet or a turboprop. The noise indices and the average value are calculated automatically. In this case the A320 is equipped with jet engines. Therefore only the table of the jet engines should be provided with data and the table of the turboprops should be empty.

The average noise index value, in the orange cell, is rated according to the rating scale given in Table 4.8. This results in a rating of classification C.



| ***Noise Rating Jets*** | | | |
|---|---|---|---|
| | Lateral | Flyover | Approach |
| **Noise Level (EPNdB)** | 93,5 | 84,7 | 95,5 |
| **Noise Limit (EPNdB)** | 96,9 | 91,6 | 100,6 |
| **Level/Limit** | 0,9649 | 0,9247 | 0,9493 |
| **Average** | 0,9463 | | |
| **Normalized 0-1** | 0,7040 | | |

**Figure 5. 2** Example of A320 of the noise rating for jets block in the tool

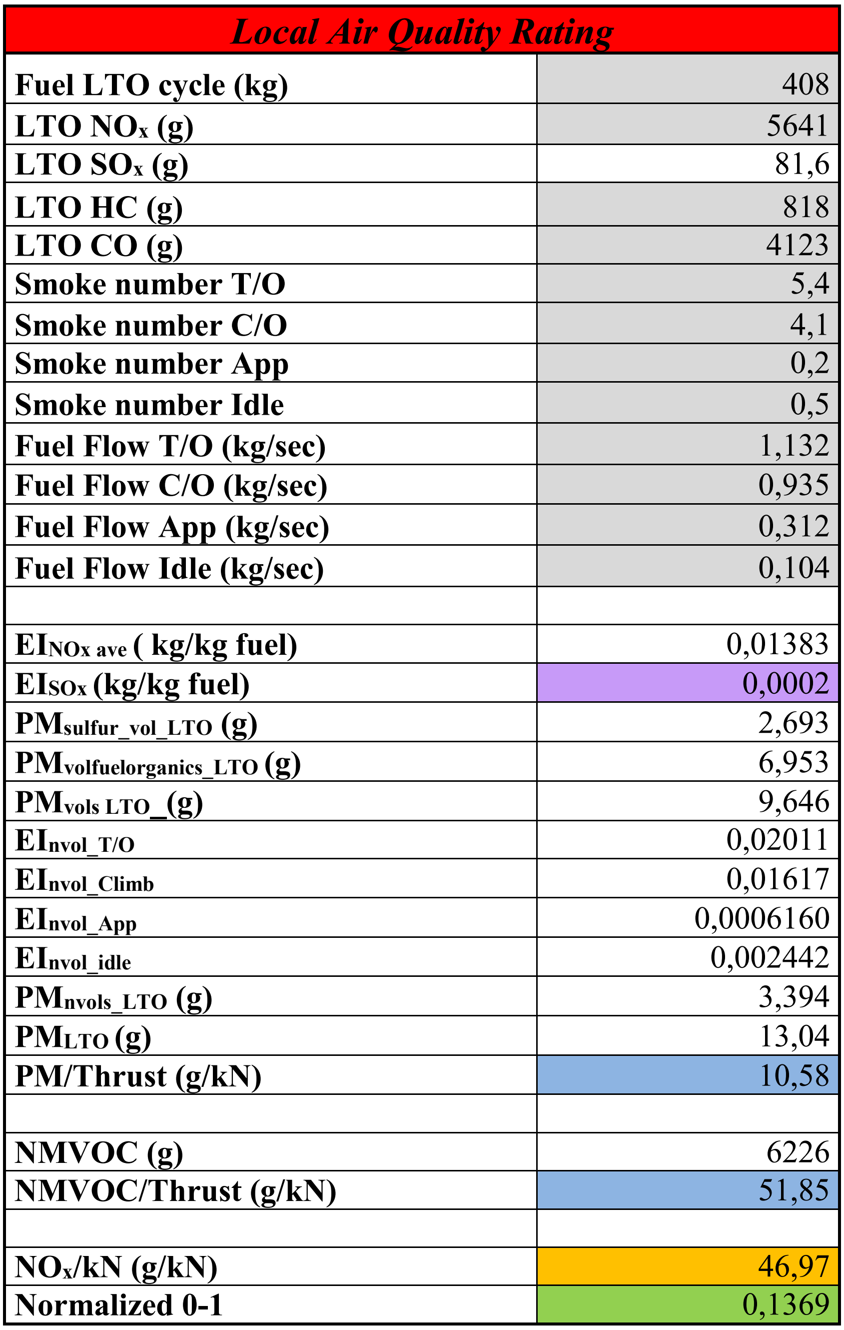


| ***Noise Rating Props*** | | | |
|---|---|---|---|
| | Lateral | Flyover | Approach |
| **Noise Level (EPNdB)** | | | |
| **Noise Limit (EPNdB)** | | | |
| **Level/Limit** | | | |
| **Average** | Unknown | | |
| **Normalized 0-1** | | | |

**Figure 5. 3** Example of A320 of the noise rating for turboprops block in the tool

### 5.1.3 Local Air Quality Rating

In case of an aircraft with jet engines, the air quality in the vicinity of the airport can be assessed. The program is again developed in such manner that only data obtained from the Engine Emissions Databank should be inputted and everything will be calculated automatically. The database is frequently updated and the most recent version is provided in the main Excel file under the tab 'ICAO Emissions Databank'. The tabs 'Column Description' and 'Record of changes' provide extra information about the database itself. The automatic calculations are discussed in section 4.2. In Figure 5.4 the example for the A320 is elaborated.



| ***Local Air Quality Rating*** | |
|---|---|
| **Fuel LTO cycle (kg)** | 408 |
| **LTO $NO_x$ (g)** | 5641 |
| **LTO $SO_x$ (g)** | 81,6 |
| **LTO HC (g)** | 818 |
| **LTO CO (g)** | 4123 |
| **Smoke number T/O** | 5,4 |
| **Smoke number C/O** | 4,1 |
| **Smoke number App** | 0,2 |
| **Smoke number Idle** | 0,5 |
| **Fuel Flow T/O (kg/sec)** | 1,132 |
| **Fuel Flow C/O (kg/sec)** | 0,935 |
| **Fuel Flow App (kg/sec)** | 0,312 |
| **Fuel Flow Idle (kg/sec)** | 0,104 |
| | |
| **$EI_{NOx\ ave}$ ( kg/kg fuel)** | 0,01383 |
| **$EI_{SOx}$ (kg/kg fuel)** | 0,0002 |
| **$PM_{sulfur\_vol\_LTO}$ (g)** | 2,693 |
| **$PM_{volfuelorganics\_LTO}$ (g)** | 6,953 |
| **$PM_{vols\ LTO\_}$(g)** | 9,646 |
| **$EI_{nvol\_T/O}$** | 0,02011 |
| **$EI_{nvol\_Climb}$** | 0,01617 |
| **$EI_{nvol\_App}$** | 0,0006160 |
| **$EI_{nvol\_idle}$** | 0,002442 |
| **$PM_{nvols\_LTO}$ (g)** | 3,394 |
| **$PM_{LTO}$ (g)** | 13,04 |
| **PM/Thrust (g/kN)** | 10,58 |
| | |
| **NMVOC (g)** | 6226 |
| **NMVOC/Thrust (g/kN)** | 51,85 |
| | |
| **$NO_x$/kN (g/kN)** | 46,97 |
| **Normalized 0-1** | 0,1369 |

**Figure 5. 4** Example of the A320 of the local air quality rating in the tool

The amount of $NO_x$ emissions is rated according to Table 4.7. The A320 is situated in the classification D.

### 5.1.4 Resource Depletion Rating

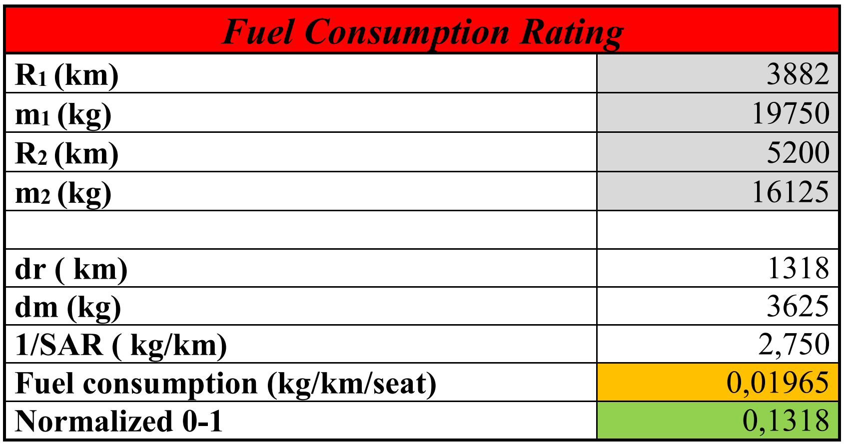
**Average Fuel Consumption Rating**

As stated in section 4.1 the fuel consumption can be determined with two pairs of coordinates of the payload range diagram. Preferable are the coordinates of the two points marked in Figure 4.1, but any pair of coordinates situated on this slope can be used to calculate the specific air range and hence the fuel consumption.

For most airplanes the payload-range diagrams are given in the documents for the airport planning. These documents are often provided by the manufacturer and are public available. The large manufactures as Airbus, Boeing, Embraer and Bombardier supply the airport planning documents for all their commercial aircraft on their webpages. For some turboprops and small business jets the airport planning is not public available. Then the payload-diagram can be found in brochures of the airplane, on aviation forums (not really recommended) or in books like 'Jane's All the Aircraft of the World' or 'Avions civils à reaction: Plan 3 vue et données caractéristiques' From Élodie Roux.

In Figure 5.5 the fuel consumption of the A320 is calculated. The input data is obtained from the airport planning documents of the A320 found on the webpage of Airbus. Again everything is calculated if the input data is given.

The fuel consumption of the A320 is rated according to the rating scale given in Table 4.2.
It is situated in the classification B.

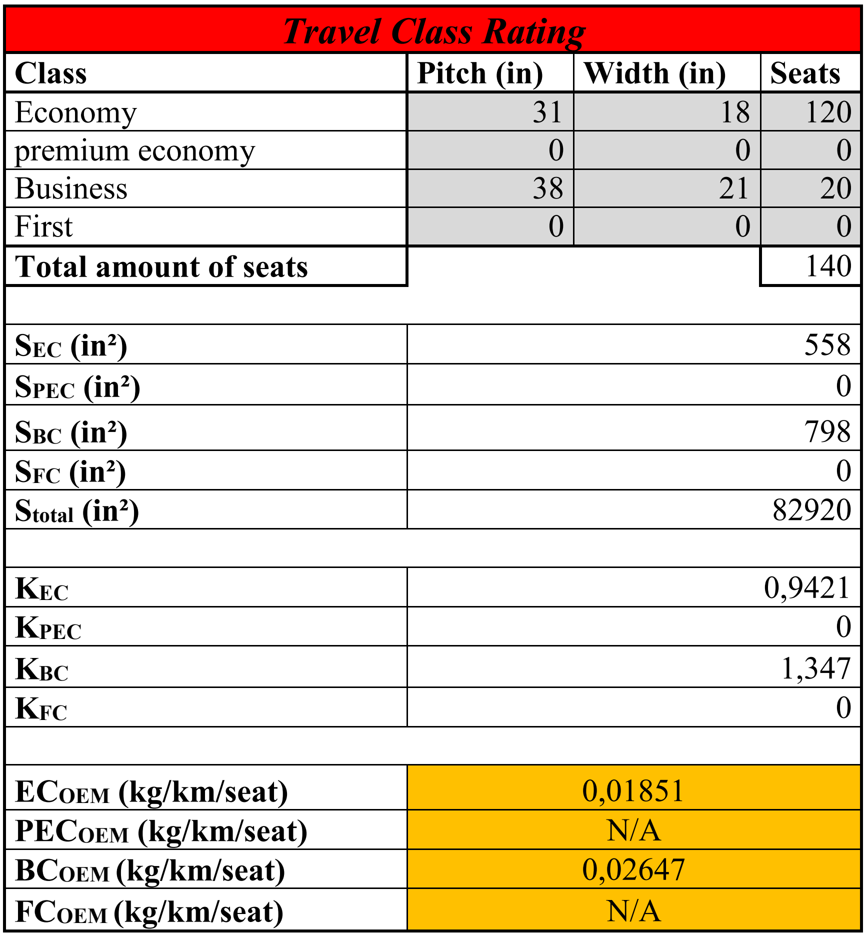


| *Fuel Consumption Rating* | |
|---|---|
| **$R_1$ (km)** | 3882 |
| **$m_1$ (kg)** | 19750 |
| **$R_2$ (km)** | 5200 |
| **$m_2$ (kg)** | 16125 |
| | |
| **dr ( km)** | 1318 |
| **dm (kg)** | 3625 |
| **1/SAR ( kg/km)** | 2,750 |
| **Fuel consumption (kg/km/seat)** | 0,01965 |
| **Normalized 0-1** | 0,1318 |

**Figure 5. 5** Example of the A320 of the fuel consumption rating block in the tool

### Travel Class Rating

As stated in section 4.1.4, if a seat is accommodated with more comfort and has therefore more space, its specific share in the fuel consumption will be larger. Therefore, the ecolabel will provide the fuel consumption for each travel class of the aircraft. All the calculations are done automatically. The user only has to insert three parameters of each class which are the pitch of the seats, the width of the seats and the number of seats. The data can be found on the website ‘seatguru.com’. Therefore the correct airline and aircraft should be chosen. The data for the A320 is given in Figure 5.6.



| ***Travel Class Rating*** | | | |
|---|---|---|---|
| **Class** | **Pitch (in)** | **Width (in)** | **Seats** |
| Economy | 31 | 18 | 120 |
| premium economy | 0 | 0 | 0 |
| Business | 38 | 21 | 20 |
| First | 0 | 0 | 0 |
| **Total amount of seats** | | | 140 |
| | | | |
| **$S_{EC}$ (in$^2$)** | 558 | | |
| **$S_{PEC}$ (in$^2$)** | 0 | | |
| **$S_{BC}$ (in$^2$)** | 798 | | |
| **$S_{FC}$ (in$^2$)** | 0 | | |
| **$S_{total}$ (in$^2$)** | 82920 | | |
| | | | |
| **$K_{EC}$** | 0,9421 | | |
| **$K_{PEC}$** | 0 | | |
| **$K_{BC}$** | 1,347 | | |
| **$K_{FC}$** | 0 | | |
| | | | |
| **$EC_{OEM}$ (kg/km/seat)** | 0,01851 | | |
| **$PEC_{OEM}$ (kg/km/seat)** | N/A | | |
| **$BC_{OEM}$ (kg/km/seat)** | 0,02647 | | |
| **$FC_{OEM}$ (kg/km/seat)** | N/A | | |

**Figure 5. 6** Example of the A320 of the travel class rating block in the tool

In the example the A320 exists out of two classes: economy and business class. They are both rated according to the rating scale in Table 4.2. The economy class is situated in the classification B and the business class in G. There is no premium economy class nor first class. Therefore it will be indicated on the label that these classes are not applicable for this specific aircraft.

Two remarks should be made. Firstly as mentioned in section 5.1.1 and shown in Figure 5.1 and Figure 5.6, the total number of seats is calculated of the inputted data for each class. In this manner the probability on making a counting mistake is reduced to a minimum. Secondly, if a class is not included in the aircraft, the input data of this class should be implemented with zero. If there is nothing inputted for this class the program will fail to calculate the rating for the other classes.

### 5.1.5 Climate Impact Rating

One of the key parameters to calculate the $CO_2$-equivalent is the emission index of nitrogen oxides. As mentioned in section 4.4.2 the determination of this parameter is not that simple. Furthermore the flight altitude in cruise of the aircraft plays a big role in the calculation. A public available database called '1.A.3.a Aviation 1 Master emissions calculator 2016' of EEA is used to determine the emission index of $NO_x$. The calculations in this database are done with the most recent empirical data available. If the airplane for the label is included only a representative cruise stage length, or cruise range, should be entered. Then the cruise altitude can be read directly in the database and the emission index of $NO_x$ can be calculated by dividing the amount of $NO_x$ by the amount of burned fuel.

It was discovered that the cruise stage length can be determined be taking the half of the range for maximum payload. As the range for maximum payload, $R_1$, is already used in the calculation for the fuel consumption (see Figure 4.1), the stage length is very quickly obtained by dividing $R_1$ by two. In the example for the A320 the stage length entered in the database of EEA is:

$$\text{Cruise stage length} = \frac{R_1}{2} \tag{5.1}$$

$$\text{Cruise stage length} = \frac{2096{,}15\ \text{NM}}{2} \tag{5.2}$$

$$\text{Cruise stage length} \cong 1048\ \text{NM} \tag{5.3}$$

It should be noticed that the cruise stage length should be entered in the units of Nautical Miles. Most of the payload-range diagrams are in the units of pounds and Nautical Miles so the values should not be converted into SI-units. For the calculation of the fuel consumption a conversion was necessary. Also noticeable is the altitude, which is given in feet in the database. Again this should not be converted into SI-units as the altitude is used to determine the forcing factor of the emission products with Figure 4.15.

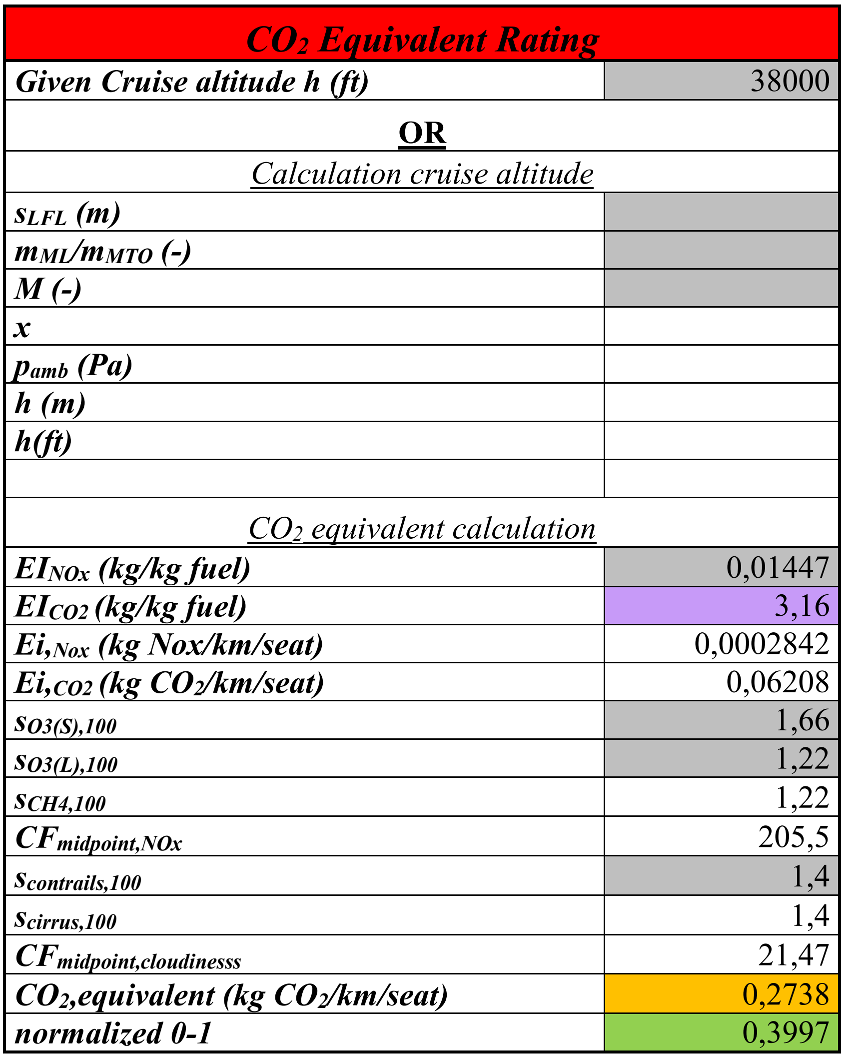
For the A320 with cruise stage length of 1048 Nautical Mile, a cruise altitude of 38000 feet is found as well as an amount of fuel burn of 5512,91 kilograms and an amount of $NO_x$ of 79,76 kilograms. Therefore the emission index of $NO_x$ is calculated for the A320:

$$EI_{NO_x} = \frac{\text{Amount of emitted } NO_x}{\text{Amount of burned fuel}} \tag{5.4}$$

$$EI_{NO_x} = \frac{79{,}76 \text{ kg } NO_x}{5512{,}91 \text{ kg fuel}} \tag{5.5}$$

$$EI_{NO_x} = 0{,}01447 \frac{\text{kg } NO_x}{\text{kg fuel}} \tag{5.6}$$

This value should be entered in the program. As mentioned before, the cruise altitude is used to determine the forcing factor of each pollutant with Figure 4.14. The values of the forcing factors are given in the example of the A320 in Figure 5.7. Also the emission index of $CO_2$ should be entered. As this is a constant, 3,16 kg $CO_2$/kg fuel, it is fixed. This is indicated by the purple color of the cell.



| ***$CO_2$ Equivalent Rating*** | |
|---|---|
| ***Given Cruise altitude h (ft)*** | 38000 |
| **OR** | |
| *Calculation cruise altitude* | |
| ***$s_{LFL}$ (m)*** | |
| ***$m_{ML}/m_{MTO}$ (-)*** | |
| ***M (-)*** | |
| ***x*** | |
| ***$p_{amb}$ (Pa)*** | |
| ***h (m)*** | |
| ***h(ft)*** | |
| | |
| *$CO_2$ equivalent calculation* | |
| ***$EI_{NOx}$ (kg/kg fuel)*** | 0,01447 |
| ***$EI_{CO2}$ (kg/kg fuel)*** | 3,16 |
| ***$Ei,_{Nox}$ (kg Nox/km/seat)*** | 0,0002842 |
| ***$Ei,_{CO2}$ (kg $CO_2$/km/seat)*** | 0,06208 |
| ***$s_{O3(S),100}$*** | 1,66 |
| ***$s_{O3(L),100}$*** | 1,22 |
| ***$s_{CH4,100}$*** | 1,22 |
| ***$CF_{midpoint,NOx}$*** | 205,5 |
| ***$s_{contrails,100}$*** | 1,4 |
| ***$s_{cirrus,100}$*** | 1,4 |
| ***$CF_{midpoint,cloudinesss}$*** | 21,47 |
| ***$CO_2$,equivalent (kg $CO_2$/km/seat)*** | 0,2738 |
| ***normalized 0-1*** | 0,3997 |

**Figure 5. 7** Example of the A320 of the $CO_2$ equivalent rating block in the tool

The result for the $CO_2$-equivalent of the A320 is rated according to the rating scale given in Table 4.11. The aircraft is situated in the classification E.

If the airplane is not included in the database of EEA and the aircraft is equipped with jet engines, the user should first look if the engine type is included in the database. The engine type is indicated with its unique identification number (UID) in the database. The UID of each jet engine type can be found in the Engine Emissions Databank. If the engine type is included in the database of EEA, those values can be used.

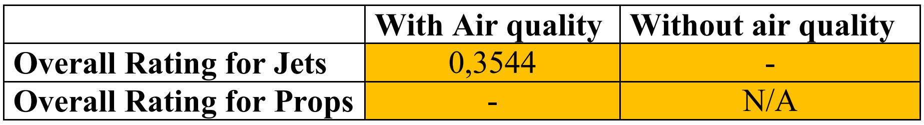
If the jet airplane as well as the jet engines are not included in the database of EEA, then the cruise altitude has to be calculated. Also a different method should be used to determine the emission index of $NO_x$. The method that is used then is called the ‘Boeing fuel flow method 2’. The explanation of these calculations and methods is given in section 5.2.

If the airplane is not included in the database of EEA and the aircraft is equipped with turboprop engines, the user should first look if the engine type is included in the database. As the engine type in this case is indicated with ‘turboprop’ in the database, all the turboprops included in the database of EEA are given in Appendix G.

If even the engine is not included in the database, and therefore also not in the appendix, the cruise altitude and the emission index of the $NO_x$ has to be calculated. The calculation of the cruise altitude, which is explained in section 5.2.1, is also applicable for turboprops. The problem is the calculation of the emission index of $NO_x$. The method proposed by Boeing is only applicable for aircraft with jet engines. Therefore, no other method is available to calculate the emission index of $NO_x$ of a turboprop aircraft. At this moment, the only solution that can be provided is that the user should choose an aircraft that is similar to the aircraft for which the ecolabel is being calculated.

### 5.1.6 Overall Rating

The overall rating of the airplane is calculate automatically of all the normalized values given in the previous tables. Nothing has to be inserted anymore. The result for the A320 is given in Figure 5.8. This is rated according to the rating scale shown in Table 4.12 in this case. The overall rating for the A320 of Aeroflot is situated in the classification E.



| | **With Air quality** | **Without air quality** |
|---|---|---|
| **Overall Rating for Jets** | 0,3544 | - |
| **Overall Rating for Props** | - | N/A |

**Figure 5. 8** Example of the A320 of the overall rating in the tool

It will practically never occur that an aircraft with a jet engine will be assessed without the local air quality as well as a turboprop with air quality. Therefore they are indicated with a dash. In the case of the example the A320 is an aircraft with jet engines. Therefore the overall rating for an airplane with a turboprop is indicated as not applicable N/A.

### 5.1.7 Design of the Ecolabel

The most elements of the ecolabel are generated automatically, where the user should not do anything, or they are fixed. To finalize the label, the user of the program should adjust the classifications in the black arrows to the appropriate ones that are determined with the above mentioned procedures. Also the black arrow of the overall rating should be placed at the right classification. At last, the value of the overall rating should be changed into the correct value as this is not automatically done.

The ecolabel of the A320 of Aeroflot is presented in Figure 5.9.

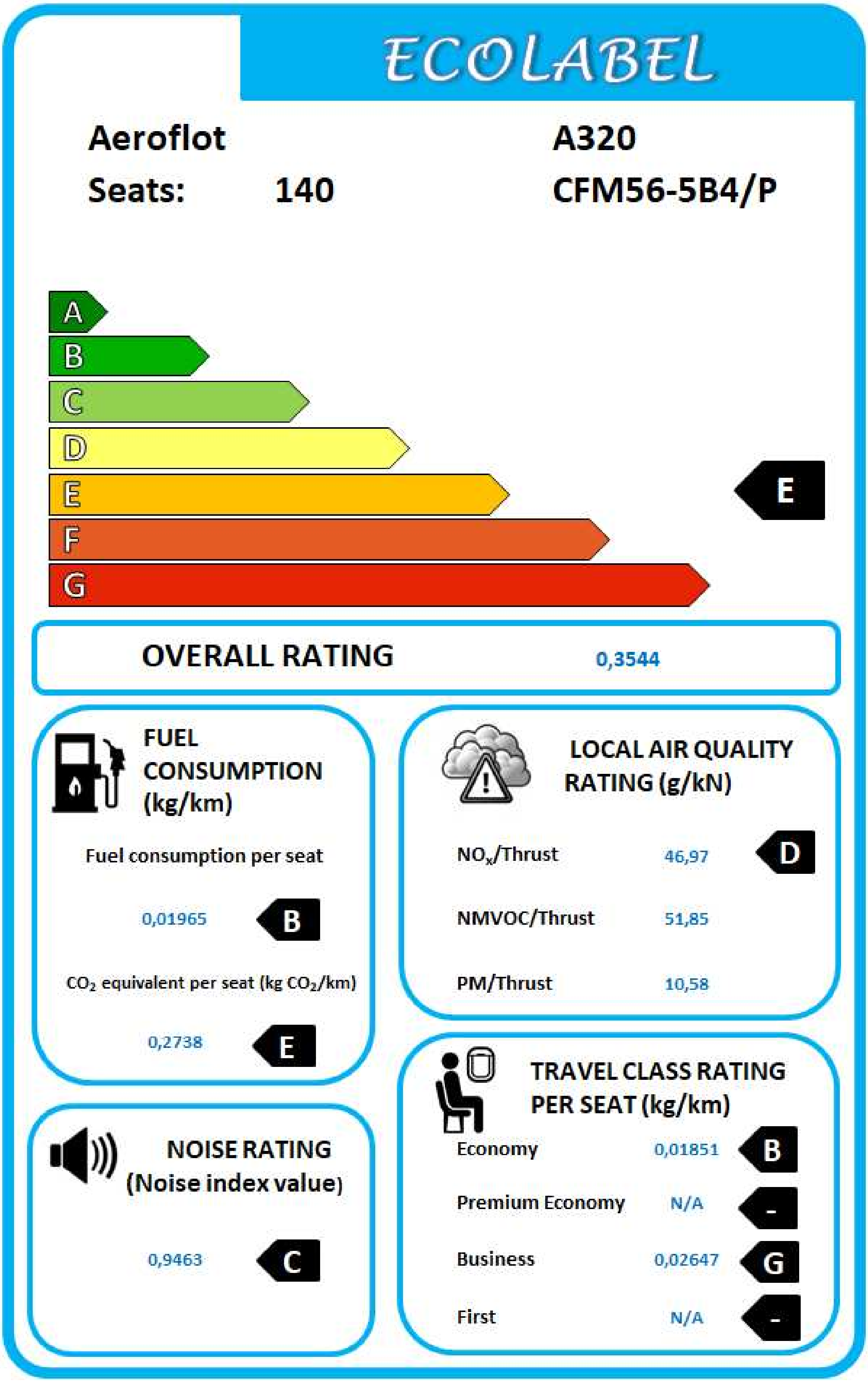


**Figure 5. 9** Example of the ecolabel of the A320 generated in the tool

## 5.2 Alternative Methods for the $CO_2$-Equivalent Rating

If an aircraft is not included in the database of EEA and no other method would be used for the determination of the emission index of $NO_x$ and the cruise altitude, it would not be possible to calculate the $CO_2$ equivalent. Therefore other methods are developed and found to determine these two parameters. The calculation of the flight altitude is based on the preliminary sizing of an aircraft. To calculate the emission index of $NO_x$ a method is developed by Boeing that is used as an alternative to be able to determine the ecolabel. As an example for this section the A320neo of Easyjet is used.

### 5.2.1 Determination of the Cruise Altitude

In the preliminary sizing phase of the design of an aircraft some requirements are demanded. These requirements are put together in a matching chart to determine the optimum design point of the aircraft (**Scholz 2013**). A theoretical example is given in Figure 5.10.

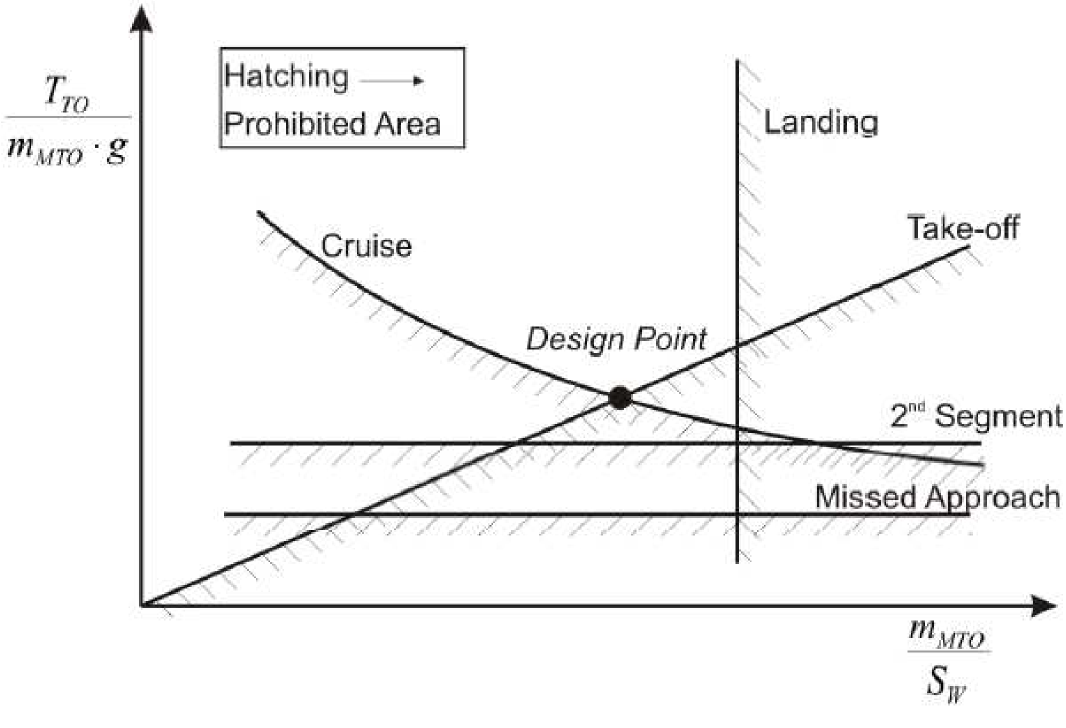


**Figure 5. 10** Illustrative example of a matching chart of preliminary sizing (**Scholz 2013**)

If the matching chart is analyzed by the two requirements of landing phase and cruise phase, it is possible to find an expression for the pressure at a certain altitude and thus is it possible to determine the altitude itself. The requirement of the landing distance provides information about the wing loading of the aircraft.

$$\left(\frac{m_{MTO}}{S_W}\right)_{landing} = \frac{k_L \cdot \sigma \cdot C_{L,max,landing} \cdot s_{LFL}}{{}^{m_{ML}}/_{m_{MTO}}} \tag{5.7}$$

The same applies for the requirement of the cruise phase.

$$\left(\frac{m_{MTO}}{S_W}\right)_{cruise} = \frac{C_L \cdot {M_{cr}}^2}{g} \cdot \frac{\gamma}{2} \cdot p(h) \tag{5.8}$$

If these two requirements are equated to each other, the expression for the air pressure can be found.

$$p(h) = \frac{2 \cdot k_L \cdot \sigma \cdot C_{L,max,landing} \cdot g}{C_L \cdot \gamma} \cdot \frac{s_{LFL}}{{M_{cr}}^2 \cdot m_{ML}/m_{MTO}} \tag{5.9}$$

It would be possible to determine the altitude with the International Standard Atmosphere (ISA) from this expression for the pressure. This formula consists of a lot of factors depending on the aerodynamics which cannot be found or which are very difficult to calculate. Therefore a statistic is performed. In this manner the unknown parameters are bounded together and will appear as a known factor in the formula. The statistic takes into account the landing field length, the Mach number in cruise and the ratio between the maximum landing mass and the maximum take-off mass of the aircraft. The statistic group exists of the group airplanes given in Appendix E excluding the 6 aircraft: ATR42, ATR72, Beechcraft 1900D, B737-900, DHC Twin Otter and Dornier 228. For these aircraft not all the necessary data could be found or they are outliers. For the statistic the pressure is calculated with the ISA by using the cruise altitude. The cruise altitude for the airplanes included in the statistic group can be found in books like 'Jane's All the Aircraft of the World' or 'Avions civils à reaction: Plan 3 vue et données caractéristiques' From Élodie Roux.

$$p(h) = p_0 \cdot \left(1 - 0{,}0065 \cdot \frac{h_{cr}}{T_0}\right)^{5{,}2561} \tag{5.10}$$

The result of the statistic is given in Figure 5.11 and formula 5.11. This statistic results in a formula for the pressure where the unknown parameters are represented with the factor that determines the slope of the function. The user is able to calculate the ambient pressure with a correctness of 62 percent by entering the cruise Mach number, the ratio between the maximum landing mass and the maximum take-off mass and the landing field length. This will be shown in Figure 5.18 in section 5.2.3 where the example will be elaborated. The ambient pressure is expressed in units of Pascal.

$$p(h) = 3{,}3769 \cdot \frac{s_{LFL}}{m_{ML}/m_{MTO} \cdot {M_{cr}}^2} + 1{,}2180 \cdot 10^4 \qquad (5.11)$$

The cruise altitude can be determined with the ISA by using the calculated pressure in formula 5.11.

$$h_{cr} = \frac{T_0}{0{,}0065} \cdot \left(1 - \frac{p}{p_0}\right)^{\frac{1}{5{,}2561}} \qquad (5.12)$$

With the temperature and pressure at standard conditions $T_0$ = 288,15 K and $p_0$ = 101325 Pa. This cruise altitude will be used then to determine the forcing factors as mentioned in section 5.1.

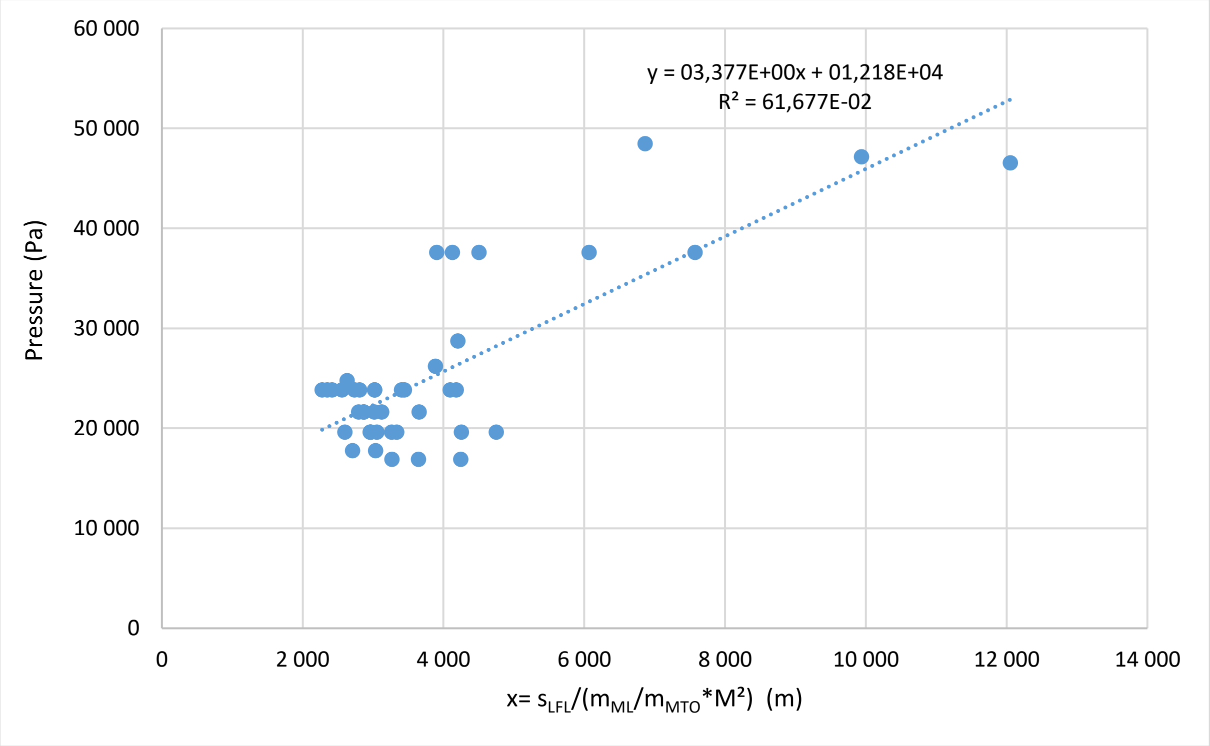


**Figure 5. 11** Statistic of the ambient pressure

The calculation is inserted in the main Excel program mentioned in section 5.1. In Figure 5.7 it is shown that the cruise altitude can be entered by a value obtained from the database of EEA or can be calculated according to the formula mentioned above.

### 5.2.2 Determination of the Emission Index of $NO_x$

The calculation of the emission index of $NO_x$ is mostly based on the Fuel Flow Method 2 by Boeing (BFFM2) which is developed to model the CO, HC and $NO_x$ emissions. This will be explained in the following paragraphs. The method uses the fuel flows and the corresponding emission indices from the Engine Emissions Databank of ICAO for the various emission products. They will be related to each other and will be adjusted for the atmospheric effects.

First of all the fuel flows given in the emission databank of ICAO will be adapted for installation effects of the engine on the aircraft. The values will be multiplied with a correction factor which is determined by Boeing. This factor depends on the operation mode of the aircraft and is given in Table 5.1 for the four different modes.

$$W_{f,adapt} = W_{f,unadapt} \cdot r \tag{5.13}$$

**Table 5. 1** The correction factors fort he fuel flow according to BFFM2 (**FAA 2005**)

| Operation mode | Boeing's correction factor 'r' |
|---|---|
| Take-off | 1,010 |
| Climb out | 1,013 |
| Approach | 1,020 |
| Idle | 1,100 |

Secondly, a relation between the adjusted fuel flows and the emission indices given in the databank should be developed. This is done by producing a graph which plots the fuel flow against the emission index and this with a logarithmic scale. An illustrative example is given in Figure 5.12. Then a regression line is generated which will provide the formula for the relation between the two parameters.

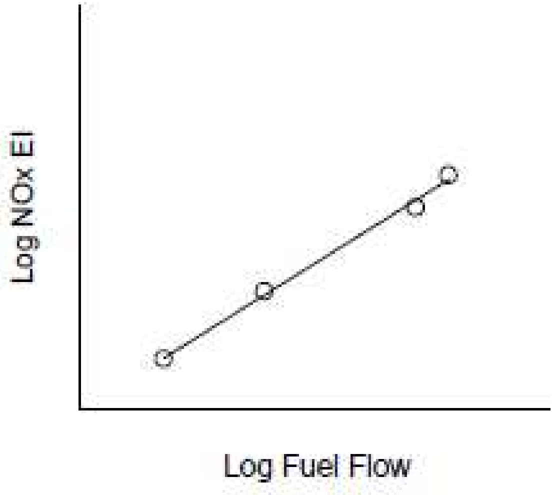


**Figure 5. 12** Illustrative example of the log-log plot (**FAA 2005**)

Subsequently the fuel flow is determined by the fuel consumption multiplied with the airspeed. The airspeed is calculated with the speed of sound at the specific altitude and the cruise Mach number.

$$W_{f,uncorr} = \frac{1}{SAR} \cdot V \tag{5.14}$$

This obtained fuel flow has to be adjusted to the altitude. This is done according to the following formula:

$$W_{f,corr} = \left(\frac{W_{f,uncorr}}{\delta_{amb}}\right) \cdot \left({\theta_{amb}}^{3,8} \cdot e^{0,2 \cdot {M_{cr}}^{2}}\right) \tag{5.15}$$

With

$$\delta_{amb} = \frac{p_{amb}}{p_0} \tag{5.16}$$

Where $p_0 = 101325$ Pa and $T_0 = 288,15$ K for:

$$\theta_{amb} = \frac{T_{amb} + 273,15}{288,15} \tag{5.17}$$

Both, the ambient pressure as well as the ambient temperature, are determined with the calculated cruise altitude in the previous section. The last step is to calculate the emission index of $NO_x$ itself. Therefore the corrected fuel flow, calculated in formula 5.15, is used to determine the uncorrected emission index of $NO_x$ by inserting it in the formula generated in step 2. Then this factor should be corrected for the atmospheric effects.

$$EI_{NOx,corr} = EI_{NOx,uncorr} \cdot e^{H} \cdot \left(\frac{{\delta_{amb}}^{1,02}}{{\theta_{amb}}^{3,3}}\right)^{0,5} \tag{5.18}$$

With H defined as the humidity correction factor. The factor also has to be derived. This according to the next three formulas:

$$H = -19,0 * \left(\frac{0,37318 \cdot p_v}{p_{amb} - 0,6 \cdot p_v} - 0,0063\right) \tag{5.19}$$

With:

$$p_v = 6895 \cdot 0,014504 \cdot 10^{\beta} \tag{5.20}$$

And with:

$$\beta = 7{,}90298 \cdot \left(1 - \frac{373{,}16}{T_{amb} + 0{,}01}\right) + 3{,}00571 + 5{,}02808 \cdot \log_{10}\left(\frac{373{,}16}{T_{amb} + 0{,}01}\right) + 1{,}381610^{-7} \cdot \left[1 - 10^{11{,}344 \cdot \left(1 - \frac{T_{amb} + 0{,}01}{373{,}16}\right)}\right] + 8{,}1328 \cdot 10^{-3} \cdot \left[10^{3{,}49149 \cdot \left(1 - \frac{373{,}16}{T_{amb} + 0{,}01}\right)} - 1\right] \tag{5.21}$$

The corrected value for the emission index of $NO_x$ has to be inserted into the main Excel program. In Figure 5.7 it is shown that a value should be entered for the emission index for $NO_x$. This can be a value determined from the database of EEA as described in section 5.1 or the value calculated in the formulas above.

### 5.2.3 Example of the Usage of the Tools

General information about the tool for the calculation of the emission index of $NO_x$ should be provided. This is an Excel file called 'NOx calculator if jet is not included'. The grey colored cells indicate that a value should be entered. The white cells are parameters that are calculated automatically and the yellow one is the cell with the result for the emission index that should be entered in the main program. As example an A320neo of Easyjet is used.

First the fuel flows and the emission indices of the Engine Emissions Databank of ICAO should be entered. This is shown in Figure 5.13 and Figure 5.14.

| | $W_{f\_unadapt}$ ( kg/s) | r (-) | $W_{f,adapt}$ (kg/s) |
|---|---|---|---|
| **T/O** | 1,058 | 1,01 | 1,069 |
| **C/O** | 0,684 | 1,013 | 0,6929 |
| **App** | 0,282 | 1,02 | 0,2876 |
| **Idle** | 0,096 | 1,1 | 0,1056 |

**Figure 5. 13** Example of the A320neo of adapting the fuel flows of the Engine Databank

| | $EI_{NOx}$ (g/kg fuel) |
|---|---|
| **T/O** | 18,77 |
| **C/O** | 11,16 |
| **App** | 8,67 |
| **Idle** | 4,63 |

**Figure 5. 14** Example of the A320neo of entering the $EI_{NOx}$ of the Engine Databank

This results in the graph, which is shown in Figure 5.15. The formula necessary for the calculations is provided in the graph.

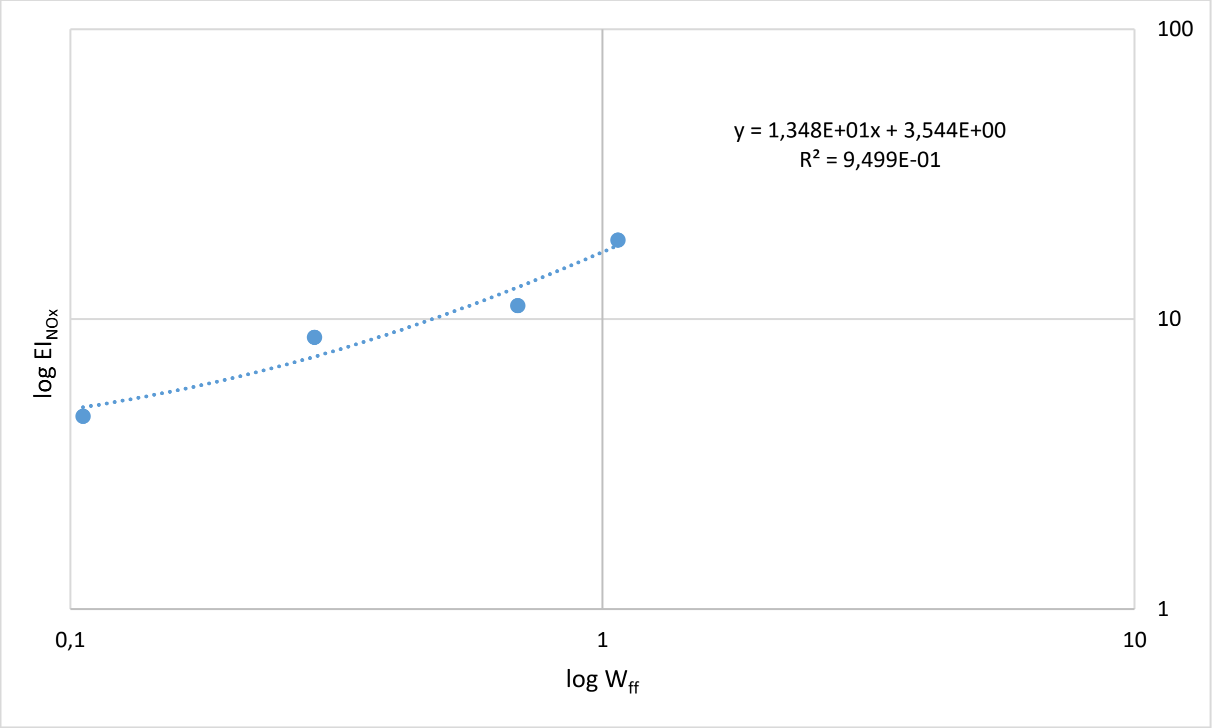
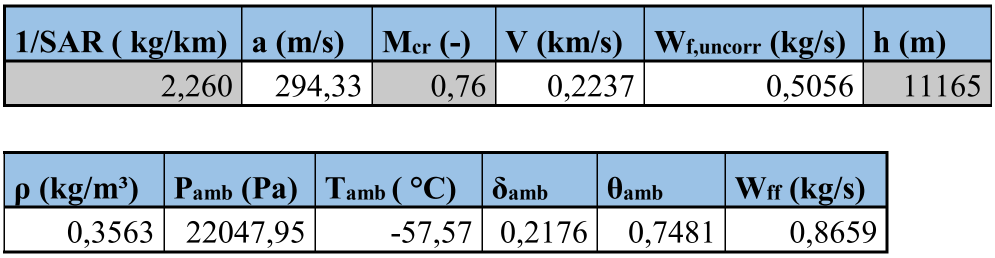


**Figure 5. 15** Relation between fuel flow and emission index

The calculation of the uncorrected and the corrected value for the fuel flow are calculated in Figure 5.16. The input data for the altitude is calculated in the main program.

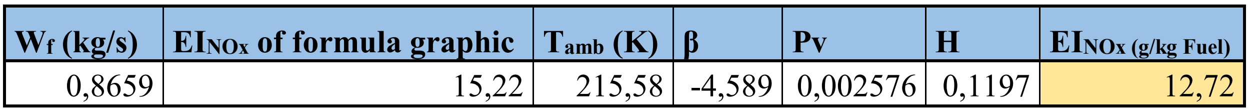


| 1/SAR ( kg/km) | a (m/s) | $M_{cr}$ (-) | V (km/s) | $W_{f,uncorr}$ (kg/s) | h (m) |
|---|---|---|---|---|---|
| 2,260 | 294,33 | 0,76 | 0,2237 | 0,5056 | 11165 |

| ρ (kg/m³) | $P_{amb}$ (Pa) | $T_{amb}$ ( °C) | $\delta_{amb}$ | $\theta_{amb}$ | $W_{ff}$ (kg/s) |
|---|---|---|---|---|---|
| 0,3563 | 22047,95 | -57,57 | 0,2176 | 0,7481 | 0,8659 |

**Figure 5. 16** Example of the A320neo of the calculation of the corrected fuel flow

Finally the corrected value for the emission index for $NO_x$ can be calculated. This is shown in Figure 5.17.

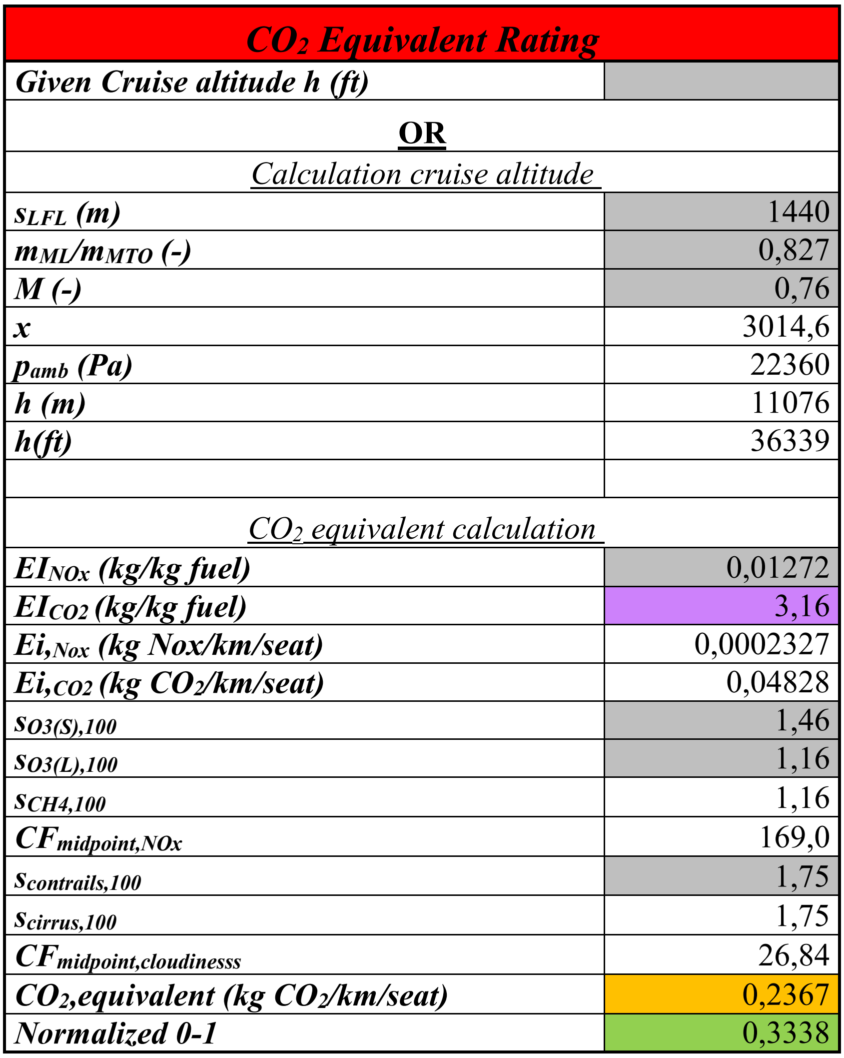


| $W_f$ (kg/s) | $EI_{NOx}$ of formula graphic | $T_{amb}$ (K) | β | Pv | H | $EI_{NOx}$ (g/kg Fuel) |
|---|---|---|---|---|---|---|
| 0,8659 | 15,22 | 215,58 | -4,589 | 0,002576 | 0,1197 | 12,72 |

**Figure 5. 17** Example of the A320neo of the calculation of the corrected $EI_{NOx}$

The value should be inserted in the main program. The user should pay attention to the units. The unit of the calculated emission index is grams of $NO_x$ divided by kilograms of fuel. In the main program the unit is kilograms of $NO_x$ divided by kilograms of fuel. Hence, a conversion factor is necessary.

In Figure 5.18 the calculation of the $CO_2$ equivalent is shown, but this time with the usage of the procedures mentioned above.



| ***$CO_2$ Equivalent Rating*** | |
|---|---|
| ***Given Cruise altitude h (ft)*** | |
| **OR** | |
| *Calculation cruise altitude* | |
| ***$s_{LFL}$ (m)*** | 1440 |
| ***$m_{ML}/m_{MTO}$ (-)*** | 0,827 |
| ***M (-)*** | 0,76 |
| ***x*** | 3014,6 |
| ***$p_{amb}$ (Pa)*** | 22360 |
| ***h (m)*** | 11076 |
| ***h(ft)*** | 36339 |
| | |
| *$CO_2$ equivalent calculation* | |
| ***$EI_{NOx}$ (kg/kg fuel)*** | 0,01272 |
| ***$EI_{CO2}$ (kg/kg fuel)*** | 3,16 |
| ***$Ei,_{Nox}$ (kg Nox/km/seat)*** | 0,0002327 |
| ***$Ei,_{CO2}$ (kg $CO_2$/km/seat)*** | 0,04828 |
| ***$s_{O3(S),100}$*** | 1,46 |
| ***$s_{O3(L),100}$*** | 1,16 |
| ***$s_{CH4,100}$*** | 1,16 |
| ***$CF_{midpoint,NOx}$*** | 169,0 |
| ***$s_{contrails,100}$*** | 1,75 |
| ***$s_{cirrus,100}$*** | 1,75 |
| ***$CF_{midpoint,cloudinesss}$*** | 26,84 |
| ***$CO_2$,equivalent (kg $CO_2$/km/seat)*** | 0,2367 |
| ***Normalized 0-1*** | 0,3338 |

**Figure 5. 18** Example of A320neo of $CO_2$ equivalent rating in the tool for jets not included in the database of EEA

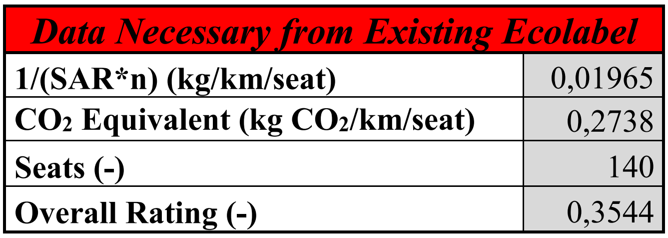
The climate impact of the A320neo of Easyjet is rated according to Table 4.11 and is situated in the classification D.

## 5.3 Customers Tool

A small and easy in use calculator is developed for the customer. With this calculator the costumer will be able to determine the fuel consumption, the $CO_2$ equivalent and the overall rating if a different seat layout is given for an aircraft for which already an ecolabel is defined. The only data the user should be enter are the fuel consumption, $CO_2$ equivalent, number of seats and overall rating of the existing ecolabel as well as the three parameters for each class of the new seat layout which are mentioned in section 5.1.4.2. The program can only be used if the aircraft have the same engines.

As an example the A320 can be used again. An A320 of Aeroflot was assessed in section 5.1. If the costumer has booked a flight with Air France or just wants to know the difference between the aircraft of both airlines, the calculator can be used. The calculator is an Excel file called 'Customer Tool'. The data of the new seat layout can again be found on the webpage 'seatguru.com'. The data of the A320 of Aeroflot can be found on the ecolabel. The example is elaborated in the following tables. The necessary information of the existing ecolabel is given in Figure 5.19.

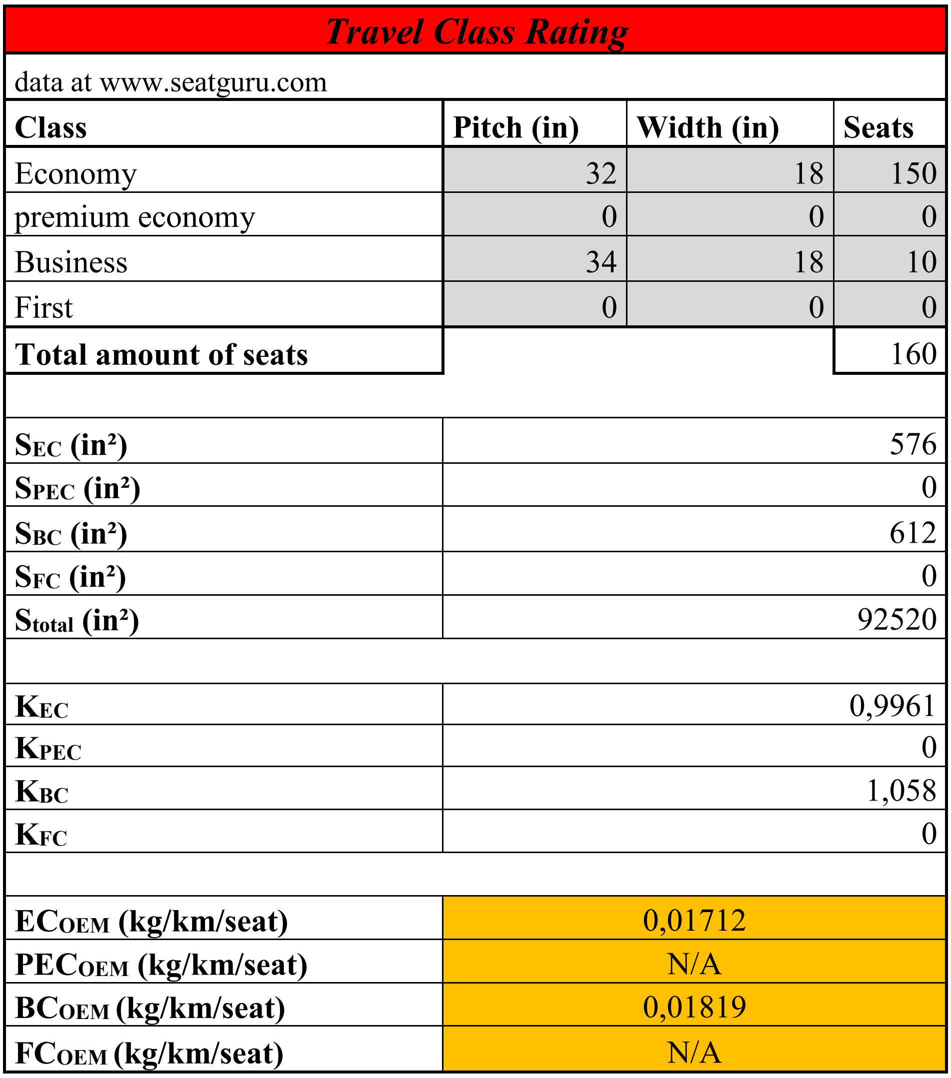
The general information about the program is the same as the main program explained in section 5.1. If a cell is colored grey, data should be entered. If they are colored white, the data is calculated automatically. Orange cells are results that are rated according to the rating scales developed in chapter 4. The green ones are normalized results and are used to determine the overall rating.



| *Data Necessary from Existing Ecolabel* | |
|---|---|
| **1/(SAR*n) (kg/km/seat)** | 0,01965 |
| **$CO_2$ Equivalent (kg $CO_2$/km/seat)** | 0,2738 |
| **Seats (-)** | 140 |
| **Overall Rating (-)** | 0,3544 |

**Figure 5. 19** Example of A320 of the necessary data for the cumstomers tool

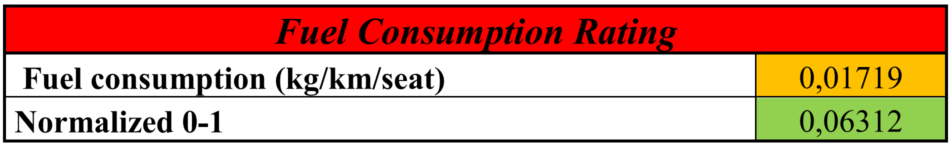
The data of the new seat layout and the results are given in Figure 5.20.



| ***Travel Class Rating*** | | | |
|---|---|---|---|
| data at www.seatguru.com | | | |
| **Class** | **Pitch (in)** | **Width (in)** | **Seats** |
| Economy | 32 | 18 | 150 |
| premium economy | 0 | 0 | 0 |
| Business | 34 | 18 | 10 |
| First | 0 | 0 | 0 |
| **Total amount of seats** | | | 160 |
| | | | |
| **$S_{EC}$ (in$^2$)** | | | 576 |
| **$S_{PEC}$ (in$^2$)** | | | 0 |
| **$S_{BC}$ (in$^2$)** | | | 612 |
| **$S_{FC}$ (in$^2$)** | | | 0 |
| **$S_{total}$ (in$^2$)** | | | 92520 |
| | | | |
| **$K_{EC}$** | | | 0,9961 |
| **$K_{PEC}$** | | | 0 |
| **$K_{BC}$** | | | 1,058 |
| **$K_{FC}$** | | | 0 |
| | | | |
| **$EC_{OEM}$ (kg/km/seat)** | 0,01712 | | |
| **$PEC_{OEM}$ (kg/km/seat)** | N/A | | |
| **$BC_{OEM}$ (kg/km/seat)** | 0,01819 | | |
| **$FC_{OEM}$ (kg/km/seat)** | N/A | | |

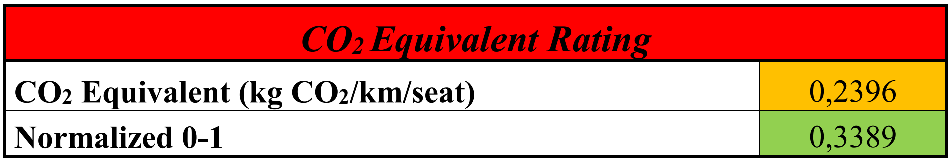
**Figure 5. 20** Example of the A320 of the travel class rating block in the customers tool

The results for the average fuel consumption, the $CO_2$ equivalent and the overall rating are given in respectively Figure 5.21, Figure 5.22 and Figure 5.23. The rating scales are provided in the program.



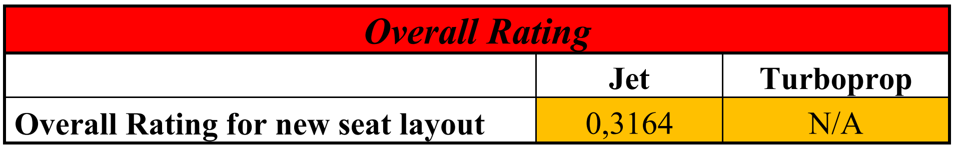
| ***Fuel Consumption Rating*** | |
|---|---|
| **Fuel consumption (kg/km/seat)** | 0,01719 |
| **Normalized 0-1** | 0,06312 |

**Figure 5. 21** Example of the A320 of the fuel consumption rating block in the customers tool



| ***$CO_2$ Equivalent Rating*** | |
|---|---|
| **$CO_2$ Equivalent (kg $CO_2$/km/seat)** | 0,2396 |
| **Normalized 0-1** | 0,3389 |

**Figure 5. 22** Example of the A320 of the $CO_2$ equivalent rating block in the customers tool



| Overall Rating | | |
|---|---|---|
| | **Jet** | **Turboprop** |
| **Overall Rating for new seat layout** | 0,3164 | N/A |

**Figure 5. 23** Example of the A320 of the overall rating block in the customers tool

The average fuel consumption, as well as the specific fuel consumption for each class, are rated according to Table 4.2. The average fuel consumption is situated in classification A. The economy class and business class are rated respectively A and B.

The climate impact through the $CO_2$ equivalent is rated according to Table 4.11. The result is located in classification D. In this case the overall rating is assessed according to the rating scale given in Table 4.12. The A320 of Air France has an overall score of C.

With this example the influence of the seat layout is shown. It is also shown that the calculator can help the costumer to make a well-considered choice towards the class and/or the airline for their journey.

# 6 Discussion of the Results

There are 13 ecolabels calculated. These labels are given in the appendices from H until S. The label will be briefly discussed as well compared with another label in the upcoming sections. Firstly, it will be mentioned if the label fulfills the requirements of the ISO standards.

## 6.1 The Requirements for the ISO Standards

In this section it is briefly discussed if the requirements of the ISO standards are met. As stated in section 2.2 the ecolabel should be voluntary, life cycle based, verifiable and open to third parties and so on. As every calculation method is based on data that is official, certified and public available, all requirements of the ISO standards are fulfilled. Section 2.2 also stated that an independent third party should handle the administration of the ecolabel. So far no organization is found to perform this task. Therefore, one requirement, an important one, is not fulfilled yet.

## 6.2 Ceo versus Neo

In this section the classical and new engine options of the A320 are compared with each other. Both labels are given respectively in Appendix H and Appendix I. This means that the dimensions of the aircraft are unchanged. It is logical that the aircraft with the new engines shows an improvement on each parameter compared with the classical engines. The progress of each parameter is such that the A320neo is at least rated one classification better than the A320ceo for each parameter. The noise parameter is even from category C to A increased. This results in an overall rating that differs a lot. The A320ceo has an overall rating of E. The A320neo on the other has an overall rating of B.

Off course, the main reason of the improvements is the usage of other and newer engines. These new engines produce less emissions, less noise and are more fuel efficient. Another explanation for the improvements can be the calculation of the $CO_2$ equivalent. The cruise altitude for the A320neo is calculated with the formula derived in section 5.2.1. This results in an altitude of 36000 feet. The A320ceo is included in the EEA database which declares that the cruise altitude is 38000 feet. This difference causes also a change in the forcing factors of the greenhouse gases and therefore the $CO_2$ equivalent is not only influenced by the new engines but also by the cruise altitude. A remark should be made in the case of these two specific airplanes in the label. The seat layout differs with 40 passengers. This has to be kept in my mind by comparing these specific two aircraft.

## 6.3 Same Aircraft Owned by Different Airlines

In this section the same aircraft owned by different airlines are compared with each other. The airplane chosen for this comparison is the B747-400. Both ecolabels are given in Appendix M.

The B747-400 owned by the airline 'United' is equipped with the engine type 'PW4056' from Pratt & Whitney. The seat layout exists out of 374 seats. The other one is owned by the airline 'British Airways' with engines from Rolls Royce. The number of seats in this B747-400 are 299.

The B747-400 of United has a rather mediocre overall score of classification D. The same applies for the parameters separately. Only for the average fuel consumption scores this specific airplane badly with a classification of F. The B747-400 of British Airways scores much worse on each parameter, except on the noise indicator, and therefore also on the overall rating. For the noise, the rating results in a B category, but all the other parameters get the worst score of G.

This means that the engines of Pratt & Whitney emit much less than the engines of Rolls Royce, but they produce a bit more noise. As both of these factors account for the same share of the overall rating (20%), it can be concluded that the bad score for the local air quality of the aircraft of British Airways has a large influence on the overall score which is much worse than that of United. A second reason for the bad score of the British Airways is the seat layout. The typical number of seats in a B747-400 is 400. The aircraft of United has 374 seats. This is not that much less than the typical number, but the aircraft of British Airways only counts 299 seats. United chose to offer more economy and premium economy places than British Airways who chose to provide more business seats. This has, in this case, a bad influence on the fuel consumption and climate impact.

## 6.4 Aircraft with Approximately Same Dimensions

The B737-400 was developed by Boeing to compete with the MD-80 series of McDonnell Douglas. Since 1997 McDonnell Douglas is merged with Boeing. The airplanes have approximately the same dimensions as well as the same maximum possible seating layout. Therefore, these are compared with each other in this section. The ecolabel of the B737-400 and the MD-83 are respectively given in Appendix L and Appendix P.

This specific B737-400, owned by Japan Airliners, is equipped with engines of CFM International and has a seat layout with 145 seats divided into two classes. The overall score is bad and is situated in the category F. This due to bad ratings for the climate impact, F, as well as the noise pollution G. Furthermore the average fuel consumption scores also rather low with an E and finally the local air quality scores mediocre with a C. The two chosen classes are the economy and the business class. The seats in the economy class have a specific fuel consumption that is rated better than the average fuel consumption. More specific it scores D. The business class consumes much more and is rated with G.

The MD-83 of the airline ‘Allegiant’ has a seat layout with 166 seats in total. Here it was chosen to split the seat layout in two classes, the economy class and the premium economy class. The aircraft is equipped with Pratt & Whitney engines. This aircraft scores very good on the fuel consumption on both, the resource depletion and the climate impact. On the other hand this type of engine produces a lot noise pollution and is rated with the worst score possible G. The amount of produced emissions in the vicinity of the airport are relatively large and are situated in classification E. As it was chosen to provide two classes with a standard comfort, both classes score very well on the fuel consumption. The Economy class scores an A and the premium economy, which offers a bit more space, is situated in the B category. As the parameters included in the fuel consumption have the largest share in the overall rating, the MD-83 has an overall score of B.

Both aircraft and therefore also the engines, are developed in the mid to late eighties. In those years noise regulations were different from now, which can be an explanation why both airplanes produce a lot of noise and score very poor on this parameter. As the MD-83 is more fuel efficient than the B737-400, the climate impact is lower than the B737-400 which results in a better classification for the MD-83. Another parameter that has an influence on the climate impact is the cruise altitude. The MD-83 flies according to the database of EEA at flight level 340, while the B737-400 flies at flight level 360. This dissimilarity causes a difference in the forcing factors of the greenhouse gases and therefore a discrepancy in the $CO_2$ equivalent. This can be an explanation why the MD-83 scores better than the B737-400 on the parameter of the climate impact. The large distinction in the overall scores is due to the large share of the fuel consumption in the overall rating, which is much better rated for the MD-83 than the B737-400.

## 6.5 Turboprop versus Small Jet

To compare a turboprop with a small jet, the ecolabels for an ATR-72-500 and a bombardier CRJ 900 are calculated. Both labels are respectively given in Appendix S and Appendix Q.

American Airlines possesses some regional jets. The Bombardier CRJ900 is one of them. The airplane is equipped with engines of General Electric. The aircraft exists of two classes, an economy class and a first class. The total number of seats is 79. The overall score for CRJ900 is rated an F due to the poor results for the fuel consumption and climate impact. The amount

$CO_2$ equivalent per seat is so large, that the climate impact is rated with G. The average fuel consumption is rated with E. If the fuel consumption for each class is evaluated, it can be concluded that the seats in the economy class consume a bit less than the average and is rated with D. The seats of the first class on the other hand consumes much more and is rated with G. On the parameters of the local air quality and the noise pollution the aircraft scores well with B on both parameters.

The ATR 72-500 of Air France is, in this case, an aircraft with only one class, the economy class. The airplane counts 70 seats. The engines on this plane are from the manufacturer Pratt & Whitney. First of all, it should be mentioned again for clarity, that turboprops are rated according to a different rating scale than jets for the noise indicator as well as the overall rating. The impact of the aircraft on the local air quality cannot be determined and is noted as unknown. The noise pollution is low and therefore the aircraft scores a good rating of B. The fuel consumption of the airplane is rated somewhere in between good and mediocre with C. The emitted $CO_2$ equivalent and therefore the impact on the climate is so low that the ATR 72-500 scores the best rating possible with A. Due to the rather good score on each parameter, the aircraft has an overall rating of B.

The main reason of the better result of the ATR 72-500 compared to the Bombardier CRJ900 is the climate impact of both airplanes. An explanation of this can be the cruise altitude. In general, turboprops fly at a lower altitude than jets because they fly slower. Again, this low cruise altitude results in smaller forcing factors for the greenhouse gases, especially for the short-lived ozone and the contrails and cirrus clouds. Therefore, the emitted $CO_2$ equivalent will be smaller and this leads to the result, that the impact on the climate is smaller and will be rated better.

## 6.6 Small Jets versus Large Jets

To compare small jets with large jets, four large jets and two small jets are discussed. It was chosen to use two airplanes of Airbus, the A350 and the A380, and two types of Boeing, the B777-300ER and the B787-9, as representation for the large jets. The labels are respectively given in Appendix J, Appendix K, Appendix O and Appendix N. For the small jets, the Bombardier CRJ900 and the Embraer 170 are chosen. The ecolabels of these aircraft are respectively given in Appendix Q and Appendix R.

The A350-900 of Finnair with Rolls Royce engines has a seat layout that exists out of 3 classes. These classes are the economy, premium economy and the business class. The total amount of seats is 297. This airplane scores on each parameter good, expect for the local air quality. The emitted mass of $NO_x$ is large and situated in the classification F. It is a very young aircraft, which means that the engines are also rather new. This is an explanation for the A-rating for the noise pollution. The average fuel consumption scores B. The fuel consumption of each class differs. The both economy classes score A and the business class scores G. The impact on the climate is still situated in the ‘green zone’ with a C-rating. All together the aircraft scores well with B.

Emirates is in possession of an A380-800 with the engines ‘GP7270’ of Engines Alliance. The seat layout exists out of the 489 seats divided into three classes. These classes are economy, business and first class. This aircraft is like the A350 still very young. It shows the same tendency as the A350 with a bad result for the local air quality with a score that is F and a good score, with A, for the noise pollution. The climate impact is mediocre and scores D. This can be explained with the bad fuel consumption. The average consumption scores F. Even the fuel consumption for each class scores bad. The economy class results in C as the other classes score G. The A380 is the biggest passenger aircraft in the world. It is designed and used for (very) long range flights. This means that the flight time is long. Therefore, the passengers should experience more comfort with more leg-space. This is the reason why even the economy class scores only in category C and the others with G. Overall this A380 of Emirates scores mediocre with D.

The B777-300ER, owned by Air Canada, is equipped with engines of General Electric. It has a three-class seat configuration with a total of 450 seats. The classes available are economy class, premium economy and business class. Also this aircraft shows the same tendency for the local air quality and noise pollution. The air quality scores badly with G. This means a lot of $NO_x$ is emitted in the vicinity of the airport. The noise pollution is low and rated with a B. The B777-300ER is a very efficient airplane in terms of fuel consumption. It is rated with the highest score A. This is one reason for the low impact on the climate, which is rated with B. The more fuel-efficient the airplane, the lower is the fuel consumption. This means that less fuel is burned per kilometer so it is logical that also less $CO_2$ equivalent is emitted. The fuel consumption per class has different ratings. The economy class scores also with A. The premium economy scores in category D and the business class in G. As they offer more comfort and therefore space, their score is worse than the average fuel consumption and the economy class rating. The overall score of the B777-300ER is just in the green zone with category C.

The B787-9 of Air New Zealand with Rolls Royce engines has a seat configuration of three classes: economy class, premium economy and business class. The total amount of seat is 302. The noise pollution is rated with the highest score A. The local air quality scores again badly with F. The average fuel consumption scores in A and therefore, the B787-9 is very fuel-efficient. The climate impact scores C. Again the economy class is rated with category A. The premium economy scores a bit worse with C and the business class G. Overall is this aircraft rated with B.

These airplanes are all relatively young. All of them show the same tendency on each parameter. They all score well for the noise rating which can be possibly explained by the young age of the installed engines. All of them have a bad result for the local air quality, which means they emitted rather a large amount of $NO_x$ during the LTO cycle. All of them, except for the A380, score very well on the fuel consumption. Also the climate impact has good ratings for the aircraft. One explanation for this is that the aircraft are very fuel-efficient. Differences between the ratings of the climate impact can be explained by the difference in cruise altitude. These large aircraft scores overall well.

The Bombardier CRJ900 of American Airlines is already discussed in section 6.4.

The Embraer ERJ 170-100 is owned by the airline 'Delta'. The aircraft is equipped with engines of General Electric. The engines are almost the same as those on the Bombardier CRJ900. The seat layout consists of three classes: economy, premium economy and first class. The local air quality scores B. If the results for the air quality are compared with the Bombardier, they are almost completely the same. This is logical because the engines have almost the same technical requirements. Striking is the difference in the noise rating. The Bombardier scored B. The Embraer 170 scores much worse with F. The aircraft is not fuel efficient with a rating of G for the average fuel consumption. This inefficiency has certainly an effect on the climate impact which is rated with F. All three classes score very bad. All of them are scoring in G for the fuel consumption. This is rather odd. Off course, the overall rating of this Embraer ERJ 170-100 is not that good with F.

Both of these small aircraft score badly. The main reason for this is their bad result for fuel consumption as well as for the climate impact. The local air quality scores well for both. This is explained in the text before. The difference in the noise rating cannot be explained unambiguously.

It has to be mentioned that all aircraft, the large ones as well as the small ones, that are discussed in this section are rather young or new. Generally the large aircraft are very fuel-efficient but they still emit a large amount of $NO_x$ during the LTO cycle. Partially due to their fuel-efficiency, they also have a smaller impact on the climate. On the other hand the small aircraft have the opposite tendency. They score well on the local air quality, but they show bad results for the fuel consumption as well as for their impact on the climate.

# 7 Conclusions and Recommendations

## 7.1 Conclusions

First of all, it can be concluded that the usage of the carbon dioxide ($CO_2$) equivalent, to assess the climate impact during cruise flight, is much more accurate than the methods proposed previously. It was recently discovered that the influence of the contrails and clouds, or more generally water, is more severe for the environment as thought before. Therefore, the calculation method of the climate impact is very up-to-date with the insertion of not only the carbon dioxide, but also the altitude-dependent nitrogen oxide as well as the altitude-dependent contrails and cirrus clouds. Therefore, the ecolabel itself is elevated to a higher level of accuracy and meaningfulness than before.

Furthermore, it can be concluded that still not all necessary data is directly ascertainable. Certified data for the fuel consumption of aircraft is not provided. Unfortunately also the development of Volume III of Annex 16 of ICAO (International Civil Aviation Organization), which describes the $CO_2$ certification requirement will not provide useful data. Therefore, fuel consumption is determined from payload-range diagrams as published by manufacturers. As the standard to define particular matter is still under development, also no certified data of this emission product is available yet. Therefore, an estimation had to be made with calculations based on emission data provided in the Engine Emissions Databank during the landing and take-off cycle.

It can also be concluded that by using solely official and certified data that is public available, the ecolabel meets all the requirements imposed by these ISO standards except for one. So far no (scientific) organization has been chosen that would best qualify to do the administration of the ecolabel. Certainly Hamburg University of Applied Sciences could do this, but another organization well established in aviation may be better qualified to take up this task.

Finally it can be concluded the harmonization of the scientific and environmental information, presented in an easy understandable label, enables the traveling customers to make a well informed and educated choice when booking a flight, selecting among airline offers with different types of aircraft and seating arrangements. Furthermore, the ecolabel can function as an encouragement for the manufactures to optimize their products on each performance category to achieve an overall (large) improvement on the environmental impact of their products.

## 7.2 Recommendations

It is advised to perform a follow-up investigation as there are still new standards about aircraft emissions under development. Once these developments are finished and docements are published, it would be advisable to base the rating scales, as for example the one for the fuel consumption, and/or calculation methods, as the calculation of particular matter on the new standards and procedures.

Secondly it is recommended to focus on finding an organization which wants to participate in the idea of the ecolabel and that wants to take care of the administration of the label to fulfill the last requirement of ISO 14025. The Hamburg University of Applied Sciences could take up this role upon itself as it is a scientific organization, but it is doubtful if the idea of the ecolabel will take off in this manner as well as if the industry will accept the idea. If a well accepted organization could be found in the aviation sector, it could increase the chance of acceptance of the idea of the Ecolabel for Aircraft.

Furthermore, it is advised to investigate the merger of the noise parameter of jets and turboprops. If one rating scale is developed for both types of airplanes instead of two rating scales separately, the both types could be compared better with each other. Also, this would lead to only one rating scale for the overall score of environmental impact of the aircraft. In this manner the possibility that the costumer confuses the ratings presented on the ecolabel could be reduced.

This thesis has only looked at aircraft using conventional fuel and at aircraft with conventional configurations. Therefore, it is recommend doing research whether the developed calculation methods are also applicable alternative fuels and for unconventional aircraft.

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# Appendix A

# ICAO Annex 16 Volume II – Aircraft Engine Emmisions

Standards for certification of emissions produced by the engines of aircraft are determined in Volume II of Annex 16 of ICAO. It is focused on the measurements of carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides ($NO_X$) and smoke (SN) (**ICAO 2008**). It also sets a regulatory limit on the concentration of these emission products during the landing and take-off cycle (LTO).

To allow comparison of the measurements and provide a standardization, a reference procedure was defined which is called the landing and take-off cycle (LTO). Every movement of the aircraft below 3000 feet is included in this cycle which is shown in Figure A.1. This means that landing and take-off as well as taxi-in and taxi-out of the aircraft is included. Both taxi-modes can be combined together which is also called the 'idle' mode.

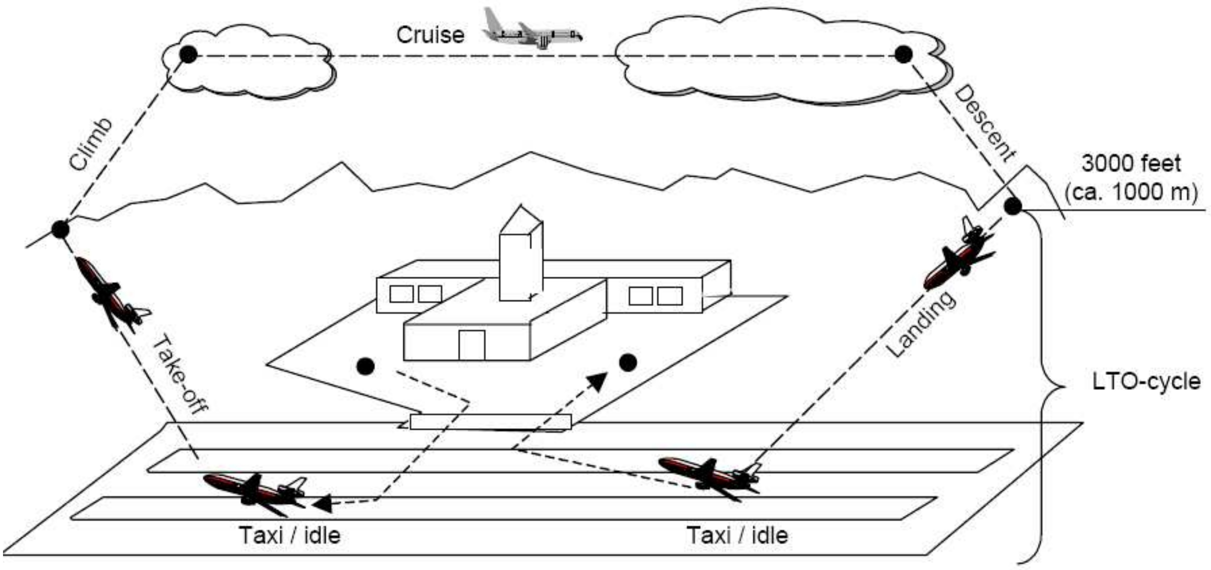


**Figure A. 1** Definition of the landing and take-off cycle (LTO) (**EMEP 2006**)

For certification procedures, the engine has to be tested at various thrust settings which have to represent the operation modes during the LTO cycle. This has to be done for a certain amount of time. Both the trust setting and the required operating time are given for each mode in Table A.1.

**Table A. 1** Engine thrust and operating time for each operating mode

| Operating mode | Engine thrust (%) | Operating time (min) |
|---|---|---|
| Take-off | 100 | 0,7 |
| Climb-out | 85 | 2,2 |
| Approach | 30 | 4 |
| Taxi-in | 7 | 19 |
| Taxi-out | 7 | 7 |

During this test, the emitted mass of each pollutant stated above are measured at various probe sampling positions. Also the mass of the burned fuel is measured. Therefore it is easy to calculate the emission indices of the different species by dividing the amount of emitted species by the amount of used fuel.

# Appendix B

# ICAO Annex 16 Volume I – Aircraft Noise

Standards procedures as well as reference conditions for aircraft noise certification are determined in Volume I of Annex 16 of ICAO. The ICAO document 9501-AN/929 'Environmental Technical Manual on the Use of Procedures in the Noise Certification of Aircraft' explains how the procedures should be performed.

The reference points of noise measurement are shown in Figure B.1. They are defined as follow:

- Lateral point on a line parallel to the runway at 450 meters 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 meters distance (from break release point/ start of roll)
- Flyover point at approach on the extended center line of the runway at 2000 meters from the runway threshold

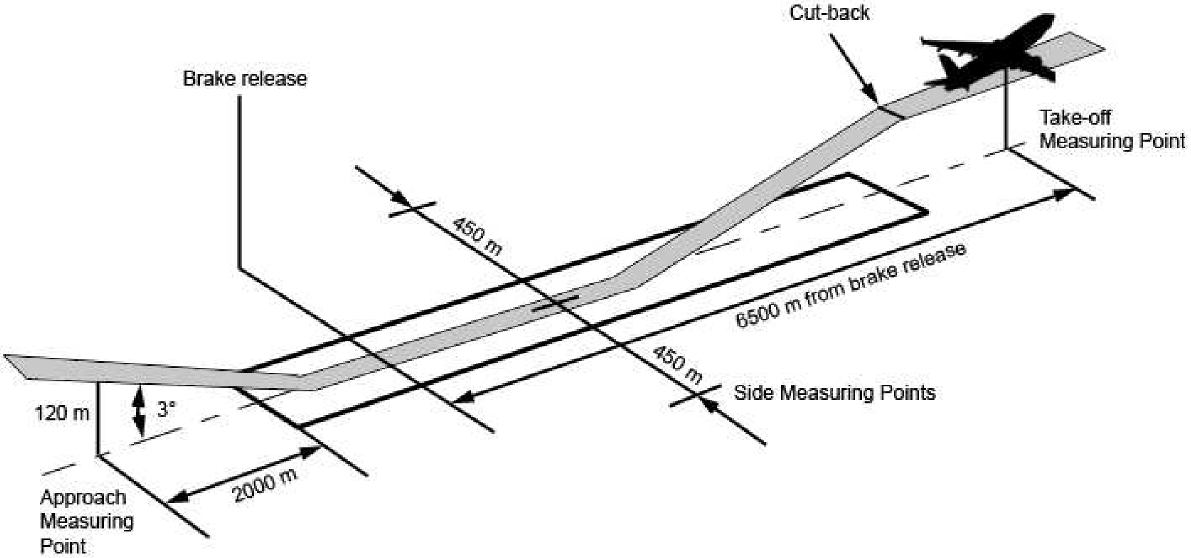


**Figure B. 1** Reference points for the noise measurement (**Hass 2015**)

Noise limits are defined as a function of MTOW with taking into account the number of engines. The applicable limit is either determined by a minimum or maximum value or a logarithmic function which depends on the MTOW.

Noise levels are stated in Effective Perceived Noise Level (EPNL). Values for EPNL have to be determined according to the specification, using the following steps:

1. Conversion of sound pressure level (SPL) to perceived noise level (P?L) by means of a noy table
2. Calculation of a tone correction factor (C)
3. Summation of tone correction 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)

# Appendix C

# Rating Scales of Flybe

## 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**)

| 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 |

**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 |

# Appendix D

# Complete List of all Commercial Transport Aircraft

**Table D. 1** Complete list of all commercial transport aircraft

| Aircraft type | number of passenger A/C | A/C cumulative | No A/C | % A/C cumulative | % calculation | error² |
|---|---|---|---|---|---|---|
| Boeing 737-800 | 4033 | 4033 | 1 | 15,5% | 28,7% | 0,0175 |
| Airbus A320 | 3865 | 7898 | 2 | 30,3% | 32,0% | 0,0003 |
| Airbus A319 | 1327 | 9225 | 3 | 35,4% | 35,2% | 3E-06 |
| Airbus A321 | 1265 | 10490 | 4 | 40,2% | 38,3% | 0,0004 |
| Boeing 737-700 | 1039 | 11529 | 5 | 44,2% | 41,1% | 0,001 |
| Boeing 777-300ER | 657 | 12186 | 6 | 46,8% | 43,9% | 0,0008 |
| ATR 72 | 647 | 12833 | 7 | 49,2% | 46,5% | 0,0007 |
| Airbus A330-300 | 616 | 13449 | 8 | 51,6% | 49,0% | 0,0007 |
| Bombardier CRJ100/200 | 560 | 14009 | 9 | 53,7% | 51,4% | 0,0005 |
| Boeing 767-300 | 549 | 14558 | 10 | 55,9% | 53,7% | 0,0005 |
| Airbus A330-200 | 507 | 15065 | 11 | 57,8% | 55,9% | 0,0004 |
| Embraer ERJ-145 | 479 | 15544 | 12 | 59,6% | 57,9% | 0,0003 |
| Embraer 190 | 478 | 16022 | 13 | 61,5% | 59,9% | 0,0002 |
| Bombardier Dash 8Q400 | 463 | 16485 | 14 | 63,2% | 61,8% | 0,0002 |
| Boeing 737-900 | 441 | 16926 | 15 | 64,9% | 63,6% | 0,0002 |
| Boeing 777-200/200ER | 436 | 17362 | 16 | 66,6% | 65,3% | 0,0002 |
| Boeing MD-80 | 404 | 17766 | 17 | 68,2% | 66,9% | 0,0002 |
| Bombardier CRJ900 | 387 | 18153 | 18 | 69,6% | 68,5% | 0,0001 |
| Embraer 175 | 373 | 18526 | 19 | 71,1% | 69,9% | 0,0001 |
| Boeing 757-200 | 361 | 18887 | 20 | 72,5% | 71,3% | 0,0001 |
| Boeing 737-300 | 334 | 19221 | 21 | 73,7% | 72,7% | 0,0001 |
| Bombardier CRJ700 | 317 | 19538 | 22 | 75,0% | 74,0% | 1E-04 |
| Boeing 787-8 | 299 | 19837 | 23 | 76,1% | 75,2% | 9E-05 |
| De Havilland Canada Twin Otter | 281 | 20118 | 24 | 77,2% | 76,3% | 7E-05 |
| Boeing 747-400 | 272 | 20390 | 25 | 78,2% | 77,5% | 6E-05 |
| Saab 340 | 232 | 20622 | 26 | 79,1% | 78,5% | 4E-05 |
| Fairchild Metro/Merlin | 225 | 20847 | 27 | 80,0% | 79,5% | 2E-05 |
| Beechcraft 1900D | 214 | 21061 | 28 | 80,8% | 80,5% | 1E-05 |
| Airbus A300 | 210 | 21271 | 29 | 81,6% | 81,4% | 5E-06 |
| ATR 42 | 194 | 21465 | 30 | 82,4% | 82,3% | 8E-07 |
| Airbus A380 | 193 | 21658 | 31 | 83,1% | 83,1% | 6E-11 |
| Bombardier Dash 8 Q100 | 173 | 21831 | 32 | 83,8% | 83,9% | 2E-06 |
| Boeing 737-500 | 169 | 22000 | 33 | 84,4% | 84,6% | 5E-06 |
| Bombarbier Dash 8 Q300 | 162 | 22162 | 34 | 85,0% | 85,4% | 1E-05 |
| Boeing 737-400 | 159 | 22321 | 35 | 85,6% | 86,0% | 2E-05 |
| Boeing 717-200 | 154 | 22475 | 36 | 86,2% | 86,7% | 2E-05 |
| Embraer 170 | 150 | 22625 | 37 | 86,8% | 87,3% | 3E-05 |
| Embraer 195 | 145 | 22770 | 38 | 87,4% | 87,9% | 3E-05 |
| Antonov An-26 | 141 | 22911 | 39 | 87,9% | 88,5% | 3E-05 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Boeing 787-9 | 124 | 23035 | 40 | 88,4% | 89,0% | 4E-05 |
| Boeing MD-11 | 123 | 23158 | 41 | 88,9% | 89,5% | 5E-05 |
| Beechcraft 1900C | 120 | 23278 | 42 | 89,3% | 90,0% | 5E-05 |
| Airbus A340-300 | 118 | 23396 | 43 | 89,8% | 90,5% | 5E-05 |
| Fokker 100 | 116 | 23512 | 44 | 90,2% | 90,9% | 5E-05 |
| Antonov An-24 | 115 | 23627 | 45 | 90,6% | 91,4% | 5E-05 |
| Beechcraft B99 | 106 | 23733 | 46 | 91,1% | 91,8% | 5E-05 |
| Ilyushin Il-76 | 105 | 23838 | 47 | 91,5% | 92,2% | 5E-05 |
| BAe Jetstream 31 | 101 | 23939 | 48 | 91,8% | 92,5% | 5E-05 |
| BAe Systems Avro RJ | 98 | 24037 | 49 | 92,2% | 92,9% | 4E-05 |
| Embraer EMB-120 Brasilia | 96 | 24133 | 50 | 92,6% | 93,2% | 4E-05 |
| Dornier 228 | 95 | 24228 | 51 | 93,0% | 93,5% | 3E-05 |
| Fokker 50 | 73 | 24301 | 52 | 93,2% | 93,8% | 4E-05 |
| Airbus A340-600 | 72 | 24373 | 53 | 93,5% | 94,1% | 4E-05 |
| Boeing 747-8 | 66 | 24439 | 54 | 93,8% | 94,4% | 4E-05 |
| Boeing MD-90 | 65 | 24504 | 55 | 94,0% | 94,7% | 4E-05 |
| Sukhoi Superjet 100 | 63 | 24567 | 56 | 94,3% | 94,9% | 4E-05 |
| Boeing 737-200 | 60 | 24627 | 57 | 94,5% | 95,1% | 4E-05 |
| Bombardier Dash 8 Q200 | 57 | 24684 | 58 | 94,7% | 95,4% | 4E-05 |
| BAe Jetstream41 | 55 | 24739 | 59 | 94,9% | 95,6% | 5E-05 |
| Boeing 757-300 | 55 | 24794 | 60 | 95,1% | 95,8% | 4E-05 |
| Boeing 777-200LR | 55 | 24849 | 61 | 95,3% | 96,0% | 4E-05 |
| BAEe146 | 54 | 24903 | 62 | 95,5% | 96,2% | 4E-05 |
| Boeing 737-600 | 54 | 24957 | 63 | 95,8% | 96,4% | 4E-05 |
| Boeing 777-300 | 53 | 25010 | 64 | 96,0% | 96,5% | 3E-05 |
| Airbus A310 | 47 | 25057 | 65 | 96,1% | 96,7% | 3E-05 |
| Bombardier CRJ1000 | 47 | 25104 | 66 | 96,3% | 96,8% | 3E-05 |
| Xian MA60 | 46 | 25150 | 67 | 96,5% | 97,0% | 3E-05 |
| Shorts 360 | 45 | 25195 | 68 | 96,7% | 97,1% | 2E-05 |
| Embraer ERJ-135 | 44 | 25239 | 69 | 96,8% | 97,3% | 2E-05 |
| Airbus A318 | 43 | 25282 | 70 | 97,0% | 97,4% | 2E-05 |
| Antonov An-12 | 38 | 25320 | 71 | 97,1% | 97,5% | 1E-05 |
| Embraer EMB-110 Bandeirante | 38 | 25358 | 72 | 97,3% | 97,6% | 1E-05 |
| Fokker 70 | 38 | 25396 | 73 | 97,4% | 97,7% | 1E-05 |
| Boeing 767-400 | 37 | 25433 | 74 | 97,6% | 97,9% | 7E-06 |
| Saab 2000 | 35 | 25468 | 75 | 97,7% | 98,0% | 6E-06 |
| Yakovlev Yak-42 | 35 | 25503 | 76 | 97,8% | 98,0% | 4E-06 |
| BAe ATP | 33 | 25536 | 77 | 98,0% | 98,1% | 3E-06 |
| Airbus A330-200F | 31 | 25567 | 78 | 98,1% | 98,2% | 2E-06 |
| Yakovlev Yak-40 | 31 | 25598 | 79 | 98,2% | 98,3% | 1E-06 |
| Embraer ERJ-140 | 30 | 25628 | 80 | 98,3% | 98,4% | 4E-07 |
| Airbus A350-900 | 29 | 25657 | 81 | 98,4% | 98,5% | 7E-08 |
| Antonov An-72/74 | 27 | 25684 | 82 | 98,5% | 98,5% | 3E-09 |
| Antonov An-32 | 25 | 25709 | 83 | 98,6% | 98,6% | 1E-07 |
| Dornier 328Jet | 21 | 25730 | 84 | 98,7% | 98,7% | 2E-07 |
| Tupolev Tu-204 | 21 | 25751 | 85 | 98,8% | 98,7% | 4E-07 |
| Antonov An-124 | 20 | 25771 | 86 | 98,9% | 98,8% | 7E-07 |
| Lockheed L-100 Hercules | 20 | 25791 | 87 | 99,0% | 98,8% | 1E-06 |

| | | | | | | |
|---|---|---|---|---|---|---|
| McDonnell Doulgas DC-9-30 | 20 | 25811 | 88 | 99,0% | 98,9% | 2E-06 |
| Boeing 747-200 | 19 | 25830 | 89 | 99,1% | 99,0% | 2E-06 |
| Boeing 767-200 | 18 | 25848 | 90 | 99,2% | 99,0% | 3E-06 |
| BAe (HS) 748 | 17 | 25865 | 91 | 99,2% | 99,0% | 3E-06 |
| De Havilland Canada Dash 7 | 17 | 25882 | 92 | 99,3% | 99,1% | 4E-06 |
| Tupolev Tu-154 | 13 | 25895 | 93 | 99,4% | 99,1% | 5E-06 |
| Airbus C212 | 12 | 25907 | 94 | 99,4% | 99,2% | 5E-06 |
| Shorts 330 | 12 | 25919 | 95 | 99,4% | 99,2% | 5E-06 |
| Harbin Y-12 | 11 | 25930 | 96 | 99,5% | 99,3% | 5E-06 |
| McDonnell Doulgas DC-9-10 | 11 | 25941 | 97 | 99,5% | 99,3% | 6E-06 |
| Tupolev Tu-134 | 11 | 25952 | 98 | 99,6% | 99,3% | 6E-06 |
| Airbus A320neo | 10 | 25962 | 99 | 99,6% | 99,4% | 7E-06 |
| McDonnell Doulgas DC-3 | 10 | 25972 | 100 | 99,6% | 99,4% | 7E-06 |
| Fokker F27 | 8 | 25980 | 101 | 99,7% | 99,4% | 7E-06 |
| Ilyushin Il-18 | 8 | 25988 | 102 | 99,7% | 99,4% | 7E-06 |
| Antonov An-148 | 7 | 25995 | 103 | 99,7% | 99,5% | 7E-06 |
| Ilyushin Il-62 | 7 | 26002 | 104 | 99,8% | 99,5% | 7E-06 |
| Ilyushin Il-114 | 7 | 26009 | 105 | 99,8% | 99,5% | 8E-06 |
| Antonov An-158 | 6 | 26015 | 106 | 99,8% | 99,5% | 8E-06 |
| Ilyushin Il-96 | 6 | 26021 | 107 | 99,8% | 99,6% | 8E-06 |
| Antonov An-3 | 5 | 26026 | 108 | 99,9% | 99,6% | 8E-06 |
| Airbus A340-500 | 4 | 26030 | 109 | 99,9% | 99,6% | 7E-06 |
| Antonov An-38 | 4 | 26034 | 110 | 99,9% | 99,6% | 7E-06 |
| Boeing 727-100 | 4 | 26038 | 111 | 99,9% | 99,6% | 7E-06 |
| Boeing 747-300 | 4 | 26042 | 112 | 99,9% | 99,7% | 7E-06 |
| Boeing 727-200 | 3 | 26045 | 113 | 99,9% | 99,7% | 7E-06 |
| Airbus A340-200 | 2 | 26047 | 114 | 99,9% | 99,7% | 6E-06 |
| Comac ARJ21 | 2 | 26049 | 115 | 99,9% | 99,7% | 6E-06 |
| Lockheed C-130 | 2 | 26051 | 116 | 100,0% | 99,7% | 6E-06 |
| Lockheed L-188 Electra | 2 | 26053 | 117 | 100,0% | 99,7% | 5E-06 |
| McDonnell Doulgas DC-8 | 2 | 26055 | 118 | 100,0% | 99,7% | 5E-06 |
| NMAC YS-11 | 2 | 26057 | 119 | 100,0% | 99,8% | 5E-06 |
| Antonov An-22 | 1 | 26058 | 120 | 100,0% | 99,8% | 5E-06 |
| Antonov An-140 | 1 | 26059 | 121 | 100,0% | 99,8% | 4E-06 |
| Antonov An-225 | 1 | 26060 | 122 | 100,0% | 99,8% | 4E-06 |
| Boeing 747SP | 1 | 26061 | 123 | 100,0% | 99,8% | 4E-06 |
| Bombardier CSeries | 1 | 26062 | 124 | 100,0% | 99,8% | 4E-06 |
| Fokker F28 | 1 | 26063 | 125 | 100,0% | 99,8% | 3E-06 |
| McDonnell Doulgas DC-9-50 | 1 | 26064 | 126 | 100,0% | 99,8% | 3E-06 |
| Boeing 777F | 0 | 26064 | 127 | 100,0% | 99,8% | 3E-06 |
| Airbus A319neo | 0 | 26064 | 128 | 100,0% | 99,8% | 3E-06 |
| Airbus A321neo | 0 | 26064 | 129 | 100,0% | 99,8% | 2E-06 |
| Airbus A330neo | 0 | 26064 | 130 | 100,0% | 99,9% | 2E-06 |
| Airbus A350-800 | 0 | 26064 | 131 | 100,0% | 99,9% | 2E-06 |
| Airbus A350-1000 | 0 | 26064 | 132 | 100,0% | 99,9% | 2E-06 |
| Antonov An-178 | 0 | 26064 | 133 | 100,0% | 99,9% | 2E-06 |
| Boeing 737 Max 7 | 0 | 26064 | 134 | 100,0% | 99,9% | 1E-06 |
| Boeing 737 Max 8 | 0 | 26064 | 135 | 100,0% | 99,9% | 1E-06 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Boeing 737 Max 9 | 0 | 26064 | 136 | 100,0% | 99,9% | 1E-06 |
| Boeing 737 Max-Series TBD Total | 0 | 26064 | 137 | 100,0% | 99,9% | 1E-06 |
| Boeing 777-8X | 0 | 26064 | 138 | 100,0% | 99,9% | 1E-06 |
| Boeing 777-9X | 0 | 26064 | 139 | 100,0% | 99,9% | 9E-07 |
| Boeing 787-10 | 0 | 26064 | 140 | 100,0% | 99,9% | 8E-07 |
| Comac C919 | 0 | 26064 | 141 | 100,0% | 99,9% | 7E-07 |
| Embraer 175 E2 | 0 | 26064 | 142 | 100,0% | 99,9% | 7E-07 |
| Embraer 190 E2 | 0 | 26064 | 143 | 100,0% | 99,9% | 6E-07 |
| Embraer 195 E2 | 0 | 26064 | 144 | 100,0% | 99,9% | 6E-07 |
| Irkut MC-21 | 0 | 26064 | 145 | 100,0% | 99,9% | 5E-07 |
| McDonnell Doulgas DC-10 | 0 | 26064 | 146 | 100,0% | 99,9% | 5E-07 |
| Mitsubishi MRJ | 0 | 26064 | 147 | 100,0% | 99,9% | 4E-07 |
| **Total** | **26064** | | | | | **0,0266** |

# Appendix E

# Reference Group for Rating the Fuel Consumption

**Table E. 1** Reference group for rating the fuel consumption

| **Aircraft Type** |
|---|
| Beechcraft 1900D |
| De Havilland Canada Twin Otter |
| Dornier 228 |
| Embraer EMB-120 Brasilia |
| Saab 340 |
| Bombardier Dash 8 Q100 |
| Antonov An-26 |
| Bombardier CRJ100/200 |
| Bombardier CRJ100/200 |
| ATR 42 |
| Antonov An-24 |
| Embraer ERJ-145 |
| Bombarbier Dash 8 Q300 |
| Fokker 50 |
| ATR 72 |
| Bombardier CRJ700 |
| Embraer 170 |
| Bombardier Dash 8Q400 |
| Embraer 175 |
| Bombardier CRJ900 |
| Fokker 100 |
| Embraer 190 |
| Boeing 717-200 |
| Embraer 195 |
| Boeing 737-500 |
| Airbus A319 |
| Boeing 737-700 |
| Boeing 737-300 |
| Boeing 737-400 |
| Airbus A320 |
| Boeing MD-80 |
| Boeing 737-800 |
| Boeing 737-900 |
| Boeing 757-200 |
| Airbus A321 |
| Airbus A300 |
| Boeing 767-300 |
| Boeing 787-8 |
| Airbus A330-200 |
| Airbus A330-300 |

| |
|---|
| Airbus A340-300 |
| Boeing 787-9 |
| Boeing MD-11 |
| Airbus A340-600 |
| Boeing 777-300ER |
| Boeing 777-200/200ER |
| Boeing 747-400 |
| Boeing 747-8 |
| Airbus A380 |

# Appendix F

# Normalized Fuel Consumption for the Reference Group

**Table F. 1** Normalized fuel consumption for the reference group

| **Aircraft Type** | **OEM based fuel consumption (kg/km/seat)** | **Number** |
|---|---|---|
| Airbus A321 | 0,0149 | **1** |
| De Havilland Canada Twin Otter | 0,0154 | 2 |
| Airbus A330-300 | 0,0160 | 3 |
| Boeing 777-200/200ER | 0,0170 | 4 |
| Boeing 737-900 | 0,0171 | 5 |
| Boeing 737-800 | 0,0174 | 6 |
| Embraer 175 | 0,0177 | **7** |
| Boeing 787-9 | 0,0179 | 8 |
| Airbus A320 | 0,0183 | 9 |
| Airbus A319 | 0,0185 | 10 |
| Boeing MD-80 | 0,0190 | 11 |
| Boeing 787-8 | 0,0191 | 12 |
| Boeing 737-700 | 0,0196 | 13 |
| Fokker 50 | 0,0198 | **14** |
| Boeing 767-300 | 0,0198 | 15 |
| ATR 72 | 0,0204 | 16 |
| Boeing 777-300ER | 0,0209 | 17 |
| Bombardier Dash 8Q400 | 0,0213 | 18 |
| Boeing 737-300 | 0,0213 | 19 |
| Boeing 747-8 | 0,0213 | 20 |
| Airbus A380 | 0,0213 | **21** |
| Airbus A330-200 | 0,0216 | 22 |
| Bombardier CRJ900 | 0,0217 | 23 |
| Embraer 195 | 0,0219 | 24 |
| Bombardier CRJ700 | 0,0220 | 25 |
| Airbus A340-300 | 0,0221 | 26 |
| Boeing 717-200 | 0,0223 | 27 |
| Boeing 737-400 | 0,0225 | **28** |
| Airbus A300 | 0,0227 | 29 |
| Embraer EMB-120 Brasilia | 0,0233 | 30 |
| Boeing MD-11 | 0,0234 | 31 |
| Boeing 757-200 | 0,0235 | 32 |
| Boeing 747-400 | 0,0235 | 33 |
| Boeing 737-500 | 0,0237 | 34 |
| Embraer ERJ-145 | 0,0239 | **35** |
| Bombarbier Dash 8 Q300 | 0,0239 | 36 |
| Embraer 190 | 0,0244 | 37 |
| Bombardier CRJ100/200 | 0,0249 | 38 |

| | | |
|---|---|---|
| Fokker 100 | 0,0249 | 39 |
| Antonov An-24 | 0,0254 | 40 |
| Bombardier CRJ100/200 | 0,0258 | 41 |
| Saab 340 | 0,0260 | **42** |
| ATR 42 | 0,0261 | 43 |
| Bombardier Dash 8 Q100 | 0,0270 | 44 |
| Embraer 170 | 0,0280 | 45 |
| Airbus A340-600 | 0,0282 | 46 |
| Dornier 228 | 0,0378 | 47 |
| Antonov An-26 | 0,0463 | 48 |
| Beechcraft 1900D | 0,0507 | **49** |

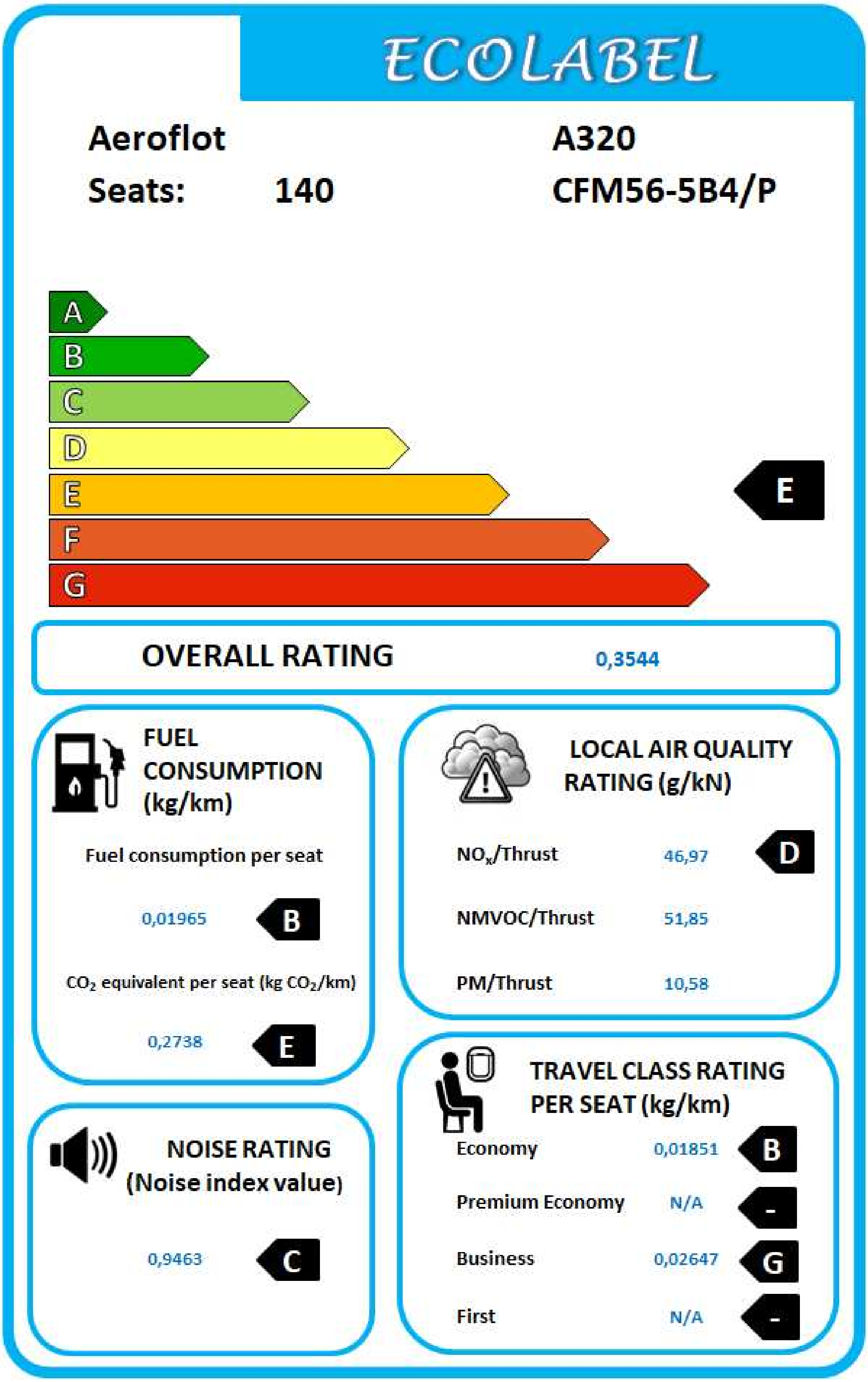
# Appendix G

# List of Turboprops Included in the Database of EEA

**Table G. 1** List of aircraft with turboprop engines included in the database of EEA

| Aircraft type | Engine type |
|---|---|
| An 12 | Ivchenko AI-20L or AI-20M |
| An 24 | AI-24A |
| An 26 | AI-24T |
| An 30 | ZMKB Progress AI-24T |
| An 32 | ZMKB Progress AI-20DM |
| ATP british aerospace | Pratt & Whitney Canada PW126 |
| BE 99 airliner | Pratt & Whitney Canada PT6A-36 |
| Cessna grand caravan | Pratt & Whitney PT6A-114A |
| Cessna conquest 1 | Pratt & Whitney Canada PT6A-112 |
| Cessna conquest 2 | Garrett TPE331-8-403S |
| DHC-6 twin otter | PT6A-34 |
| Emb-110 Bandeirante | Pratt & Whitney PT6A-34 |
| Emb-120 Brasilia | PW118A |
| Embraer Xingu | Pratt & Whitney Canada PT6A-135 |
| EA-500 | Rolls-Royce Model 250-B17F/2 |
| F27 (Fokker/Fairchild) | Rolls-Royce Dart R.Da.7 Mk.532 |
| Fokker 50 | PW 125B |
| Il-24 | Ivchenko AI-20M |
| Il-18 | Ivchenko AI-20M |
| Il-20 | AM-47 Liquid-cooled V-12 |
| L-188 Electra | Allison 501-D13 |
| Turbolet ( aircraft industries) | Walter M601E |
| L-410 Turbolet | Walter M601E |
| L-420 Turbolet | Walter M601E |
| Pilatus U-28 | Pratt & Whitney Canada PT6A-67P |
| PC-12 | Pratt & Whitney Canada PT6A-67P |
| Pilatus spectre | Pratt & Whitney Canada PT6A-67P |
| Pilatus Eagle | Pratt & Whitney Canada PT6A-67P |
| PC-21 | Pratt & Whitney Canada PT6A-68B |
| PC-9 | Pratt & Whitney Canada PT6A-62 |
| Pilatus Hudournik | Pratt & Whitney Canada PT6A-62 |

# Appendix H Ecolabel of A320



**Aeroflot** **A320**

**Seats: 140** **CFM56-5B4/P**

E

**OVERALL RATING** 0,3544

**FUEL CONSUMPTION (kg/km)**

| | | |
|---|---|---|
| Fuel consumption per seat | 0,01965 | B |
| CO$_2$ equivalent per seat (kg CO$_2$/km) | 0,2738 | E |

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| NO$_x$/Thrust | 46,97 | D |
| NMVOC/Thrust | 51,85 | |
| PM/Thrust | 10,58 | |

**NOISE RATING (Noise index value)**

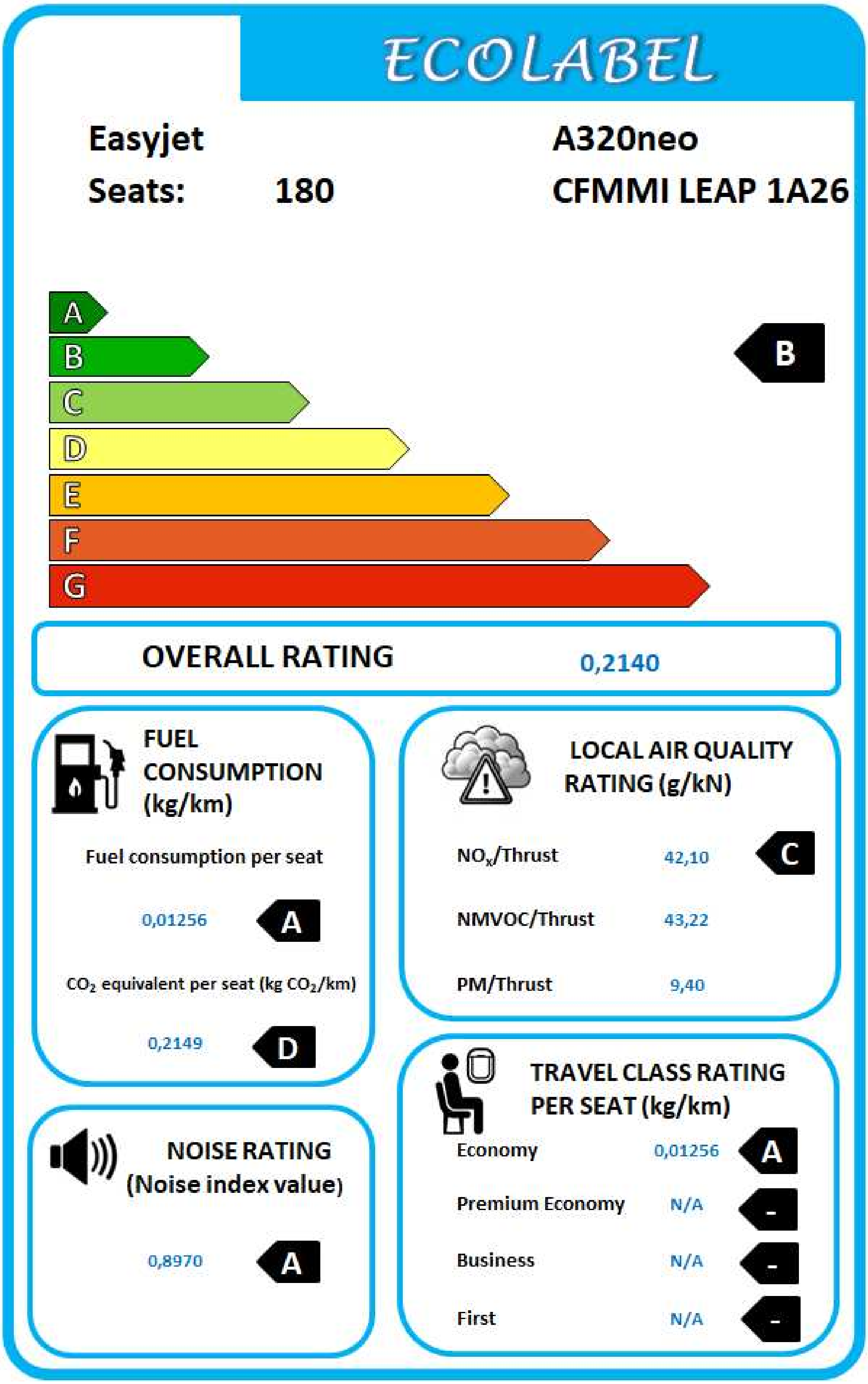
0,9463 C

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,01851 | B |
| Premium Economy | N/A | - |
| Business | 0,02647 | G |
| First | N/A | - |

**Figure H. 1** Ecolabel of A320

# Appendix I Ecolabel of A320neo



ECOLABEL

Easyjet | A320neo

Seats: 180 | CFMMI LEAP 1A26

A B C D E F G — B

OVERALL RATING 0,2140

**FUEL CONSUMPTION (kg/km)**

Fuel consumption per seat

0,01256 A

CO₂ equivalent per seat (kg CO₂/km)

0,2149 D

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| $NO_x$/Thrust | 42,10 | C |
| NMVOC/Thrust | 43,22 | |
| PM/Thrust | 9,40 | |

**NOISE RATING (Noise index value)**

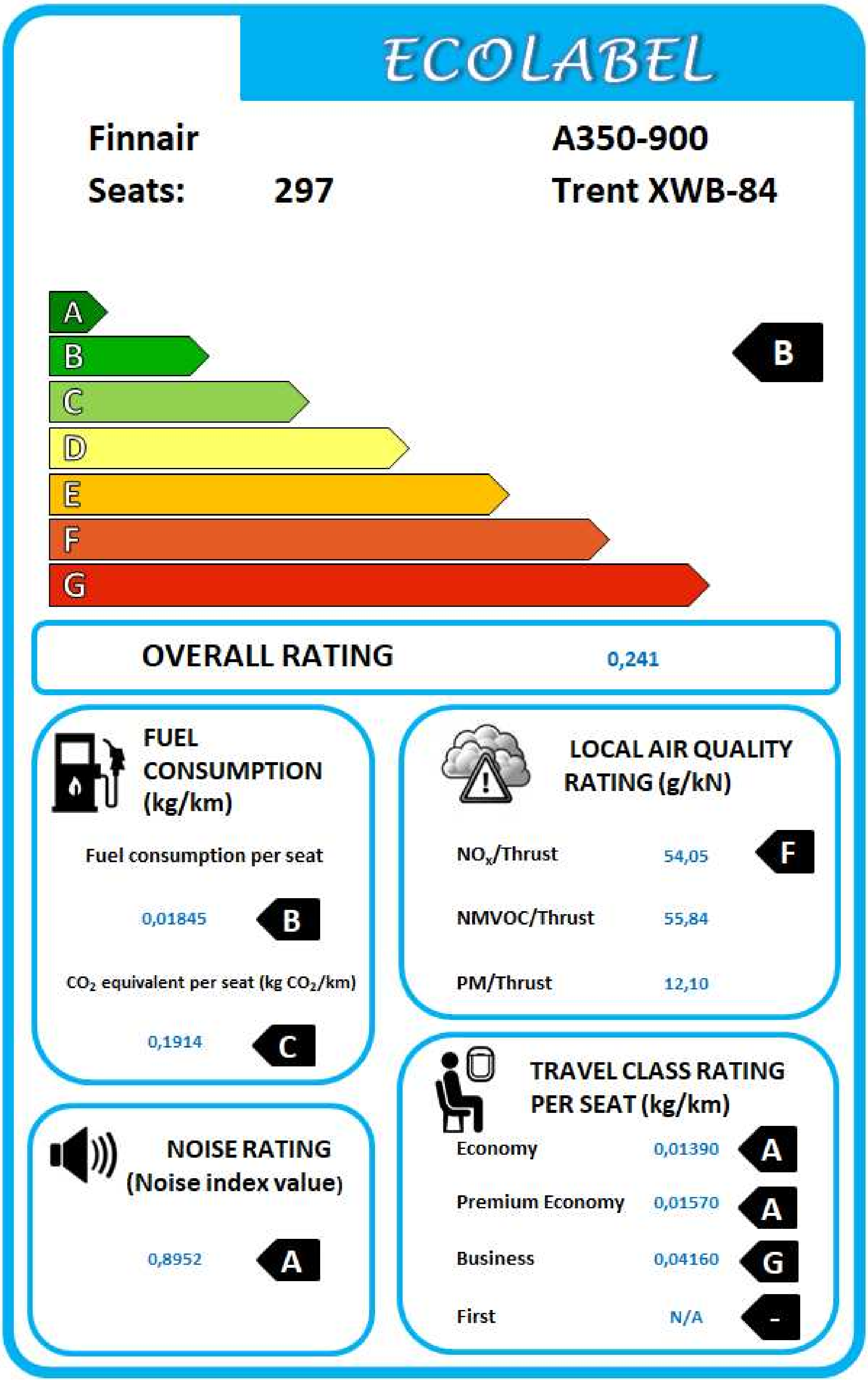
0,8970 A

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,01256 | A |
| Premium Economy | N/A | - |
| Business | N/A | - |
| First | N/A | - |

**Figure I. 1** Ecolabel of A320neo

# Appendix J Ecolabel of A350



Finnair
Seats: 297

A350-900
Trent XWB-84

OVERALL RATING 0,241

**FUEL CONSUMPTION (kg/km)**

| | | |
|---|---|---|
| Fuel consumption per seat | 0,01845 | B |
| $CO_2$ equivalent per seat (kg $CO_2$/km) | 0,1914 | C |

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| $NO_x$/Thrust | 54,05 | F |
| NMVOC/Thrust | 55,84 | |
| PM/Thrust | 12,10 | |

**NOISE RATING (Noise index value)**

0,8952 A

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,01390 | A |
| Premium Economy | 0,01570 | A |
| Business | 0,04160 | G |
| First | N/A | - |

**Figure J. 1** Ecolabel of A350

# Appendix K  Ecolabel of A380

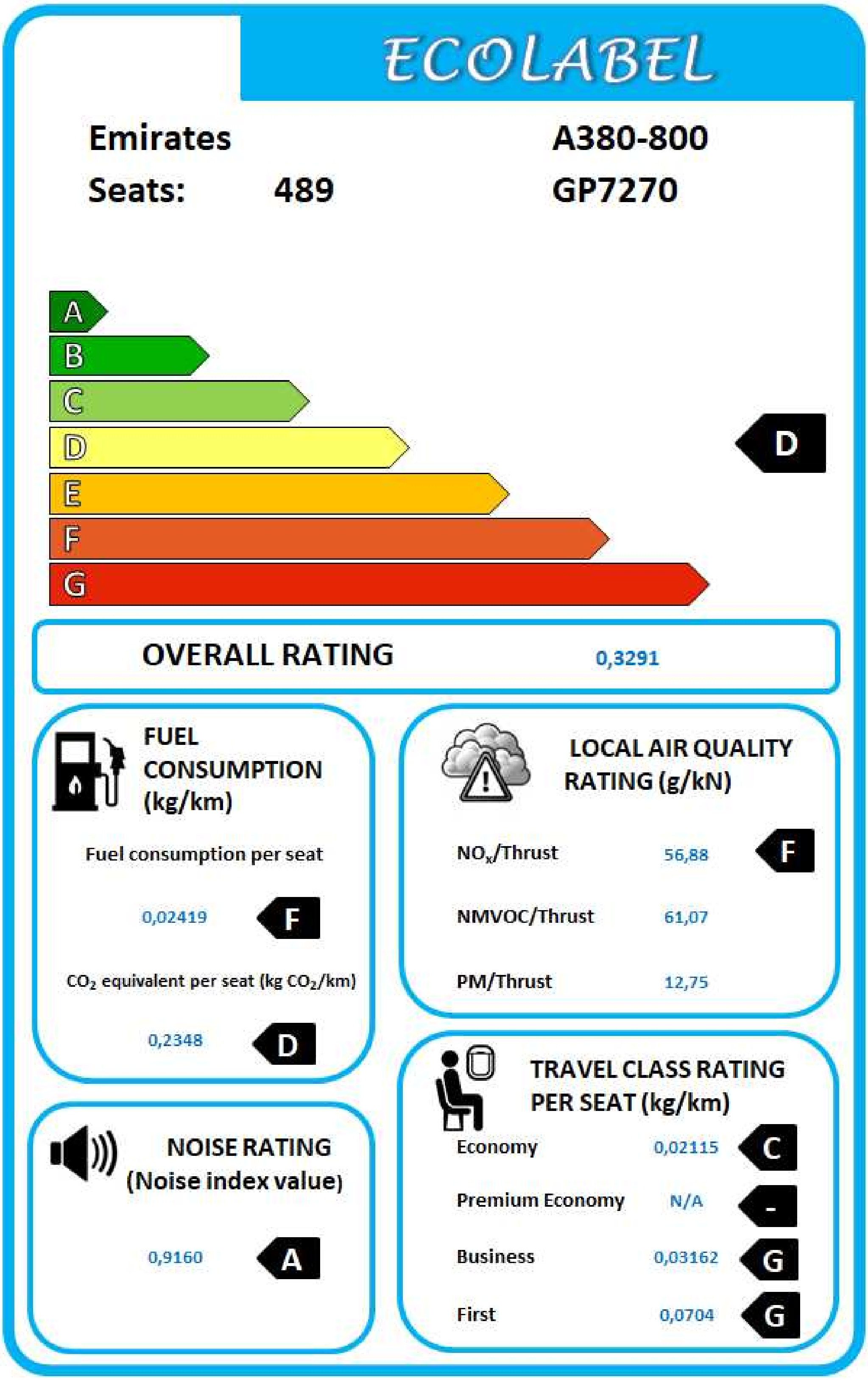


**Figure K. 1** Ecolabel of A380

# Appendix L Ecolabel of B737-400

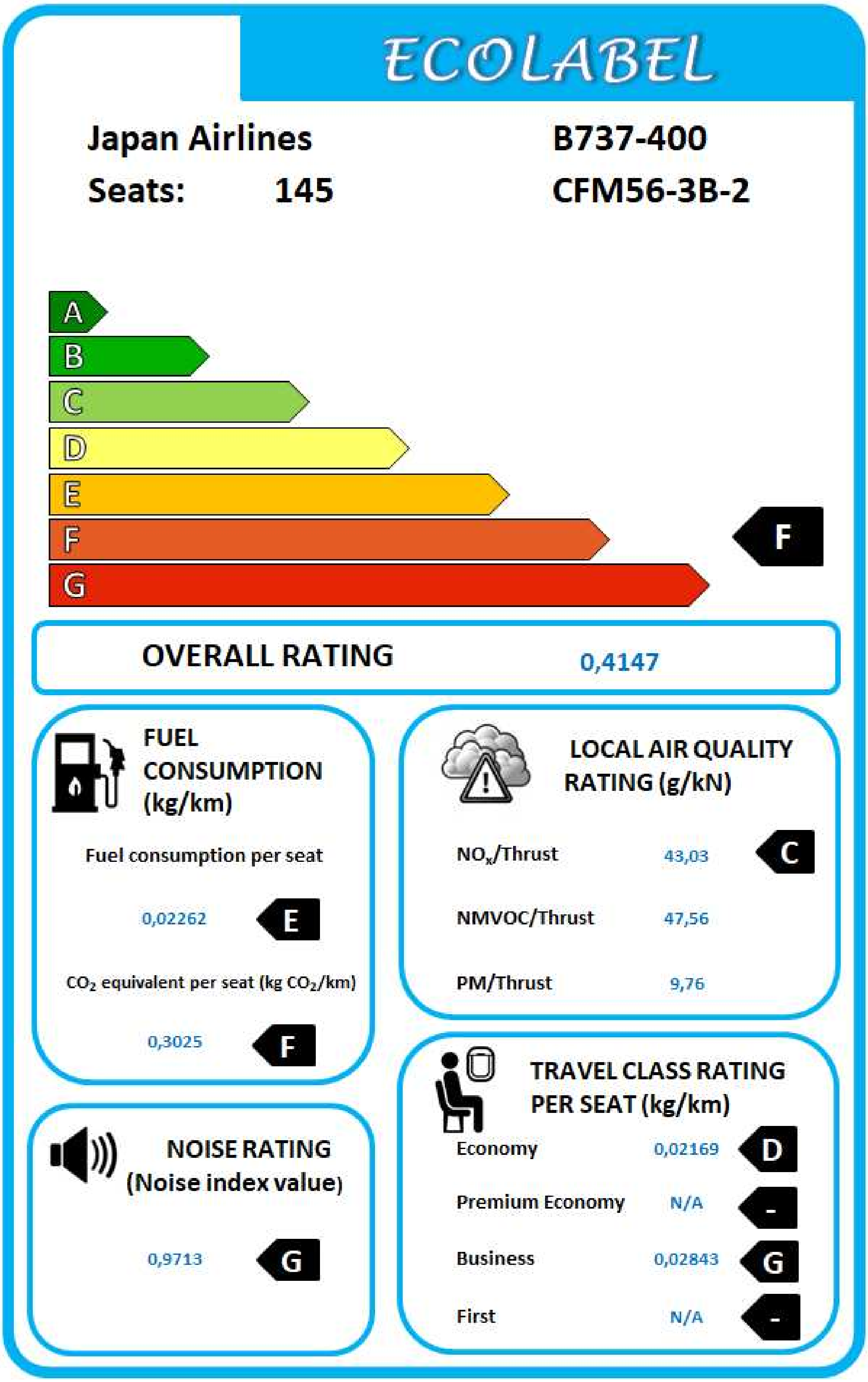
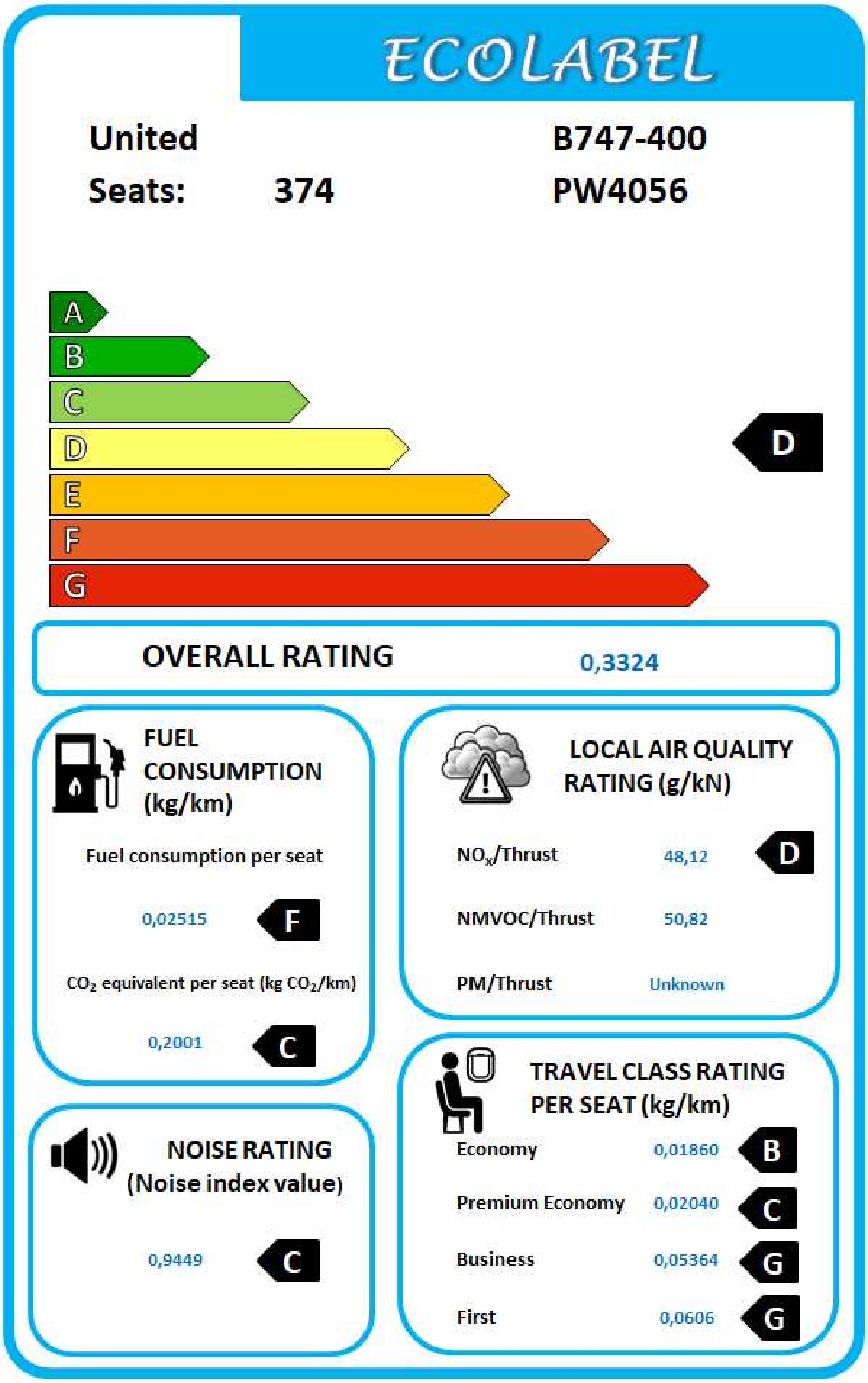


**Figure L. 1** Ecolabel of B737-400

# Appendix M Ecolabel of B747-400

## M.1 United



United
Seats: 374
B747-400
PW4056

OVERALL RATING 0,3324

FUEL CONSUMPTION (kg/km)

Fuel consumption per seat
0,02515 F

$CO_2$ equivalent per seat (kg $CO_2$/km)
0,2001 C

LOCAL AIR QUALITY RATING (g/kN)

$NO_x$/Thrust 48,12 D
NMVOC/Thrust 50,82
PM/Thrust Unknown

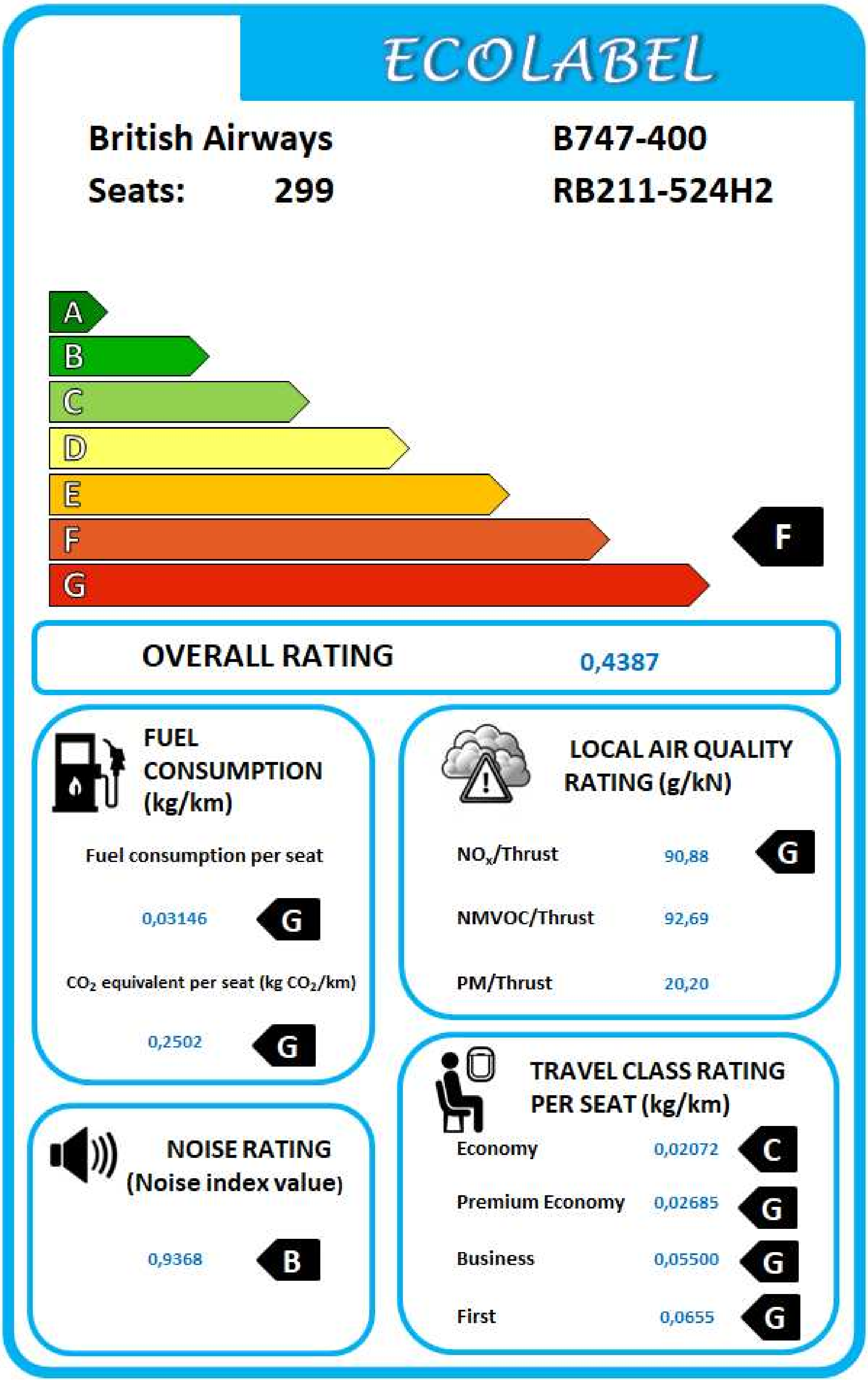
NOISE RATING (Noise index value)
0,9449 C

TRAVEL CLASS RATING PER SEAT (kg/km)

| | | |
|---|---|---|
| Economy | 0,01860 | B |
| Premium Economy | 0,02040 | C |
| Business | 0,05364 | G |
| First | 0,0606 | G |

**Figure M. 1** Ecolabel of B747-400 of the airline ‘United’

## M.2 British Airways



British Airways

Seats: 299

B747-400

RB211-524H2

F

OVERALL RATING 0,4387

FUEL CONSUMPTION (kg/km)

Fuel consumption per seat

0,03146 G

$CO_2$ equivalent per seat (kg $CO_2$/km)

0,2502 G

LOCAL AIR QUALITY RATING (g/kN)

| | | |
|---|---|---|
| $NO_x$/Thrust | 90,88 | G |
| NMVOC/Thrust | 92,69 | |
| PM/Thrust | 20,20 | |

NOISE RATING (Noise index value)

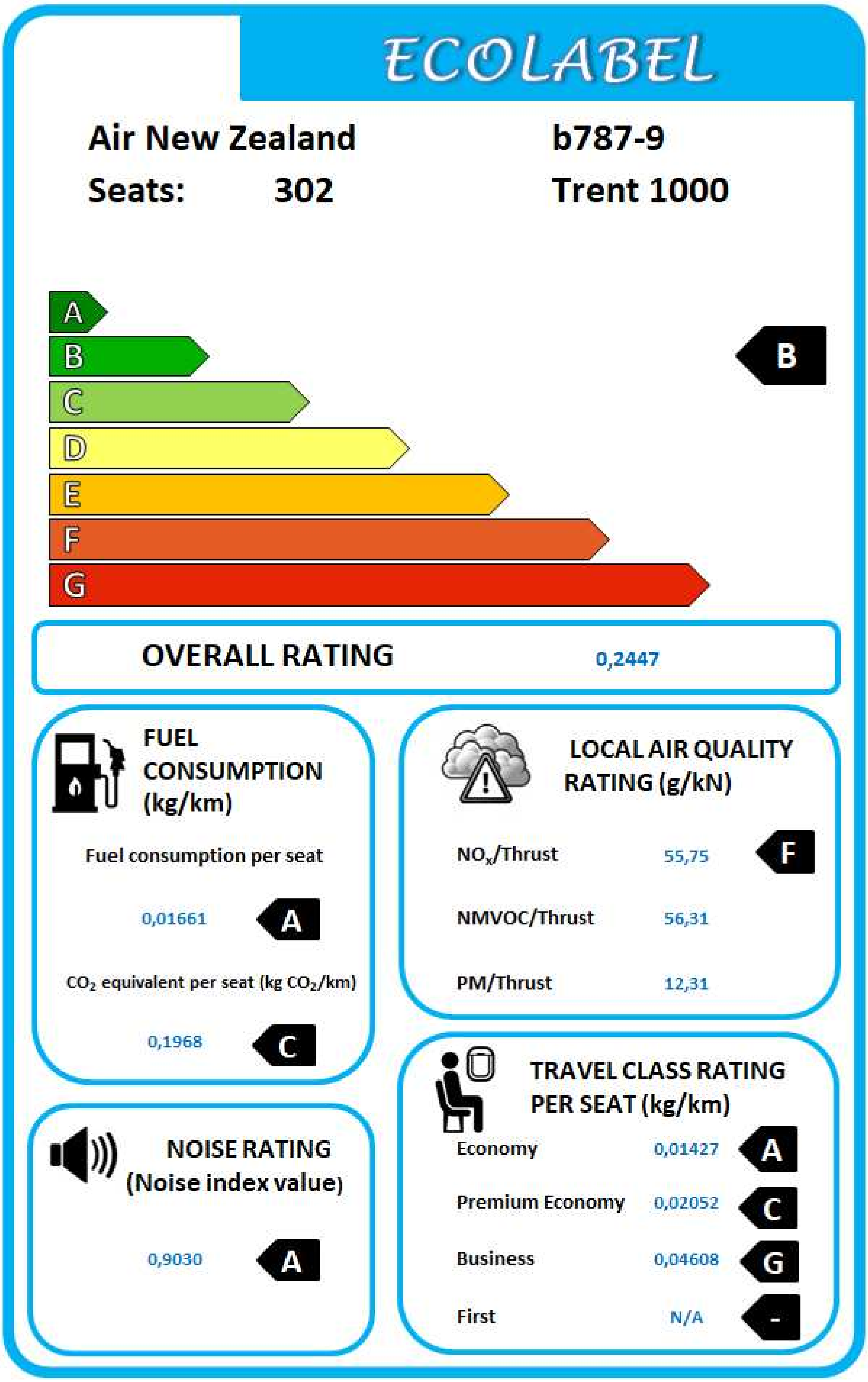
0,9368 B

TRAVEL CLASS RATING PER SEAT (kg/km)

| | | |
|---|---|---|
| Economy | 0,02072 | C |
| Premium Economy | 0,02685 | G |
| Business | 0,05500 | G |
| First | 0,0655 | G |

**Figure M. 2** Ecolabel of the B747-400 of the airline 'British Airways'

# Appendix N Ecolabel of B787-9



Air New Zealand
Seats: 302
b787-9
Trent 1000

B

OVERALL RATING 0,2447

FUEL CONSUMPTION (kg/km)
Fuel consumption per seat
0,01661 A
CO$_2$ equivalent per seat (kg CO$_2$/km)
0,1968 C

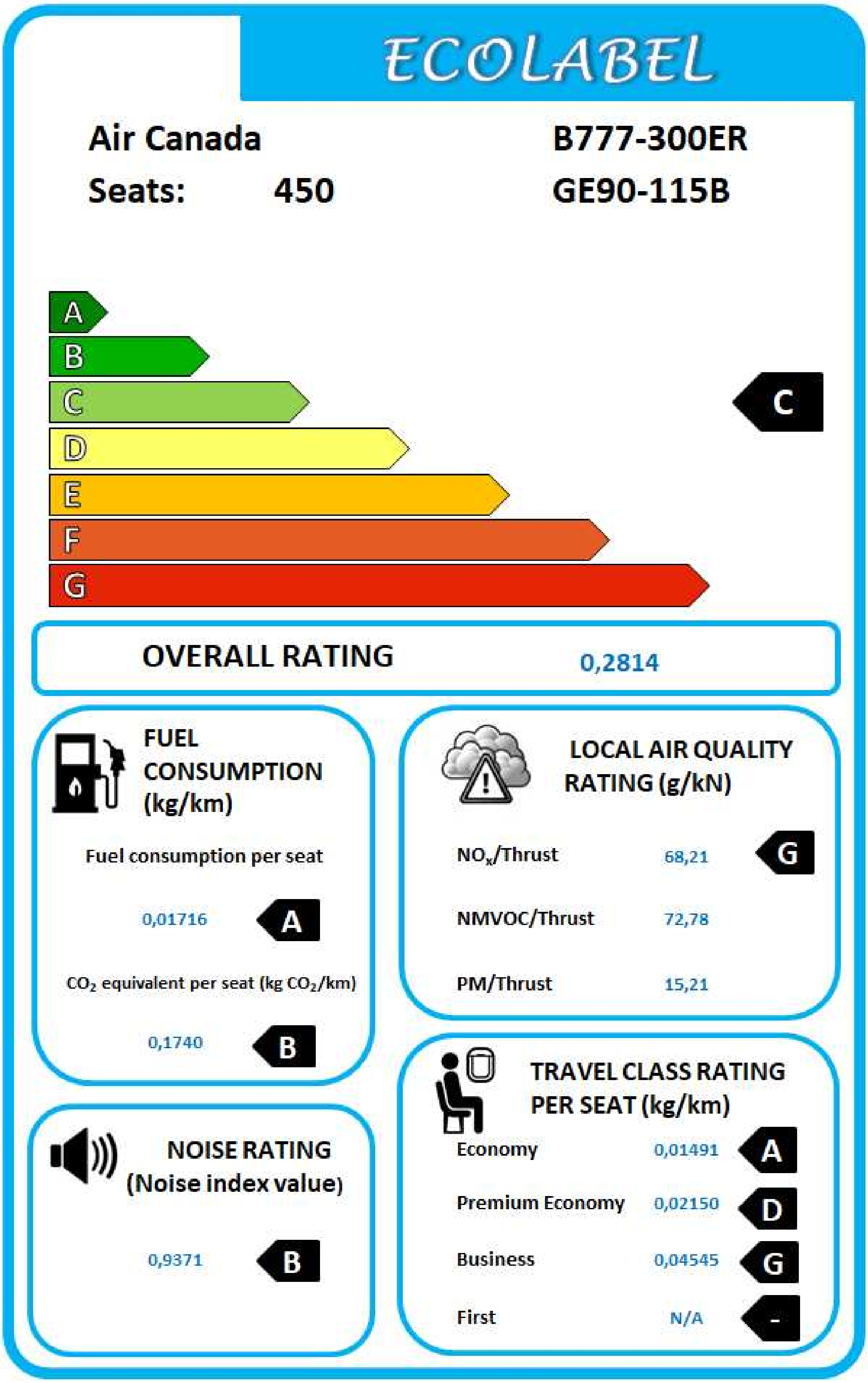
LOCAL AIR QUALITY RATING (g/kN)
NO$_x$/Thrust 55,75 F
NMVOC/Thrust 56,31
PM/Thrust 12,31

NOISE RATING (Noise index value)
0,9030 A

TRAVEL CLASS RATING PER SEAT (kg/km)
Economy 0,01427 A
Premium Economy 0,02052 C
Business 0,04608 G
First N/A -

**Figure N. 1** Ecolabel of the B787-9

# Appendix O  Ecolabel of B777-300ER



ECOLABEL

Air Canada
Seats: 450

B777-300ER
GE90-115B

C

OVERALL RATING 0,2814

FUEL CONSUMPTION (kg/km)

Fuel consumption per seat

0,01716 A

CO₂ equivalent per seat (kg CO₂/km)

0,1740 B

LOCAL AIR QUALITY RATING (g/kN)

| | | |
|---|---|---|
| $NO_x$/Thrust | 68,21 | G |
| NMVOC/Thrust | 72,78 | |
| PM/Thrust | 15,21 | |

NOISE RATING (Noise index value)

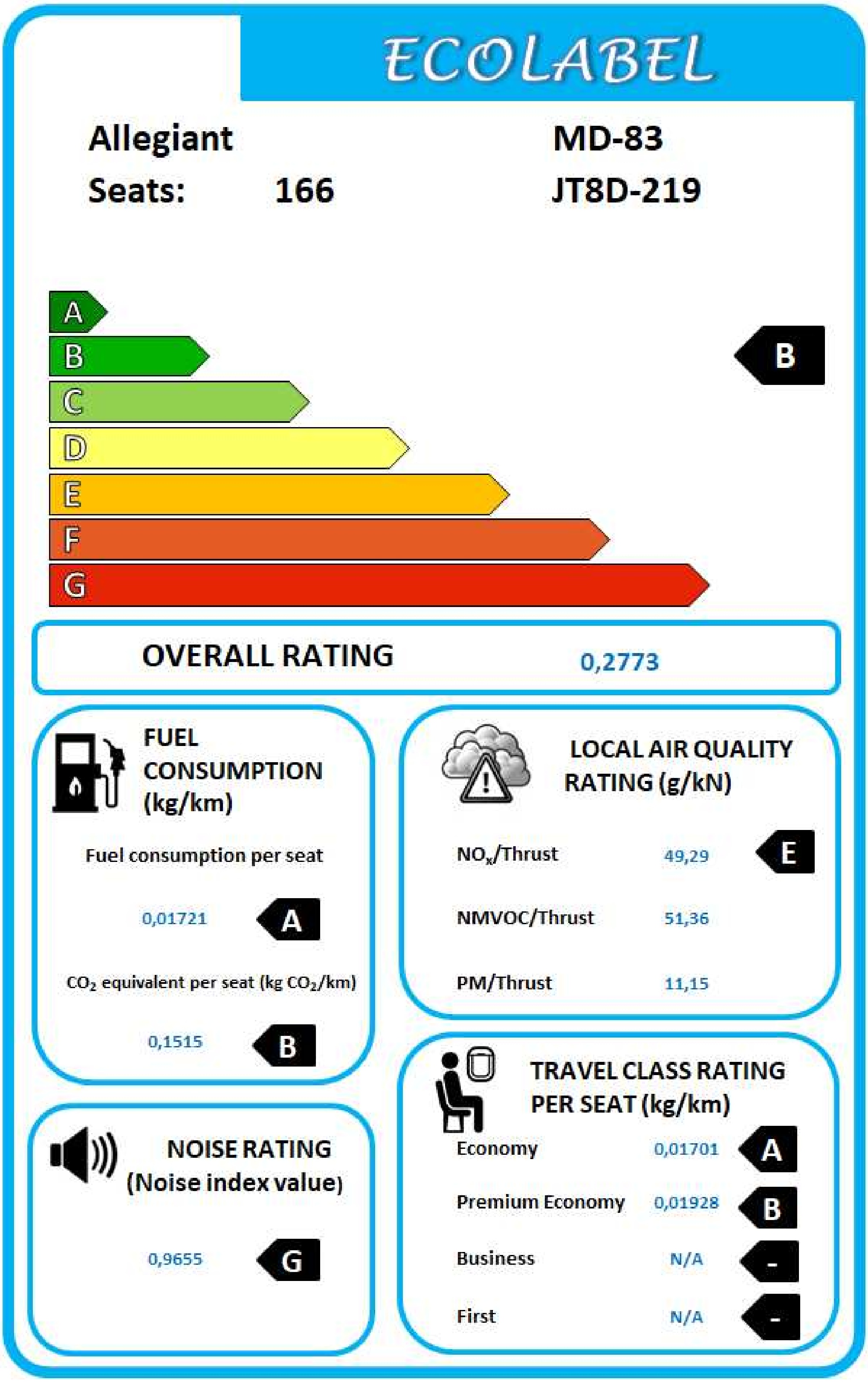
0,9371 B

TRAVEL CLASS RATING PER SEAT (kg/km)

| | | |
|---|---|---|
| Economy | 0,01491 | A |
| Premium Economy | 0,02150 | D |
| Business | 0,04545 | G |
| First | N/A | - |

**Figure O. 1** Ecolabel of the B777-300ER

# Appendix P Ecolabel of MD-83



**Allegiant** **MD-83**

**Seats:** **166** **JT8D-219**

B

**OVERALL RATING** 0,2773

**FUEL CONSUMPTION (kg/km)**

Fuel consumption per seat

0,01721 A

$CO_2$ equivalent per seat (kg $CO_2$/km)

0,1515 B

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| $NO_x$/Thrust | 49,29 | E |
| NMVOC/Thrust | 51,36 | |
| PM/Thrust | 11,15 | |

**NOISE RATING (Noise index value)**

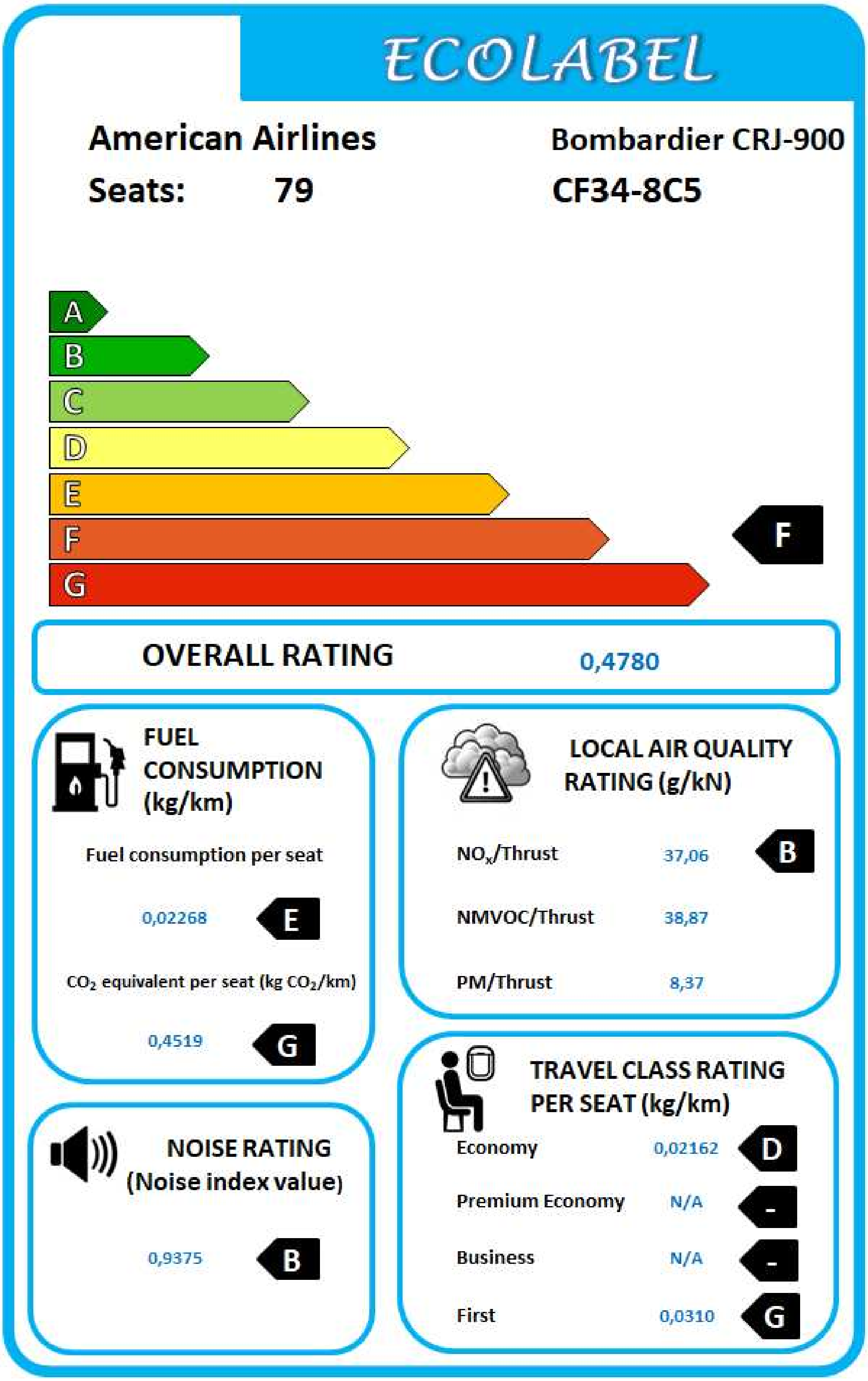
0,9655 G

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,01701 | A |
| Premium Economy | 0,01928 | B |
| Business | N/A | - |
| First | N/A | - |

**Figure P. 1** Ecolabel of the MD-83

# Appendix Q Ecolabel of Bombardier CRJ900



ECOLABEL

American Airlines
Seats: 79

Bombardier CRJ-900
CF34-8C5

F

OVERALL RATING 0,4780

**FUEL CONSUMPTION (kg/km)**

Fuel consumption per seat
0,02268 E

$CO_2$ equivalent per seat (kg $CO_2$/km)
0,4519 G

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| $NO_x$/Thrust | 37,06 | B |
| NMVOC/Thrust | 38,87 | |
| PM/Thrust | 8,37 | |

**NOISE RATING (Noise index value)**

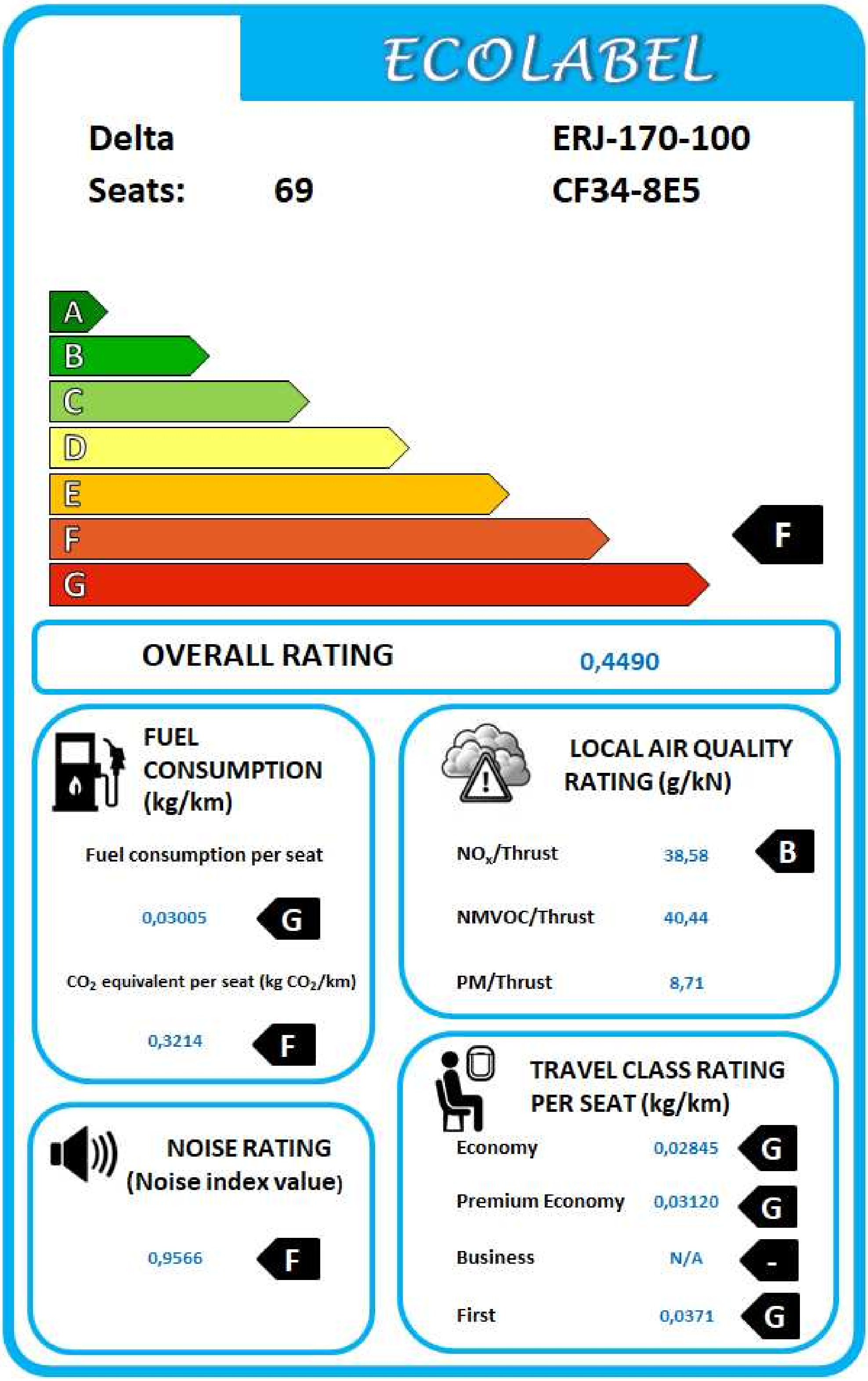
0,9375 B

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,02162 | D |
| Premium Economy | N/A | - |
| Business | N/A | - |
| First | 0,0310 | G |

**Figure Q. 1** Ecolabel of the Bombardier CRJ-900

# Appendix R Ecolabel of Embraer 170



ECOLABEL

Delta

ERJ-170-100

Seats: 69

CF34-8E5

F

OVERALL RATING 0,4490

**FUEL CONSUMPTION (kg/km)**

| | | |
|---|---|---|
| Fuel consumption per seat | 0,03005 | G |
| CO$_2$ equivalent per seat (kg CO$_2$/km) | 0,3214 | F |

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| NO$_x$/Thrust | 38,58 | B |
| NMVOC/Thrust | 40,44 | |
| PM/Thrust | 8,71 | |

**NOISE RATING (Noise index value)**

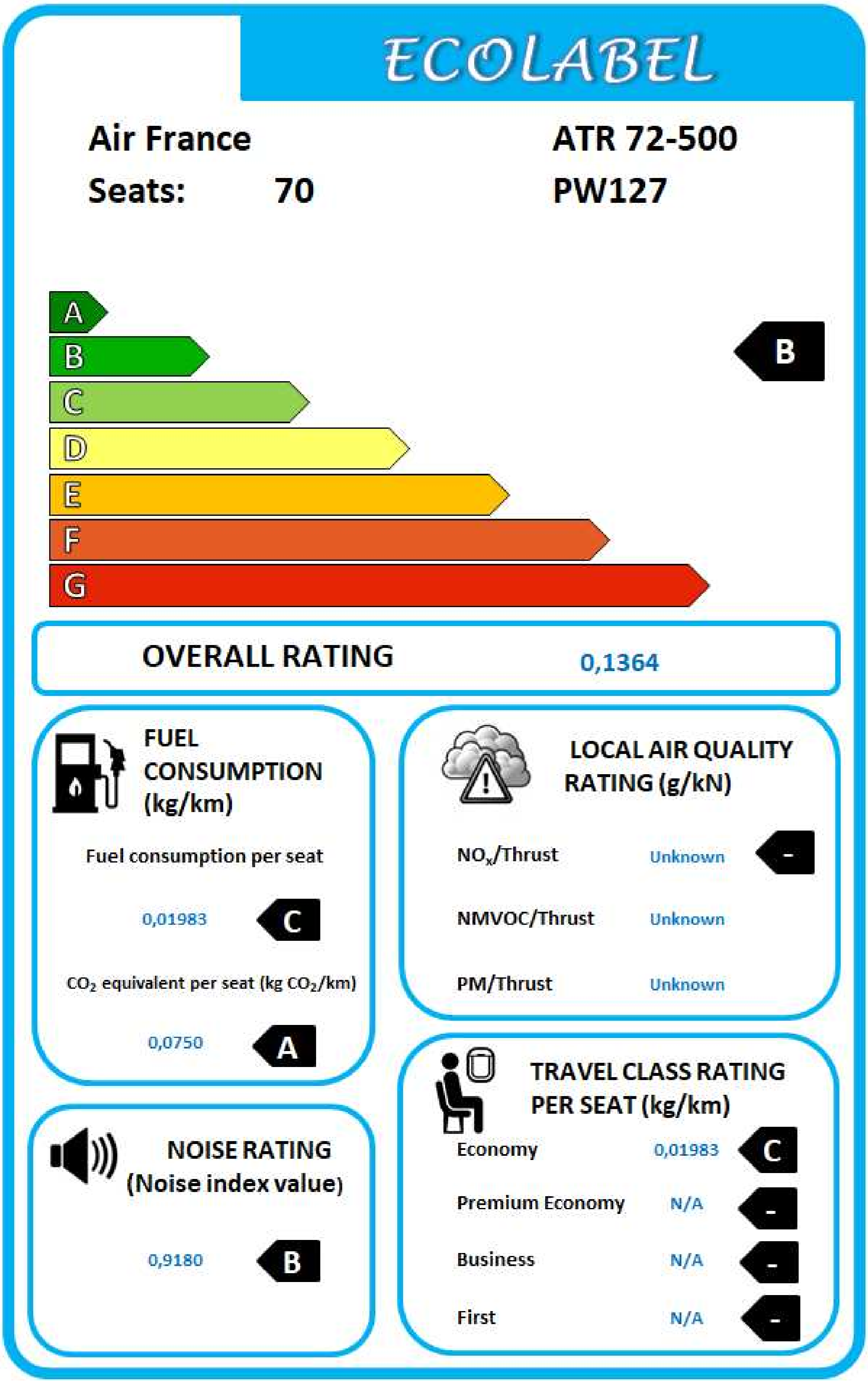
0,9566 F

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,02845 | G |
| Premium Economy | 0,03120 | G |
| Business | N/A | - |
| First | 0,0371 | G |

**Figure R. 1** Ecolabel of the Embraer 170

# Appendix S Ecolabel of ATR 72-500



Air France
Seats: 70

ATR 72-500
PW127

OVERALL RATING 0,1364

**FUEL CONSUMPTION (kg/km)**

Fuel consumption per seat

0,01983 C

$CO_2$ equivalent per seat (kg $CO_2$/km)

0,0750 A

**NOISE RATING (Noise index value)**

0,9180 B

**LOCAL AIR QUALITY RATING (g/kN)**

| | | |
|---|---|---|
| $NO_x$/Thrust | Unknown | - |
| NMVOC/Thrust | Unknown | |
| PM/Thrust | Unknown | |

**TRAVEL CLASS RATING PER SEAT (kg/km)**

| | | |
|---|---|---|
| Economy | 0,01983 | C |
| Premium Economy | N/A | - |
| Business | N/A | - |
| First | N/A | - |

**Figure S. 1** Ecolabel of the ATR 72-500