**Master Thesis**

# Environmental Labels in Aviation – Aircraft Label, Airline Label, Flight Label


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# Abstract

**Purpose** – Introducing Environmental Labels for aircraft according to the ISO 14025 standard allowing to compare the environmental impact of different air travel options based on the combination of the following aspects: aircraft type, engine type, seating configuration (Aircraft Label); airline environmental performance (Airline Label); number of legs of a trip, time, cost and environmental information (Flight Label).
**Methodology** – The existing environmental label for aircraft considered resource depletion (fuel consumption), global warming (equivalent $CO_2$ emission, including altitude-dependent $NO_x$ and aviation induced cloudiness), local air quality ($NO_x$) and noise pollution. The data for determining fuel consumption and equivalent $CO_2$ emissions was revised for existing aircraft and was extended with new aircraft types. Equivalent $CO_2$ emissions were made dependent on the specific engine of the aircraft. The methodology for calculating $CO_2$ equivalent emissions was refined with aviation induced cloudiness now being a function of fuel consumption.
This improved aircraft label was used to evaluate the fleet of the 50 most important airlines with an airline label, which takes type and number of aircraft of an airline into consideration. Different methodologies of calculating the environmental impact of a flight used by flight booking engines were compared and discussed. Approaches for a multimodal trip score and a flight label were presented.
**Findings** – An improved more accurate aircraft label was created. The database of aircraft, airline and engine combinations was extended. The environmental performance of over 50 airlines were calculated using the airline label, which resulted in an airline ranking. Different methods to incorporate a flight label into a flight booking engine were proposed based on the aircraft label approach.
**Research Limitations** –The airline label does not consider airline specific data like the passenger/cargo load factor. Because of the nature of an environmental label to only focus on the most important criteria, there is no distinction made between the technical efficiency of different airlines. The local air pollution for turboprop aircraft could not be calculated due to a lack of publicly available data and missing access to the Swedish Defense Research Agency (FOI).
**Practical Implications** – Passengers understand the most important criteria of a flight affecting its environmental burden. They can make an educated choice regarding the combination of aircraft, engine, airline and the chosen route. Obviously, a modern aircraft with an efficient engine, a ticket in the economy class and a direct flight should be chosen.
**Social Implications** – The multimodal trip score does provide the user with the ability to choose a flight based on their personal preferences and circumstances.
**Originality** – A logical trinity of the environmental labels in aviation plus an outlook to the multimodal trip score was not presented so far.

DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

# Environmental Labels in Aviation – Aircraft Label, Airline Label, Flight Label

Task for a *Master Thesis*

## Background

New commercial aircraft are often advertised with many claims about their environmental advantages over reference and competitor models. These advertisement claims are often not verifiable, not based on any reporting standards (often due to a lack of such standards), and generally not backed up by reviewed scientific publications. This published PR information does not help the traveling public to choose the least environmentally damaging aircraft among those offered for a passenger flight. Therefore, an **Ecolabel for Aircraft** (aircraft label) was introduced and applied to many aircraft as part of previous theses. 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 oxides emission in the vicinity of airports), and noise pollution. A calculation method was developed for each impact category based solely on official, certified, and publicly available data. To ensure that every parameter is evaluated independently of aircraft size, which allows comparison between different aircraft, normalizing factors such as the number of seats, rated thrust, and noise level limits were used. In addition, it was already presented how airlines can be compared by combining the information of the Ecolabels for Aircraft for all aircraft in an airline fleet. The result is called the **Ecolabel for Airlines** (airline label). The best aircraft and airline evaluation does not help, if a direct flight is split into two or more legs with environmental pollution at each airport and an enormous detour. For each leg of a flight, values of parameters responsible for resource depletion, global warming, local air pollution, and noise are added up by means of derived weighting factors to form the **Ecolable for Flights** (flight label), should be displayed in an online booking engine. The flight with the lowest weighted sum of emissions could be chosen. Similarly, a *Trip Emission Ecolabel* has already been conceived and tested. It adds all environmental burden from all legs of a trip and compares it with the burden from a non-stop-2400-km flight of a Boeing 737-800. Moreover, a **Multimodal Trip Score** combines the three main evaluation criteria for a flight – or likewise for the whole *multimodal trip* from origin to destination: environmental burden, ticket price (with and without compensation) and travel time (total time, time in vehicles, usable time) based on user-adjustable weighting factors for the three main evaluation criteria and their sub criteria. The user of the online booking engine decides, if the weighted Multimodal Trip Score or alternatively only one of the three main and weighted evaluation criteria is used to determine the sequence, in which the offered travel choices are listed.

## Task

Task of this Master Thesis is to combine the main results from previous students, to close open issues, to benefit from ideas, by bringing them to light, and to present a logical trinity of the Environmental Labels in Aviation plus an outlook to the Multimodal Trip Score. The subtasks are:

- Systematic review of (emission based) airline rankings.
- Systematic review of flight booking engines and their data on environmental burden, ticket price, and travel time.
- Check of the Ecolabel Calculator – an Excel table (support is provided).
- Extension of the Ecolabel Calculator to easily accept more aircraft types (support is provided).
- Use of the Ecolabel Calculator to calculate more ecolabels of propeller-driven passenger aircraft.
- Comparison of airlines with the Ecolabel for Airlines. Release of the results.
- Definition of equations for the Ecolable for Flights. Design of the label.
- Definition of equations for the Multimodal Trip Score. Design of a possible display of the data in a (flight) booking engine.
- Proposal of means to economically safeguard the labels.
- Final discussion of the trinity of the Environmental Labels in Aviation plus the Multimodal Trip Score.

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

This is a Master Thesis at TU Berlin with Prof. Dr. Bardenhagen as examiner. It is supervised at HAW Hamburg by Prof. Dr. Scholz.

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# List of Symbols

| | |
|---|---|
| $AR$ | Airline rating |
| $BR$ | Breathing rate |
| $C_j$ | Concentration of a substance in a region j |
| $C_{Standard}$ | Standard fuel consumption |
| $CF_{midpoint,AIC}$ | Characterization factor AIC |
| $CF_{midpoint,CO_2}$ | Characterization factor $CO_2$ |
| $CF_{midpoint,NO_x}$ | Characterization factor $NO_x$ |
| $CFe_{x,c,a}$ | Endpoint Characterization factor with the cultural perspective c, the area of protection a and midpoint impact category x |
| $CFm_{x,c,}$ | Midpoint Characterization factor with cultural perspective c and midpoint impact categrory x |
| $CO_2\ eq.$ | $CO_2$ equivalent rating |
| $CO_2\ eq._{avg}$ | Average $CO_2$ equivalent rating |
| $CO_2\ eq._{direct}$ | $CO_2$ equivalent rating of a direct flight |
| $D_{eff}$ | Particle effective diameter |
| $EI_{CO_2}$ | Emission index $CO_2$ |
| $EI_{NO_x}$ | Emission index $NO_x$ |
| $EI_{AIC}$ | Emission index AIC |
| $F_{M\rightarrow E,x,c,a}$ | Midpoint to endpoint conversion factor with cultural perspective c, area of protection a and midpoint impact category x |
| $f_{NM}$ | Fuel consumption per nautical mile |
| $f_{NM,ref}$ | Reference fuel consumption per nautical mile |
| $f_{km}$ | Fuel consumption per kilometer |
| $FP$ | Fuel performance |
| $FP_{avg}$ | Average fuel performance |
| $FP_{direct}$ | Fuel performance of a direct flight |
| $HOFP_x$ | Photochemical ozone formation potential of an emission x |
| $i$ | ID of the aircraft type of an airline |
| $iF_{x,i}$ | Intake fraction of an emission x |
| $iF_{PM2.5,world}$ | World intake fraction of PM2.5 |
| $LAP$ | Local air pollution rating |
| $LAP_{avg}$ | Average local air pollution rating |
| $LAP_{direct}$ | Local air pollution rating of a direct flight |
| $LNL$ | Local noise level rating |
| $LNL_{avg}$ | Average local noise level rating |
| $LNL_{direct}$ | Local noise level rating of a direct flight |
| $m_{fuel,LTO}$ | Mass of fuel used during the LTO cycle |
| $m_{CO_2,eq}$ | Equivalent mass of $CO_2$ emissions |

| | |
|---|---|
| $m_{NO_x,equivalent,LTO}$ | Equivalent mass of emission of $NO_x$ of an LTO cycle |
| $m_{MTOW}$ | Maximum take off mass |
| $m_{MZFW}$ | Maximum zero fuel weight |
| $m_{PM2.5,equivalent,LTO}$ | Equivalent mass of emission of PM2.5 of an LTO cycle |
| $M_{x,i}$ | Change in emission of a substance x in a region j |
| $m_{x,LTO}$ | Mass of emission of an poluttant x during an LTO cycle |
| $n_{airline}$ | Number of seats of an aircraft in an airline |
| $N_{aircraft}$ | Number of aircaft type in fleet |
| $n_{ice}$ | Particle number densities |
| $n_{calc}$ | Number of seats standard in seating configuration calculated |
| $NIV_{approach}$ | Noise level of aircraft at reference point approach |
| $NIV_{average}$ | Average noise level of aircraft |
| $NIV_{flyover}$ | Noise level of aircraft at reference point flyover |
| $NIV_{lateral}$ | Noise level of aircraft at reference point lateral |
| $N_j$ | Affected population in a region j |
| $n_{max}$ | Maximum number of seats |
| $NO_{x,equivalent,LTO}$ | Impact of equivalent photochemical ozone formation on human health during an LTO cycle |
| $(NO_{x,equivalent,LTO})_{normalized}$ | Normalized impact of equivalent photochemical ozone formation on human health during an LTO cycle |
| $NO_{x,LTO}$ | Impact of nitrous oxide formation on human health during an LTO cycle |
| $n_{seat}$ | Number of seats |
| $n_{Standard}$ | Number of seats in standard seating configuration |
| $O_{aircraft}$ | Overall aircraft rating |
| $PM_{equivalent,LTO}$ | Impact of equivalent particulate matter formation on human health during an LTO cycle |
| $(PM_{equivalent,LTO})_{normalized}$ | Normalized impact of equivalent particulate matter formation on human health during an LTO cycle |
| $PM_{LTO}$ | Impact of particulate matter formation on human health during an LTO cycle |
| $PMFP_x$ | Particulate matter formation potential of an emission x |
| $R_1$ | Harmonic range |
| $R_{NM}$ | Stage length |
| $S_{aircraft}$ | Number of seats per aircraft |

## Greek Symbols

| | |
|---|---|
| $\tau$ | Optical depth |

# List of Abbreviations

| | |
|---|---|
| AAI | Atmosfair Airline Index |
| AEED | ICAO Aircraft Engine Emissions Databank |
| AGOs | Airline Green Operations |
| AHP | Analytical Hierarchy Process |
| AIC | Aviation Induced Cloudiness |
| APK | Available Passenger Kilometer |
| ATK | Available Tonne Kilometer |
| AFTK | Available Freight Tonne Kilometer |
| BA | British Airways |
| BDL | Bundesverband der Deutschen Luftverkehrswirtschaft [German Aviation Association] |
| CER | Corporate Environmental Report |
| DLRK | Deutscher Luft- und Raumfahrtkongress [German Congress of Aeronautics and Astronautics] |
| CC | Closeness Coefficient |
| CF | Characterization Factor |
| $CO_2$ | Carbon Dioxide |
| CRF | Contrail Radiative Forcing |
| DEA | Data Envelopment Analysis |
| DEMATEL | Decision-Making Trial, Evaluation Laboratory |
| DGLR | Deutsche Gesellschaft für Luft- und Raumfahrt [German Society for Aeronautics and Astronautics] |
| DJSI | Dow Jones Sustainability Index |
| DOC | Direct Operating Costs |
| EASA | European Union Aviation Safety Agency |
| EEA | European Environment Agency |
| EI | Emission Index |
| ERF | Effective Radiative Forcing |
| FBE | Flight Booking Engine |
| FSC | Full Size Carrier |
| GHG | Greenhouse Gas |
| GHG1 | Greenhouse Gases Emissions, scope1 |
| GHG2 | Greenhouse Gases Emissions, scope2 |
| IATA | International Air Transport Association |
| ICCT | International Council on Clean Transportation |
| IAE | International Aero Engines |
| IOC | International Olympic Committee |
| IRM | Impact Relationship Map |
| IPCC | Intergovernmental Panel on Climate Change |

| | |
|---|---|
| LCC | Low Cost Carrier |
| LTO | Landing and Take Off |
| MAD | Multilingual Aeronautical Dictionary |
| MSL | Mean Sea Level |
| MTOW | Maximum Take Off Weight |
| NIS | Negative Ideal Solution |
| NMVOC | Non-Methane Volatile Organic Compounds |
| PIS | Positive Ideal Solution |
| PMFP | Particulate Matter Formation Potential |
| RPK | Revenue Passenger Kilometer |
| RTK | Revenue Tonne Kilometer |
| RPTK | Revenue Freight Tonne Kilometer |
| TIM | Travel Impact Model |
| TOPSIS | Techniques to Order Preferences by Similarity to Ideal Solution |

# 1 Introduction

## 1.1 Motivation

Geoengineering approaches, such as altering flight trajectories, aim to positively influence the climate by cooling it down. This could be achieved by flying through regions with intense solar radiation that are also supersaturated with ice. These conditions foster the formation of vapor trails that evolve into long-lasting cirrus clouds, which can reduce solar radiation through increased reflection caused by aviation-induced cloudiness (AIC) (Niklass 2019). However, this method can only be utilized under these specific atmospheric conditions, and even then, only for certain segments of a flight – if at all.

Researchers from UCL and Harvard have explored another geoengineering technique: injecting sulfur dioxide into the stratosphere. Their findings suggest that this approach could mitigate climate hazards without significantly worsening conditions in specific regions (Irvine 2020). While widespread use of this technology could substantially reduce overall climate change, it could also exacerbate climate effects in 9 % of the land area, highlighting the potential risks.

Understandably, geoengineering is a subject of significant controversy, and much more research is required before it can be widely implemented. It is crucial to emphasize that solar geoengineering addresses only the symptoms of climate change, not its root cause – the accumulation of $CO_2$ and other greenhouse gases in the atmosphere. As such, it should be considered a complementary measure to emissions reductions rather than a standalone solution. Ultimately, the best way to protect the environment remains avoiding emissions in the first place. When this is not feasible, minimizing environmental impact should be the priority. This thesis seeks to explore how this can be achieved.

The environmental impact of aviation must be viewed in a broader context. While it is often noted that $CO_2$ emissions from air traffic account for approximately 3 % of global $CO_2$ emissions, this figure may seem relatively small. However, when focusing specifically on the transport sector, aviation ranks as the second-largest emitter, surpassed only by road transport (see Figure 1.1). The disparity between these two sectors is significant, with road transport producing about six times more $CO_2$ emissions than air traffic (BDL 2020).

However, assessing the environmental impact of aviation solely based on $CO_2$ emissions can be misleading, as the location and altitude of these emissions play a crucial role. Recent research suggests that AIC may have a more substantial environmental impact than traditional pollutants like $CO_2$ or $NO_x$, further distinguishing aviation from road transport. These non-$CO_2$ effects, including $NO_x$ and AIC, are estimated to have three times the climate impact of $CO_2$ emissions alone (Scholz 2021).

This evolving understanding poses a significant challenge for synthetic fuels, which are often marketed as "climate neutral." When taking non-$CO_2$ emissions into account, it becomes clear that these fuels are far from being climate neutral. Additionally, the high energy consumption required to produce synthetic fuels introduces another layer of environmental concerns, challenging the notion that they are a greener alternative to conventional fuels.

When comparing air and road transport, electrification emerges as a potential option for aviation as well. However, one of the most significant challenges lies in the low energy density of batteries, especially when compared to kerosene. For instance, Figure 1.2 illustrates that a lithium battery (0.5 MJ/kg) possesses only about 1.2 % of the energy density of Jet A-1 aviation fuel (43.3 MJ/kg). While current advancements, such as Tesla's batteries with around 1 MJ/kg and Amprius's silicon anode battery with a record high energy density of nearly 2 MJ/kg (Patel 2023), are promising, they still fall short. Silicon-air batteries, with a theoretical energy density of approximately 30 MJ/kg, come closer to Jet A-1. But several technical, design and corrosion problems associated with Si–air battery systems have to be resolved for its mass scale deployment (Bansal 2020).

Moreover, battery efficiency must be considered, as conventional aircraft have the advantage of becoming lighter as they burn fuel. Currently and for the foreseeable future, battery-powered or hybrid aircraft are not suitable for long flights due to the low energy density and high weight of the batteries. Short-range flights, in particular, should be replaced by trains, which consume less energy. Additionally, urban air mobility currently only serves the elites and does this with a much worse efficiency due to the vertical take-off and landing in hover flight (Plötner 2020).

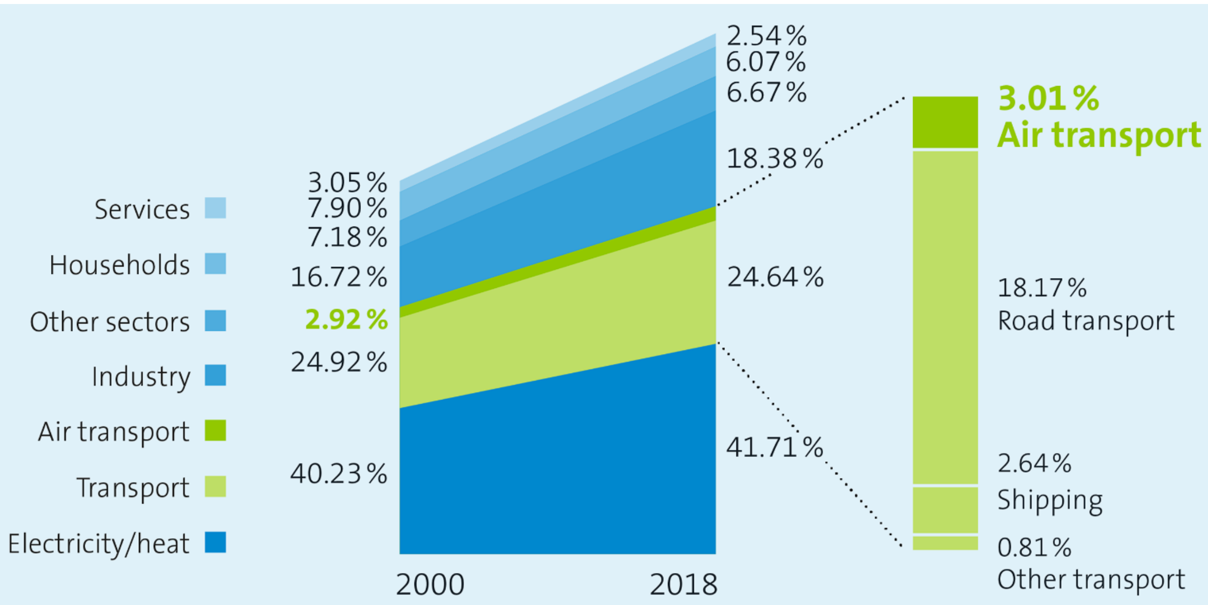


**Figure 1.1** Trend and share of global $CO_2$ emissions of different sectors (BDL 2020)

Hydrogen, as shown in Figure 1.2, boasts the highest energy density among potential aviation fuels. However, its low volumetric density and the complexities of storage in aviation applications are well-known challenges. Beyond these factors, hydrogen combustion in aircraft engines, much like in conventional engines, leads to the emission of $NO_x$. More critically, hydrogen combustion produces 2.6 times more water vapor than burning kerosene (IATA 2019). Since water vapor is a potent greenhouse gas, this increase could contribute significantly to global warming.

Unlike kerosene, which produces soot that serves as a condensation nucleus for water vapor, hydrogen combustion does not generate soot. This absence results in fewer solid particles in the exhaust, which in turn reduces the formation of ice crystals. However, recent research suggests that the increased water vapor in hydrogen combustion exhaust may lead to the formation of fewer but larger ice crystals. These larger crystals, with a smaller overall surface area, could theoretically reduce radiative forcing. Ponater (2006) estimates that the overall radiative forcing from aviation could be reduced by 20-30 % by 2050 and 50-60 % by 2100 if $LH_2$-powered aircraft were widely adopted. However, these projections are not definitive, and much more research is needed to fully understand the environmental impact of hydrogen-powered flight, as well as to address the associated storage and infrastructure challenges.

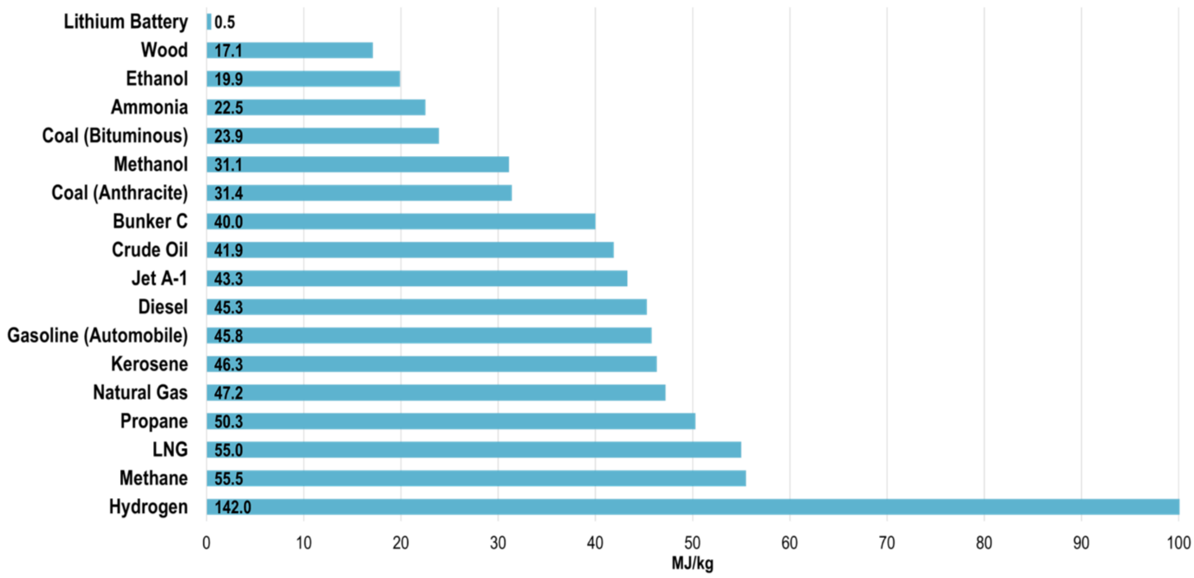


**Figure 1.2** Energy density of some combustibles (Rodrigue 2020)

Even if there were a groundbreaking breakthrough in technologies like batteries or hydrogen, it would likely take decades to fully capitalize on these advancements. This delay is due to the lengthy development cycles and the long lifespan of aircraft, assuming no major political interventions or investments. By the time these technologies could be widely implemented, it might already be too late to mitigate the environmental damage, despite the promise of technological leaps.

Hermann (2022) argues that the concept of green growth may be a misleading promise. One of her central points is the rebound effect, where technological advancements often lead to increased consumption rather than a reduction in environmental impact. As technology advances, people quickly adapt to new standards, often opting for larger TVs, bigger cars, or longer flights to distant destinations instead of making more sustainable choices. These behaviors, which can be seen as triumphs of capitalism – especially alongside significant advances in healthcare – are ultimately neither sustainable nor socially equitable in the long run.

Ulrike Herrmann advocates for degrowth instead of green growth, challenging the idea that continuous technological progress can solve environmental issues. A look back at aviation history reveals that efficiency improvements of just 1.5 % per year are insufficient to offset the trend of global air passenger numbers doubling every 15 years (BDL 2020). This underscores the need for a more fundamental shift in how we approach sustainability, beyond relying solely on technological advancements.

Given this understanding, it is clear that avoiding air travel is the most environmentally friendly option. However, since flying is sometimes unavoidable, the environmental impact of a flight will continue to depend on various factors for the foreseeable future. To assess this impact, elements such as the engine type, flight altitude, distance, and seating configuration must all be considered. Building on previous research, this thesis proposes the development of labeling systems for aircraft, airlines, and individual flights to guide travelers in choosing the least environmentally harmful options.

## 1.2 Title Terminology

“Environmental Labels in Aviation – Aircraft Label, Airline Label, Flight Label”

**Environmental**
According to the Cambridge Dictionary the word *environmental* means:

> *relating to the environment in which people, animals, and plants live*

The main objective of this thesis is to show how to fly with the least environmental impact possible (with regard to time and cost), therefore protecting said people, animals and plants.

**Label**
A l*abel* is defined by the Cambridge Dictionary as follows:

> *a piece of paper or other material that gives you information about the object it is attached to*

In previous thesis – on which this thesis is based – a more specific *ecolabel* was introduced. It describes the presentation of information backed up by reviewed scientific publications. The *ecolabel* sits very close to the (EU) *energy label* in regard to the meaning. Both designations are nearly interchangeable which is already explained in the thesis by Hurtecant (2021). For the sake of completeness follows the definition of the *energy label* by the European Commission:

> *The energy label has been a key driver for helping consumers choose products which are more energy efficient. At the same time, it also encourages manufacturers to drive innovation by using more energy efficient technologies (European Commission 2020).*

The main incentive to change the designation resolves out of the fact, that the ecolabel was launched as an aircraft Label. It will work fine with direct flights, but not when there are one or more stopovers to be made. Therefore, the flight label is introduced which will be explained in much more detail in Chapter 6. Put in simple terms, the object to which the information is attached to is different referring to the definition of the *label*. This becomes clear looking at the airline label, which obviously compares the environmental performance of airlines.

**Aircraft & Aircraft Category**
Corresponding to Hurtecant (2021), the definitions of *aircraft* and *aircraft category* by the International Civil Aviation Organization (ICAO) are:

An *aircraft* is defined as (ICAO 2005):

> *Any machine that can derive support in the atmosphere from the reaction of the air.*

The definition of *aircraft category* is (ICAO 2020b):

> *Classification of aircraft according to specified basic characteristics, e.g., airplane, glider, rotorcraft, free balloon.*

The specific basic characteristics are dependent on the certification of the aircraft. Subject of this thesis are airplane either certified by FAR Part 25, Transport Category Airplanes (USA) or EASA CS-25, Large Airplanes (Europe). Too keep the title short and simple, it was decided not to include this specification, but providing a clarification here.

**Airline**
The definition of an a*irline* is given by the Dictionary of Aviation (Crocker 2005):

> *a company which manages air transport services for passengers or goods*

This thesis will be focusing on the comparison of environmental performance of air transport services for passengers using a certain aircraft category as made clear beforehand.

**Flight**
The AGARD: Multilingual Aeronautical Dictionary defines a *flight* as:

> *The movement of an object through the atmosphere or through space, sustained by aerodynamic, aerostatic, or reaction forces, or by orbital speed; especially, the movement of a man-operated or man-controlled device, such as a rocket, a space probe, a space vehicle or an aircraft.*

At this point, it should be obvious, that this thesis pivots around objects which move through the atmosphere, sustained by aerodynamic forces in a man-operated device – an aircraft.

**Aviation**
The term aviation is defined by the AGARD: Multilingual Aeronautical Dictionary as follows:

> *(a) The operation of aircraft*
> *(b) A synonym for `aeronautics´.*

It was chosen to shorten the title in order to keep it simple. Applicable are the restrictions for aeronautics already stated.

## 1.3 Objectives

The main objective is to assist travelers in selecting the most environmentally friendly option among available flights. While numerous flight booking engines (FBEs) provide emissions data for various flights, the lack of standardization can make it challenging to compare options effectively. This thesis will offer a scientific overview and comparison of existing FBEs, incorporating factors such as travel time and cost. By analyzing their strengths and weaknesses, the study aims to demonstrate how these tools can be improved to better support sustainable travel choices.

While flight selection should ideally be made on a case-by-case basis, this study will also rank airlines based on their environmental performance. Initially, existing airline rankings will be reviewed to understand current methods and criteria. Following this, a new approach for comparing airlines will be proposed and discussed, providing an updated perspective on evaluating their environmental impact.

The existing ecolabel calculator (Excel Tool) requires revision, particularly to incorporate updated data on pollutant and noise emissions. In order to be able to calculate as many environmental labels as possible, the database of aircraft-engine-airline combinations must be expanded. This includes adding more aircraft types, with a particular focus on propeller-driven passenger aircraft. Calculating Environmental labels of turboprop engines and comparing these to the more commonly used turbofan engines will help highlight the strengths and weaknesses of each engine type.

A direct flight can be split into two or more legs with environmental pollution at each airport and an enormous detour. Suitable equations have to be defined to account for the summation of negative impacts for each leg of a flight. The results have to be displayed in a visually attractive label, which is easy to understand. Because of economic or social circumstances, the environmental impact of a flight cannot be the priority for all people. Given that flight durations can differ quite a lot, time constraints could be important as well. These issues are addressed by the multimodal trip score. Its idea is to introduce the environmental impact, cost and time as independent weighting factors and implement them into the flight booking process. Customers should be able to adjust the weighting factors freely in accordance to their own priorities. Developing a method for calculating and presenting these scores is another key objective of this thesis.

## 1.4 Previous Research

Thanks to the contributions of previous students involved in the Ecolabel, this thesis can build on previous work of Haß (2015), van Endert (2017), Sokour and Bähr (2018), Ridao Velasco (2020) and Hurtecant (2021).

Hass initiated the series of thesis and projects, as he was the first to develop an Ecolabel. He already introduced a rating similar to the Travel Class Fuel Performance used in the latest version of the Ecolabel by Hurtecant (see Figure 2.1). Additionally, an overall rating like in the EU energy label was presented which consisted of the weighted rating of *Fuel Consumption and Climate Impact* (60 %), *Air Quality Impact* (20 %) and *Noise* (20 %).

Van Endert reviewed the work of Hass, optimizing the metrics and improving the design (oriented at the EU Energy Label). The previous category *fuel consumption and climate impact* was split and one more environmental impact category, namely the *$CO_2$ equivalent per seat* was introduced. Non-methane volatile organic compounds equivalents or ozone formation potential (NMVOC) were included. Rating the emission of particulate matter important in relation to nitrogen oxides was added. As a result, the categories responsible for the overall rating changed to *Fuel consumption per seat* (20 %), *$CO_2$ equivalent per seat* (40 %), *Noise rating* (20 %) and *Local air quality rating* (20 %).

Sokour and Bähr (2018) automated the necessary data implementation/transfer in the Excel Ecolabel calculator, allowing a faster and easier way to calculate Ecolabels for Aircraft and comparing them. The evolution of the Ecolabel up to this point in more detail can be retraced in Section 6.3 at (Ridao Velasco 2020). Additionally, a lot of important topics regarding environmental information for aviation passengers like offsetting strategies of carbon emissions or the systematics of environmental information for aviation passengers are discussed, which are highly relevant for this thesis as well.

Hurtecant addressed the flaws of the Ecolabel pointed out by Ridao Velasco. For example, the ecolabel for aircraft was defined as a type III environmental declaration according to ISO 14025 (2006): Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures. This added credibility of the ecolabel for aircraft as an independent and reliable source of information. Among other improvements, the presentation of the variables (and their units) and the overall rating has been updated for enhanced clarity and understanding. Every part of the ecolabel was explained in a short and understandable text that will be displayed when the reader scans the added QR code on the ecolabel. A first concept for a Trip Emission Ecolabel was presented as a first step towards a flight label.

## 1.5 Structure

This work consists of 5 main chapters. The structure of the thesis is as follows:

**Chapter 2** The calculation methodology of the aircraft label is presented. Changes and improvements to the existing method are explained.

**Chapter 3** A systematic literature review of emission-based airline rankings is conducted to give an overview of existing research and a summarization of its contents. The state of various airline rankings is discussed.

**Chapter 4** The calculation of the airline label is presented and the environmental performance of each airline of a reference group is calculated. The resulting airline ranking is discussed.

**Chapter 5** A brief comparison between different flight booking engines and their calculation methodology of the environmental burden of a flight is presented.

**Chapter 6** Different possibilities of implementing a flight label in a flight booking engine are discussed.

# 2 Aircraft Label

This chapter refines the *Ecolabel for Aircraft* defined by Hurtecant (2021). Since this project is part of a series of consecutive student-led efforts, the original structure developed by Hurtecant has been maintained for consistency and clarity.

Hurtecant (2021) conducted a comprehensive life cycle assessment to evaluate the environmental impact of aircraft, focusing on *resource depletion*, *air quality*, *climate change*, and *noise pollution*. From this analysis, four key ratings were identified as critical for determining an aircraft's environmental impact: fuel performance, $CO_2$ equivalent emissions, l*ocal noise levels*, and *local air pollution*.

In this Chapter the *Ecolabel for Aircraft* defined by Hurtecant (2021) is being refined. As it is a consecutive project from different students, his structure is maintained for better understanding. Hurtecant (2021) examined *resource depletion*, *air quality*, *climate change* and *noise pollution* via a life cycle assessment. It was concluded, that the following four ratings are used to determine the environmental impact of an aircraft: *fuel performance*, *$CO_2$ equivalent emissions*, *local noise level* and *local air pollution*.

The ratings are displayed in the middle section of the Ecolabel for aircraft, as shown in Figure 2.1. The ecolabel takes into account the airline's specific seating layout and the actual aircraft-engine combination. This information is provided in the upper section of the label.

Each rating is expressed in its respective unit. To facilitate comparison, a letter grading system from A to G is used, giving a clear indication of how well or poorly an aircraft performs in various categories.

The overall rating is a composite score that incorporates all individual ratings, weighted as follows: 40 % for $CO_2$ equivalent emissions, 20 % for Fuel Performance, 20 % for Local Air Pollution, and 20 % for Local Noise Level. This overall rating ranges from zero to ten. The weighting factors are based on life cycle assessments and are derived from the work of Johanning (2016) and Hurtecant (2021).

Additionally, the label includes a travel class fuel performance metric in the bottom section. This metric emphasizes the impact of seating configuration and the selected seat on fuel efficiency.

The rating is calculated via the Ecolabel Calculator, which was checked and improved in the scope of this thesis. The results are discussed in the following chapters.

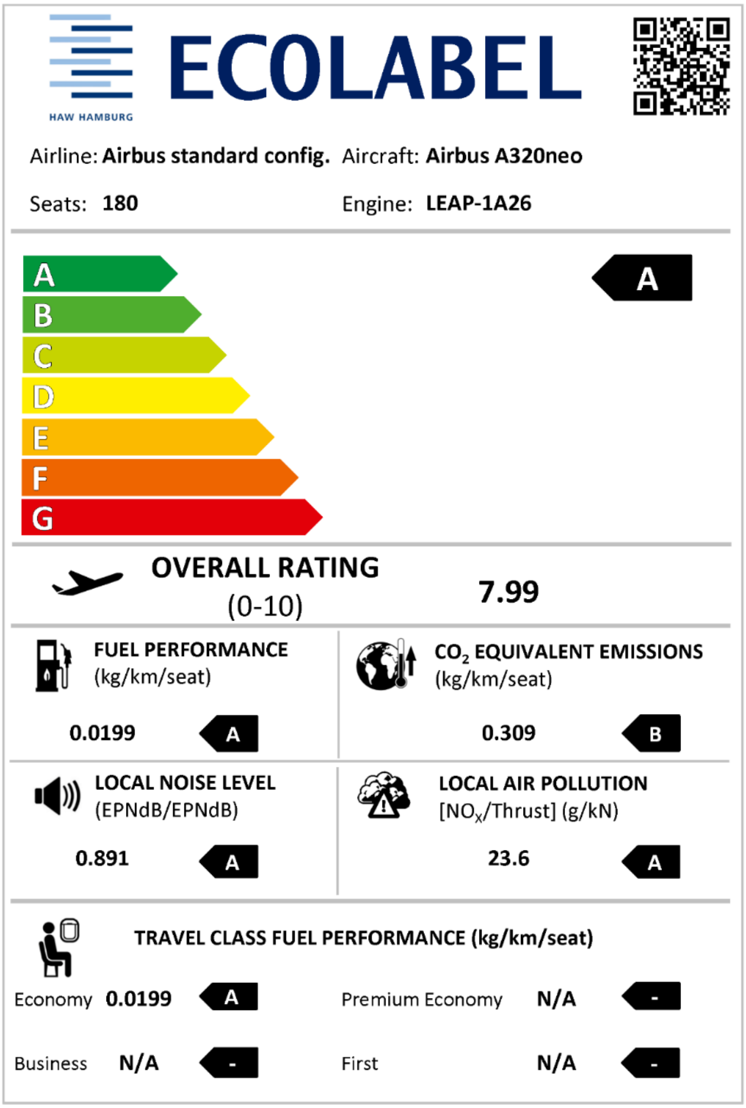


**Figure 2.1** Ecolabel for Passenger Aircraft

## 2.1 Fuel Performance

Fuel consumption is a good indicator for the contribution of aviation to oil depletion, but aircraft manufacturers rarely disclose this information in a standardized matter. There are different methods to calculate fuel consumption, which are discussed by Hurtecant (2021) and Kühn (2023). An overview about the different methods applied to the 50 most used passenger aircraft are displayed in Figure 2.3. The results give a good first indication of an aircraft's fuel consumption. But there is also a pretty big deviation among the results. A standard for the fuel performance of an aircraft was developed by Hurtecant (2021). A point performance metric based on the specific air range (SAR) is being used, which only needs the maximum take off weight (MTOW) $m_{MTOW}$, the maximum zero fuel weight (MZFW) $m_{MZFW}$, the harmonic range ($R_1$) and the number of seats $n_{Standard}$ of an aircraft to determine the standard fuel consumption $C_{standard}$ per passenger, kilometer and seat via (2.1).

$$C_{Standard} = \frac{1}{n_{Standard}} \cdot m_{MTOW} \cdot \left(1 - \frac{m_{MZFW}}{m_{MTOW}}\right) \cdot \frac{1}{R_1} \quad \text{[kg/km/seat]} \tag{2.1}$$

This data can be obtained from specific corporate documents[1] and the associated extended payload-range diagrams. However, the various designations of these documents highlight a lack of standardization, making it challenging to obtain accurate data. For instance, the Airbus A320 comes in 19 different weight variants, with Maximum Takeoff Weights (MTOWs) ranging from 66,000 kg (WV006) to 78,000 kg (WV017), each with its own Maximum Zero-Fuel Weight (MZFW) (Airbus, 2020c). Unfortunately, not all weight variants have corresponding extended payload range diagrams, which limits the available harmonic range data for different weights.

This lack of standardization is manageable when considering a single aircraft, but it becomes problematic when comparing different aircraft models, particularly across manufacturers. For example, Figure 2.2 displays the extended payload range diagrams for three Airbus A320 weight variants. The harmonic range (the range at maximum payload) varies significantly, with an Airbus A320 having an MTOW of 73,500 kg achieving approximately 1,750 nautical miles and one with an MTOW of 78,000 kg reaching about 2,000 nautical miles – a difference of around 250 nautical miles. The smallest variant (WV006 with an MTOW of 66,000 kg) and several other variants lack harmonic range data, underscoring the method's limitations. Therefore, it is crucial to select comparable weight variants across different manufacturers to minimize discrepancies in the results.

[1] Airport Operations and Aircraft Characteristics (Airbus)
Airplane Characteristics for Airport Planning (Boeing)

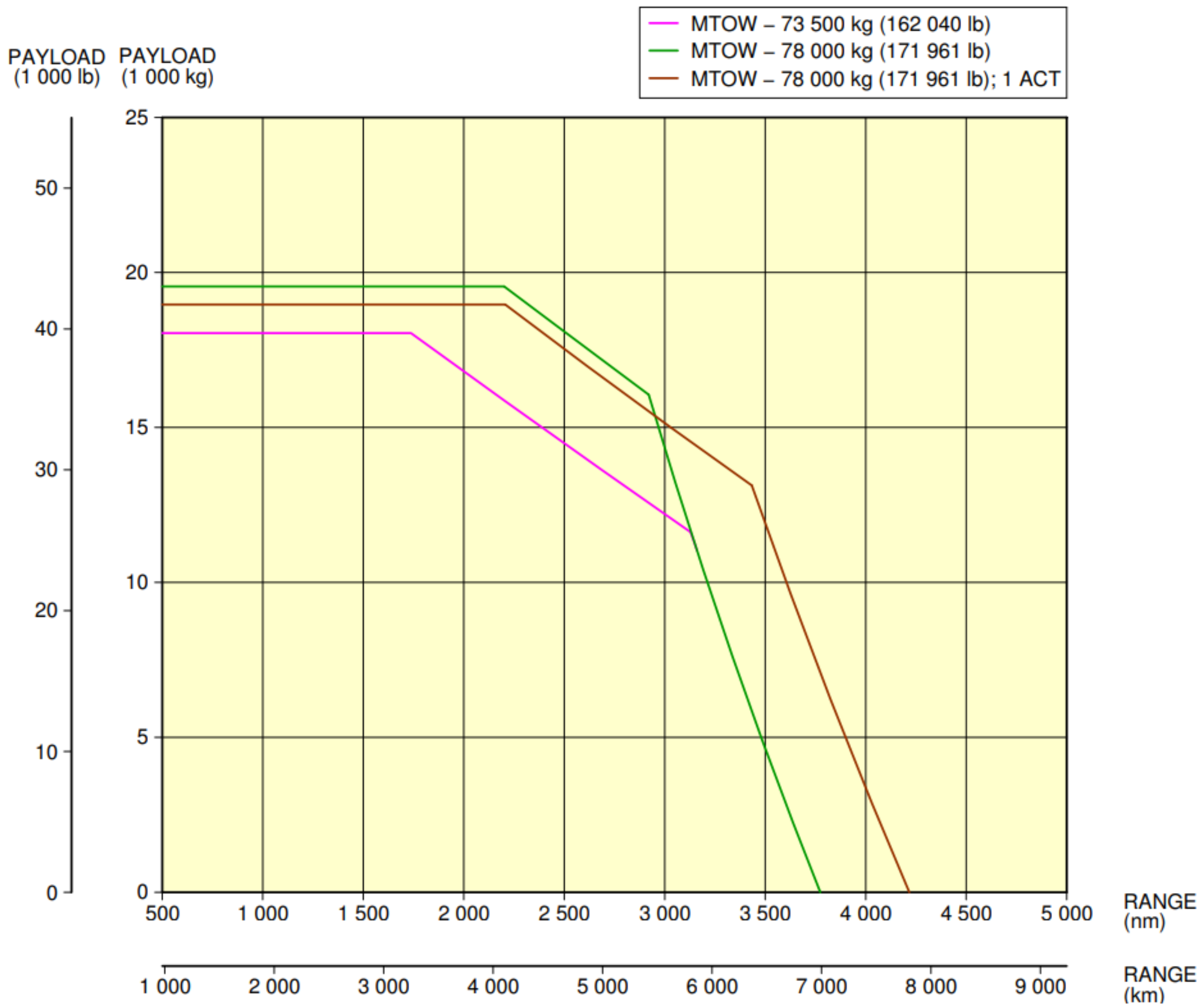


**Figure 2.2** Payload range diagram of different Airbus A320 weight variants (Airbus 2020c)

The standard number of seats of an aircraft of an airline $n_{Standard}$ is also not determined in an easy way. In some documents a standard seating capacity is given. But every manufacturer could have a different method to calculate the standard seating capacity, which does not allow for a comparison. Boeing often states standard seating capacity for different layouts (one class, two class, three class). It would be up to the author again to choose comparable "standard" seating layouts. And there are documents of aircraft manufacturers, which do not state any standard seating capacity. Therefore, it was decided to use one unified method to determine the standard seating capacity of an aircraft. The estimation of the typical seating arrangement of an aircraft was done via the maximum number of passengers $n_{max}$ and (2.2) found by Hurtecant (2021).

$$n_{OEM} = 0.6696 \cdot n_{max} + 22.858 \tag{2.2}$$

To assess aircraft fuel consumption, a rating scale from A to G has been introduced, where an A represents excellent fuel efficiency and a G indicates relatively poor performance. Each grade on this scale corresponds to a specific range of fuel consumption per kilometer and per passenger.

A reference group of aircraft is essential for establishing this rating scale. Previously, the World Airliner Census 2020 was used to represent the global commercial fleet. Although this remains the most recent dataset available, it has been utilized again to develop a revised reference group. The updated reference group now includes newer aircraft models, such as the Boeing 737 MAX 9 and the Airbus A321 Neo, aiming to cover at least 95 % of the world's aircraft fleet. The old reference group included 61 aircraft models, while the new one features 86 different models.

Additionally, the data for each aircraft model has been reviewed and updated as necessary. The goal was to minimize deviations and ensure that the reference group accurately reflects current fuel consumption realities. This level of accuracy was not achieved with the previous reference group. Details of the new reference group can be found in Appendix A, and guidelines for incorporating new aircraft into the ecolabel calculator are provided in Appendix M.

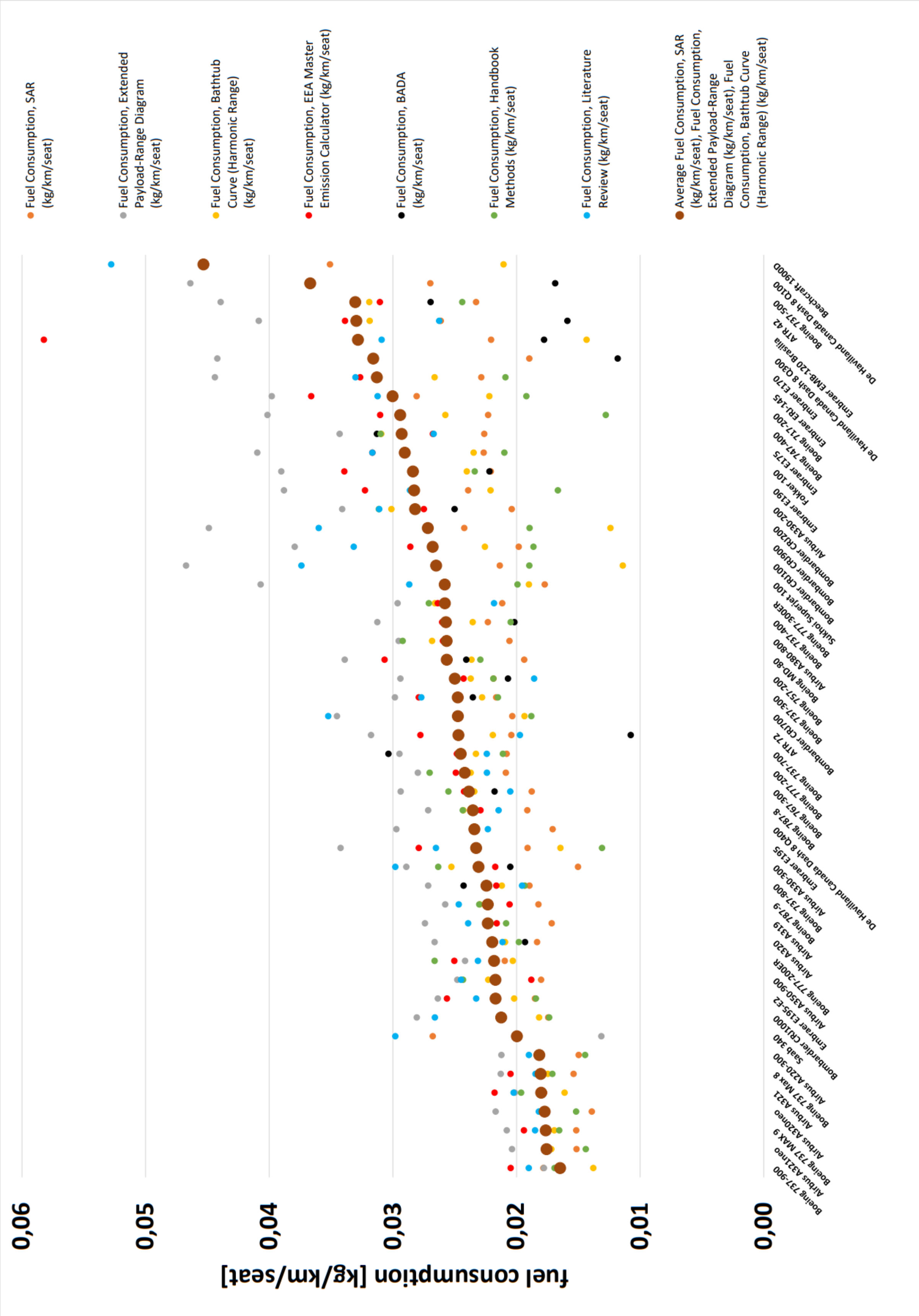


**Figure 2.3** Fuel Consumption of the 50 most used passenger Aircraft (Kühn 2023)

## 2.2 Fuel Performance Rating Scale

The fuel consumption of every aircraft in the reference group was calculated via (2.1). This fuel consumption depicts the amount of burnt fuel per traveled kilometer and per seat with a calculated standard seating layout via (2.2). An overview of the fuel consumption for all the aircraft in the reference group is given in Appendix B. The distribution of fuel consumption of the reference group of aircraft is depicted in Figure 2.4.

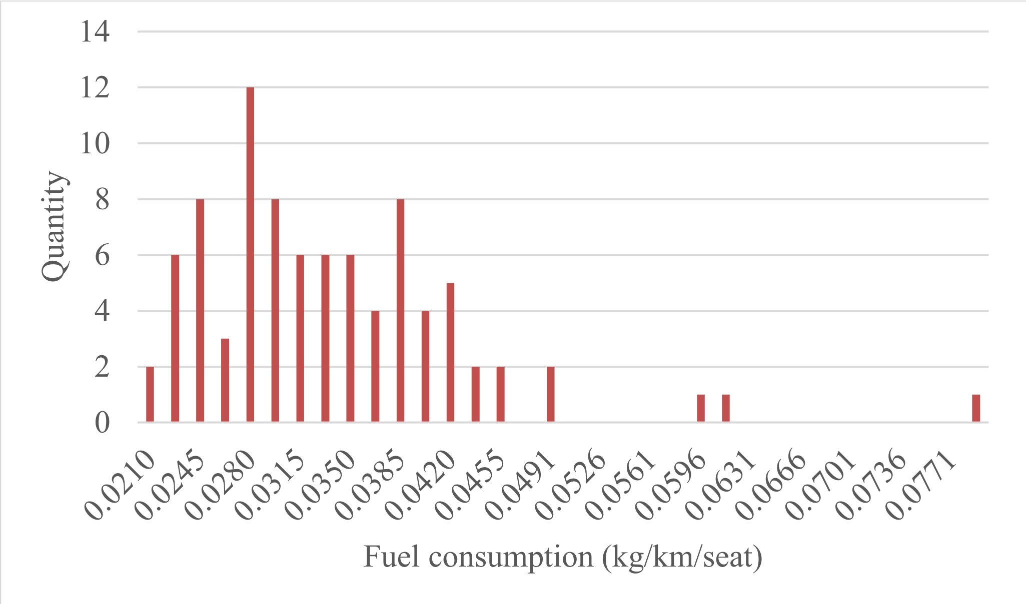


**Figure 2.4** Histogram of the fuel consumption for the reference group of aircraft (kg/km/seat)

Since the rating scale consists of seven classifications (A to G), the range of fuel consumptions for every classification should reflect the approximately normally distributed histogram in Figure 2.4. This means, that the 86 aircraft in the reference group have to be equally distributed to a classification. There are roughly twelve aircraft to be found in each classification. The twelve aircraft with the best fuel consumption will be represented in class A, the worst twelve aircraft will make up class G and so on. The rating scale for every classification can be obtained from Table 2.1.

**Table 2.1** Fuel Performance rating scale (kg/km/seat)

| Rating | Range | | Normalized 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| **A** | 0.0220 | 0.0246 | 0.0000 | 0.0450 |
| **B** | 0.0246 | 0.0286 | 0.0450 | 0.1146 |
| **C** | 0.0286 | 0.0309 | 0.1146 | 0.1545 |
| **D** | 0.0309 | 0.0360 | 0.1545 | 0.2421 |
| **E** | 0.0360 | 0.0398 | 0.2421 | 0.3080 |
| **F** | 0.0398 | 0.0456 | 0.3080 | 0.4075 |
| **G** | 0.0456 | 0.0798 | 0.4075 | 1.0000 |

## 2.3 $CO_2$ Equivalent Emission

The essential information about the relevant emissions of a flight are given by Hurtecant (2021). Some further and more recent information especially of non-$CO_2$ emissions and their altitude effects are described in the following Chapter.

### 2.3.1 Aviation Induced Cloudiness and Radiative Forcing

To evaluate the environmental impact of the aviation sector, it is useful to compare it with a more eco-friendly mode of transportation: the train. Scholz (2021) demonstrates that air travel has 18.3 times the environmental impact of rail travel. This significant difference arises from two main factors: the nearly threefold higher energy consumption of aircraft and the additional impact of flying at high altitudes, where non-$CO_2$ emissions, such as aviation-induced cloudiness (AIC) and nitrogen oxides ($NO_x$), amplify the environmental damage by six times compared to trains.

The precise multiplier may be less critical than acknowledging the substantial role of non-$CO_2$ effects, which are estimated to account for two-thirds of the environmental impact of a flight (Niklass, 2019). This is vividly illustrated in the lower portion of Figure 2.5. The first bar, representing contrail cirrus, underscores the significant impact of AIC, which contributes to more than half of the global aviation effective radiative forcing (ERF). The second most significant non-$CO_2$ contributor is nitrogen oxide emissions, which account for roughly one-sixth of the ERF. In comparison, $CO_2$ emissions represent only about one-third of the net aviation ERF. The estimates for radiative forcing (RF) are even more striking, with non-$CO_2$ emissions contributing three times the impact of $CO_2$ emissions.

It's also crucial to consider where emissions are released, as their radiative forcing (RF) is highly dependent on altitude, as shown in Figure 2.6. The total RF, depicted by the black line, is significantly lower when flying at lower altitudes. Emissions like contrails, nitrogen oxides, short-term ozone ($O_{3S}$), long-term ozone ($O_{3L}$), methane ($CH_4$), and water vapor ($H_2O$) all contribute less to temperature increases as altitude decreases. The only exception is carbon dioxide ($CO_2$), which has a lower RF at higher altitudes. This altitude-dependent effect is reflected in the forcing factors established by Schwartz (2009), which vary for each emission species and are used to calculate the characterization factors (CF) for $NO_x$ and AIC in (3.1), as detailed by Hurtecant (2021).

In summary, flying at an altitude of 6500 meters could reduce environmental impact by 70% with only a slight increase in fuel consumption (6 %), leading to just a 0.6 % rise in Direct Operating Cost (DOC). This reduction could be achieved even by aircraft designed for higher altitudes (Scholz 2020).

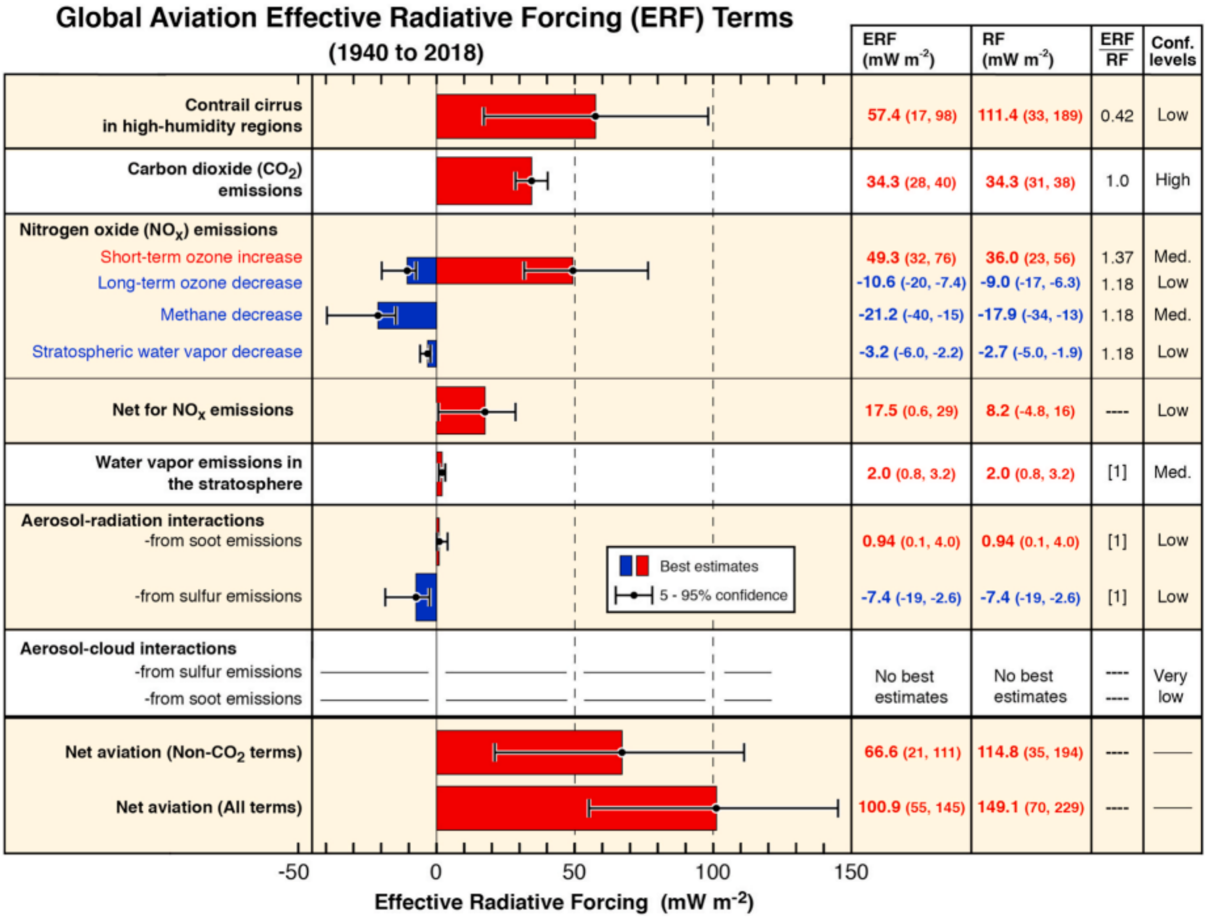


**Figure 2.5** Best-estimates for climate forcing terms from global aviation from 1940 to 2018 (Lee 2021)

Figure 2.7 illustrates the varying residence times of different pollutants. $CO_2$, located in the upper right-hand corner, remains in the atmosphere the longest, persisting for up to 100 years. In contrast, $NO_x$ have a much shorter atmospheric lifespan, lingering for only about a day. Water vapor is considered a moderately long-lived trace substance. Contrails are typically categorized into persistent and non-persistent types, with long-lived contrails defined by the World Meteorological Organization as cirrus homogenitus, persisting for at least 10 minutes (Kärcher 2018). Methane also has a relatively long residence time, lasting just under 10 years.

When flying at lower altitudes, these residence times must be carefully considered. A balance must be struck between reducing the environmental impact of short-lived species, like $NO_x$, and mitigating the long-term effects of pollutants such as $CO_2$. This approach aims to minimize the environmental burden passed on to future generations. Expressed differently:

*A new generation of planes, however, may be designed for minimum fuel consumption at other flight altitudes than today. Hence, a fundamental task for reaching optimal mitigation will be the reduction of the climate impact of short-lived species while keeping the counteracting effect of $CO_2$ at an absolute minimum. This could be achieved e.g. by including the mitigation aspect in the aircraft design process or by reducing speed (Frömming 2012).*

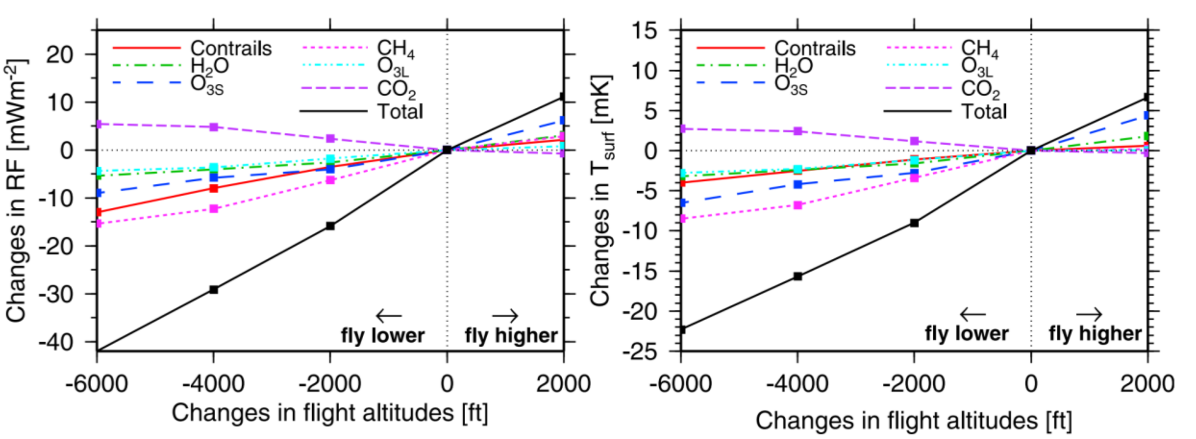


**Figure 2.6** Global annual mean changes of (left) net radiative forcing and (right) surface temperature in 2100 due to $CO_2$, contrails, H2O, O3S, CH4 and O3L for all flight altitude change scenarios relative to a base case flying at conventional flight altitude (Frömming 2012).

Mitigating environmental impact, particularly from non-$CO_2$ emissions, can be achieved not only by altering cruise altitudes but also by rerouting individual flight paths, as previously mentioned. Niklass (2019) explores how, in rare cases, flying through specific regions at certain times could even cool the atmosphere. To avoid emission-sensitive areas, he proposes a system of rewards and penalties to guide airline behavior. This concept is highlighted here to demonstrate the diverse strategies available for minimizing environmental impact and to emphasize the critical role of non-$CO_2$ emissions.

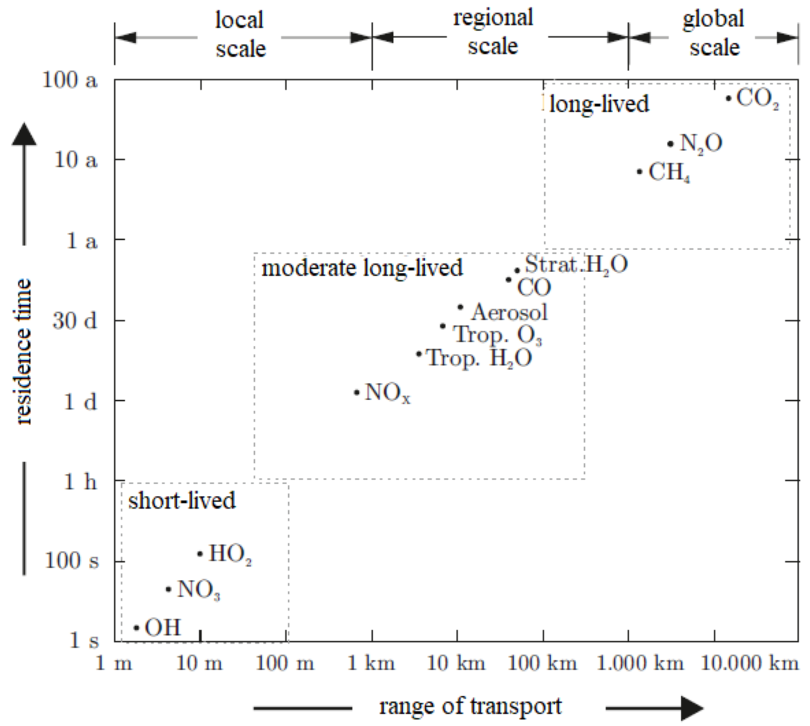


**Figure 2.7** Ranges of transport and residence time of climate-relevant trace substances in the atmosphere (following Brasseur 1999)

### 2.3.2 Calculation Methodology Refinement

**Emission Index for Nitrous Oxide**

A check of the ecolabel calculator revealed, that a simplified Emission Index (EI) for nitrous oxide $EI_{NO_x}$ was used in the following equation to determine the altitude-dependent equivalent $CO_2$ mass.

$$\begin{aligned} m_{CO_2,eq} = & \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NO_x} \\ & + \frac{R_{NM}}{R_{NM} \cdot n_{seat}} \cdot CF_{midpoint,AIC} \end{aligned} \tag{2.3}$$

The terms of (2.1), which were derived from Hurtecant (2021), are used to calculate the contribution of $CO_2$, $NO_x$ and AIC to the $CO_2$ equivalent emissions rating. It was found that just an average $EI_{NO_x}$ value for all engines of an aircraft type was used. It made no difference to the equivalent $CO_2$ emissions if an A320 was equipped with a different engine, because there was always used the mean value of all known possible A320 engines (according to the ICAO engine emissions databank). Exact $EI_{NO_x}$ values for each engine of an aircraft model are now applied resulting in different $NO_x$ emissions for each engine reflecting in different $CO_2$ equivalent emissions.

In the following cases of aircraft-engine combinations of some airlines there was no information available which specific engine is being used:

- Boeing 737 MAX 8/9 with a CFM International LEAP-1B engine
- Boeing 747-8 with a General Electric GEnx-2B67 engine
- Boeing 787-8/9/10 with either a General Electric GEnx-1B or a Rolls-Royce Trent 1000 engine
- COMAC C919 with a CFM International LEAP-1C engine
- Embraer E195-E2 with a Pratt & Whitney PW1900G engine

For those rare cases, a mean value engine was calculated from all available variants of the aircraft engine. There are e.g. the engines LEAP-1B27 and LEAP-1B28 commonly used for a Boeing 787 MAX 9. There emission index for $NO_x$ differ slightly. Therefore, the mean value of both engines was used to calculate $EI_{No_x}$.

A complete list of every possible aircraft-engine combination and its $CO_2$ equivalent emissions is given in Appendix D.

**Aircraft Size and Aviation Induced Cloudiness**

The metric combining the effects of the three most significant emission contributors - $CO_2$, $NO_x$, and AIC has been improved as well. The effects of AIC are influenced by the formation of contrail cirrus and persistent contrails, with their relative contribution to global warming measured by contrail radiative forcing (CRF). Schwartz's (2009) climate model calculates AIC effects based on altitude and contrail length, making CRF a function of these variables. This model underscores the importance of understanding altitude and flight distance in assessing the climate impact of aviation-induced cloudiness.

Jeßberger (2013) further explores the climate impact of contrails, factoring in contrail cover, optical depth, solar radiation, and various microphysical and atmospheric parameters. Despite the difficulty in separating aircraft and meteorological influences on contrail formation, Jeßberger's research finds that fuel consumption per unit flight path scales linearly with total extinction, which is determined by the contrail's optical depth and horizontal width. This relationship highlights the need for precise measurements and modeling to accurately assess contrail-induced climate effects.

The optical depth of a contrail is primarily dependent on particle effective diameter ($D_{eff}$), number densities ($n_{ice}$), and vertical extension. Jeßberger (2013) indicates that while the effective diameters of different aircraft are quite similar (5.2-5.9 µm), variations in particle number density (162-235 $cm^{-3}$ for particles larger than 0.93 µm) and vertical extension (120-190 m) result in significant differences in contrail optical depths (0.25-0.94). These findings highlight the substantial impact of aircraft-specific parameters on contrail formation and their subsequent climate effects, as summarized in Table 2.2.

**Table 2.2** Microphysical, macrophysical and optical contrail properties together with total extinction and fuel consumption per unit flight path from A319, A340 and A380 aircraft. (Jeßberger et al. 2013)

| Aircraft | $D_{eff}$ (µm) | $n_{ice}$ (cm$^{-3}$) | Vertical extension (m) | Optical depth τ | Contrail width (m) | Total extinction (extinction × contrail cross section) (m) | Fuel Consumption $f_{km}$ per flight distance (kg km$^{-1}$) |
|---|---|---|---|---|---|---|---|
| A319 | 5.2(±1.5) | 162±18 | 120 | 0.25 | 51 | 10 | 2.2 |
| A340 | 5.8(±1.7) | 164±0.11 | 220 | 0.55 | 90 | 39 | 6.4 |
| A380 | 5.9(±1.7) | 235±10 | 290 | 0.94 | 119 | 88 | 15.9 |

There are different aircraft influences beyond fuel consumption that are important as well. Higher fuel consumption correlates to higher emissions, with water vapor and soot being particularly decisive. Contrail analysis can be divided into primary and secondary wake phases. A clear separation between these phases can be observed in the contrail of a four-engine aircraft, with the secondary vortex becoming persistent in most cases. This separation has not been detected for two-engine aircraft. During the first wake phase, soot acts as an aerosol that gets activated at high relative humidity during contrail formation. Liquid droplets, including water vapor from the engine exhaust, form and then freeze into ice particles. Within a wing-span behind the aircraft or earlier (temperature dependent), ice nucleation occurs, creating two vortex structures that capture most of the exhaust material.

During a downward movement, part of this material escapes from the vortex pair, rises due to buoyancy, and mixes with exhaust that has not been captured by the vortex pair, forming a secondary wake regime. Soot and water vapor initiate the contrail-forming process, but many more exhaust materials contribute to contrail formation. Each engine produces a different chemical composition, resulting in varying CRF despite similar fuel consumption. Modeling these vortex structures with different particles under changing conditions is very difficult. Therefore, current scientific results should be seen as a qualitative indication of the importance of aircraft impacts on contrails.

This complexity underscores the task of an environmental label, which should be kept as simple as possible. It was therefore decided that the metric determining the equivalent $CO_2$ mass would be extended by the CRF as a function of fuel flow. A reference fuel flow ($f_{NM,ref}$) was determined to incorporate the influence of fuel consumption on AIC in the current metric, as shown in (2.4). This approach aims to provide a clearer understanding of the environmental impact of different aircraft and their emissions, facilitating better environmental labeling and decision-making.

$$\begin{aligned} m_{CO2,eq} = & \frac{EI_{CO_2} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{seat}} \cdot CF_{midpoint,NO_x} \\ & + \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{seat}} \cdot CF_{midpoint,AIC} \end{aligned} \tag{2.4}$$

The reference fuel $f_{NM,ref}$ was calculated via the reference group of aircraft and is weighted according to the frequency of the aircraft model indicated by the World Airliner Census 2020. This calculation can be comprehended in Appendix D. Altogether it is quite possible, that larger aircraft may have smaller climate impact per transport unit than a smaller aircraft. The differences between the climate impact resulting from the CRF per seat and kilometer of different aircraft are expected to be pretty small. But since the metric to determine the mass of equivalent $CO_2$ is composed of the sum of the impact of $CO_2$, $NO_x$ and AIC. These ratios among each other could vary quite a bit. This will be investigated in Chapter 2.8.

## 2.4 CO2 Equivalent Emission Rating Scale

The rating scale is determined via the reference group of aircraft again. Due to lack of data the following aircraft from the group of 87 reference aircraft could not be included: De Havilland Canada Dash 8 Q100, Q200, Q400, Dornier 228, Fokker 70 and Saab 340. The mass of equivalent $CO_2$ is determined with (3.20) using the calculated standard seating capacity $n_{calc}$ for all aircraft with (2.5).

$$\begin{aligned} m_{CO2,eq} = &\frac{EI_{CO_2} \cdot f_{NM}}{n_{calc}} \cdot CF_{midpoint,CO_2} + \frac{EI_{NO_x} \cdot f_{NM}}{n_{calc}} \cdot CF_{midpoint,NO_x} \\ &+ \frac{R_{NM} \cdot f_{NM}}{R_{NM} \cdot f_{NM,ref} \cdot n_{calc}} \cdot CF_{midpoint,AIC} \end{aligned} \tag{2.5}$$

The distribution of $m_{CO_2,eq}$ of aircraft within the reference group are shown in Figure 2.8. The equivalent $CO_2$ emission mass was then sorted from minimum to maximum and subsequently divided into seven classes (A to G). The resulting rating scale is presented in Table 2.3.

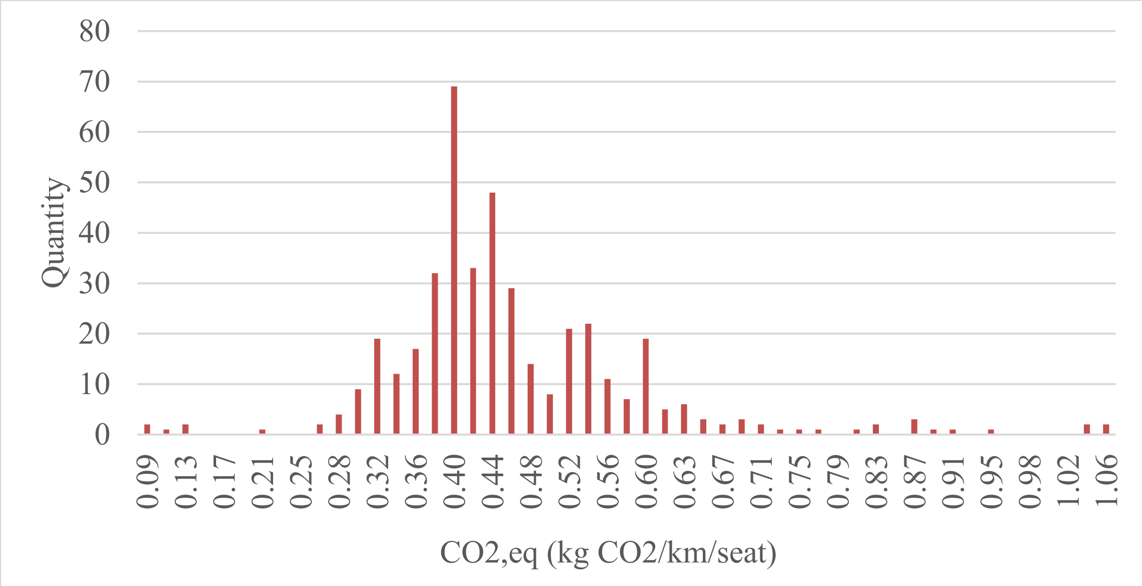


**Figure 2.8** Distribution of the normalized equivalent $CO_2$ emission (kg $CO_2$/km/seat)

**Table 2.3** Equivalent $CO_2$ emission rating scale (kg $CO_2$/km/seat)

| **Rating** | **Range** | | **Normalized 0-1** | |
|---|---|---|---|---|
| | min | max | min | max |
| **A** | 0.08940 | 0.37420 | 0 | 0.2927 |
| **B** | 0.37420 | 0.39766 | 0.2927 | 0.3168 |
| **C** | 0.39766 | 0.43016 | 0.3168 | 0.3502 |
| **D** | 0.43016 | 0.46023 | 0.3502 | 0.3811 |
| **E** | 0.46023 | 0.50362 | 0.3811 | 0.4257 |
| **F** | 0.50362 | 0.57959 | 0.4257 | 0.5037 |
| **G** | 0.57959 | 1.06250 | 0.5037 | 1.0000 |

## 2.5 Local Air Pollution

The air quality in the vicinity of an airport is affected by the following aviation-related emissions: nitrogen oxides ($NO_x$), hydrocarbons (HC), methane ($CH_4$), carbon monoxide (CO), sulfur oxides ($SO_x$) and particulate matter (PM) (FAA 2015). How dangerous each substance is to human health and how to develop a metric suited for the aircraft label is discussed in the next Chapter.

### 2.5.1 Effects on Air Quality

The metric used to assess Local Air Quality (LAQ) is based on the ReCiPe 2016 methodology (Huijbregts 2016). Any deviations, assumptions, or simplifications made in adapting this method will be thoroughly explained to ensure clarity. Given that the development of the environmental labels was a collaborative effort involving many students, these detailed explanations are essential for understanding the metric and facilitating future work in this area. However, for a more straightforward understanding of the LAQ metric, readers can refer directly to Chapter 2.5.3.

With the revision of the latest report and the work on the Ecolabel for Aircraft, it remains unclear whether the conversion from midpoint impact categories to endpoint areas of protection was previously addressed. According to the ReCiPe method, there are eight midpoint impact categories that can lead to damage to human health through different pathways, as illustrated in Figure 2.9. Among these, four categories are relevant to aviation: particulate matter, ozone formation, global warming, and water use. Notably, the categories of global warming and water use impact not only human health but also ecosystems, as indicated by the arrows pointing to different damage pathways.

Since LAQ focuses specifically on human health in the vicinity of airports, only the impact categories of fine particulate matter formation and photochemical ozone formation are considered. These categories are directly relevant to assessing the local air quality around airports, making them the most appropriate for this analysis.

The majority of aviation-related emissions occur during the cruise phase of flight. Therefore, it would be insufficient to assess the impact of global warming on human health by only considering the emissions from the Landing and Take-Off (LTO) cycle, as defined by ICAO Annex 16, Volume II (ICAO 2017b). To provide a comprehensive evaluation, it is essential to account for the equivalent $CO_2$ emissions generated throughout the entire flight, as outlined in Chapter 2.3.

Compared to the environmental impact calculations using the ReCiPe method, this approach incorporates a more sophisticated model that accounts for the significant altitude effects specific to aviation. These altitude effects play a crucial role in understanding the full environmental impact of aircraft emissions.

Another important aspect is the water usage associated with aviation, most of which is linked to kerosene production. Since kerosene production usually occurs far from airports, its impact is not directly felt in the vicinity of airports. However, given that the goal of this thesis is to develop an ecolabel for aircraft in accordance with ISO 14025 (2006) – "Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures" – the label must meet specific criteria. These criteria include providing "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]."

Johanning (2014) demonstrated in his life cycle assessment that the cruise phase of flight is responsible for the largest share of environmental impact, accounting for 70 %, with kerosene production contributing an additional 24 %. Given that an environmental label should be as straightforward as possible, the impacts of water usage and emissions from kerosene production are indirectly addressed through the calculation of fuel performance, as explained in Chapter 2.1.

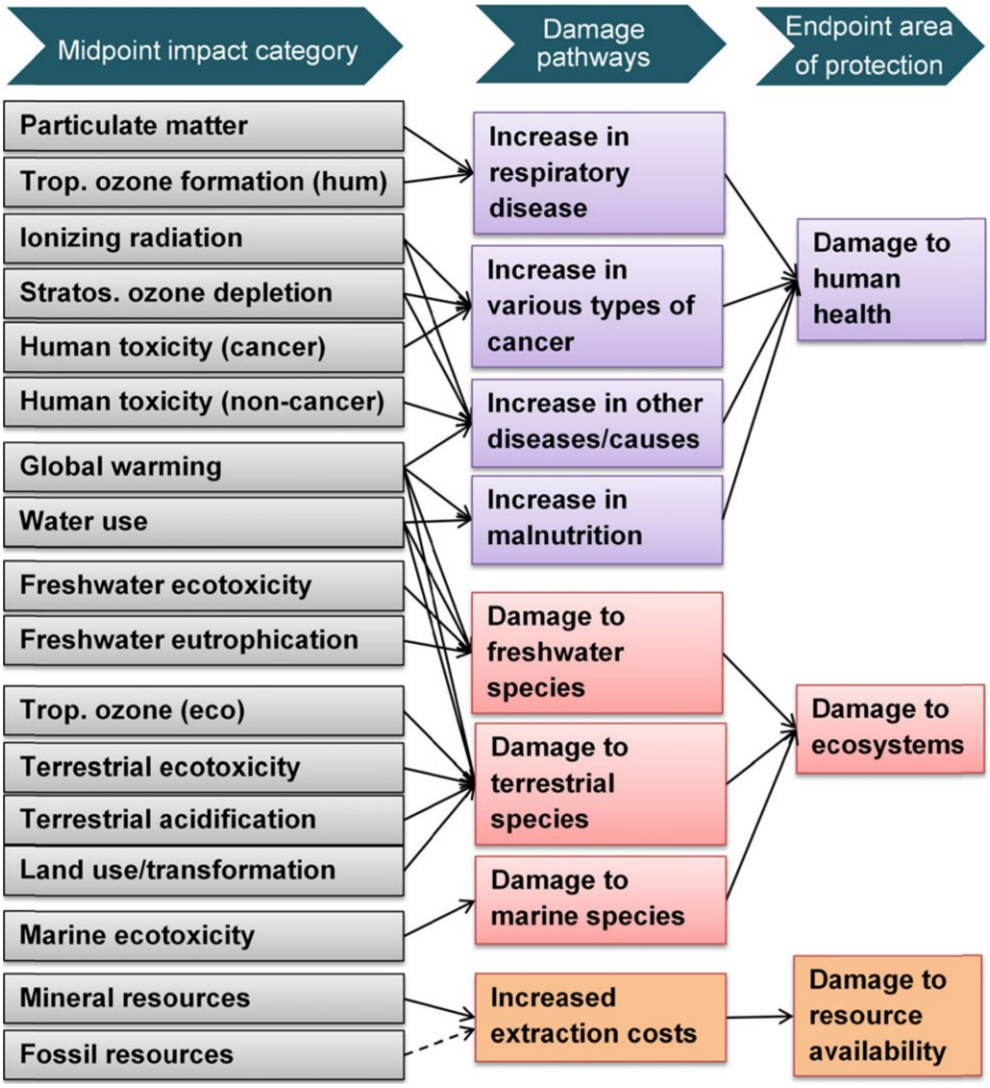


**Figure 2.9** Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection.

**Fine Particulate Matter Formation**

According to Zelm and Huijbregts (2016) an evaluation of the impact on human health is done by a conversion of the midpoint category *fine particulate matter formation* to the endpoint category *human health*. The severity of an impact on human health is measured by the loss of life years due to the caused disability. To get to the endpoint characterization factor $CFe_{x,c,a}$, the midpoint characterization factor $CFm_{x,c}$ is simply multiplied by a so-called midpoint to endpoint conversion factor $F_{M\rightarrow E,x,c,a}$.

$$CFe_{x,c,a} = CFm_{x,c} \cdot F_{M\rightarrow E,x,c,a} \tag{2.6}$$

One of the updates of the revised ReCiPe 2016 report (Huijbregts 2016) is the addition of world-region specific characterization factors. This cultural perspective is described by the index c in (2.6). Since the environmental labels described in this thesis are not region-specific, the world average factor is used. The index a denotes the area of protection (human health, terrestrial ecosystems, freshwater ecosystems, marine ecosystems or resource scarcity) and x denotes the stressor of concern – in the case of particulate matter formation those can be primary aerosols and secondary aerosols displayed in Table 2.4.

**Table 2.4** Value choices in modelling the effect of fine particulate matter derived from ReCiPe 2016

| Choice category | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|
| **Included effects** | Primary aerosols | Primary aerosols, secondary aerosols from $SO_2$, $NH_3$ and $NO_x$ | Primary aerosols, secondary aerosols from $SO_2$, $NH_3$ and $NO_x$ |

The displayed so-called value choices describe the perspectives used to group similar types of assumptions and choices according to the "cultural theory" by Thompson. Three perspectives were included in ReCiPe 2016:

1. *The individualistic perspective is based on the short-term interest, impact types that are undisputed, and technological optimism with regard to human adaptation.*
2. *The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms.*
3. *The egalitarian perspective is the most precautionary perspective, taking into account the longest time frame and all impact pathways for which data is available.*

It was decided, that the hierarchist perspective fits the description of the environmental label best, which will be used to determine the impact of particulate matter formation on human health. The midpoint to endpoint conversion factors for the Individualist (I), Hierarchist (H) and Egalitarian (E) perspectives are displayed in Table 2.5.

**Table 2.5** Midpoint to endpoint factors for the Individualist (I), Hierarchist (H) and Egalitarian (E) perspectives derived from Huijbregts (2016)

| Impacts on human health | Unit | I | H | E |
|---|---|---|---|---|
| Fine particulate matter formation | yr/kg PM2.5 to air | 6.3×10-4 | 6.3×10-4 | 6.3×10-4 |
| Photochemical ozone formation | y/kg $NO_x$ to air | 9.1×10-7 | 9.1×10-7 | 9.1×10-7 |

It can be seen, that the conversion factor for the hierarchist perpective (H) of fine particulate matter formation $F_{M\rightarrow E,PM2.5,world,human\ health} = 6.3\times10^{-4}$ is significantly greater than the conversion factor for photochemical ozone formation $F_{M\rightarrow E,HO3,world,human\ health} = 9.1\times10^{-7}$. The much higher conversion factor for fine particulate matter suggests, that a lot less pollutant is necessary to cause similar damage to human health (reduced life years due to disability). The pollutants relevant for particulate matter formation potential (PM2.5-eq/kg, PMFP) are shown in Table 2.6.

**Table 2.6** World average particulate matter formation potentials ($PM_{2.5}$-eq/kg) of emitted substance x, derived from Huijbregts (2016)

| Pollutant | Emmited substance | Individualist | Hierarchist | Egalitarian |
|---|---|---|---|---|
| $PM_{2.5}$ | $NH_3$ | - | 0.24 | 0.24 |
| | $NO_x$ | - | 0.11 | 0.11 |
| | $SO_2$ | - | 0.29 | 0.29 |
| | $PM_{2.5}$ | 1 | 1 | 1 |

The index $PM_{2.5}$ indicates, that only fine particulate matter with a diameter of less than 2.5 µm is considered in the metric, because WHO studies show that the mortality effects of chronic PM exposure are likely to be attributable to $PM_{2.5}$ rather than to coarser particles of PM (WHO 2006). For the chosen hierarchist perspective **secondary** $PM_{2.5}$ aerosols are important as well, as they are formed in air from emissions of sulfur dioxide ($SO_2$), ammonia ($NH_3$) and nitrogen oxides ($NO_x$). The midpoint factors of particulate matter formation $CFm_{x,c}$:

$$CFm_{x,c} = \frac{iF_{x,i}}{iF_{PM2.5,world}} \quad . \tag{2.7}$$

, whereas the intake fraction $iF$ of a substance in a region (e.g. in the vicinity of an airport) is put into relation to the world average intake fraction of $PM_{2.5}$ to account for the sum in change in intake rate of $PM_{2.5}$ in each receiving region $j$. For the purpose of this thesis it was decided to set $iF_{PM_{2.5},world}$ equal to 1. The assumption is made, that there is only fine particulate matter formation because of aviation in the vicinity of airports. The region-specific intake fraction $CFm_{x,c} = iF_{x,i}$:

$$iF_{x,i} = \frac{\sum_j dC_j \cdot N_j \cdot BR}{dM_{x,i}} \tag{2.8}$$

whereas $dC_j$ describes the change in concentration of $PM_{2.5}$ in each receptor region. $N_j$ stands for the affected population in the receptor region $i$ and $BR$ for the average breathing rate per person. The change in emission of a precursor substance in region $i$ is described by $dM_{x,i}$. Although it does make sense to calculate the intake fraction $iF_{x,i}$ with the number of people affected by the emission $N_j$ and their average breathing rate $BR$, those factors are excluded from the rating for the purpose of this thesis. In consequence, the informative value of the calculation of loss of life in years caused by disability is compromised.

The same simplifications are applicable with the calculation of the impact of *photochemical ozone formation* in the following Chapter. Therefore, a comparison between the impact on human health between those two categories is still given. The main goal of this thesis of comparing different aircraft operated by different airlines on various routes is not compromised by those simplifications. Instead of lost life years, an equivalent emission mass of fine particulate matter $m_{PM2.5,equivalent,LTO}$ is calculated. Because of the assumption, that there is only fine particulate matter formation because of aviation in the vicinity of airports, the equation further simplifies to:

$$iF_{x,i} \triangleq m_{PM2.5,equivalent,LTO} = \sum m_{x,LTO} \cdot PMFP_{x,i} \quad . \tag{2.9}$$

The mass of emission of a pollutant $x$ of an LTO cycle is described by $m_x$. The world average weighting factors of each pollutant $x$ listed in Table 2.6, are described by the particulate matter formation potential $PMFP_x$. Ammonia ($NH_3$) is also listed in this table, but is not emitted from the engine. Free ammonia, as it is referred to, is already in the air acting as a background concentration. Higher $NH_3$ is a critical condition to produce more aerosols, which are also determined by the local temperature and relative humidity. But the concentration of $NH_3$ is one of the most important key factor under similar meteorological conditions (Nowak 2010). Since the goal of this thesis is the comparison between different aircraft and this background concentration affects all aircraft, it does not have to be considered. The impact of particulate matter formation on human health is described at the ReCiPe 2016 method by the endpoint characterization factor $CFe_{x,c,a}$. Because of the changes made, this factor is exchanged by $PM_{equivalent,LTO}$.

$$CFe_{x,c,a} \triangleq PM_{equivalent,LTO} = m_{PM2.5,equivalent} \cdot F_{M\rightarrow E,x,c,a} \tag{2.10}$$

$$\begin{aligned} PM_{equivalent,LTO} &= (m_{PM2.5,LTO} \cdot PMFP_{PM2.5} + m_{NO_x,LTO} \cdot PMFP_{NO_x} + m_{SO_2,LTO} \\ &\quad \cdot PMFP_{SO_2}) \cdot F_{M\rightarrow E,PM2.5,world,human\ health} \end{aligned} \tag{2.11}$$

$$\begin{aligned} PM_{equivalent,LTO} &= \left(m_{PM2.5,LTO} \cdot 1 + m_{NO_x,LTO} \cdot 0.11 + m_{SO_2,LTO} \cdot 0.29\right) \\ &\quad \cdot F_{M\rightarrow E,PM2.5,world,human\ health} \end{aligned} \tag{2.12}$$

The mass of emission of an LTO cycle of particulate matter with a diameter smaller than 2.5 µm $m_{PM2.5,LTO}$ is extracted from the ICAO Database. In the same way the mass of emission of an LTO cycle of nitrous oxide $m_{NO_x,LTO}$ is gathered. In the database particulate matter is indicated as non-volatile Particulate Matter (nvPM) with an extremely small geometric mean diameter which ranges roughly from 15 nm to 60 nm (0.06 Microns) (ICAO 2016). This is also much smaller than the 2.5 µm required by ReCiPe. Figure 2.10 shows the size of different particles. To put this into perspective, e.g. the cross section of a humain hair is up to 15000 times bigger than those nvPM exhaust particles.

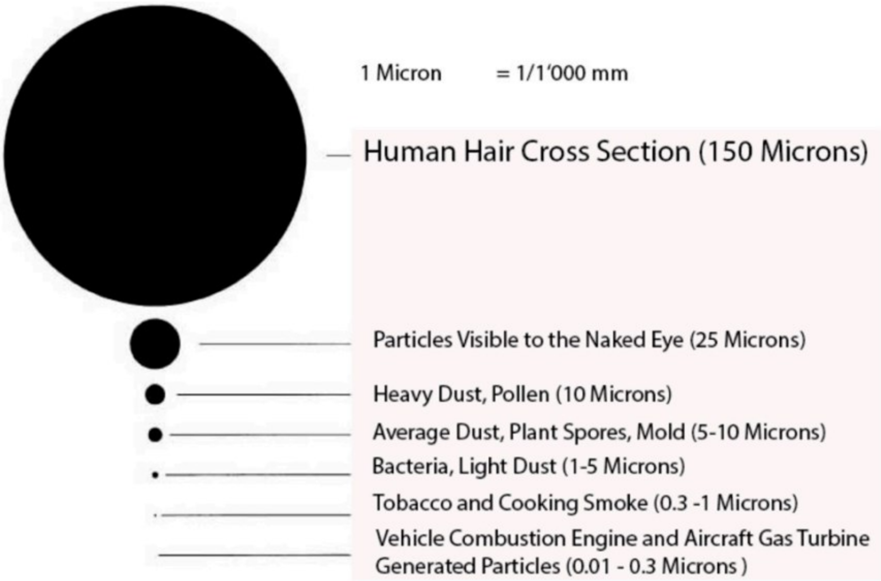


**Figure 2.10** Comparison of particle sizes from different sources (ICAO 2016)

The mass of sulfur dioxide ($SO_2$) is calculated via an Emission Index (EI) derived from Lee (2010), see Table 2.7 and (2.13). The mass of fuel used at an LTO cycle is extracted from the ICAO Database again.

$$m_{SO_2,LTO} = m_{fuel,LTO} \cdot EI_{SO_2} \tag{2.13}$$

**Table 2.7** Fuel consumption and emitted kerosene, mean emission indices (mass of emissions per unit mass of burned fuel, for the fleet of aircraft in 2000) derived from Lee (2010)

| Kerosene | Emission index, g $kg^{-1}$ (ranges) |
|---|---|
| $CO_2$ | 3160 |
| $H_2O$ | 1240 |
| $NO_x$ | 14 (12-17) |
| $SO_2$ | 0.025 (0.01-0.05) |
| CO | 0.8 (0.6-1.0) |
| HC | 0.4 (0.1-0.6) |

**Photochemical Ozone Formation**

The impact of photochemical ozone formation on human health is calculated in a similar way by the ReCiPe 2016 like it was done in the previous Chapter for particulate matter formation. The most relevant pollutant is nitrous oxide ($NO_x$) followed by non-methane volatile organic compounds (NMVOCs). Their world average human health ozone formation potentials (HOFPs in NOx-eq/kg) are displayed in Table 2.8.

**Table 2.8** World average human health ozone formation potentials (NOx-eq/kg) of emitted substance x derived from ReCiPe (2016)

| **Pollutant** | **Emitted Substance** | **Individualist** | **Hierarchist** | **Egalitarian** |
|---|---|---|---|---|
| Ozone | $NO_x$ | 1 | 1 | 1 |
| | NMVOC | 0.18 | 0.18 | 0.18 |

First, there has to be calculated the midpoint factors $CFm_{x,c}$, which can be adopted from (2.9):

$$m_{NO_x,equivalent,LTO} = \sum m_{x,LTO} \cdot HOFP_{x,i} \quad . \tag{2.14}$$

To get the impact on human health caused by photochemical ozone formation, the calculation of an endpoint factor $CFe_{x,c,a}$ via a conversion factor $F_{M\rightarrow E,x,c,a}$ is needed. Analog to (2.10), (2.11) and (2.12):

$$CFe_{x,c,a} \triangleq NO_{x_{equivalent,LTO}} = m_{NO_x,equivalent} \cdot F_{M\rightarrow E,x,c,a} \tag{2.15}$$

$$NO_{x_{equivalent,LTO}} = (m_{NO_x,LTO} \cdot HOFP_{NO_x} + m_{NMVOC,LTO} \cdot HOFP_{NMVOC}) \cdot F_{M\rightarrow E,ozone,world,human\ health} \tag{2.16}$$

$$NO_{x_{equivalent,LTO}} = \left(m_{NO_x,LTO} \cdot 1 + m_{SO_2,LTO} \cdot 0.081 + m_{CO,LTO} \cdot 0.046 + m_{HC,LTO} \cdot 0.467\right) \cdot F_{M\rightarrow E,ozone,world,human\ health} \tag{2.17}$$

The characterization factors of the individual NMVOCs sulfur dioxide ($SO_2$), carbon monoxide (CO) and hydrocarbons (HC) are shown in Table 2.9. The mass of emissions of an LTO cycle of $NO_x$, $SO_2$, CO and HC are extracted from the ICAO Database again.

**Table 2.9** Characterization factors ReCiPe (Goedkoop 2013)

| **Midpoint category** | **$NO_x$** | **$SO_2$** | **PM** | **CO** | **HC** |
|---|---|---|---|---|---|
| Photochemical oxidant formation (ozone) | 1 | 0.081 | - | 0.046 | 0.467 |
| Particulate matter formation | 0.22 | 0.2 | 1 | - | - |

### 2.5.2 Local Air Pollution of Different Aircraft

To illustrate the metric explained in the previous chapters the local air pollution of an Airbus A320 equipped with an CFM56-5B4/3 engine is calculated. CFM Internationals CFM56 series of engines is the bestselling civil engine family up to this date (Ebner 2017). Some engines are using a so-called Phase 5 (RQL — rich/quench/lean) combustor technology, which goal it is to reduce nitrous oxide emissions. But this technology has its downsides as well.

> *While RQL designs have helped to drastically reduce Nitrous oxide emissions, they tend to be prone to nvPM formation due to the especially rich combustion found in their primary zones.*
> *(Harper 2022)*

Since the CFM56-5B4/3 engine does not use this technology, it would be interesting to compare it to an engine which uses RQL like an International Aero Engine (IAE) V2527-A5. Both engines have similar thrust values: 120.1 kN (CFM56-5B4/3) and 110.3 kN (V2527-A5).
Teoh (2022) made an important observation when looking at the influence of nvPM emissions (non-volatile particulate matter, i.e. soot):

> *In particular, while one specific very large wide-body aircraft is only used in 2.4 % of all flights, it accounted for 18.0 % (6.4 %) of flights with strongly warming (cooling) contrails. Comparing the effects of different aircraft types shows that 43.4 % (17.4 %) of flights with strongly warming (cooling) contrails are powered by one engine combustor type, the "phase 5 rich–quench–lean combustor" (Rolls-Royce), which has one of the highest nvPMEIn.*

Therefore, it was intended to include two common engines for large wide-body aircraft – one engine using the Phase 5 (RQL) combustor technology and one that does not. Unfortunately, a short review of the engines included in the ICAO engine emissions databank was not successful in finding an engine of a large wide-body aircraft, which does not use the Phase 5 (RQL) combustor technology or an adaption of it. A Rolls-Royce Trent 1000-J3 with a thrust of 350.9 kN and RQL combustor technology therefore was only used as a comparison to the engines of the narrow-body aircraft. To determine the impact of fine particulate matter on human health (2.18) and (2.19) are used.

$$PM_{equivalent,LTO} = \left(m_{PM2.5,LTO} \cdot 1 + m_{NO_x,LTO} \cdot 0.11 + m_{SO_2,LTO} \cdot 0.29\right) \cdot F_{M\rightarrow E,PM2.5,world,human\ health} \tag{2.18}$$

To calculate the mass of sulfur dioxide $m_{SO_2,LTO}$ the corresponding Emission Index $EI_{SO_2} = 0.8$ g/kg and the mass of burnt fuel from the ICAO engine emissions databank are used:

$$m_{SO_2,LTO} = m_{fuel,LTO} \cdot EI_{SO_2} = 407\ kg \cdot 0.8\ \frac{g}{kg} = 325.6\ g \quad . \tag{2.19}$$

The masses of all relevant pollutants (aerosols in this case) are shown in Table 2.10. Therefore, the mass of equivalent fine particulate matter $PM_{equivalent,LTO}$ is calculated as follows:

$$\begin{aligned} PM_{equivalent,LTO} &= (8.304\ g \cdot 1 + 4511\ g \cdot 0.11 + 325.6 \cdot 0.29) \cdot 6.3 \cdot 10^{-4} \\ &= 0.377\ g\ \approx 0.38\ g\ \ . \end{aligned} \tag{2.20}$$

This value describes the impact of fine particular matter formation on human health, because of the multiplication of the equivalent masses ($m_{eqPM,PM2.5,LTO}$, $m_{eqPM,NO_x,LTO}$, $m_{eqPM,SO_2,LTO}$) with the conversion factor $F_{M\rightarrow E,PM2.5,world,human\ health}$. Alternatively, solely the impact of fine particulate matter formation could be calculated as well – considering just the mass of fine particulate matter and the conversion factor.

$$PM_{LTO} = 8.304\ g \cdot 6.3 \cdot 10^{-4} = \ 5.23 \cdot 10^{-3}\ g\ \ \approx 0.01\ g\ \ . \tag{2.21}$$

**Table 2.10** Masses of primary and secondary aerosols contributing to fine particulate matter formation for an LTO cycle

| **Particulate matter formation category** | **Mass of aerosol / particulate matter CFM56-5B4/3 (g)** | **Mass of aerosol / particulate matter V2527-A5 (g)** | **Mass of aerosol / particulate matter Trent 1000-J3 (g)** |
|---|---|---|---|
| $m_{PM2.5,LTO}$ | 8.3 | 82.53 | 45.77 |
| $m_{NO_x,LTO}$ | 4511 | 5102 | 23599 |
| $m_{SO_2,LTO}$ | 325.6 | 357.6 | 792.8 |
| | | | |
| $m_{eqPM,PM2.5,LTO}$ | 8.3 | 82.53 | 45.77 |
| $m_{eqPM,NO_x,LTO}$ | 496.21 | 561.22 | 2595.89 |
| $m_{eqPM,SO_2,LTO}$ | 94.4 | 103.7 | 229.91 |
| | | | |
| $PM_{LTO}$ | 0.01 | 0.05 | 0.03 |
| $PM_{NO_x,LTO}$ | 0.31 | 0.35 | 1.64 |
| $PM_{SO_2,LTO}$ | 0.06 | 0.07 | 0.14 |
| **$PM_{equivalent,LTO}$** | 0.38 | 0.47 | 1.81 |

The impact of photochemical ozone formation on human health is calculated in a similar way using (2.22) and Table 2.11.

**Table 2.11** Masses of pollutants and photochemical ozone formation ($NO_{x,equivalent,LTO}$)

| **Mass of Pollutant / Nitrous Oxide** | **Mass of Pollutant / Nitrous Oxide CFM56-5B4/3 (g)** | **Mass of Pollutant / Nitrous Oxide V2527-A5 (g)** | **Mass of Pollutant / Nitrous Oxide Trent 1000-J3 (g)** |
|---|---|---|---|
| $m_{NO_x,LTO}$ | 4511 | 5102 | 23599 |
| $m_{SO_2,LTO}$ | 325.6 | 357.6 | 792.8 |
| $m_{CO,LTO}$ | 5386 | 2741 | 2585 |
| $m_{HC,LTO}$ | 314 | 39 | 0 |
| $m_{eqNO_x,NO_x,LTO}$ | 4511 | 5102 | 23599 |
| $m_{eqNO_x,SO_2,LTO}$ | 26.37 | 28.97 | 64.22 |
| $m_{eqNO_x,CO,LTO}$ | 247.76 | 126.1 | 118.91 |
| $m_{eqNO_x,HC,LTO}$ | 149.46 | 18.56 | 0 |
| $NO_{x,LTO}$ | $4.11 \times 10^{-3}$ | $4.64 \times 10^{-3}$ | $2.15 \times 10^{-2}$ |
| $NO_{x,SO_2,LTO}$ | $2.4 \times 10^{-5}$ | $2.64 \times 10^{-5}$ | $5.84 \times 10^{-5}$ |
| $NO_{x,CO,LTO}$ | $2.25 \times 10^{-4}$ | $1.15 \times 10^{-4}$ | $1.1 \times 10^{-4}$ |
| $NO_{x,HC,LTO}$ | $1.4 \times 10^{-4}$ | $1.7 \times 10^{-5}$ | 0 |
| $\boldsymbol{NO_{x,equivalent,LTO}}$ | $4.5 \times 10^{-3}$ | $4.8 \times 10^{-3}$ | $2.16 \times 10^{-2}$ |

$$NO_{x_{equivalent,LTO}} = (m_{NO_x,LTO} \cdot 1 + m_{SO_2,LTO} \cdot 0.081 + m_{CO,LTO} \cdot 0.046 + m_{HC,LTO} \cdot 0.476) \cdot F_{M\rightarrow E,ozone,world,human\ health} \tag{2.22}$$

$$NO_{x_{equivalent,LTO}} = (4511\ g + 325.6\ g \cdot 0.081 + 5386\ g \cdot 0.046 + 314\ g \cdot 0.476) \cdot 9.1 \cdot 10^{-7} = \ 0.000494\ g\ \triangleq 4.94 \cdot 10^{-4}\ g \tag{2.23}$$

Alternatively, just the ozone formation caused by Nitrous oxide ($NO_x$) could be used as well.

$$NO_{x,LTO} = (m_{NO_x,LTO} \cdot 1) \cdot F_{M\rightarrow E,ozone,world,human\ health} \tag{2.24}$$

$$NO_{x,LTO} = (4511\ g) \cdot 9.1 \cdot 10^{-7} = \ 0.0004511\ g\ \triangleq 4.51 \cdot 10^{-4}\ g \tag{2.25}$$

It has to be said, that newer engines using RQL could have lower particulate matter formation like the PW1127G-JM from Pratt & Whitney with a comparable thrust to the CFM56-5B4/3 with a 120.4 kN and a lower mass of particulate matter $m_{PM2.5,LTO} = 6.464\ g$.

For better comparison between different engines, the emission value is normalized with the engines maximum rated thrust at mean sea level (MSL) in kN, which is derived from the ICAO engine emissions databank again.

$$\left(PM_{equivalent,LTO}\right)_{normalized} = \frac{\left(m_{PM2.5,LTO} + m_{NO_x,LTO} \cdot 0.11 + m_{SO_2,LTO} \cdot 0.29\right) \cdot F_{M\to E,PM2.5}}{Rated\ thrust} \tag{2.26}$$

$$\left(NO_{x\,equivalent,LTO}\right)_{normalized} = \frac{(m_{NO_x,LTO} + m_{SO_2,LTO} \cdot 0.081 + m_{CO,LTO} \cdot 0.046 + m_{HC,LTO} \cdot 0.476) \cdot F_{M\to E,HO3}}{Rated\ thrust} \tag{2.27}$$

The impact of particulate matter formation on human health is much more significant than any damage from photochemical ozone formation as can be seen in Figure 2.11. This can be attributed to the fact that the conversion factor of fine particulate matter formation $F_{M\to E,PM2.5,world,human\ health} = 6.3\times10^{-4}$ is significantly greater than the conversion factor for photochemical ozone formation $F_{M\to E,O_3,world,human\ health} = 9.1\times10^{-7}$.

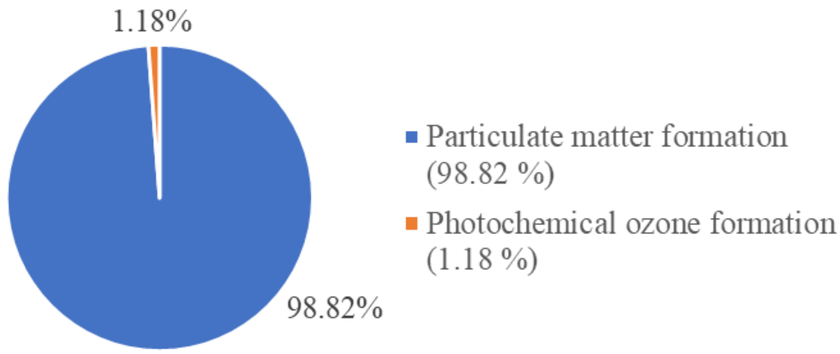


**Figure 2.11** Impact of particulate matter and ozone formation on human health of a CFM56-5B4/3

Three kinds of emissions contribute to health damage due to particulate matter formation, which can be classified as primary and secondary aerosols.

> *Aerosols injected into the atmosphere directly are known as 'primary aerosols'. Sea spray, mineral dust, smoke, and volcanic ash are all primary aerosols. Secondary aerosols are aerosols which were emitted in another form (e.g. gases), then become aerosol particles after going through chemical reactions in the atmosphere, such as sulfate aerosols from volcanoes or industrial emissions (Chen 2015).*

Anthropogenic particulate matter $PM_{2.5}$ is acting as a primary aerosol, nitrous oxide and sulfur dioxide as secondary aerosols. Their damage to human health is displayed in Figure 2.12. The main contributor is not the primary aerosol itself with only a small share of 1.59 %, but rather secondary aerosols formed because of nitrous oxide (90.4 %) and sulfur dioxide (8.01 %). Nitrous oxide has by far the largest share because their emissions are up to 2-3 orders of magnitudes higher compared to $PM_{2.5}$ and one order of magnitude compared to sulfur dioxide. Although just around 10 percent of those emissions are relevant for particulate matter formation (see $PMFP_{NO_x}$ *at (3.7))*, it is enough to be the most important emission in particulate matter formation.

Health damage due to ozone in the atmosphere caused by aviation can be attributed to the four kinds of emissions displayed in Figure 2.13. The combined emissions of sulfur dioxide (0.53 %), carbon monoxide (5.02 %) and hydrocarbons (3.03 %) are not even resulting in a 10 percent share. The emissions of the other engines are even lower (see Appendix C). By far the biggest share is represented by nitrous oxide emissions again.

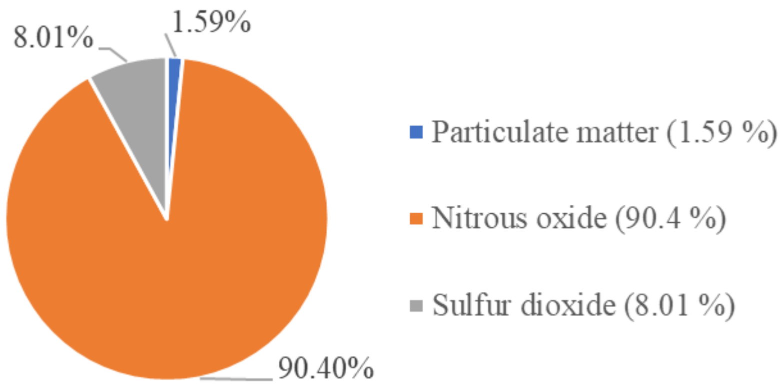


**Figure 2.12** Contribution of aerosols to the impact of particulate matter formation on human health of a Trent 1000-J3

The diagrams and tables of the other engines are shown in Appendix C. Especially the differences of a comparison between the impact of particulate matter and ozone formation (Figure 2.11) of different engines is very small. In any case by far the most important contributor are nitrous oxide emissions. Even the engine with one of the highest $PM_{2.5}$ emissions (V2527-A5) in the entire ICAO engine emissions database cannot change that. Nitrous oxide emissions are still accounting for 75 % of the health impact flying with the V2527-A5.

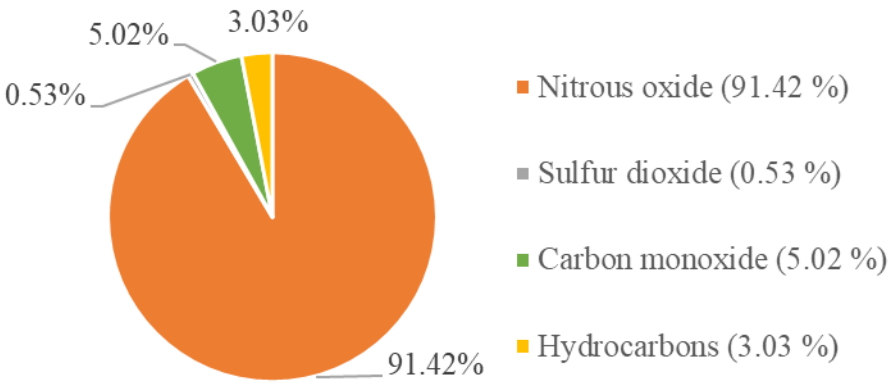


**Figure 2.13** Contribution of pollutants to the impact of ozone formation on human health of a CFM56-5B4/3

The distribution of emissions showed in Figure 2.11, Figure 2.12, Figure 2.13 are just representing a fraction of engines in the database. But an examination of the database showed, that there are no engines in the database that would change the outcome drastically. Since the goal of an environmental label is to provide a single source of easily accessible, easy-to-understand data – it was decided to base the local air pollution rating solely on the emission of nitrous oxide.

### 2.5.3 Local Air Pollution Rating

Since aircraft are responsible for the air quality in the vicinity of an airport, the emissions of a landing and take-off (LTO) cycle are considered. The LTO cycle is defined by ICAO (2020) and consists of four phases of aircraft operations: approach, taxi, takeoff, and climb.

The ICAO Aircraft Engine Emissions Databank (AEED) provides the amount of emitted $NO_x$ during the LTO cycle for a specific engine measured by the manufacturers according to the procedures in ICAO Annex 16, Volume II.

To allow for comparisons between different aircraft and engine types, the amount of emitted $NO_x$ is divided by the maximum rated thrust of the engine at sea level.

$$Normalized\ amount\ of\ emitted\ NO_x = \frac{(NO_x)_{LTO}}{Rated\ thrust} \tag{2.28}$$

A rating scale has to be established again to distribute the best and worst engines equally into classes from A to G. The results of the calculation of the normalized amount of emitted $NO_x$ for every engine is shown in Figure 2.14. There are 787 engines and their emission data in the ICAO aircraft engine emissions databank. Dividing those aircraft number by seven classes distributes roughly 112 aircraft into each category. The resulting Local Air Pollution rating scale is given in Table 2.12.

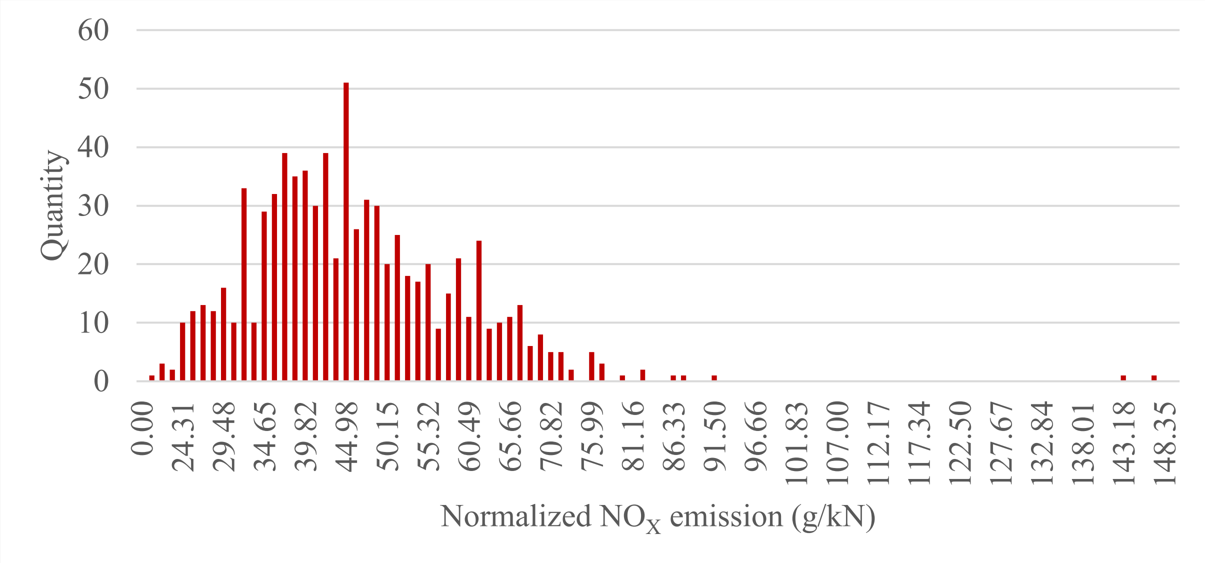


**Figure 2.14** Normalized emitted $NO_x$ for the LTO cycle (g $NO_x$/kN thrust)

**Table 2.12** Local Air Pollution rating scale (g $NO_x$/kN thrust)

| Range | Range | | Normalized 0-1 | |
|---|---|---|---|---|
| | min | max | min | max |
| **A** | 20.4348 | 33.2583 | 0 | 0.0662 |
| **B** | 33.2583 | 38.7102 | 0.0662 | 0.0943 |
| **C** | 38.7102 | 43.0263 | 0.0943 | 0.1166 |
| **D** | 43.0263 | 46.9653 | 0.1166 | 0.1369 |
| **E** | 46.9653 | 52.5600 | 0.1369 | 0.1658 |
| **F** | 52.5600 | 61.2618 | 0.1658 | 0.2107 |
| **G** | 61.2618 | 214.239 | 0.2107 | 1.0000 |

## 2.6 Local Noise Level

The metric to determine the local noise level was adopted from Hurtecant (2021). Noise pollution is relevant especially in the vicinity of an airport. Therefore, the noise level of aircraft is measured at the reference points of an LTO cycle: lateral, flyover and approach. The noise measurement values are obtained from EASA´s type certificate data sheet for noise (TCDSN) database. The noise emissions are calculated via the average of the measurements of these reference points. Because larger and heavier aircraft require more engine power resulting in more noise, they are allowed a higher noise limit. This noise level is determined according to ICAO Annex 16, Volume I (ICAO 2017a). The normalized noise level is called the Noise Index Value (NIV). The effective perceived noise level (EPNL) is expressed in units of effective perceived noise in decibels (EPNdB) and is calculated via (2.29) – (2.32).

$$NIV_{lateral} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{lateral}} \tag{2.29}$$

$$NIV_{flyover} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{flyover}} \tag{2.30}$$

$$NIV_{approach} = \left(\frac{Noise\ level}{Noise\ limit}\right)_{\text{approach}} \tag{2.31}$$

$$NIV_{average} = \frac{NIV_{lateral} + NIV_{flyover} + NIV_{approach}}{3} \tag{2.32}$$

## 2.7 Local Noise Level Rating Scale

The distribution of the noise index values for jet aircraft and turboprop aircraft as well as the local noise level rating scale is given in Figure 2.15 and Table 2.13.

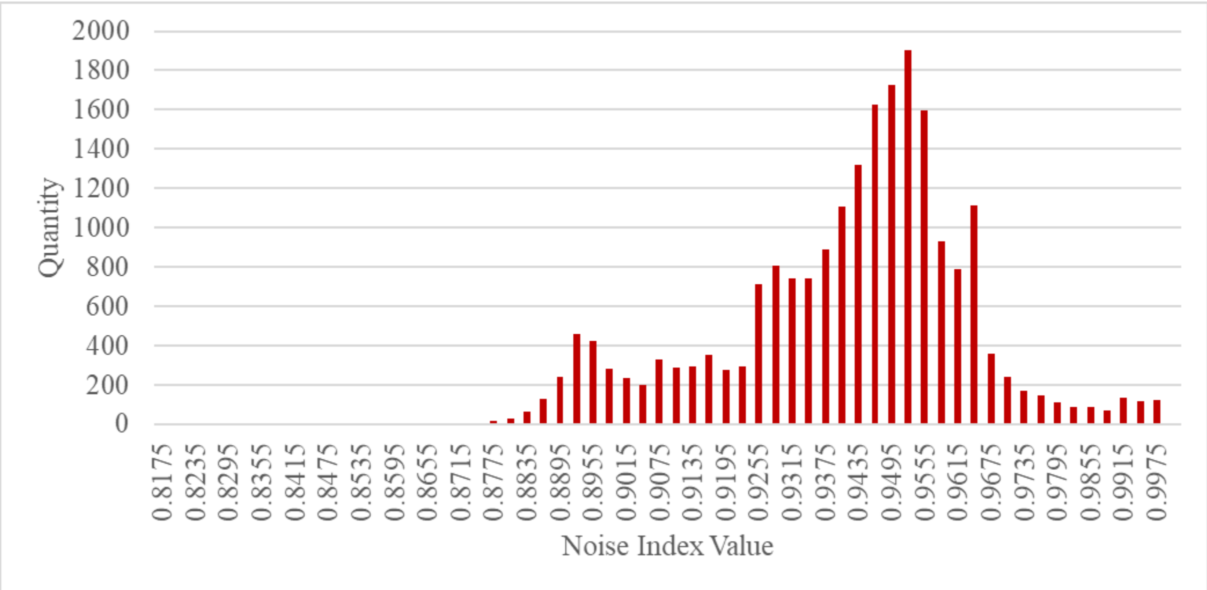


**Figure 2.15** Distribution of the noise index values for jet aircraft and turboprop aircraft (EPNdB/EPNdB)

**Table 2.13** Local Noise Level rating scale (EPNdB/EPNdB)

| Rating | Range | | Overall Rating | |
|---|---|---|---|---|
| | min | max | min | max |
| **A** | 0.8175 | 0.9171 | 0 | 0.1089 |
| **B** | 0.9171 | 0.9344 | 0.1089 | 0.1278 |
| **C** | 0.9344 | 0.9442 | 0.1278 | 0.1385 |
| **D** | 0.9442 | 0.9503 | 0.1385 | 0.1452 |
| **E** | 0.9503 | 0.9554 | 0.1452 | 0.1508 |
| **F** | 0.9554 | 0.9633 | 0.1508 | 0.1594 |
| **G** | 0.9633 | 1.0004 | 0.1594 | 0.2000 |

## 2.8 Contributions to Equivalent Carbon Dioxide Emissions

A comparison of contributions to equivalent $CO_2$ emissions of different aircraft is shown in Figure 2.19. It can be seen that there is no significant difference in the distribution of contributing factors of $CO_2$ equivalent emissions between an Airbus A320 and a Boeing 737 and their different engine options. The contributions of $CO_2$ equivalent emissions of an A318/A319/A220 are also very similar in distribution and total amount of emissions, which is why they are not included in Figure 2.19. A different engine often does not result in a change in distribution but can influence the total amount of emissions. All engine options of the aircraft displayed in Figure 2.19 were checked for a significant difference in environmental burden. If there was no meaningful difference, a distinction was not made.

The Boeing 737 MAX produces almost three times the amount of $NO_x$ emissions compared to the Airbus A320 Neo, which explains why airlines operating these aircraft are not found in the top places of the airline ranking (see Chapter 4.3). The Airbus A320 with the V2533-A5 engine also produces almost twice the $NO_x$ emissions than the CFM56-5B5/3 (see Chapter 2.5.2). If aircraft of comparable size performed very similarly, a comparison between different manufacturers was not included.

Similar aircraft in size that performed very differently include the Airbus A340-600 (MTOW: 365 t, thrust of one engine: 261.5 kN) and the Boeing 777-300ER (MTOW: 351.5 t, thrust of one engine: 513.9 kN). The Airbus produces almost twice the total amount of $CO_2$ equivalent emissions due to more than twice the $NO_x$ emissions. It seems that aircraft with two more powerful engines are more efficient than those with four less powerful ones. This likely explains why modern long-haul aircraft like the Airbus A350 and the Boeing 787 are equipped with two engines. Both aircraft perform very similarly with their different engine options, although the Rolls-Royce Trent 1000 variants seem to produce more $NO_x$ than the GEnx-1B equivalents.

The worst-performing aircraft is the Airbus A380-800 equipped with a GP7270, though only Korean Air and Qatar Airways use this engine. The other airlines flying with the Rolls-Royce Trent 970-84 perform a lot better. Surprisingly, the much older Boeing 747-8 burdens the environment less than an Airbus A380, even with the better engine Trent 970-84. However, it must be kept in mind that the Boeing 747-8 is approximately 125 t (MTOW) lighter. The aircraft with the least environmental burden is the ATR 72, which produces almost no AIC due to its low cruise altitude. Nitrous oxide emissions can also shorten the lifespan of methane, likely causing a cooling effect from the $NO_x$ emissions of the ATR 72 (Atmosfair 2021).

A comparison of contributions to equivalent $CO_2$ emissions of different aircraft are shown in Figure 2.19. It can be seen, that there is no big difference in the distribution of contributing factors of $CO_2$ equivalent emissions between an Airbus A320 and a Boeing 737 and their different engine options. The typical distribution of factors contributing to $CO_2$ equivalent emissions is shown in Figure 2.16. Aircraft with more powerful engines and especially aircraft with four engines do seem to emit more nitrous oxides like it is shown in Figure 2.17. Aircraft with turboprop engines do cause the least environmental burden with some parts ($NO_x$) even cooling the atmosphere (see Figure 2.18).

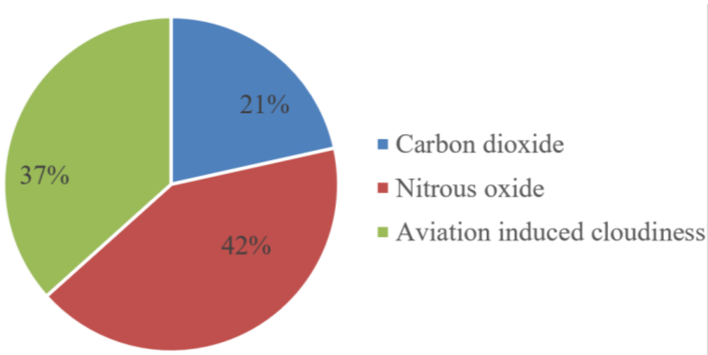


**Figure 2.16** Contribution to equivalent $CO_2$ emissions of an Airbus A320 with a CFM56-5B4/P engine

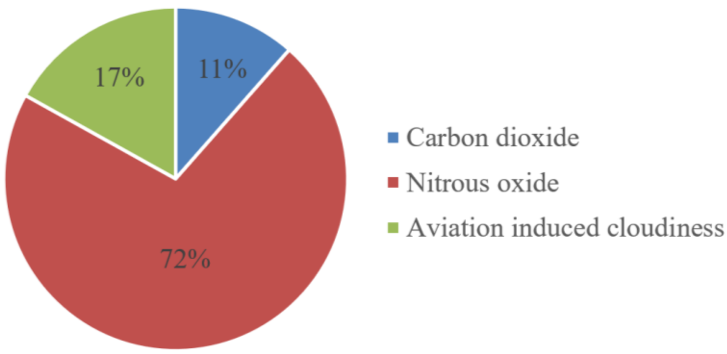


**Figure 2.17** Contribution to equivalent $CO_2$ emissions of an Airbus A380-800 with a GP7270 engine

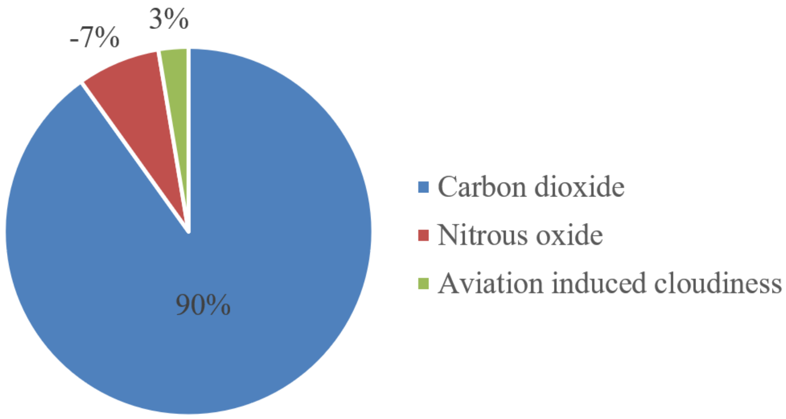


**Figure 2.18** Contribution to equivalent $CO_2$ emissions of an ATR 72 with a PW127 engine

It can be concluded, that the contributions to $CO_2$ equivalent emissions are highly dependent on the aircraft-engine-combination. There are quite big variations even between comparable aircraft in size and thrust like it can be seen with a comparison between an Airbus A340 and a Boeing 777-300ER. The Airbus does produce more than twice the $NO_x$ emissions than the Boeing. This results in different ratios of $CO_2$ to non-$CO_2$ emissions. In Chapter 5 it will be seen, that most available flight emissions calculator like Atmosfair account for non-$CO_2$ emissions with a constant factor of two or three. In order to determine the $CO_2$ equivalent emissions even more precisely, this factor should be dependent on the specific aircraft-engine combination.

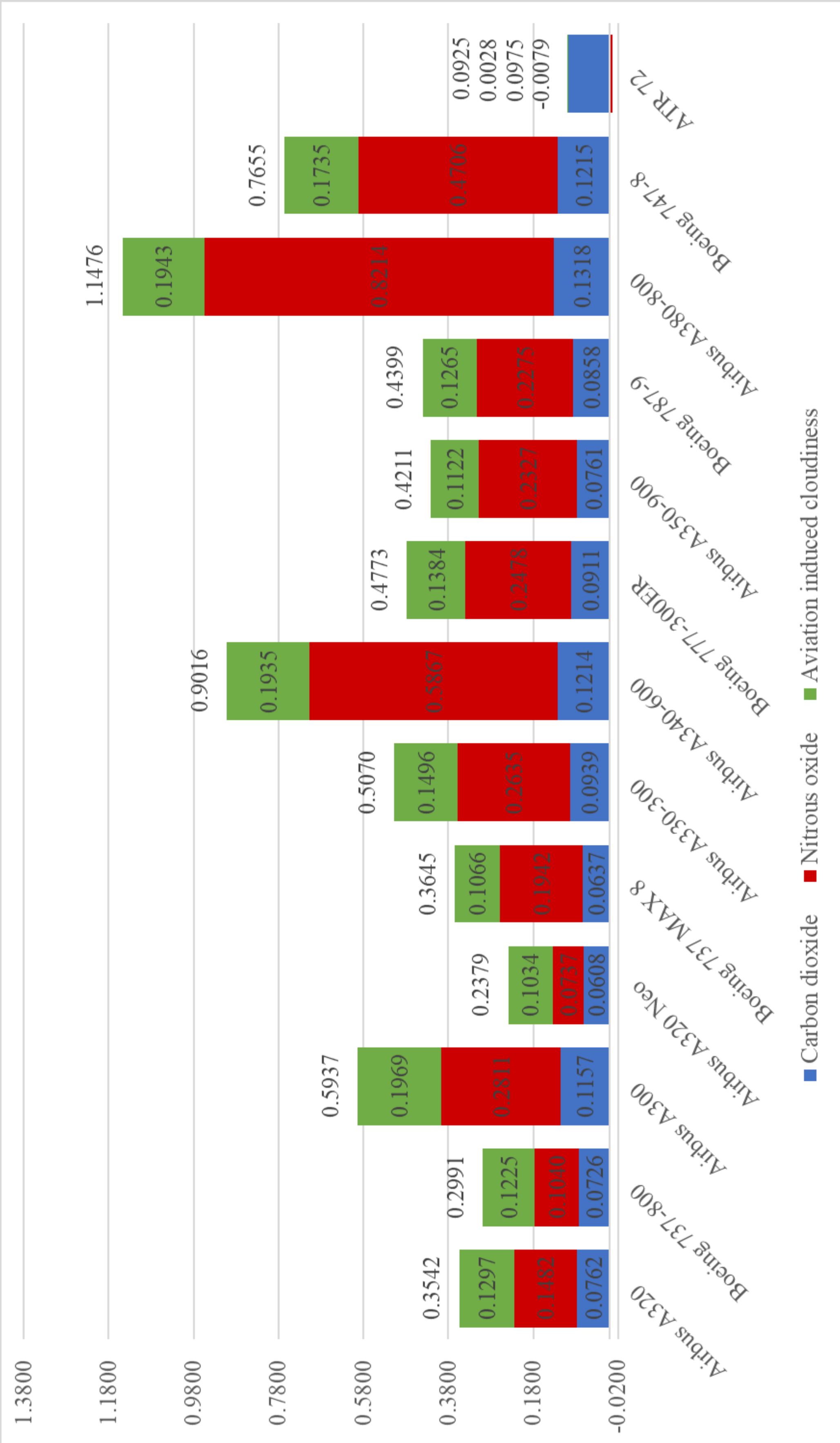


**Figure 2.19** Comparison of contributions to equivalent $CO_2$ emissions of different aircraft (kg $CO_2$/km/seat)

# 3 Airline Rankings

## 3.1 Systematic Literature Review of Emission Based Airline Rankings

A systematic literature review of emission based airline rankings is conducted to give an overview of existing research and a summarization of its contents. A biased literature selection is prevented following this methodological approach. The electronic databases Scopus (Elsevier) and Google Scholar are used to answer the main research question:
**In which state are current emission based airline rankings and the rules on which they are based on?**

The keywords in Elsevier´s Scopus are determined and combined by the help of boolean search, which uses operators as AND, OR, (), or NOT to specify one's literature research. Using the keywords displayed in Table 3.1 generated to much results (7984) to screen. But the search can be limited by only searching for keywords appearing in the literature title, finding just 44 subjects.

**Table 3.1** Keywords for first systematic literature review in Elsevier´s Scopus

| Keyword 1 | Operator | Keyword 2 |
|---|---|---|
| ("emission based ranking") OR ("emission based rating") OR ("emission based performance") OR ("emission based index") OR ("environmental ranking") OR ("environmental rating") OR ("environmental performance") OR ("environmental index") OR ("emission ranking") OR ("emission rating") OR ("emission performance") OR ("emission index") | AND | (airline) OR (aircraft) OR (aviation) OR (airplane) OR ("Air Transport Industry") |

Examining title and abstract of the search results left only seven results from the first search in Elsevier's Scopus. A second search aiming to find more publications was conducted with less specific terms, which are displayed in Table 3.5. Now the total dataset involved 735 documents, which are also too much to screen. Limiting the search to keywords appearing just in the literature title again, reduced the dataset to 18 documents. After screening the results of this second search just another two documents remained.

**Table 3.2** Keywords for second systematic literature review in Elsevier´s Scopus

| Keyword 1 | Operator 1 | Keyword 2 | Operator 2 | Keyword 3 |
|---|---|---|---|---|
| emission OR environmental | AND | ranking OR performance OR benchmarking OR rating OR index OR label | AND | airline |

Google Scholar does not support many of the features required for a systematic literature review, such as advanced search options (Gusenbauer 2020). It was still being used as a supplementary search system. The first search with the keywords used displayed in Table 3.3 brought back 2 Mio. results, which could be reduced to 683 limiting the search for keywords just in the title, which are still too much to screen.

**Table 3.3** Keywords for first search in Google Scholar

| Keyword 1 | Operator | Keyword 2 |
|---|---|---|
| emission OR environmental OR ranking OR performance OR benchmarking OR rating OR index OR label | AND | airline |

The use of the keywords was more refined and it was again searched for keywords appearing just in the title. This second search used the keywords displayed in Table 3.4 and brought back just 11 results (6 remaining after excluding “only citation”), from which just one document (Mombiedro 2021) was relevant for this thesis.

**Table 3.4** Keywords for second search in Google Scholar

| Keyword 1 | Operator 1 | Keyword 2 | Operator 2 | Keyword 3 |
|---|---|---|---|---|
| emission OR environmental | AND | ranking OR performance OR benchmarking OR rating OR index OR label | AND | airline |

Up to this point there were just 12 documents found. But because the searches were restricted only to the title of the documents it is possible, that some important documents with the keywords in the abstract could have been sorted out. To address this issue, another boolean search in Elsevier´s Scopus with the same parameters displayed in Table 3.2 was conducted – including a search in the abstract and for author keywords, resulting in 580 documents found. Sreening those, left 44 additional documents, which help answering the research question.

Due to the large volume of documents identified in the search, and not just those with keywords in the title, Google Scholar was revisited as well. Unlike Elsevier's Scopus, Google Scholar does not allow for filtering by title, abstract, or author-specified keywords. Other advanced search options, such as limiting results by year, also proved less useful. The selection process within Google Scholar is somewhat opaque; it ranks results based on algorithms that Google frequently updates, and these rankings can be influenced by factors like language settings or location, which are not easily traceable. Using the same keywords listed in Table 3.4, the search yielded 523.000 results. Despite the overwhelming number of results and the limitations of using Google Scholar, the first 100 search results were screened, yielding 12 additional relevant documents. In total, 68 documents were identified through the systematic literature review, as detailed in Table 3.5.

The **chronological development** of the publications is shown in Figure 3.1. The first document was published just before the turn of the millennium in 1999 – indicating that emission-based airline rankings are still a fairly new subject. In the next 20 years 34 documents were published.

But since 2020 already 36 documents originated just in the last roughly 4 years. It seems, that there are more documents about emission-based airline rankings emerging with rising ecological awareness.

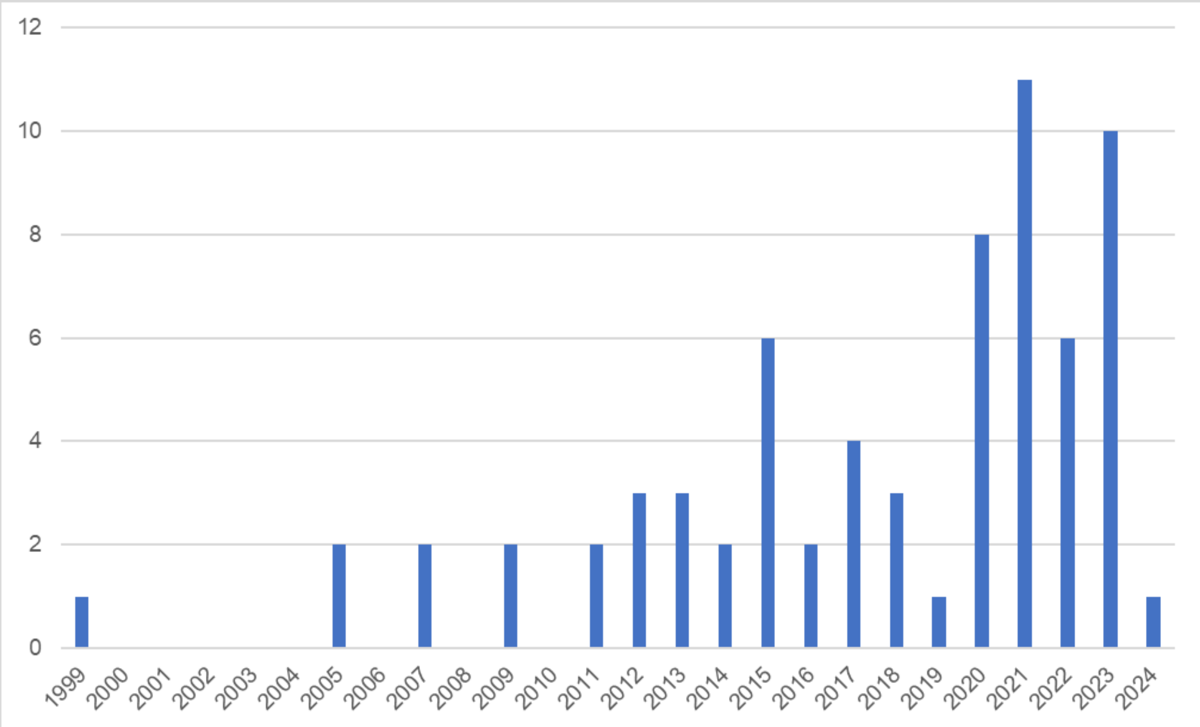


**Figure 3.1** Documents on emission-based airline rankings published per year

The majority of the documents were published in China, significantly outnumbering those from other countries. This is largely attributed to key contributors such as Qiang Cui from Southeast University in China, who has published 13 documents, and Ye Li from the Key Laboratory of Road and Traffic Engineering of the State Ministry of Education in Shanghai, China, with nine documents (based on the most recent publication). Australia ranks second, largely due to the contributions of Amir Arjomandi from the University of Wollongong, who has four publications.

Another noteworthy observation is the wide international participation in the issue of emission-based airline rankings, with contributions from 34 different countries. The majority of documents (50) come from Asia, including the Middle East and Near East. Europe, including Turkey and Russia, is the second-largest contributor with 30 documents. Australia (including Oceania) has contributed nine documents, North America eight, and Africa three. Notably, no documents were found from South America.

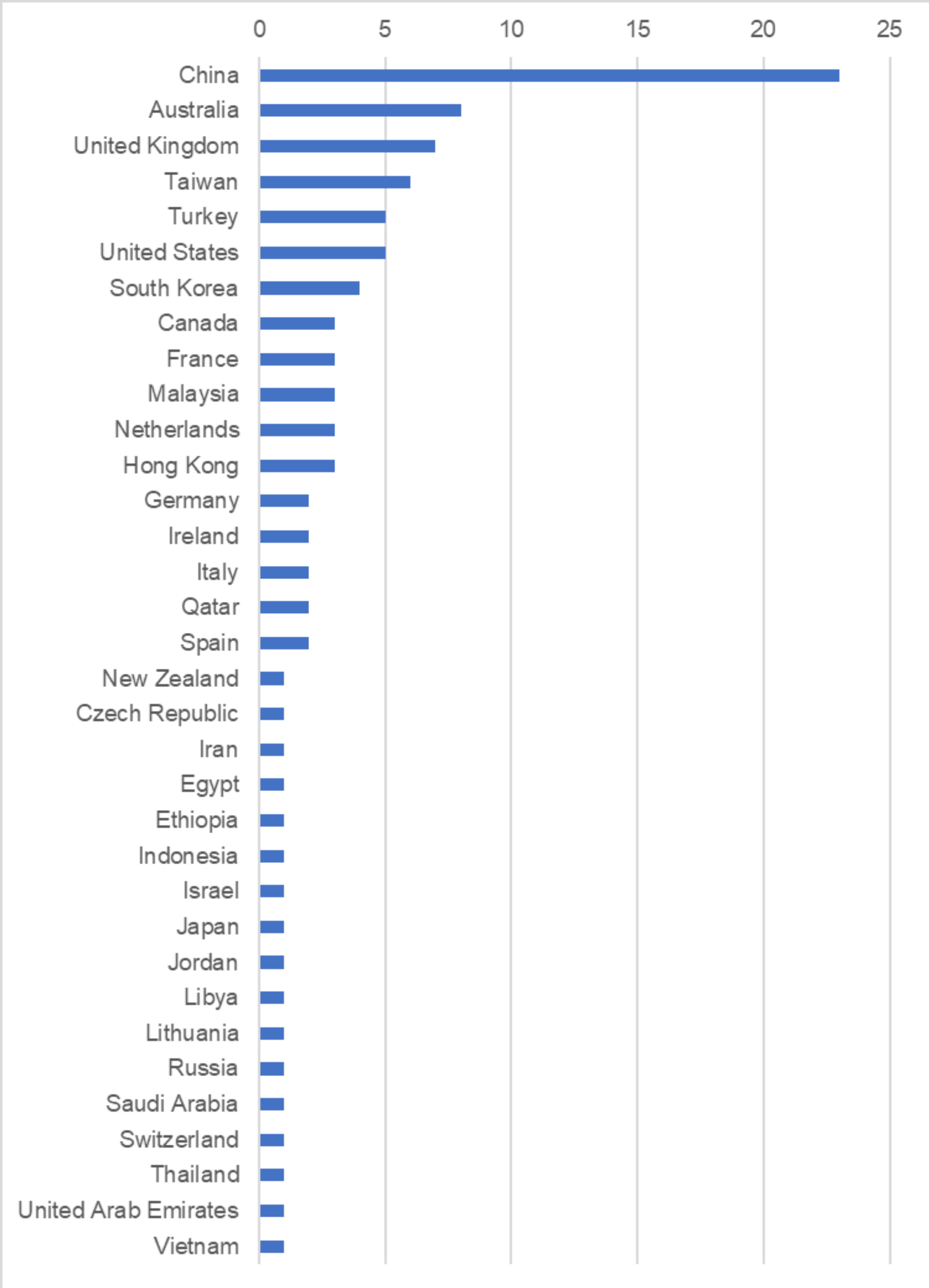


**Figure 3.2** Documents on emission-based airline rankings published by country

The 68 documents mainly consist of Journal Articles (84 %) followed by Conference papers (6 %) as can be seen in Figure 3.3. The following document types are represented equally (1 %) over the remaining share: books and book chapters, short surveys, bachelor and master theses and other articles.

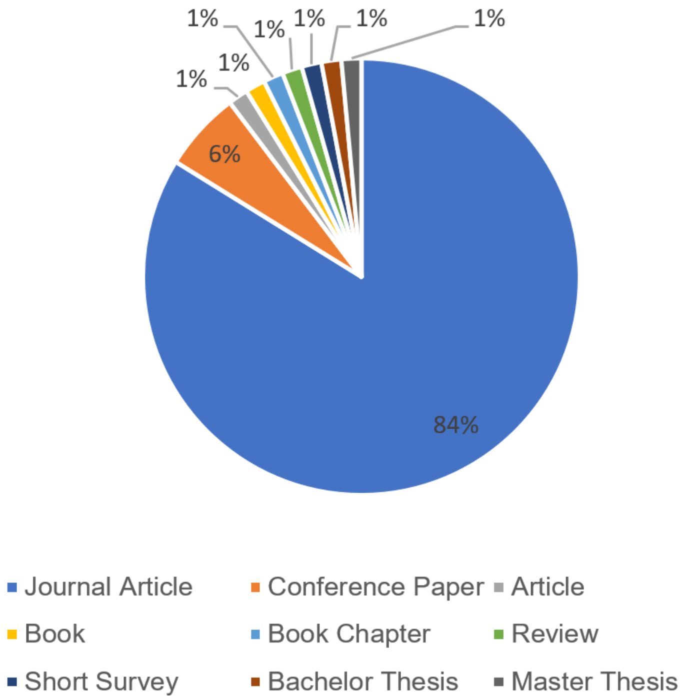


**Figure 3.3** Document type of systematic literature review results (in %)

### 3.1.1 Systematic Literature Review Results

**Table 3.5** Systematic literature review results

| Author | Title | Year | Journal |
|---|---|---|---|
| Adler, N., Martini, G., Volta, N. | Measuring the environmental efficiency of the global aviation fleet | 2013 | Transportation Research Part B: Methodological 53, pp. 82-100 |
| Aldahmashi, F.A., Hassan, T.H., Abdou, A.H., (…), Salem, A.E., Radwan, S.H. | Managing Airline Emissions, Noise, and Bird Strikes: Passengers' Perspectives on Airlines' Extrinsic and Intrinsic Environmental Practices | 2023 | Sustainability (Switzerland) 15(17),12734 |
| Alkhatib, S.F., Migdadi, Y.K.A.-A. | A novel technique for evaluating and ranking green airlines: benchmarking-base comparison | 2021 | Management of Environmental Quality: An International Journal 32(2), pp. 210-226 |
| Arjomandi, A., Dakpo, K.H., Seufert, J.H. | Have Asian airlines caught up with European Airlines? A by-production efficiency analysis | 2018 | Transportation Research Part A: Policy and Practice 116, pp. 389-403 |
| Arjomandi, A., Seufert, J.H. | An evaluation of the world's major airlines' technical and environmental performance | 2014 | Economic Modelling 41, pp. 133-144 |
| Aydogan, F., Zafeirakopoulos, I.B. | Leg base airline flight carbon emission performance assessment using fuzzy ANP | 2020 | Advances in Intelligent Systems and Computing 1029, pp. 812-819 |

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| Caraveo Gomez Llanos, A.F., Vijaya, A., Wicaksono, H. | Rating ESG key performance indicators in the airline industry | 2023 | Environment, Development and Sustainability |
| Chan, W.W., Mak, B. | An Analysis of the Environmental Reporting Structures of Selected European Airlines | 2005 | International Journal of Tourism Research 7, 249–259 |
| Chen, Y., Cheng, S., Zhu, Z. | Exploring the operational and environmental performance of Chinese airlines: A two-stage undesirable SBM-NDEA approach | 2021 | Journal of Cleaner Production 289,125711 |
| Cowper-Smith, A., de Grosbois | The adoption of corporate social responsibility practices in the airline industry | 2011 | Journal of Sustainable Tourism 19(1), pp. 59-77 [Closed Access] |
| Cregan, C., Kelly, J.A., Clinch, J.P. | Are environmental, social and governance (ESG) ratings reliable indicators of emissions outcomes? A case study of the airline industry | 2023 | Corporate Social Responsibility and Environmental Management |
| Cui, Q., Yu, L.-T. | Airline environmental efficiency comparison through two non-separable inputs disposability Range Adjusted Measure models | 2021 | Journal of Cleaner Production 320,128844 |
| Cui, Q. | A data-based comparison of the five undesirable output disposability approaches in airline environmental efficiency | 2021 | Socio-Economic Planning Sciences 74,100931 |
| Cui, Q., Li, Y. | A cross efficiency distinguishing method to explore the cooperation degree in dynamic airline environmental efficiency | 2020 | Transport Policy 99, pp. 31-43 |
| Cui, Q., Jin, Z.-Y. | Airline environmental efficiency measures considering negative data: An application of a modified network Modified Slacks-based measure model | 2020 | Energy 207,118221 |
| Cui, Q. | Airline energy efficiency measures using a network range-adjusted measure with unified natural and managerial disposability | 2020 | Energy Efficiency 13(6), pp. 1195-1211 |
| Cui, Q., Li, Y. | Airline environmental efficiency measures considering materials balance principles: an application of a network range-adjusted measure with weak-G disposability | 2018 | Journal of Environmental Planning and Management 61(13), pp. 2298-2318 [Closed Access] |
| Cui, Q., Li, Y., Lin, J.-L. | Pollution abatement costs change decomposition for airlines: An analysis from a dynamic perspective | 2018 | Transportation Research Part A: Policy and Practice 111, pp. 96-107 |
| Cui, Q., Li, Y. | Airline energy efficiency measures considering carbon abatement: A new strategic framework | 2016 | Transportation Research Part D: Transport and Environment 49, pp. 246-258 |

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|---|---|---|---|
| Cui, Q., Wei, Y.-M., Li, Y. | Exploring the impacts of the EU ETS emission limits on airline performance via the Dynamic Environmental DEA approach | 2016 | Applied Energy<br>183, pp. 984-994 |
| Cui, Q., Li, Y. | Evaluating energy efficiency for airlines: An application of VFB-DEA | 2015 | Journal of Air Transport Management 44-45, pp. 34-41 |
| Day, B.R. | The European Phenomenon: European Environmental Reporting | 1999 | Massey University, Master Thesis |
| Dempere, J., Modugu, K. | Tourist destination competitiveness and ESG performance in the airline industry | 2022 | Problems and Perspectives in Management<br>20(4), pp. 153-165 |
| Elhmoud, E.R., Kutty, A.A., Abdalla, G.M., (…), Bulak, M.E., Elkharaz, J.M. | Eco-efficiency performance of airlines in eastern Asia: A principal component analysis based sustainability assessment | 2021 | Proceedings of the International Conference on Industrial Engineering and Operations Management, pp. 6566-6579<br>[Closed Access] |
| Fan, W., Sun, Y., Zhu, T., Wen, Y. | Emissions of HC, CO, $NO_x$, $CO_2$, and $SO_2$ from civil aviation in China in 2010 | 2012 | Atmospheric Environment<br>56, pp. 52-57 |
| Geng, H., Jia, H., Chen, J. | A significant efficiency evaluation method based on DEA for airline carbon emission reduction | 2013 | Proceedings – 2013 Chinese Automation Congress, CAC 2013, 6775730, pp. 212-215<br>[Closed Access] |
| Hagmann, C., Semeijn, J., Vellenga, D.B. | Exploring the green image of airlines: Passenger perceptions and airline choice | 2015 | Journal of Air Transport Management 43, pp. 37-45 |
| Hooper, P.D., Greenall, A. | Exploring the potential for environmental performance benchmarking in the airline sector | 2005 | Benchmarking<br>12(2), pp. 151-165 |
| Huang, F., Zhou, D., Hu, J.-L., Wang, Q. | Integrated airline productivity performance evaluation with $CO_2$ emissions and flight delays | 2020 | Journal of Air Transport Management 84,101770 |
| Jordao, T.C., Sampedro, E. L.-V., Durisova, J. | An analysis of the contribution of flight route and aircraft type in environmental performance of airlines based on life cycle assessment: The Lutfhansa case | 2011 | University of Pardubice |
| Kao, F.-C., Ting, I.W.K., Chou, H.-C., Liu, Y.-S. | Exploring the Influence of Corporate Social Responsibility on Efficiency: An Extended Dynamic Data Envelopment Analysis of the Global Airline Industry | 2022 | Sustainability (Switzerland)<br>14(19),12712 |
| Kaya Aydin, G., Aydin, U. | Is there any convergence in the $CO_2$ emission efficiency of airlines? | 2022 | Environmental Science and Pollution Research<br>29(12), pp. 17811-17820 |
| Kılkış, Ş., Kılkış, Ş. | Benchmarking aircraft metabolism based on a Sustainable Airline Index | 2017 | Journal of Cleaner Production<br>167, pp. 1068-1083 |

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| Kim, H., Son, J. | Analyzing the environmental efficiency of global airlines by continent for sustainability | 2021 | Sustainability (Switzerland) 13(3),1571, pp. 1-16 |
| Kuo, T.-C., Chen, H.-M., Meng, H.-M. | Do corporate social responsibility practices improve financial performance? A case study of airline companies | 2021 | Journal of Cleaner Production 310,127380 |
| Lee, B.L. | Productivity and Efficiency Measurement of Airlines: Data Envelopment Analysis using R (Book) | 2023 | Productivity and Efficiency Measurement of Airlines: Data Envelopment Analysis using R pp. 1-259 |
| Lee, B.L., Wilson, C., Pasurka, C.A. | The good, the bad, and the efficient: Productivity, efficiency, and technical change in the airline industry, 2004-11 | 2015 | Journal of Transport Economics and Policy 49, pp. 338-354 [Closed Access] |
| Li, Y., Huang, X.-C., Cui, Q. | Exploring the environmental efficiency of airlines through a parallel RAM approach | 2022 | Energy Efficiency 15(7),45 |
| Li, Y., Cui, Q. | Analyzing the role of competition and cooperation in airline environmental efficiency through two dynamic environmental cross-efficiency models | 2021 | International Journal of Sustainable Transportation 15(11), pp. 850-864 [Closed Access] |
| Li, Y., Cui, Q. | Carbon neutral growth from 2020 strategy and airline environmental inefficiency: A Network Range Adjusted Environmental Data Envelopment Analysis | 2017 | Applied Energy 199, pp. 13-24 |
| Liu, X., Hang, Y., Wang, Q., Zhou, D. | Drivers of civil aviation carbon emission change: A two-stage efficiency-oriented decomposition approach | 2020 | Transportation Research Part D: Transport and Environment 89,102612 |
| Liu, X., Zhou, D., Zhou, P., Wang, Q. | Dynamic carbon emission performance of Chinese airlines: A global Malmquist index analysis | 2017 | Journal of Air Transport Management 65, pp. 99-109 |
| Losa, E.T., Arjomandi, A., Hervé Dakpo, K., Bloomfield, J. | Efficiency comparison of airline groups in Annex 1 and non-Annex 1 countries: A dynamic network DEA approach | 2020 | Transport Policy 99, pp. 163-174 |
| Majcher, K. | World green aviation council ranks operators' sustainability | 2012 | Aviation Week and Space Technology (New York) 174(7), pp. 48 [Closed Access] |
| Mak, B.L.M., Chan, W.W. | A study of environmental reporting: International Japanese Airlines | 2007 | Asia Pacific Journal of Tourism Research 12(4), pp. 303-312 [Closed Access] |
| Mak, B.L.M., Chan, W.W.H., Wong, K., Zheng, C. | Comparative studies of standalone environmental reports - European and Asian airlines | 2007 | Transportation Research Part D: Transport and Environment 12(1), pp. 45-52 |
| Mayer, R., Ryley, T., Gillingwater, D. | Eco-positioning of airlines: Perception versus actual performance | 2015 | Journal of Air Transport Management 44-45, pp. 82-89 |

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| Mayer, R., Ryley, T., Gillingwater, D. | Passenger perceptions of the green image associated with airlines | 2012 | Journal of Transport Geography 22, pp. 179-186 |
| Miyoshi, Chikage; Merkert, Rico | The Economic and $CO_2$ Emissions Performance in Aviation: An Empirical Analysis of Major European Airlines | 2015 | Green Logistics and Transportation, pp. 175-190 |
| Miyoshi, C., Mason, K.J. | The carbon emissions of selected airlines and aircraft types in three geographic markets | 2009 | Journal of Air Transport Management 15(3), pp. 138-147 |
| Mombiedro, Santiago Luqué | Green Aviation: An Airline Environmental Rating and its Institutional Impact | 2021 | Adventia, European College of Aeronautics |
| Nguyen, M.-A.T., Yu, M.-M., Lirn, T.-C. | Airlines' eco-productivity changes and the European Union Emissions Trading System | 2022 | Transportation Research Part D: Transport and Environment 102,103100 |
| Omrani, H., Shamsi, M., Emrouznejad, A. | Evaluating sustainable efficiency of decision-making units considering undesirable outputs: an application to airline using integrated multi-objective DEA-TOPSIS | 2022 | Environment, Development and Sustainability (2023) 25:5899–5930 |
| Oum, T.H., Pathomsiri, S., Yoshida, Y. | Limitations of DEA-based approach and alternative methods in the measurement and comparison of social efficiency across firms in different transport modes: An empirical study in Japan | 2013 | Transportation Research Part E: Logistics and Transportation Review 57, pp. 16-26 |
| Payán-Sánchez, B., Pérez-Valls, M., Plaza-úbeda, J.A. | The contribution of global alliances to airlines' environmental performance | 2019 | Sustainability (Switzerland) 11(17),4606 |
| Saini, A., Truong, D., Pan, J.Y. | Airline efficiency and environmental impacts – Data envelopment analysis | 2023 | International Journal of Transportation Science and Technology 12(2), pp. 335-353 |
| Scotti, D., Volta, N. | An empirical assessment of the $CO_2$-sensitive productivity of European airlines from 2000 to 2010 | 2015 | Transportation Research Part D: Transport and Environment 37, pp. 137-149 |
| Seufert, J.H., Arjomandi, A., Dakpo, K.H. | Evaluating airline operational performance: A Luenberger-Hicks-Moorsteen productivity indicator | 2017 | Transportation Research Part E: Logistics and Transportation Review 104, pp. 52-68 |
| Sobieralski, J.B. | Sustainable air transportation through the operational use of a social cost index | 2023 | Journal of Cleaner Production 385,135663 |
| Tanrıverdi, G., Merkert, R., Karamaşa, Ç., Asker, V. | Using multi-criteria performance measurement models to evaluate the financial, operational and environmental sustainability of airlines | 2023 | Journal of Air Transport Management 112,102456 |

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|---|---|---|---|
| Van Dorland, N., Van Der Zwan, F., Ghijs, S., Santema, S., Curran, R. | Aviation and the environment: Rating airlines on their $CO_2$ efficiency | 2009 | 9th AIAA Aviation Technology, Integration and Operations (ATIO) Conference, Aircraft Noise and Emissions Reduction Symposium (ANERS) 2009-7030 [Closed Access] |
| Wang, Z., Xu, X., Zhu, Y., Gan, T. | Evaluation of carbon emission efficiency in China's airlines | 2020 | Journal of Cleaner Production 243,118500 |
| Xu, Y., Park, Y.S., Park, J.D., Cho, W. | Evaluating the environmental efficiency of the U.S. airline industry using a directional distance function DEA approach | 2021 | Journal of Management Analytics 8(1), pp. 1-18 [Closed Access] |
| Yakath Ali, N.S., See, K.F. | Revisiting an environmental efficiency analysis of global airlines: A parametric enhanced hyperbolic distance function | 2023 | Journal of Cleaner Production 394,135982 |
| Yu, M.-M., Rakshit, I. | Target setting for airlines incorporating $CO_2$ emissions: The DEA bargaining approach | 2023 | Journal of Air Transport Management 108,102376 |
| Yu, M.-M., See, K.F. | Evaluating the efficiency of global airlines: A new weighted SBM-NDEA approach with non-uniform abatement factor | 2023 | Research in Transportation Business and Management 46,100860 |
| Yue, X., Byrne, J. | Identifying the determinants of carbon emissions of individual airlines around the world | 2024 | Journal of Air Transport Management 115,102521 |
| Zou, B., Elke, M., Hansen, M., Kafle, N. | Evaluating air carrier fuel efficiency in the US airline industry | 2014 | Transportation Research Part A: Policy and Practice 59, pp. 306-330 |

### 3.1.2 Additional Literature

The systematic literature review proofed useful in finding the most literature regarding emission-based airline rankings. But there were still more articles, papers etc. to be find via references from the already found literature, suggestions and specific searches. This additionally literature is listed in Table 3.6.

**Table 3.6** Additional literature

| **Author** | **Title** | **Year** | **Journal/Organization** |
|---|---|---|---|
| Amankwah-Amoah | Stepping up and stepping out of COVID-19: New challenges for environmental sustainability policies in the global airline industry | 2020 | Journal of Cleaner Production, Volume 271 |
| Atmosfair gGmbH | Atmosfair Airline Index | 2018 | Atmosfair |

| | | | |
|---|---|---|---|
| Chang et al. | Evaluating economic and environmental efficiency of global airlines: A SBM-DEA approach | 2014 | Transportation Research Part D: Transport and Environment, Volume 27 |
| Graver and Rutherford | Transatlantic Airline Fuel Efficiency Ranking | 2017 | International Council on Clean Transportation |
| Hadi-Vencheh et al. | Sustainability of Chinese airlines: A modified slack-based measure model for $CO_2$ emissions | 2020 | Expert Systems. 2020; 37:e12302 |
| Lee et al. | Sources of airline productivity from carbon emissions | 2017 | Journal of Productivity Analysis, 47(3), 223–246 |
| Zheng et al. | U.S. Domestic Airline Fuel Efficiency Ranking, 2017-2018 | 2019 | International Council on Clean Transportation |

## 3.2 Content Analysis

The most literature found on environmental efficiency of airlines conducted some sort of a data envelopment analysis (DEA). According to the Encyclopaedia of Social Measurement *DEA*

> *is a technique that allows for measurement of relative efficiency of organizational units. The methodology's main strength lies in its ability to capture the interplay between* ***multiple inputs and outputs****.*

Common inputs for analyzing airline performance include operational variables such as the number of employees, fleet size, and aviation kerosene usage. Outputs can be measured in terms of Revenue Passenger Kilometers[2] (RPK), Revenue Ton Kilometers (RTK), and Operating Revenue[3]. Traditionally, this analysis is used to determine the financial or technical performance of an airline. However, it is also possible to include $CO_2$ emissions as an undesirable output.

Data Envelopment Analysis (DEA) treats the production process like a "black box," neglecting any possible intervening processes. Such limitations are overcome by the Network DEA. The pros and cons of most DEA models are detailed in Lee's (2023) book. An overview of $CO_2$ emission-based airline studies, including their methodology and variables, considered periods, as well as the number and regions of airlines studied, is provided in Table 3.7. Despite the extensive list, the inputs and outputs are displayed in a simplified manner.

[2] A Revenue Passenger Kilometre indicates the number of kilometers travelled by paying passengers. A Revenue Tonne Kilometre (RPK) is a metric tonne of revenue load carried one kilometre.

[3] refers to the money a company generates from its primary business activities

Some models use multiple-stage approaches, where inputs can simultaneously be outputs, and intermediate products can occur. Table 3.7 does not differentiate between simultaneously used inputs and outputs, and intermediate products are not displayed. The list illustrates the variety and complexity of different models used to determine the environmental efficiency of airlines.

Unfortunately, within the scope of this thesis, it is not possible to compare all the different models and findings of the various papers. However, they all share a common focus on the methodology rather than the quality of inputs. The different methods and inputs/outputs are therefore summarized in Table 3.7.

A common conclusion was, that European Airlines are more efficient and also continuously improved more in efficiency over recent years than non-European Airlines (Arjomandi 2018, Aydin 2022, Cui 2021, Cui 2020, Kim 2021, Seufert 2017). The findings suggest that European airlines have put an increasing focus on environmental efficiency of their flight activities following the threat to include airlines in the EU ETS in 2009 (Arjomandi 2018). Another popular conclusion was, that LCCs are more environmentally oriented than Full Size Carries (FSCs) (Arjomandi 2015, Chen 2021, Graver 2017, Tanriverdi 2023).

**Table 3.7** $CO_2$ emission-based airline studies

| Study | Data | Period | Methodology | Variables |
|---|---|---|---|---|
| Arjomandi et al. (2018) | 21 Asian and European airlines | 2007–2013 | Meta-frontier DEA | inputs: labour, capital<br>desirable outputs: TKA<br>undesirable outputs: $CO_2$ emissions |
| Arjomandi and Seufert (2014) | 48 international airlines | 2007–2010 | Bootstrapped DEA | inputs: labor, capital<br>desirable outputs: TKA<br>undesirable outputs: $CO_2$ emissions |
| Aydogan (2020) | 1 turkish airline | 2018 | Analytical Network Process (ANP) | inputs: fuel, piloting, load<br>desired output: RTK<br>undesired outputs:<br>emission, noise heat |
| Chang et al. (2014) | 27 international airlines | 2010 | Slack based measure-data envelopment analysis (SBM-DEA) | inputs: labor, ATK, fuel<br>desirable outputs: RTK<br>undesirable outputs: $CO_2$ emissions |
| Chen et al. (2021) | 9 Chinese airlines | 2013–2018 | Two-stage undesirable SBM-NDEA | inputs: number of employees, fleet size, aviation kerosene (tons)<br>outputs: operating revenue, revenue passenger kilometers, revenue ton kilometers<br>desirable outputs: $CO_2$ emissions |
| Chen et al. (2017) | 13 Chinese airlines | 2006–2014 | Stochastic network DEA | inputs: fuel (tons), number of planes, number of employees<br>desirable outputs: cargo (tons), number of passengers<br>undesirable outputs:<br>$CO_2$ emissions, fight delays |

| | | | | |
|---|---|---|---|---|
| Cui and Yu (2021) | 22 international airlines | 2014-2019 | Range Adjusted Measure Model (DEA-RAM) | inputs: number of employees, fleet size, aviation kerosene<br>desirable output: revenue passenger kilometers<br>undesirable output: $CO_2$ emissions (greenhouse gas emissions) |
| Cui and Jin (2020) | 25 international airlines | 2008-2018 | Network Modified Slacks-based Measure (NDEA-MSBM) | inputs: number of employees, aviation kerosene, fleet size, sales cost<br>outputs: net profit<br>undesirable outputs: $CO_2$ emissions |
| Cui and Li (2017) | 29 international airlines | 2021-2023 | Network Range Adjusted Measure (NRAM-DEA) | inputs: operating expenses, available seat kilometers, fleet size, revenue passenger kilometers<br>outputs: available seat kilometers, revenue passenger kilometers, total revenue<br>undesirable output: greenhouse gas emissions ($CO_2$) |
| Cui et al. (2016) | 18 international airlines | 2008–2014 | Dynamic environmental DEA | inputs: number of employees, aviation kerosene<br>desirable outputs: total revenue<br>undesirable outputs: greenhouse gas emission (greenhouse gas emissions) |
| Cui and Li (2015) | 11 international airlines | 2008–2012 | Virtual frontier benevolent DEA cross efficiency model | inputs: employees, capital stock, tons of aviation kerosene<br>outputs: RPK, RTK, total business income, $CO_2$ emissions |
| Hadi-Vencheh et al. (2020) | 13 Chinese airlines | 2008–2015 | DEA and stochastic non-linear robust regression | inputs: fuel, number of planes, number of employees<br>desirable outputs: cargo, number of passengers<br>undesirable outputs: $CO_2$ emissions, delays |
| Huang et al. (2020) | 15 international airlines | 2011–2017 | Global Malmquist Performance Index (GMPI) | inputs: labor and feet<br>desirable outputs: RPK<br>undesirable outputs: $CO_2$ emissions |
| Kim and Son (2021) | 31 global airlines | 2014–2018 | DEA | inputs: aviation kerosene, operating cost, employee, airline feet<br>outputs: total revenue, RPK, RTK, passenger load factor, cargo load factor, $CO_2$ reduction |
| Lee et al. (2017) | 34 international airlines | 2004–2010 | Luenberger productivity indicator | inputs: hours flown, fuel, labor, average aircraft capacity<br>outputs: $CO_2$ emissions, RTK |
| Lee et al. (2015) | 35 international airlines | 2004–2011 | Malmquist-Luenberger productivity index | inputs: hours flown, fuel burn, average aircraft capacity, number of employees<br>desirable outputs: ton kilometers performed<br>undesirable outputs: $CO_2$ emissions |

| | | | | |
|---|---|---|---|---|
| Li et al. (2022) | 18 interna-tional airlines | 2014-2019 | Parallel Range Ad-justed Measure (PRAM) | inputs: available seat kilometers, avail-able ton kilometers, operating cost<br>outputs: revenue passenger kilome-ters,<br>revenue ton kilometers,<br>operating revenue<br>undesirable output: greenhouse gas ($CO_2$) |
| Liu et al. (2017) | 12 Chinese airlines | 2007–2013 | Global Malmquist carbon emission performance index (GMCPI) | inputs: plane, labor<br>desirable outputs: RTK<br>undesirable outputs: $CO_2$ emissions |
| Omrani | 16 Iranian airlines | 2019 | integrated multi-ob-jective<br>DEA-TOPSIS | inputs: fleet size, available seat kilo-meters, available ton kilometers<br>outputs: revenue passenger kilome-ters, revenue ton kilometers<br>undesirable outputs: $CO_2$ emissions |
| Seufert et al. (2017) | 33 interna-tional airlines | 2007–2013 | Luenberger-Hicks-Moorsteen indicator | inputs: labor, capital<br>desirable outputs: TKA<br>undesirable outputs: $CO_2$ emissions |
| Saini et al. (2022) | 13 interna-tional airlines | 2013-2015 | DEA | inputs: total operating costs, available seat miles, estimated $CO_2$ emissions, abatement expense<br>outputs: net income, total operating revenues<br>undesirable output: actual $CO_2$ emis-sions |
| Tanriverdi et al. (2023) | 56 interna-tional airlines | 2017-2021 | Multi-Criteria Deci-sion Making Model (MCDM) | criteria: total revenue, operating profit, net profit, revenue passenger kil-ometers, available seat kilometers, load factor, passenger numbers, $CO_2$ emis-sions |
| Wang et al. (2020) | 13 Chinese airlines | 2009–2013 | Global Slack-based measure model (GSBM), global Malmquist-Luen-berger productivity index (GML) | inputs: feet size, fight shifts times, fight hour desirable outputs: operating in-come, transportation turnover<br>undesirable outputs: $CO_2$ emissions |
| Xu et al. (2021) | 12 US air-lines | 2013–2016 | Directional distance function DEA | inputs: employment, operating ex-pense,<br>fuel consumption<br>outputs: GHG emission, revenue ton mile, fight delay |
| Yakath Ali and See (2023) | 112 interna-tional airlines | 2017 | Parametric EHDF | inputs: fuel, other operating inputs, capital<br>desirable output: available ton-kilome-ters<br>undesirable output: $CO_2$ emissions |

| | | | | |
|---|---|---|---|---|
| Yu and See (2023) | 29 international airlines | 2018 | Slack Based Measure Network Data Envelopment Analysis (SBM-NDEA) | inputs: Fleet size, number of employees, aviation kerosene<br>desirable output: revenue passenger-kilometers, revenue ton-kilometers<br>undesirable output: $CO_2$ emissions |

Apart from operational variables, $CO_2$ is the only sort of emission, which is considered important for an environmental efficiency. In Chapter 2.3.1 we showed, that there are much more indicators like $NO_x$, AIC or noise to be considered to evaluate the environmental performance of an airline.

In most cases the data for $CO_2$ emissions is obtained from RDC Aviation, which is based on the International Air Transport Association (IATA) Scheduled Reference Service (SRS) database. It contains over 99 % of all flight schedules worldwide, thus ensuring that the data reflect those filed by the airlines themselves and align with the IATA World Air Transport Statistics (WATS) database (Lee 2023). Other papers are using data provided by the Atmosfair Airline Index (Aydin 2022) just calculating their $CO_2$ emissions via there fuel consumption (Losa 2020) or using data from corporate environmental reports (CERs) (Cui 2021, 2020, 2017, 2016, 2015).

CERs are another way to determine the environmental performance of an airline, as discussed in various papers found in the literature review (Caraveo 2023, Chan 2005, Cowper-Smith 2005, Cregan 2023, Day 1999, Hooper 2005, Kao 2022, Mak 2007). Environmental reporting has been a voluntary method of communicating a company's environmental performance to its stakeholders and is a tool in a company's Environmental Management System (EMS). However, all authors express skepticism about CERs. Caraveo (2023) points out the divergence of ratings from different environmental, social, and governance (ESG) rating providers and a lack of transparency, leading companies to report voluntary indicators without standardization. He identifies ESG criteria and the most suitable set of key performance indicators (KPIs) in the airline industry, such as jet fuel consumed and sustainable aviation used.

Chan (2005) further indicates that the units in the fuel efficiency indicator are not consistent among the airlines studied, making benchmarking difficult. Cregan (2023) analyzes environmental ratings and emissions scores for commercial airlines from several major ESG ratings providers. He investigates whether emissions scores of 57 airlines from 2012 to 2021 capture and predict absolute carbon emissions and emissions intensity levels and whether scores are consistent across providers. He finds no evidence that emissions scores capture or predict reported carbon emissions and observes substantial divergence in scores from different providers.

In the early days of CERs, Day (1999) points out the positive attributes of CERs, stating that they improve EMSs and environmental performance, communication, and encourage teamwork. He also compares CERs of different industries, finding that airlines as an industry outperformed other major industry groupings. Compared to more recent studies, CERs were judged more positively 25 years ago. Just six years later, Hooper (2005) conducts an international survey of 272 IATA Airlines and confirms an increase in the availability of quantitative data and some consistency in the use of key performance indicators. However, he identifies fundamental obstacles to effective sector benchmarking due to variations in the exact definitions of the indicators used.

Kao (2022) examines the effect of Corporate Social Responsibility (CSR) on the dynamic efficiency of the global airline industry from 2013 to 2017, showing that environmental and social elements in CSR improve airline efficiency levels. Mak (2007) investigates environmental reports of a sample of airlines in Europe and the Asia Pacific region to identify the status and progress of environmental reporting. In 2007, only airlines in 12 countries had published standalone environmental reports. It was found that most elements were mentioned in the reports, but the definition of fuel efficiency in the environmental performance element differed between them, making benchmarking a challenge. In conclusion, the overwhelming majority of papers find that benchmarking airlines with data from CERs should be standardized and more transparent to enable comparison of the environmental performance of different airlines.

Adler (2013) investigates the influence of aircraft engine combinations in order to analyze the potential to reduce noise and airborne pollutants. In Chapter 2.8 it was shown the significance of aircraft engine combinations. Her results show inefficiencies of the current airline fleets and that the Intergovernmental Panel on Climate Change (IPCC) environmental charges values of externalities (HC, $NO_x$, PM, $SO_2$) are a magnitude of TEN too low to encourage changes in the global fleet. Therefore, a need for government intervention is indicated.

Several papers investigate passengers' perceptions of the environmental practices of airlines. Aldamashi (2023) found that passengers are more likely to use an airline and spread positive word of mouth when environmental practices are part of intrinsic management efforts rather than extrinsic environmental practices. This suggests that airlines should focus on implementing sustainable practices that align with their core values rather than adopting superficial measures for public relations. Sustainable practices perceived as genuine and integral to an airline's operations are more likely to gain passenger approval and loyalty.

Hagmann (2015) examines passengers' general attitudes towards the green image of different airlines, perceived differences in eco-friendliness among these airlines, and the effects on airline choice during booking. The findings show that the green image of airlines does influence airline choice during booking. However, amenities such as more legroom are often more important for passengers. Most passengers also have a specific green image in mind for different airlines, which is differentiated from their general attitude towards that airline and does not necessarily reflect its actual environmental friendliness.

Mayer (2015) finds that the eco-positioning of airlines is not correlated to their actual environmental performance. These results support previous research findings in other industries that, in many cases, actual performance is less important than effectively communicating environmental messages to the public in creating a superior eco-positioning. This indicates that perception and branding can significantly impact passengers' views and choices, even if the environmental practices are not as robust as presented.

Using newer aircraft is seen as the most effective way to improve the environmental image of an airline, according to Mayer (2012). Newer aircraft typically have better fuel efficiency and lower emissions, contributing positively to an airline’s environmental image. Therefore, investing in newer, more efficient aircraft can enhance an airline's reputation for sustainability, aligning both perceived and actual environmental performance.

Only a few papers examine more than $CO_2$ emissions in order to determine environmental efficiency. Alkhatib (2022) evaluates airline green operations and practices by means of so-called green indicators, which are:

1) Greenhouse gas scope 1 (GHG1) and fuel saving (aircraft design, flight route, operations, fuel, …)
2) Greenhouse gas scope 2 (GHG2) and energy saving (facility and building energy, …)
3) Waste management and recycling
4) Water management

Twenty airlines were ranked, with Finnair, Korean Air, and American Airlines performing the best and Qatar Airways, Air China, and Etihad Airways performing the worst. The focus of this ranking still lies heavily on the operational and technical performance of an airline, rather than its environmental impact.

Fan (2012) uses China’s 2010 flight schedules, aircraft and engine combination information, and revised emission indices from the International Civil Aviation Organization emission data bank to estimate fuel consumption and emissions (HC, CO, $NO_x$, $CO_2$, $SO_2$) from domestic flights of civil aviation in China in 2010. By using emission indices to calculate emissions based on fuel consumption, Fan finds a strong correlation between fuel consumption and pollutant emissions.

Jordao (2012) demonstrates through real Lufthansa flights that fuel consumption and emissions ($CO_2$, $H_2O$, $NO_x$, CO, HC, $SO_2$, Soot) per passenger can vary significantly between the same origin and destination depending on the distance flown and the aircraft models used. This study highlights the variability in environmental performance based on operational choices and aircraft efficiency. The findings underscore the importance of considering specific flight details and aircraft types when evaluating an airline's environmental impact.

Kilkis (2017) constructed a Sustainable Airline Index (SAI) based on four dimensions and 20 indicators to benchmark aircraft metabolism. This index provides a comprehensive framework for assessing the sustainability of airlines, taking into account a broader range of factors beyond just fuel consumption and emissions. The SAI aims to offer a more holistic view of airline sustainability, incorporating various operational, environmental, and technical aspects to provide a more accurate benchmark. The dimensions are:

1) airline services and quality
2) fuel consumption and efficiency
3) carbon dioxide emissions and intensity
4) sustainable aviation measures.

The focus also lies very much on operational/technical performance of an airline and only the amount of $CO_2$ emissions influences the SAI. But in the last dimension “sustainable aviation measures” the scope of the environmental rating is considered. An Airline, which measures all of the following emissions gets the highest so-called *pollutant emissions score* improving the overall SAI score.

- $CO_2$
- other emissions (CO, PM)
- $NO_x$ (total flight operations)
- $NO_x$ (low altitude < 3000 ft)
- $SO_x$ (low altitude < 3000 ft)
- HC/CFC-11 (LTO cycle)

The assessment of airline environmental reporting revealed, that no airline specifies all emissions listed. Most airlines do only state roughly half of the emissions listed. To get the best pollutant emissions score it is only necessary to specify four of the six emissions listed.

While operational and technical performance remains a key focus, these studies emphasize the need for a more integrated approach to evaluating airline performance, one that includes environmental impacts. By developing indices like the SAI and utilizing comprehensive data from real flights, researchers can better understand and improve the sustainability of the aviation industry.

Mombiedro (2021) developed an airline environmental rating to evaluate the airlines´ impact considering five criterias: *emmissions, noise, waste management, water management and green operational procedures*. This thesis seems to include the most environmental criteria of any rating to assess the environmental impact of airlines. Therefore, it will be discussed in more detail in Chapter 3.3.2.

Oum (2013) measures and compares social efficiency of railway firms and airlines in Japan's domestic intercity travel market. The paper shows off the limitations of DEA using a more comprehensive approach, which incorporates the life-cycle $CO_2$ emissions as an undesirable output and travelers' time and government spending on air infrastructure as inputs. He concludes, that the railway firms are more socially efficient than the airlines.

The influence of politics on airline efficiency was investigated by Losa (2020), who found that the Kyoto Protocol positively influenced airline efficiency. Similarly, Nguyen (2022) examined how the eco-productivity of airlines in the European Economic Area changed during 2012–2019, which were directly affected by the EU Emissions Trading System (EU ETS). Airlines showed continuous but slow growth in their eco-productivity since the inclusion of aviation in the EU ETS, driven by efficiency improvements and technological innovation. It was concluded that the carbon price on the EU ETS was not a strong indicator of the airlines' eco-productivity changes.

The influence of global alliances on environmental performance was investigated by Payán-Sanchez (2019). While global alliances have traditionally been related to improvements in the economic and operational performances of companies, particularly in the airline industry, they were found to have a negative impact on environmental performance. Airlines not belonging to any of the three major global alliances in the sector demonstrated better environmental results. This suggests that the different statements and commitments from alliances towards the environment and corporate social responsibility are not effectively translated into environmental performance.

Overall, these studies highlight the complex relationship between political agreements, economic systems, and environmental performance in the airline industry. While initiatives like the Kyoto Protocol and EU ETS can drive improvements in efficiency and eco-productivity, the actual impact on environmental performance may vary. Additionally, the role of global alliances appears to be counterproductive in terms of environmental outcomes, despite their economic and operational benefits.

This body of research underscores the need for a more integrated and effective approach to improving the environmental performance of airlines. Political frameworks and economic incentives must be designed and implemented in ways that ensure actual environmental benefits, and airline alliances must be held accountable for their environmental commitments to achieve tangible improvements.

The impact of the SARS-CoV-2 pandemic on the sustainability of the airline industry was examined by Tanriverdi (2023) using data from 56 airlines spanning the period before, during, and in the initial aftermath of the pandemic (2017–2021). The findings revealed that the financial pillar has become a significantly more important consideration, while the decarbonisation criterion saw a decline in importance during 2020. However, from 2021 onwards, decarbonisation began to assume greater importance once more, and the sector demonstrated signs of recovery. In terms of overall and sustained sustainability, low-cost carriers and small full-service carriers with predominantly domestic networks are regarded as the most effective performers. The renewal of the fleet and the attachment of decarbonisation conditions to government aid are identified as the most promising strategies for preparing the aviation industry for the next pandemic or disruption.

Amankwah-Amoah (2020) examined the contemporary challenges of adopting and implementing environmental sustainability policies in the global airline industry in the wake of COVID-19. The results confirmed, that airlines abandoned well-rooted practices in the face of the existential threats stemming from COVID-19.

Aydin (2022) investigates the regional differences and the effect of the share of government ownership in the $CO_2$ emission efficiency of airlines. It was found, that increases in the share of government ownership in airlines negatively affect the $CO_2$ emission efficiency in Asia, whereas it is insignificant in Europe and America.

## 3.3 Selection of Airline Rankings

### 3.3.1 Transatlantic Airline Fuel Efficiency

The most basic form of an airline ranking is illustrated in Figure 3.4, which presents the transatlantic airline fuel efficiency ranking based on passenger-kilometers per liter of fuel (passenger-km/l), as conducted by the International Council on Clean Transportation (ICCT). This ranking adjusts for the impact of cargo on passenger flights, which, while increasing the total fuel consumption of a flight, improves fuel efficiency per unit of mass transported. The results reveal a significant disparity between airlines, with British Airways (BA) consuming, on average, 63% more fuel than Norwegian.

It is also noteworthy that two low-cost carriers occupy the top two positions in the ranking, while more upscale airlines like Lufthansa and British Airways (BA), which offer business and first-class seats, rank lower. This underscores the significant influence of seating density on average fuel economy, as shown in Figure 3.5. Seating density emerges as the second most important factor driving transatlantic airline fuel efficiency, accounting for 33% of the impact. The increasing importance of this factor reflects the expansion of carriers such as Norwegian and WOW air, which operate transatlantic flights with higher seat counts and a lower proportion of premium seats compared to their competitors (Graver and Rutherford 2017). Additionally, the use of more fuel-efficient aircraft, such as the Airbus A350 or Boeing 787, proves to be the most critical factor in achieving a favorable average fuel economy.

On this particular route there was an inverse relationship between aircraft size and fuel efficiency. With increased maximum take off weight (MTOW) fuel efficiency declines - predominantly because aircraft with four engines are less fuel-efficient than those with two.

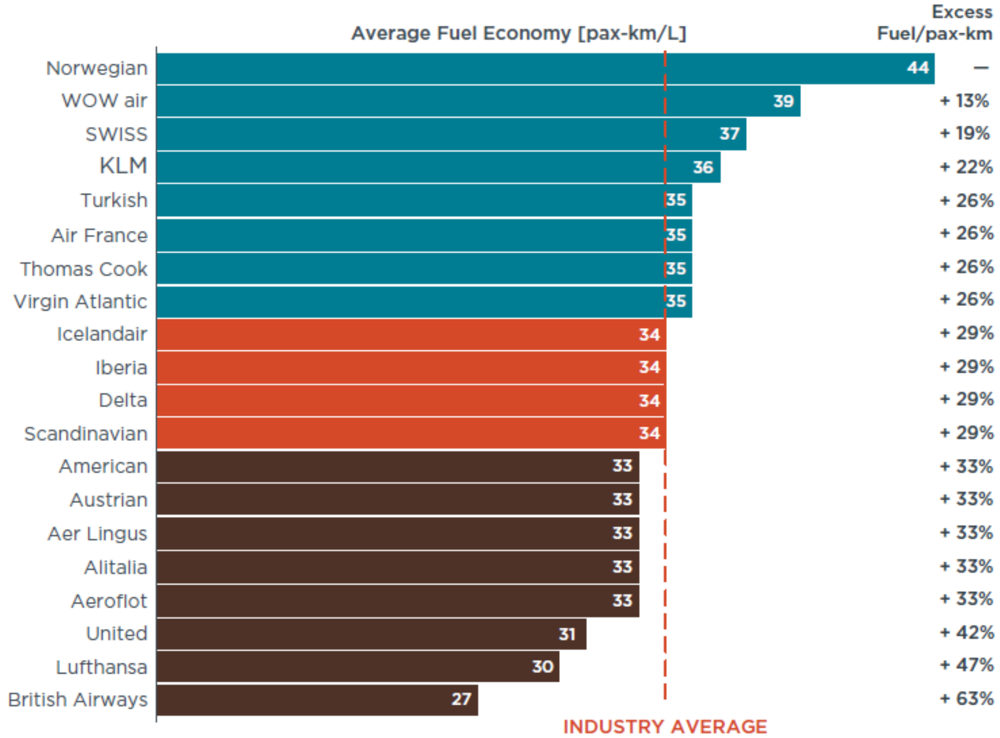


**Figure 3.4** Fuel efficiency of 20 airlines on transatlantic passenger routes (Graver 2017)

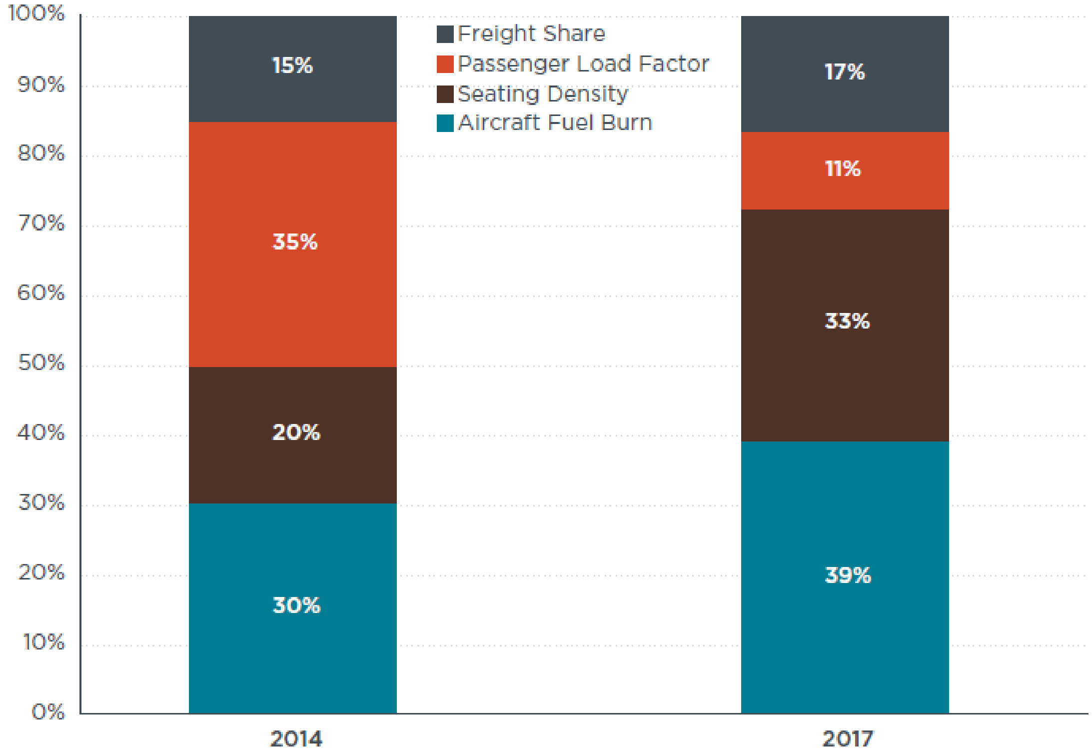


**Figure 3.5** Key drivers of transatlantic airline fuel efficiency, 2014 and 2017 (Graver 2017).

### 3.3.2 Airline Environmental Rating

The airline rating recognizing one of the most criteria to assess the environmental performance of an airline was proposed by Mombiedro (2021). The following items were considered:

- $CO_2$ per seat and kilometer (RPK)
- $NO_x$
- Water vapor (AIC)
- Soot
- $SO_2$
- Noise
- Waste management
- Water management
- Green operational procedures
- $CO_2$ Offset

All of the emissions (except noise) are assessed via the fuel consumption, which is corrected for short, medium and long range flights. This methodology gives a good indication of the emissions of a flight. But it was shown in Chapter 2.5.2 and 2.8, that the emissions of $NO_x$, $SO_2$ or water vapor can differ quite a lot dependent on the engine even with a very similar fuel consumption. The chemical composition of the exhaust is therefore not only a function of the fuel consumption, but rather depends on the specific engine used. The noise emissions are calculated in a similar way like it is done in Chapter 2.6. But Mombiedro just uses the reference points take off and approach and does not consider the lateral reference point.

Although water and waste management are important in assessing the environmental impact of an airline, Johanning (2014) identified that the cruise flight (70%) and kerosene production (24%) are the most significant contributors to an aircraft's environmental footprint. Therefore, improvements in these areas are crucial to minimize environmental burdens. Mombiedro (2021) pointed out that airlines do not maintain a surveillance program on these procedures, complicating comparisons between different airlines.

Taxiing with fewer engines can significantly reduce ground emissions. For instance, using one instead of two engines, or two instead of four, can cut ground emissions by up to 44% (Stettle 2018). However, Johanning (2014) noted that emissions from the landing and takeoff (LTO) cycle only account for 4% of an aircraft's environmental impact. Despite this, it remains essential to make changes where possible, similar to efforts in water and waste management.

Airlines are obligated to compensate for a certain amount of emissions, and some exceed these requirements through carbon offsetting programs. These programs are also considered in the environmental rating, highlighting the importance of comprehensive strategies to address the environmental impact of aviation.

Mombiedro (2021) found, that the correct literature and recent data to assess all of these environmental impacts are very hard to find. He concludes, that the rating cannot be concluded with these limitations and the parameter will remain theorized. An actual ranking of airlines therefore could not be generated.

### 3.3.3 Atmosfair Airline Index

The complete overall ranking of airlines performed by Atmosfair is presented in Appendix F.

Like the transatlantic airline fuel efficiency ranking discussed in the last Chapter, many environmental airline rankings are focusing on benchmarking actions related to one or few of so-called *green indicators* inter alia fuel consumption, aircraft utilization rate and efficiency determinants or fleet assignment. Some of these rankings and their examined green indicators are listed in Table 3.8.

**Table 3.8** References of other Airline Rankings

| Green indicator | Reference |
|---|---|
| fuel consumption | Brueckner 2017, Graver 2017 |
| fleet assignment | e.g. Ma 2018 |
| aircraft utilization rate and efficiency determinants | e.g. Liu 2017 und 2020, Joo 2014, Yu 2023, Syuhadah 2023 |
| aircraft weight | e.g. Abdullah 2016 |
| commercial air traffic | e.g. Amizadeh 2016 |
| flight procedures | e.g. Lee 2017 |
| management of airline wastes | Tofalli 2018 |
| route distribution | e.g. Liu 2017 |
| airline maintenance management | e.g. Lee 2017 |
| engine washing | e.g. Chapman 2016 |
| corporate environment management practices | e.g. Abdullah 2016 |
| strategic practices such as fleet renewal | e.g. Abdullah 2016, Chapman 2016 |
| winglets | e.g. Chapman 2016 |
| alternative bio-fuel | Lee 2017 |
| aircraft engine design | e.g. Migdadi 2018, Torija 2019 |

Only very limited studies have investigated the multiple effective green actions of several green indicators. It was shown, that most environmental airline rankings focus on the emission of $CO_2$, which were listed in Table 3.7. These rankings are considering multiple green indicators like the use of kerosene to determine fuel consumption, the comparison between APKs and RPKs to determine aircraft utilization rate and efficiency determinants or fleet size to determine fleet assignment.

One of the best examples of a very similar airline ranking is the Atmosfair airline index (AAI). It is not calculated via the DEA approach, but considers by far the most airlines (150 international passenger airlines). The AAI is furthermore based on the ICAO carbon emissions calculation method and considers $CO_2$ and $NO_x$ as well. It takes aircraft type, engine, seat and cargo capacity as well as the load factor and the use of winglets into account to determine these emissions.

Based on the results, efficiency can be optimized by various factors shown in Figure 3.6. *Passenger occupancy* is the most important factor, followed by *type of aircraft*. It is claimed, that AIC and other emissions do not differ between the airlines and are therefore not considered in the airline ranking.

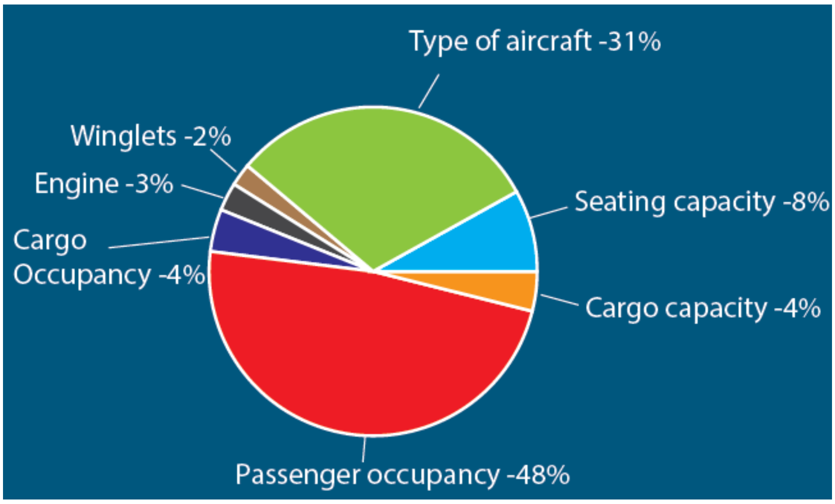


**Figure 3.6** Efficiency optimization effect of various factors on reducing $CO_2$ emissions (Atmosfair 2018a)

The Atmosfair Airline Index (AAI) aims to provide an unbiased ranking of airlines across both short and long-haul flights. One of the challenges in this comparison arises from the fact that airplanes must reach a cruise altitude, which generally results in poorer efficiency for short-haul flights compared to long-haul and mid-haul flights.

Consequently, a mid-haul flight, even if slightly less efficient, can outperform a short-haul flight in terms of overall efficiency. For instance, the effort required for an airline to achieve a specific emission target of 120 g $CO_2$ per passenger kilometer on a long-haul flight may be greater than achieving 75 g $CO_2$ per passenger kilometer on a mid-haul flight. This phenomenon, illustrated in Figure 3.7, is taken into account in the AAI ranking.

An alternative airline ranking using the newly developed airline label will be presented in the following section, with a comparative analysis against the AAI discussed in Chapter 4.4.

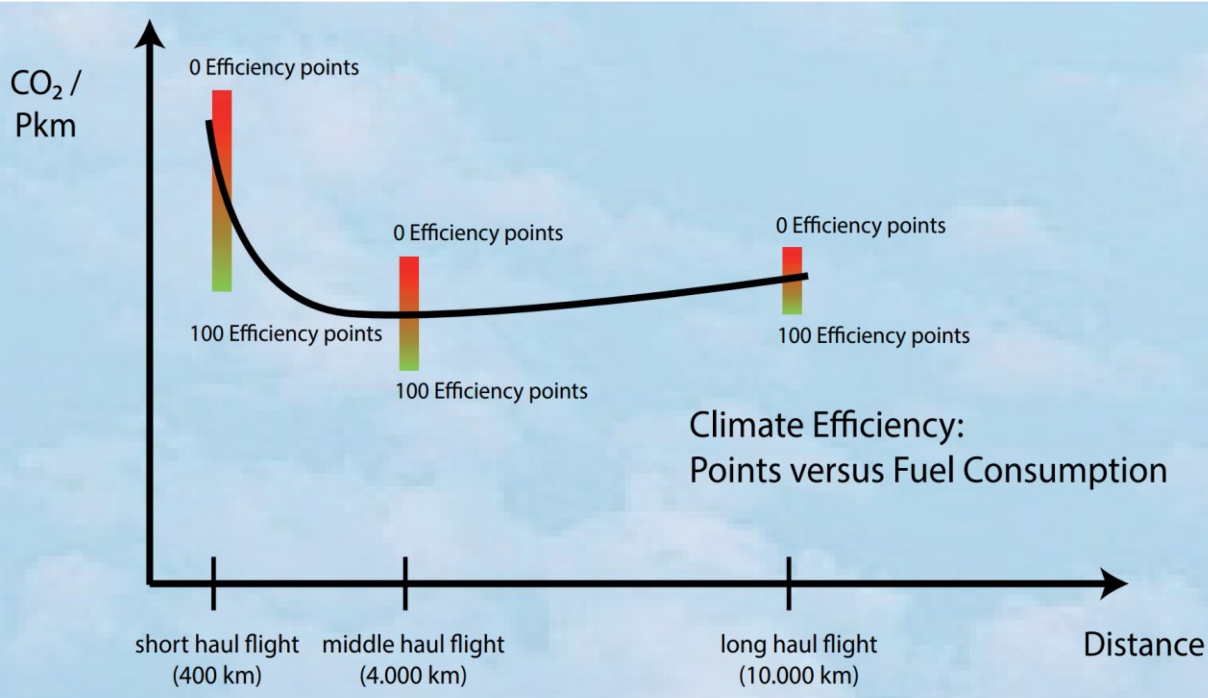


**Figure 3.7** Efficiency comparison of specific emissions $CO_2$ per passenger km in relation to flight distance (Atmosfair 2018a)

# 4 Airline Label

The following airline label is based on the calculations of the aircraft label. It therefore does not consider not only the most common *green indicators* like fuel performance or $CO_2$ emissions. It takes $CO_2$ **equivalent** emissions, local noise level and air pollution into account as well.

## 4.1 Choosing the 50 Most Important Airlines

The first airlines were chosen in regard to the most passengers carried on national and international flights according to the IATA Ranking 2021 (RND 2021). Since the environmental impact is closely related to the fleet size of an airline the ranking consists of 44 out of the 50 airlines with the biggest fleets in the world (Walther 2021). Airlines can also be rated by the number of daily departures. The biggest airlines in this regard were also added to the ranking (Flightsfrom 2023). Most of the flag carrier of the 20 biggest industrialized countries (measured in terms of GDP) were also included (Statista 2023).

Low Cost Carrier (LCC) are incorporated in the ranking as well. But it has to be considered, that many budget airlines receive subsidies, which are generally converted equally into cheaper fares. Whilst other airlines receive subsidies as well, they do not offer flights cheaper because of those. LCC and their price politics thus stimulate more flights and subsequently emissions, which are not included in the Airline Label. Many budget airlines further cause more emissions because the ground travel required to get to the often regional airports is longer than in the case of hub to hub flights. These are the reasons, why the AAI ranks LCC differently than other airlines (Atmosfair Airline Index 2018). To keep the airline ranking simple, it was decided to include those airlines anyway. But these facts have to be kept in mind evaluating LCCs with very good ratings.

The airline ranking created will be compared to the AAI 2018 in Appendix F later on. For sake of better comparison all Airlines from the AAI with a fleet of at least 100 aircraft were listed separately and most of them are incorporated in the ranking. This list of airlines can be found in Appendix G.

The final spots in the airline ranking were chosen based on editor's discretion, as many airlines are comparable when considering factors like passenger numbers, daily departures, and fleet size. Given that the thesis was written in Germany, the decision was made to include major German airlines. Consequently, Condor, TUIfly, and Eurowings were selected for the last three places in the ranking.

These German airlines were not among the world's 50 largest carriers and each had a fleet of fewer than 100 aircraft. This smaller size could provide an interesting comparison to the larger airlines in the ranking, all of which operate fleets of at least 100 aircraft.

Condor, with 7.3 million passengers and 61 aircraft, was chosen over Ethiopian Airlines (8.2 million passengers, 121 aircraft) despite their similar passenger numbers. Condor's efficiency in achieving comparable passenger numbers with fewer aircraft contributed to its high placement (9th) in the Atmosfair Airline Index (AAI).

Eurowings, operating 97 aircraft, was included as it's comparable to Wizz Air (122 aircraft) in terms of fleet size and daily departures. Both are low-cost carriers (LCCs) with similar rankings in daily departures.

TUIfly, the smallest airline in the ranking with just 23 aircraft, was included despite its size due to being a German airline and its exceptional 4th place ranking in the AAI. Its inclusion allows for an interesting comparison between a very small airline and significantly larger carriers.
Skywest Airlines, despite carrying many passengers, was excluded to avoid double-counting aircraft, as most of its fleet operates under Delta Connection or United Express, with Delta Connection already included in the ranking.

This selection process aims to provide a diverse range of airlines for comparison, including both major international carriers and smaller, regional airlines, with a focus on German carriers due to the thesis's origin.

Stating the reasons of picking the last airlines shows, that there could be made an argument for all of them underlining their interchangeability. Therefore, picking three German airlines as the last airlines do not have a major impact on the consistency of the airline ranking.
But it is thus possible, that there were airlines not introduced with more annual passenger carried, more daily departures or a fleet comprising of more aircraft. Most of the airlines are operating a fleet of at least 100 aircraft, but not all airlines with 100 or more aircraft are included. Why each airline was chosen can be traced back in the list of the 50 most important airlines found in Appendix H.

## 4.2 Defining an Airline Label

For each aircraft of an airline with a certain engine type and seating configuration the fuel performance, $CO_2$ equivalent emission mass, local air pollution and local noise level is calculated and conclusively an overall rating (OR) for this specific aircraft is obtained. The foundation of the calculation method was outlined in Chapter 2. This could look like Figure 2.1 for an Airbus A320 equipped with a LEAP-1A26 engine and the standard seating capacity defined by Airbus.

The fleet of an airline is usually comprised of a variety of aircraft types in different number. The Lufthansa fleet shown in Table 4.1 consists of 16 different aircraft types. The individual overall rating for each aircraft type reaches from 4.8 (Boeing 747-400) to 8.44 (Airbus A320 Neo). To determine the environmental performance of an airline it is important to consider how many aircraft of a certain types are used. Ideally, the airline would not use bad performing aircraft types at all, but it certainly makes a difference how many of the good or bad ones are in use. This weighting of an aircraft types is done via (5.1). and the following variables, which are defined as

- $AR$: Airline rating
- $N_{aircraft}$: Number of aircraft type in fleet
- $S_{aircraft}$: Number of seats per aircraft
- $O_{aircraft}$: Overall aircraft rating
- $i$: ID of the aircraft type of an airline

$$AR = \frac{\sum N_{aircraft,i} \cdot S_{aircraft,i} \cdot O_{aircraft,i}}{\sum N_{aircraft,i} \cdot S_{aircraft,i}} \tag{5.1}$$

The fleet data was gathered over a period of time, but checked and updated at 5th of December 2023. The database on www.planespotters.net provided information on the aircraft type and the amount of aircraft of an airline. The sources for every airline fleet are to be found in Appendix I. The installed engine type was also mainly derived from the database on www.planespotters.net. The seating configuration with details like the seat pitch and width as well as the number of seats for each class was mainly derived from www.seatmaps.com and www.seatguru.com. The sources for the aircraft-engine combination and the seating configuration chosen by the airlines for each of their aircraft type is listed in Appendix J.

**Table 4.1** Lufthansa aircraft fleet

| ID (I) | Aircraft type | No. of aircraft (*N*) | Seats per aircraft (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 35 | 138 | 7.38 | 4830 | 35645.4 |
| 2 | Airbus A320-200 | 52 | 168 | 7.31 | 8736 | 63860.16 |
| 3 | Airbus A320 Neo | 35 | 180 | 8.44 | 6300 | 53172 |
| 4 | Airbus A321-100 | 20 | 200 | 7.12 | 4000 | 28480 |
| 5 | Airbus A321-200 | 37 | 200 | 6.93 | 7400 | 51282 |
| 6 | Airbus A321 Neo | 17 | 215 | 8.01 | 3655 | 29276.55 |
| 7 | Airbus A330-300 | 10 | 255 | 5.82 | 2550 | 14841 |
| 8 | Airbus A340-300 | 17 | 279 | 4.32 | 4743 | 20489.76 |
| 9 | Airbus A340-600 | 10 | 297 | 4.39 | 2970 | 13038.3 |
| 10 | Airbus A350-900 | 21 | 293 | 7.08 | 6153 | 43563.24 |
| 11 | Airbus A380-800 | 8 | 509 | 5.03 | 4072 | 20482.16 |
| 12 | Boeing 747-400 | 8 | 317 | 4.8 | 2536 | 12172.8 |
| 13 | Boeing 747-800 | 19 | 364 | 5.36 | 6916 | 37069.76 |
| 14 | Boeing 787-9 Dreamliner | 5 | 294 | 7.53 | 1470 | 11069.1 |
| 15 | Bombardier CRJ-900 | 28 | 79 | 6.42 | 2212 | 14201.04 |
| 16 | Embraer E190LR | 7 | 100 | 6.57 | 700 | 4599 |
| | Total: | 329 | | ∑: | 69243 | 453242.27 |
| | | | | **Airline Rating** | | **6.55** |

## 4.3 Airline Ranking Analysis

The airline rating is calculated for the 50 most important airlines worldwide (Appendix H). The number and type of every aircraft with its number of seats and the corresponding airline rating for every airline is listed in Appendix K analog to Table 4.1. The results were then sorted and are presented in Table 4.2.

**Table 4.2** Airline ranking calculated via the aircraft and airline label

| Ranking | Airline | Airline Rating |
|---|---|---|
| 1 | IndiGo | **8.18** |
| 2 | SAS Scandinavian Airlines | **7.86** |
| 3 | Spring Airlines | **7.79** |
| 4 | easyjet (UK) | **7.78** |
| 5 | Spirit Airlines | **7.78** |
| 6 | Azul | **7.72** |
| 7 | TUIfly | **7.51** |
| 8 | vueling Airlines | **7.50** |
| 9 | Avianca | **7.48** |
| 10 | Ryanair | **7.33** |
| 11 | Eurowings | **7.31** |

| | | |
|---|---|---|
| 12 | LATAM Airlines Brasil | **7.26** |
| 13 | GOL Linhas Aereas | **7.26** |
| 14 | Shandong Airlines | **7.26** |
| 15 | Xiamen Airlines | **7.23** |
| 16 | Air New Zealand | **7.21** |
| 17 | WestJet Airlines | **7.20** |
| 18 | Sichuan Airlines | **7.20** |
| 19 | Southwest Airlines | **7.17** |
| 20 | American Airlines | **7.13** |
| 21 | Air India | **7.12** |
| 22 | China Southern Airlines | **7.11** |
| 23 | Shenzhen Airlines | **7.06** |
| 24 | Air Canada | **7.06** |
| 25 | Hainan Airlines | **7.04** |
| 26 | JetBlue Airways | **7.00** |
| 27 | China Eastern Airlines | **7.00** |
| 28 | Vietnam Airlines | **6.99** |
| 29 | Aeroflot | **6.82** |
| 30 | Condor | **6.76** |
| 31 | Air China | **6.73** |
| 32 | Japan Airlines | **6.73** |
| 33 | Air France | **6.73** |
| 34 | Alaska Airlines | **6.72** |
| 35 | Turkish Airlines | **6.66** |
| 36 | Delta Airlines | **6.66** |
| 37 | KLM | **6.65** |
| 38 | All Nippon Airways | **6.65** |
| 39 | Saudi Arabian Airlines | **6.61** |
| 40 | Lufthansa | **6.55** |
| 41 | Qatar Airways | **6.53** |
| 42 | United Airlines | **6.47** |
| 43 | Garuda Indonesia | **6.43** |
| 44 | British Airways | **6.36** |
| 45 | Korean Air | **6.35** |
| 46 | Qantas | **6.33** |
| 47 | Cathay Pacific | **6.23** |
| 48 | Delta Connection | **6.20** |
| 49 | Singapore Airlines | **6.10** |
| 50 | Emirates | **5.47** |

Low-cost carrier IndiGo leads the airline ranking by a significant margin compared to its competitors. The airline's fleet includes five different aircraft models, with more than half of its fleet consisting of Airbus A320 Neos. These aircraft, configured with a single class seating arrangement, boast an impressive Efficiency Rating (AR) of 8.65, representing the largest fleet of Airbus A320 Neos among the airlines considered. The second most common aircraft in IndiGo's fleet is the Airbus A321 Neo, which also achieves a strong rating of 7.71 and constitutes over a quarter of the fleet.

At first glance, it might appear that IndiGo's high ranking is due to its modern aircraft. However, other airlines with similarly modern fleets do not achieve the same ranking, suggesting there may be additional factors at play. Notably, IndiGo operates a substantial number of ATR 72s, more than any of the 50 airlines reviewed. The ATR 72's AR is higher than that of the Airbus A321 Neo and nearly matches the rating of the Airbus A320 Neo.

A comparison of the aircraft labels in Table 4.3 highlights that while the more modern Airbus A320 Neo offers superior fuel performance and quieter operation compared to the ATR 72, the ATR 72 excels in $CO_2$ equivalent emissions, outperforming the Airbus A320 Neo in this category.

**Table 4.3** Comparison of the Airbus A320 Neo and the ATR 72 of indiGO

| | Airbus A320 Neo (indiGo) | ATR 72 (indiGo) |
|---|---|---|
| Fuel performance (kg/km/seat) | 0.0192 | 0.0277 |
| Local noise level in (EPNdB/EPndB) | 0.891 | 0.949 |
| $CO_2$ equivalent emissions (kg/km/seat) | 0.238 | 0.083 |
| Local air pollution (g/kN) | 23.6 | n/a |

The turbofan-powered Airbus A320 Neo flies at altitudes approximately three times higher than the turboprop-powered ATR 72. As a result, the impact of aviation-induced cloudiness (AIC) on $CO_2$ equivalent emissions is significantly reduced for the ATR 72 compared to the Airbus. IndiGo's largest aircraft, the Boeing 777-300ER, has the lowest rating of 7.11 among their fleet. However, since only two of these wide-body aircraft are in operation, their impact on the overall fleet rating is minimal.

A similar pattern emerges with the second-ranked airline, SAS Scandinavian Airlines. Like IndiGo, SAS primarily uses the Airbus A320 Neo, though their version has a slightly lower rating due to having fewer seats – SAS manages six fewer seats per aircraft compared to IndiGo. They also operate the ATR 72, which has a marginally lower rating due to accommodating eight fewer seats than IndiGo's ATR 72s. However, the ATR 72s, making up only 8 % of their fleet, have a minimal impact on the overall rating. Notably, SAS's seating configurations are more spacious compared to those of IndiGo, reflecting a more generous seating arrangement across their aircraft.

Low-cost carriers generally benefit from operating a single-class seating configuration, which contributes to their strong performance in the ranking. This trend is evident among the airlines in the next positions: Spring Airlines (7.79), easyJet (UK) (7.78), and Spirit Airlines (7.78), which are closely grouped together. Each of these airlines primarily utilizes the Airbus A321 Neo, the largest aircraft in their fleets, which is also configured with a single-class layout. This configuration highlights that both small and modern aircraft contribute to achieving a high AR.

Azul Brazilian Airways, while categorized as a low-cost carrier, operates a diverse fleet that includes larger aircraft like the Airbus A330 and A350, which feature a multi-class layout. However, these wide-body aircraft make up less than 7 % of their fleet. The airline's strong AR is primarily driven by its most common aircraft, the Airbus A320 Neo, as well as the Embraer E195-E2, which boasts an impressive rating of 8.32. Additionally, Azul operates a substantial fleet of ATR 72s, with 39 units, achieving a very high AR. Despite the presence of larger, multi-class aircraft, Azul's extensive use of modern and efficient aircraft like the A320 Neo and ATR 72 contributes significantly to its overall excellent performance.

TUIfly's fleet consists of only two aircraft models, both of which are modern and efficient, contributing to its strong rating. Notably, TUIfly (7.51) and TUI Airways (7.55) exclusively operate Boeing aircraft. Although Airbus introduced its next-generation aircraft slightly earlier, leading to a larger number of Airbus A320 Neos (861) compared to Boeing 737 MAX 8s (692) in the reference group of 50 airlines, Boeing variants exhibit slightly better fuel consumption, as detailed in Appendix B. Despite this, the top-ranked airlines in the study predominantly operate Airbus next-generation aircraft, with none featuring Boeing models among the highest performers.

Most airlines operating the Airbus A320 Neo use either the CFM International LEAP-1A26 engine (120.6 kN) or the Pratt & Whitney PW1127G engine. In contrast, Boeing 737 MAX 8 operators typically equip their aircraft with the LEAP-1B27 (124.7 kN) or LEAP-1B28 (130.4 kN) engines. Notably, the LEAP-1A27 engine is not listed in the AEED database.

For a fair comparison, the LEAP-1A26 and LEAP-1B25 engines were selected, with the latter providing a slight advantage to the Boeing due to its lower thrust value. However, it's important to note that Boeing 737 MAX 8s are generally equipped with engines offering more thrust than their competitors, which may partly explain why no Boeing next-generation aircraft appear in the top rankings.

Another factor affecting the comparison is the availability of data. The database on www.planespotters.net often lacks specific engine details, listing only general types such as LEAP-1B. In such cases, a "mean value engine" with a thrust of 123.3 kN – calculated from various LEAP-1B variants (LEAP-1B21 to LEAP-1B28)—was used for comparison. Airlines operating with less common variants like the LEAP-1B25 (119.2 kN) may face a slight disadvantage, though few airlines use this variant. Conversely, airlines equipped with more common LEAP-1B28 engines enjoy a comparative advantage.

Table 4.4 compares the rating categories of an Airbus A320 Neo with 174 passengers (operated by Azul) and a Boeing 737 MAX 8 with 172 passengers (operated by American Airlines). While their fuel performance and noise levels are quite similar, the Boeing 737 MAX 8 produces higher CO2 equivalent emissions and has a greater impact on air quality around airports.

**Table 4.4** Comparison of Airbus A320 Neo (Azul) and Boeing 737 MAX 8 (American)

| | **Airbus A320 Neo (LEAP-1A26)** | **Boeing 737 MAX 8 (LEAP-1A25)** |
|---|---|---|
| Thrust (kN) | 120.6 | 119.2 |
| Fuel performance (kg/km/seat) | 0.0206 | 0.0198 |
| Local noise level in (EPNdB/EPndB) | 0.891 | 0.916 |
| $CO_2$ equivalent emissions (kg/km/seat) | 0.254 | 0.333 |
| Local air pollution (g/kN) | 23.6 | 43.4 |
| **Contributions to equivalent $CO_2$ (g/kN)** | | |
| $CO_2$ | 0.065 | 0.0626 |
| $NO_x$ | 0.0788 | 0.1655 |
| AIC | 0.1106 | 0.1047 |

This suggests that the LEAP-1B engine variants emit significantly more nitrous oxide compared to the Airbus LEAP-1A engines, as evidenced by the more than double amount of NOx per kN shown in Table 4.4. This higher NOx emission likely explains why no airlines using next-generation Boeing aircraft appear in the top rankings.

Vueling Airlines operates exclusively narrowbody Airbus aircraft with a single-class seating configuration, which contributes to its high rating. Similarly, Avianca's fleet is predominantly composed of Airbus aircraft, though it includes a relatively small number of Boeing 787-8s. Despite these wide-body aircraft having the lowest rating within Avianca's fleet, their impact is minimal, as their rating remains fairly good at 6.92.

Ryanair, on the other hand, operates solely Boeing aircraft. The low-cost carrier model, characterized by small, relatively new aircraft with single-class seating, also results in a high rating for Ryanair. Given that low-cost carriers (LCCs), as detailed in Appendix H, generally exhibit similar benefits, they will not be discussed further unless there are additional noteworthy aspects specific to the airline.

Examining the lower end of the ranking reveals notable insights, particularly with Emirates, which ranks at the bottom. A significant portion of their fleet comprises Boeing 777-300ERs, which already have a relatively low Aircraft Rating (AR) of 6.11. However, the primary factor contributing to their poor overall rating is their substantial fleet of Airbus A380s, which has an even lower AR of 5.04.

To contextualize this, the average AR for all aircraft types is 6.84. The A380's rating is notably worse than that of both Boeing 747s, which have historically been less efficient, with mean AR values shown in Table 4.5. In fact, the Airbus A380-800's mean AR is lower than both Boeing 747 models, and only the Airbus A340s, which are exclusively operated by Lufthansa, have a worse rating. Consequently, Lufthansa's unique position as the sole operator of all four of these aircraft types significantly impacts their overall AR, highlighting the challenges associated with operating older and less efficient aircraft.

**Table 4.5** Mean AR rating of aircraft with four engines

| | **Airbus A380-800** | **Boeing 747-400** | **Boeing 747-800** | **Airbus A340-300** | **Airbus A340-600** |
|---|---|---|---|---|---|
| Mean value | 4.7 | 4.77 | 5.38 | 4.32 | 4.39 |

The disparity between the Airbus A380-800 and the Boeing 747-400 might be influenced by differences in seating configuration. Preliminary comparisons indicate that the A380 generally emits more nitrous oxide. Although fuel consumption per seat per kilometer is similar for both aircraft and the local noise level of the 747 is slightly higher, the A380 shows increased $CO_2$ equivalent emissions and local air pollution. This observation is based on initial assumptions and merits further investigation.

All of the worst aircraft types displayed in Table 4.5 have four engines indicating that they have a worse environmental performance than aircraft with two engines.

Singapore Airlines, with a rating of 6.1, ranks just above Emirates at 5.47. A significant factor in their lower rating is their seating configuration, which is notably generous. For instance, the Airbus A350-900 typically accommodates over 330 passengers, as seen with Sichuan Airlines. However, Singapore Airlines operates the A350-900ULR with only 161 seats, achieving an Aircraft Rating (AR) of 4.42. Their standard A350 configuration, seating 253 passengers, has a higher AR of 6.64. Additionally, the presence of a substantial number of Airbus A380s (AR: 4.65) and Boeing 777-300ERs (AR: 4.96) further impacts their overall rating.

Delta Connection, a regional airline operating solely Bombardier and Embraer aircraft, faces challenges with fuel efficiency compared to its Airbus and Boeing counterparts. As shown in Appendix B, the Airbus A319 achieves a fuel consumption of 0.0288 kg/km/seat, while a relatively older Boeing 737-300 reaches 0.0307 kg/km/seat. In contrast, Delta Connection's aircraft have higher fuel consumption rates, ranging from 0.0360 kg/km/seat for the Bombardier CRJ200LR to 0.0417 kg/km/seat for the Embraer E175. Although fuel consumption is just one aspect of the Airline label, the consistently lower performance of Delta Connection's fleet in this area contributes to its overall poor rating.

## 4.4 Comparison with Atmosfair Airline Index

Only airlines with a fleet over 100 aircraft are considered for the comparison with the AAI. A ranking of these airlines is listed in Appendix G.

Initial comparisons between the AAI and the airline ranking reveal few similarities. For instance, LATAM Airlines Brazil, the top-ranked airline in the AAI, only places 12th in the ranking. However, it is important to note that the AAI evaluates low-cost carriers (LCCs) differently from full-service carriers (FSCs). When this distinction is accounted for, LATAM Airlines Brazil ranks 3rd, just behind SAS Scandinavian Airlines and Avianca. Similarly, Air New Zealand, ranked 2nd by the AAI, corresponds to 6th place, and Avianca, ranked 5th by the AAI, holds 1st place. Generally, airlines that perform well in the AAI also perform well in the ranking, while those with poor environmental performance, such as Emirates and Delta Connection, similarly rank poorly.

There are some notable exceptions, such as SAS Scandinavian Airlines. Despite being the top performer in the airline ranking, it falls to the lower end of the AAI, ranked 32nd. This discrepancy highlights that the airline label assesses the potential of an airline based on its fleet rather than its actual operational performance. The lower ranking in the AAI indicates that SAS Scandinavian Airlines might have room to improve the efficiency of its aircraft operations.

The discrepancy between the AAI and the current airline ranking can be attributed to the changes in fleet composition over time, as exemplified by SAS Scandinavian Airlines. While the AAI is based on data from 2018, the current ranking uses fleet data from 2024. In 2018, SAS Scandinavian Airlines operated only 12 Airbus A320 Neos, but by 2024, their fleet has expanded to 36 of these aircraft. Additionally, they have introduced 3 Airbus A321 Neos and 3 Airbus A350-900s, which were not part of their fleet in 2018. This significant shift in fleet composition likely contributes to the differences observed in the rankings. Since airlines have a financial incentive to operate their fleets efficiently, it can be argued that improvements in fleet composition generally reflect an airline's potential for better environmental performance.

Both airline rankings highlight the importance of seating configurations. It is very noticeable that FSCs do perform worse than LCCs. FSCs are expected to offer a multi class layout even on short range flights. A tightly packed Airbus A320 Neo could achieve a rating of 8.65 (easyjet), whereas a multi class Airbus A320 Neo with eight business seats only achieves a rating of 8.04 (All Nippon Airways). The complexity of operating multiple different aircraft usually also translates to worse efficiency.

One key difference between both rankings is the consideration of a different possible efficiency depending on the distance of the flight, which is illustrated at Figure 3.7. But since our airline label does not consider actual flight data, this is not an issue. This only means, that for example regional airlines and airlines with a lot of long haul flights would perform even worse in the AAI, which has to be kept in mind.

## 4.5 Limitations of the Airline Label

The systematics of environmental information for aviation passengers was summarized by Velasco (2020):

> *The ecolabel is thought to be an image that, with a quick glance, gives information about the efficiency of an aircraft; an excess of information would worsen its comprehension.*

Because of the nature of an environmental label it cannot include everything. It just has to display the most important data, which is described by the four categories: fuel performance, $CO_2$ equivalent emissions, local noise level and local air pollution defined in Chapter 2.

Since an airline ranking was created, it has to be compared with existing ones, which are described in more detail in Chapter 3.2. The most common DEA based airline rankings were just tools to determine the financial performance of an airline traditionally. But they evolved in measuring some environmental aspects of an airline to. Because of their history, they are really good at comparing the actual performance of an airline especially with operational variables, like (including, but not exclusive):

- Available seat kilometers (ASK)
- Available freight ton kilometers (AFTK)
- Revenue passenger kilometers (RPK)
- Revenue freight ton kilometers (RFTK)

These are some of the inputs and outputs of the most recent NDEA study (Yu 2023) to determine the technical, pure technical and scale efficiency of 29 airlines, which are not considered by the proposed airline label. ASK and AFTK are actually called “intermediate variables”, because this is the more advanced Network DEA considering a multi stage framework.

ASKs are a measure of an airline’s carrying capacity to generate revenue, obtained by multiplying the available seats on any given aircraft by the number of kilometers flown on a given flight. Broadly speaking: they describe the potential of an airline. RPKs are calculated by multiplying the number of paying passengers by the distance travelled. They describe the actual performance of an airline answering the question how well they used their potential. The same logic applies to AFTKs and RFTKs.

This is also described as the passenger/freight load factor, which is not considered by the airline label. This means, that the airline ranking in Chapter 4.3 shows off the **potential of an airline** not their actual performance. As already mentioned, an environmental label cannot include everything. This also applies to the carried freight of an airline, which is of course affecting the environment but is not considered by the airline label. Airlines also use different seating configurations for the same aircraft model, but the Airline Ranking just uses the seating configuration used most by the airline for practical reasons.

Yu (2023) also considered fleet size, employee headcount, the fuel consumed and carbon emissions emitted to calculate a scale efficiency to determine how well an airline is managing their resources.

Table 4.6 presents the technical and scale efficiency rankings as calculated by Yu (2023). Hainan Airlines stands out with top positions in both categories, demonstrating strong performance in utilizing their potential. Scandinavian Airlines and Aeroflot also perform well across both metrics, indicating effective use of their capabilities.

Incorporating these efficiency scores with the airline label— which assesses the potential of an airline— could provide valuable insights into how well airlines use their potential. Given Scandinavian Airlines' high performance in both rankings, it is likely to rank prominently if such a combined assessment were conducted. Hainan Airlines and Aeroflot, currently positioned midfield in the airline label ranking, would likely improve their standings with their impressive efficiency scores.

Surprisingly, Emirates performs well in the efficiency rankings, securing 5th place in technical efficiency and 9th in scale efficiency. This suggests that Emirates would not occupy the last position in a new ranking incorporating these efficiency metrics. Conversely, Air France shows a strong 7th place in scale efficiency but struggles with a lower 26th place in technical efficiency, highlighting the intricate and multifaceted nature of airline rankings.

**Table 4.6** Technical and scale efficiency of different airlines (Yu 2023)

| Airline | Technical efficiency | Scale efficiency |
|---|---|---|
| Scandinavian Airlines | 0.967 (4th) | 0.999 (2nd) |
| Lufthansa | 0.682 (17th) | 0.698 (25th) |
| Finnair | 0.978 (3rd) | 0.996 (3rd) |
| Aeroflot | 0.979 (2nd) | 0.979 (6th) |
| KLM | 0.773 (11th) | 0.884 (17th) |
| British Airways | 0.638 (20th) | 0.825 (20th) |
| LATAM Airlines | 0.889 (9th) | 0.993 (4th) |
| United Airlines | 0.607 (25th) | 0.607 (28th) |
| American Airlines | 0.608 (24th) | 0.608 (29th) |
| Air China | 0.660 (18th) | 0.789 (23rd) |
| Cathay Pacific Airways | 0.732 (13th) | 0.865 (18th) |
| Singapore Airlines | 0.720 (15th) | 0.791 (22nd) |
| All Nippon Airways | 0.612 (22nd) | 0.896 (16th) |
| China Eastern Airlines | 0.468 (29th) | 0.801 (21st) |
| Japan Airlines | 0.611 (23rd) | 0.933 (12th) |
| EVA Air | 0.748 (12th) | 0.946 (10th) |
| Thai Airways | 0.606 (27th) | 0.915 (13th) |
| Garuda Indonesia | 0.723 (14th) | 0.908 (14th) |
| Qantas Airways | 0.691 (16th) | 0.756 (24th) |
| Air France | 0.607 (26th) | 0.967 (7th) |
| China Southern Airlines | 0.629 (21st) | 0.692 (26th) |
| Air Canada | 0.815 (10th) | 0.857 (19th) |
| Air Mauritius | 0.906 (8th) | 0.906 (15th) |
| Icelandair | 0.652 (19th) | 0.652 (27th) |
| Emirates | 0.951 (5th) | 0.951 (9th) |
| Shandong Airlines | 0.516 (28th) | 0.963 (8th) |
| Hainan Airlines | 1.000 (1st) | 1.000 (1st) |
| Aer Lingus | 0.933 (6th) | 0.987 (5th) |
| Bangkok Airways | 0.933 (7th) | 0.933 (11th) |

# 5 Flight Booking Engines

## 5.1 Literature Review

A basic search for "flight booking engines" in the title, abstract, or keywords on Elsevier's Scopus database yielded only 22 results. Most of the existing literature focuses on financial aspects and optimizing algorithms (often with artificial intelligence) to identify the cheapest flights. However, one notable study diverges from this trend by exploring how booking platforms can promote lower-emissions air travel by providing consumers with information about the carbon emissions of different flight options. This study, which surveyed 450 employees at the University of California, found that there is

> *[...] an impressive rate of willingness to pay for lower-emissions flights: around $200/ton of CO2e saved, a magnitude higher than that seen in carbon offsets programs, and consistent with findings from a prior study with a non-university-based sample (Sanguineti 2021).*

There appears to be significant potential in encouraging consumers to choose greener air travel. A Boolean search combining "flight booking engines" with "environmental information" (refer to Table 5.1) yields just one relevant result: the aforementioned survey.

**Table 5.1** Keywords for first systematic literature review in Elsevier´s Scopus

| Keyword 1 | Operator | Keyword 2 |
|---|---|---|
| (flight AND booking AND engine) | AND | (environmental information) |

## 5.2 Google Flights

Given that Google is by far the leading desktop search engine worldwide (Statista 2024), its flight booking search service will be used as a benchmark to review flight booking engines, specifically focusing on their data related to environmental impact, ticket prices, and travel times.

The initial search result, as shown in Figure 5.1, presents the following flight information across five columns:

- time of day for the flight
- name of the airline
- duration of the flight
- number of stops
- environmental information
- price


**Figure 5.1** Initial search result of Google Flights for a flight from Berlin to Los Angeles

It is important to note that in the initial search results, the environmental information is presented with a significance comparable to other key details such as flight time, duration, and the number of stops. The only exception is the price, which stands out as it is displayed in bold digits, indicating its primary importance. The environmental information includes the total amount of so-called lifecycle greenhouse gas emissions, expressed as $CO_2e$. This figure is compared to a typical $CO_2e$ amount for the selected route. If a flight has lower emissions than the typical value, this information is highlighted in green. Conversely, if the emissions are higher, the data is not highlighted. Google also provides an option to filter out flights with emissions worse than the reference level from the search results. Additionally, users can access more detailed information about the flight (see Figure 5.2), which includes:

- time of the day for the individual flights
- name of the airline for the individual flights
- travel class
- aircraft model
- flight number
- duration of the individual flights
- in-flight service information
- environmental information for the individual flights

The emissions for each flight are estimated and displayed, but they now appear on the last line, following details about in-flight services such as legroom and Wi-Fi availability. This positioning suggests that while environmental information is provided, it is given less prominence compared to other factors. In the next chapter, the methodology used to calculate these lifecycle greenhouse emissions will be thoroughly investigated.

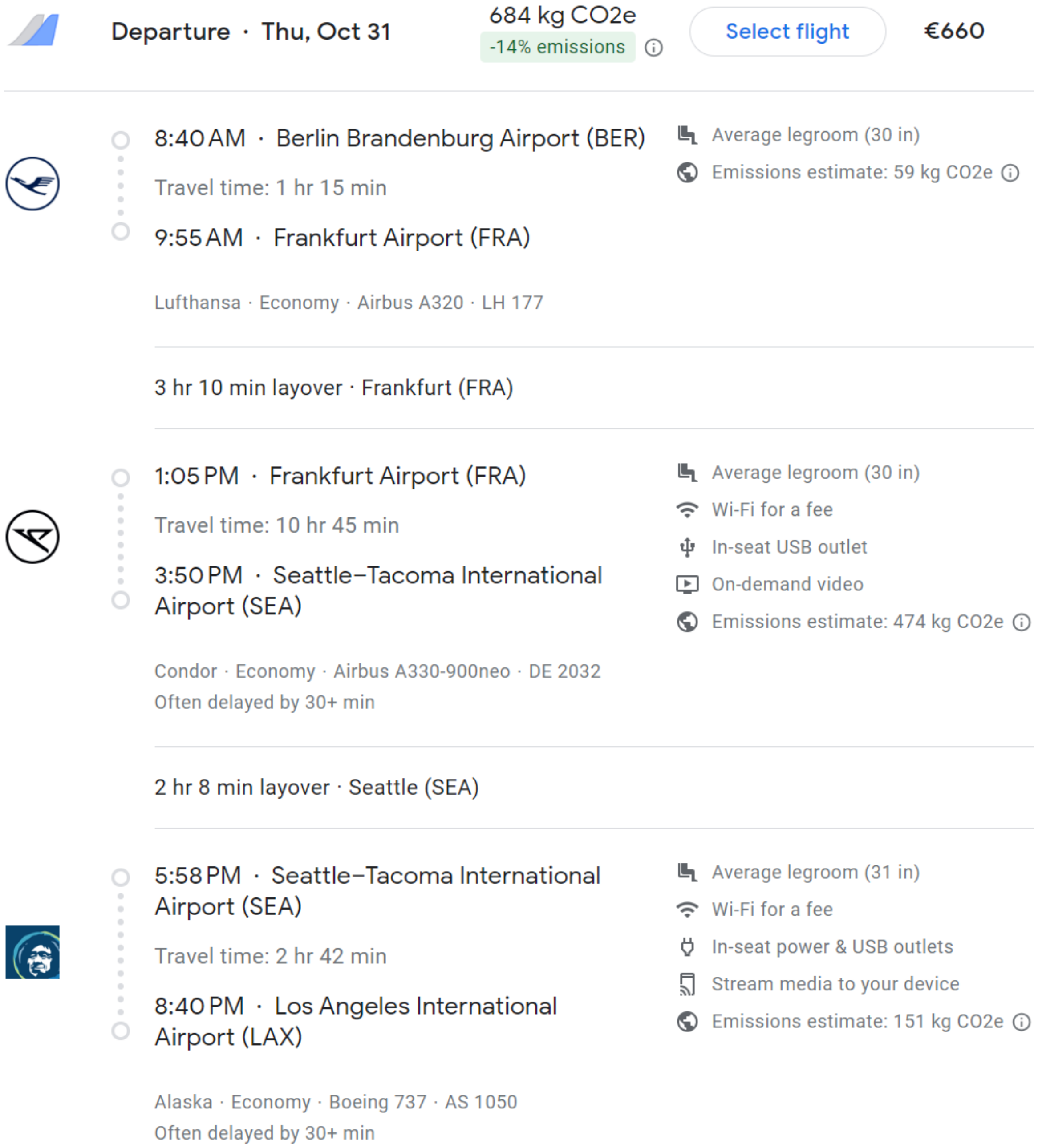


**Figure 5.2** Detailed view of the search result for a flight from Berlin to Los Angeles

## 5.3 Travel Impact Model

The emissions are estimated using the Travel Impact Model (TIM), developed under the guidance of Dr. Dan Rutherford, the Aviation Program Director at the International Council on Clean Transportation (ICCT). Dr. Rutherford is also the author of the airline ranking discussed earlier in Chapter 3.3.1, which is the most basic airline ranking presented in thesis. The TIM considers the following factors when estimating emissions:

- aircraft-specific fuel burn for take off and landing (LTO) stage
- aircraft- and distance-specific (great circle) fuel burn for cruise, climb and descend (CCD) stage
- life cycle $CO_2$ emissions
- travel class
- route-specific load factors based on historical passenger statistics

The Travel Impact Model (TIM) version 1.9.0 is based on the Tier 3 methodology for emission estimates as outlined in the Annex 1.A.3.a Aviation 2019 by the European Environment Agency (EEA). The calculation of fuel burn is primarily conducted using the EEA Master Emissions Calculator, as previously discussed by Hurtecant (2021). Emissions are categorized as:

- Well-to-Tank (WTT) Emissions: Emissions produced during the production, processing, handling, and delivery of jet fuel.
- Tank-to-Wake (TTW) Emissions: Emissions generated from burning jet fuel during flight, take-off, and landing.

The combined WTT and TTW emissions are referred to as Well-to-Wake (WTW) Emissions. This total fuel burn is then converted into $CO_2$ emissions using a conversion factor of 3.1894.

However, TIM displays the $CO_2$ *equivalent* ($CO_2e$) emissions rather than just $CO_2$, aiming to inform consumers about the global-warming potential (GWP) of various greenhouse gases. Tier 3 calculations include emissions of carbon monoxide (CO), hydrocarbons (HCs), carbon dioxide ($CO_2$), water vapor ($H_2O$), nitrous oxide ($NO_x$), and sulfur oxides ($SO_x$), along with particulate matter. The specific method for calculating these emissions is not fully detailed in Annex 1.A.3.a Aviation 2019. The model's limitation in not considering Aircraft-Induced Cirrus (AICs) is acknowledged, with plans to address this issue in future updates.

## 5.4 Discussion of other Flight Booking Engines

Determining a reference group for flight booking engines is challenging due to the complex and ever-evolving nature of the online air travel market. Each year, new rankings for the best flight booking engines are published, highlighting the fluidity and variety in this sector. As discussed in Chapter 5.1, there is a notable lack of comprehensive data on flight booking engines. Conducting a detailed analysis to establish a reference group would exceed the scope of this thesis. Consequently, this study will focus on a selection of flight booking engines rather than attempting an extensive analysis.

### 5.4.1 Route Rank

Route Rank does not display environmental information in the initial search results. However, when viewing the details of a specific flight, the platform provides the $CO_2$ emissions associated with that flight, as illustrated in Figure 5.3.

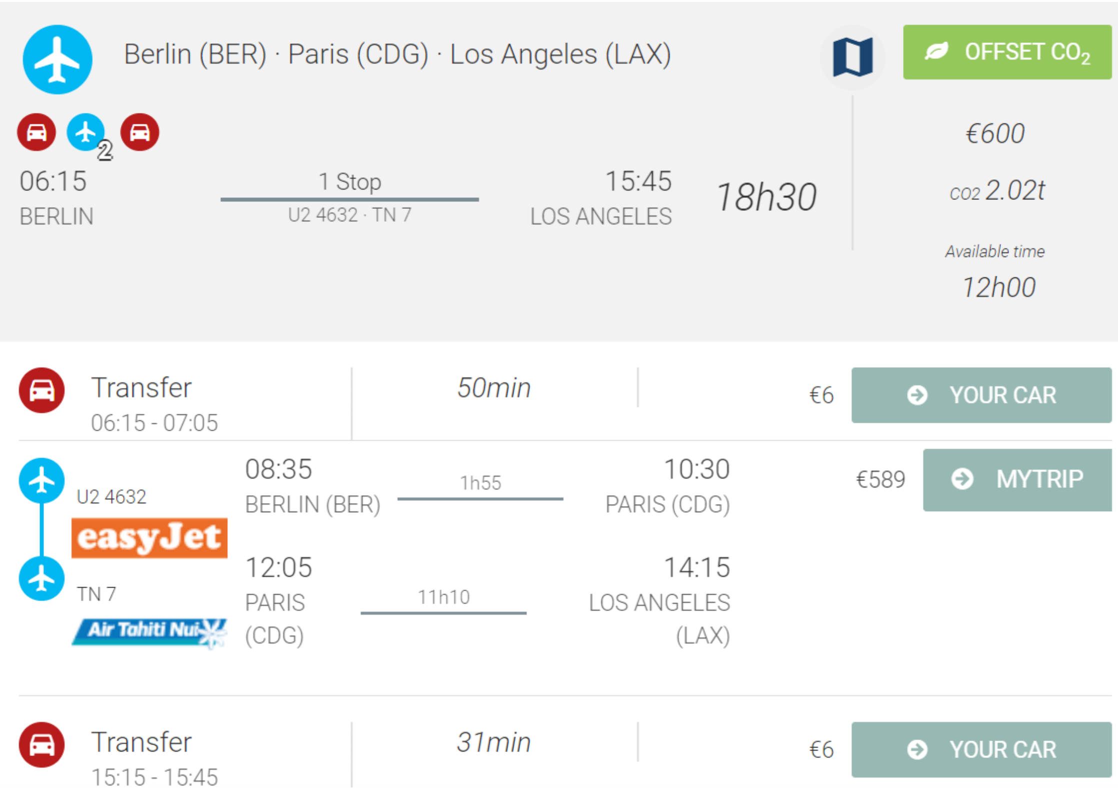


**Figure 5.3** Detailed search result of Route Rank for a flight from Berlin to Los Angeles

Users even have the option to offset their $CO_2$ emissions via www.myclimate.org, which provides detailed information on its calculation methodology, summarized in Figure 5.4. The methodology used by myclimate.org is quite similar to the one employed by Google Flights' TIM.

While TIM calculates load factors based on historical passenger data, myclimate.org differentiates between short-haul (<1500 km) and long-haul flights (>2500 km), with interpolated factors for distances between 1500 and 2500 km in order to achieve a smooth transition. Additionally, it includes an extra mileage/distance correction (DC) of 95 km, as recommended by the European standard DIN EN 16258 (2012), to account for the longer actual distances flown compared to the direct airport-to-airport distance. These examples illustrate minor technical differences between the methods.

However, the key distinction lies in their approaches to calculating non-$CO_2$ effects. Myclimate.org uses the Radiative Forcing Index (RFI) recommended by Lee (2021), which measures the overall climate impact of aviation, including non-$CO_2$ effects. This multiplier, which was previously set at 2, has been increased to 3 in the latest myclimate calculations.

Table 5.2 compares the $CO_2$ equivalent emissions for a flight from London to New York as calculated by both models. The calculation by the TIM model results in a figure only slightly more than one-third of the total calculated by myclimate.org. This discrepancy suggests that the non-$CO_2$ effects considered by TIM are relatively low, given that TIM does not consider AIC.

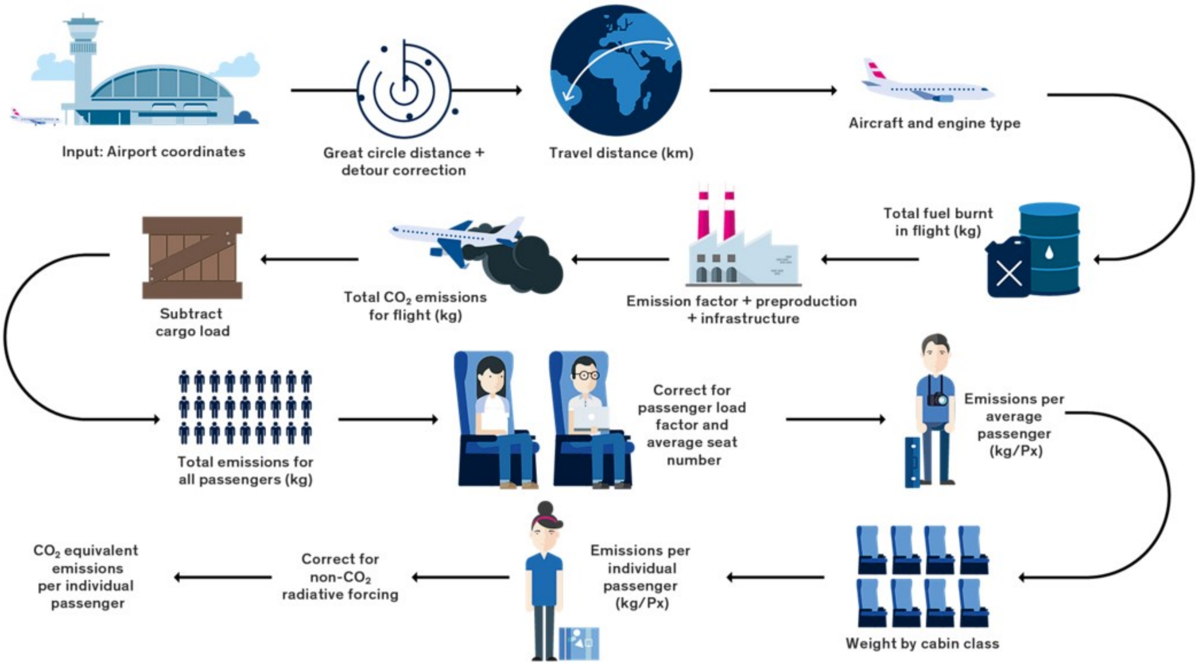


**Figure 5.4** Overview of the calculation steps of my climate (My Climate 2024)

## 5.4.2 Fly Green

The initial search results of the different flight booking engines look fairly similar in displaying price, time, duration and environmental information. Fly Green however does even recommend not to take certain flights, as can be seen in Figure 5.5.


**Figure 5.5** initial search result of Fly Green for a flight from Berlin to Los Angeles

The detailed view of the flight shown in Figure 5.6 provides information about the "ecological footprint", which is described by the amount of equivalent $CO_2$ emissions for each flight and the whole flight.

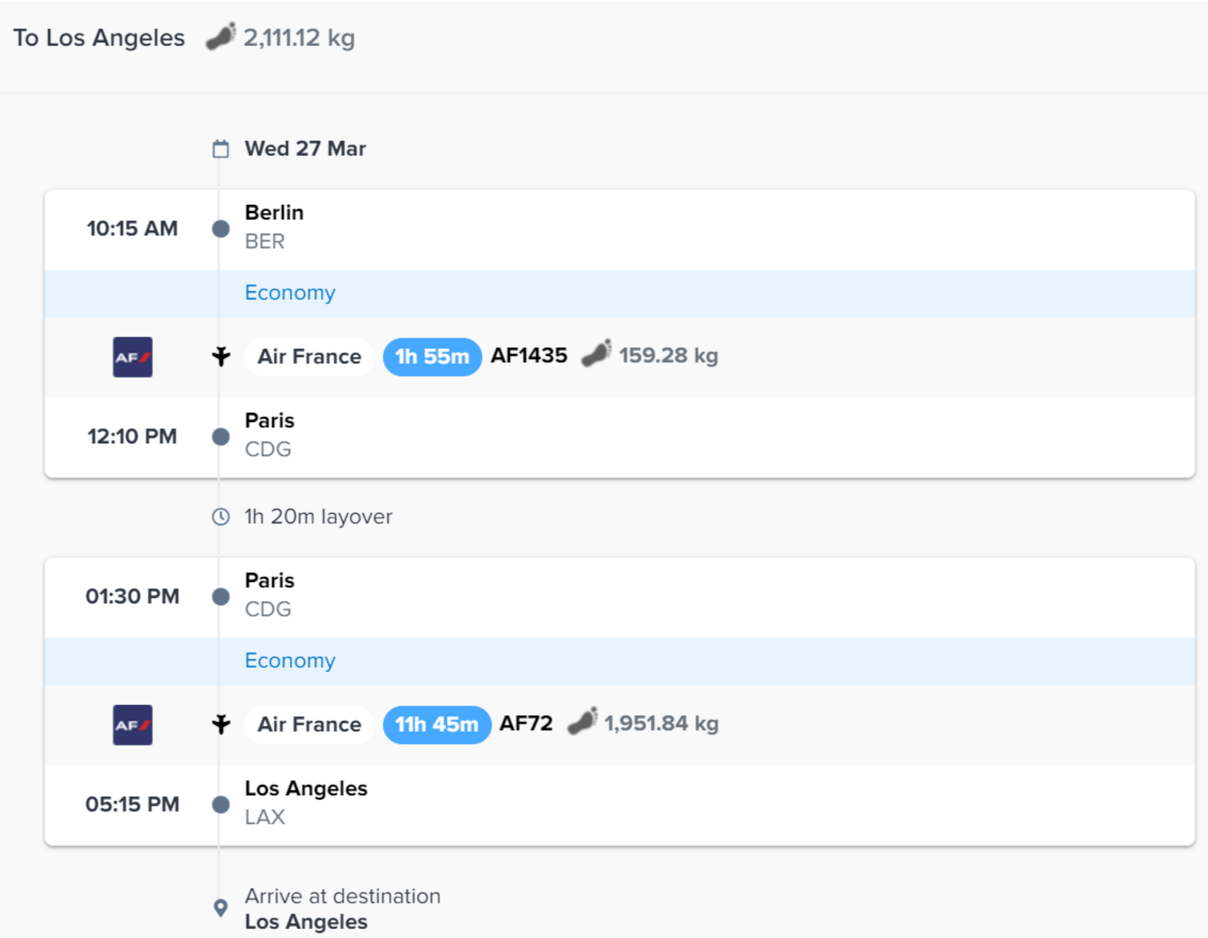


**Figure 5.6** Detailed search result of Fly Green for a flight from Berlin to Los Angeles

The calculation methodology of Fly Green is based on the non-profit organization Atmosfair. Fly Green claims, that their emissions calculator is considered one of, if not the best.

A review of the calculation methodology reveals that it closely aligns with the previously mentioned models, with only minor differences. For instance, Atmosfair accounts for taxiing (the movement of an aircraft on the ground under its own power) by estimating 2.5 kg of kerosene per passenger. Additionally, fuel consumption is adjusted for air resistance and engine weight.

However, a more significant difference is Atmosfair's inclusion of engine performance through an engine factor. This factor is influenced by the specific fuel consumption (SFC) **and** $NO_x$ emissions. The engine factor can be smaller, equal or bigger than one. This depends on the performance of an aircraft in comparison to the other engines used for an aircraft type. The critical role of $NO_x$ emissions, as discussed in Chapter 2.5.2, underscores the importance of this factor.

Non-$CO_2$ emissions are only calculated for altitudes **above 9000 m**. Since a short-haul flight of 400 km usually does not reach this altitude, non-$CO_2$ emissions are not calculated for such flights. For flights that do reach this altitude, the $CO_2$ emissions above 9000 meters are multiplied by a factor of 3, which is then added to the $CO_2$ emissions of the entire flight to estimate the non-$CO_2$ emissions. The factor of 3 is derived from a conservative, quantitative-qualitative average of two metrics: the global warming potential (GWP) over a 100-year time horizon (as per the UNFCCC convention) and the Radiative Forcing Index (RFI) (Atmosfair 2021). The combined $CO_2$ and non-$CO_2$ emissions are then displayed by the Atmosfair emissions calculator. In comparison, the Atmosfair methodology offers the most detailed approach for assessing the environmental impact of a flight.

The different methodologies were applied to calculate the equivalent $CO_2$ emissions for a direct flight from London to New York on a Boeing 787-9, as shown in Table 5.2. Myclimate estimates the highest $CO_2$ equivalent emissions, likely because it uses a factor of 3 multiplied by the **total** $CO_2$ emissions to account for non-$CO_2$ emissions. The lowest emissions are calculated by TIM, which does not include the effects of aviation-induced cloudiness (AIC). While TIM does consider other non-$CO_2$ emissions (see Table 5.2), the $CO_2$ mass it calculates represents only roughly a third (37%) of the emissions estimated by myclimate. Given the similarity between the methods, this suggests that TIM's non-$CO_2$ emissions account for just 4% of myclimate's total estimate, which appears low, especially since $NO_x$ emissions are included.

Atmosfair estimates 904 kg of $CO_2$ equivalent emissions, about 82% of myclimate's estimate. This discrepancy might be due to Atmosfair's method of only accounting for non-$CO_2$ emissions above 9000 meters, whereas myclimate applies a factor of 3 to the total $CO_2$ emissions to estimate non-$CO_2$ effects.

**Table 5.2** Comparison of $CO_2$ equivalent emissions calculated by TIM and my climate for a flight from London (GB), LGW to New York (USA), JFK with a Boeing 787-9 in travel class economy (Z0 701)

| **Calculation methodology** | **Environmental information** | **Average $CO_2$ equivalent emissions mass** | **$CO_2$ equivalent emissions mass of a Boeing 787-9** |
|---|---|---|---|
| Travel Impact Model (Google Flights) | $CO_2$, $NO_x$, $SO_x$, CO, HCs, $H_2O$, PM | 461 kg | 408.7 kg[4] |
| My climate (Route Rank) | $CO_2$ plus non-$CO_2$ effects including **AIC** via RFI factor of 3 | - | 1.100 kg[5] |
| Atmosfair (Fly Green) | $CO_2$ plus non-$CO_2$ effects including **AIC** via GWP100 factor of 3 | $CO_2$ equivalent: 1600 kg<br>$CO_2$: 551 kg<br>Contrails, ozone formation, other: 1049 kg | $CO_2$ equivalent: 904 kg[6]<br>$CO_2$: 311 kg<br>Contrails, ozone formation, other: 593 kg |

[4] Google 2024a
[5] My climate 2024a
[6] Atmosfair 2021

## 5.5 Multimodal Trip Score

In Chapter 5, the survey conducted with 450 employees of the University of California was mentioned, which investigated the effects of nudging consumers towards greener air travel (Sanguinetti 2021). This study also analyzed the impact of a flight-search interface that prioritizes carbon emissions information and displays alternatives from multiple regional airports. The study concluded that these actions could potentially save 79 tons of $CO_2$ equivalent emissions annually.

The previous chapter highlighted the significant differences in how environmental information is displayed in flight-search interfaces. For instance, Google Flights already provides a good overview by displaying $CO_2$-equivalent emissions alongside the price or duration of the flight in the initial search results, unlike Route Rank. However, Fly Green does the best job of prioritizing environmental information. In Fly Green, environmental data is highlighted in red or green in the initial search results, along with advice on whether to choose a particular flight. Most importantly, Fly Green ranks search results by environmental impact, placing the cleanest flight at the top. They even go so far as to prevent booking flights with an above-average environmental impact.

In contrast, Google Flights and Route Rank, like many other flight booking engines, sort their search results based on the “best” flight. However, the criteria used to define the "best" flight can be ambiguous. Google ranks departing flights based on a trade-off between price and convenience, considering factors such as duration, number of stops, and airport changes during layovers. Route Rank does not provide information on how it ranks its best options, but it can be assumed that similar parameters to those used by Google are applied. This approach does not factor in environmental information. While it is possible to sort results by emissions on both Google Flights and Route Rank, the default ranking does not prioritize environmental impact.

Nevertheless, the social aspect of flying green cannot be stressed enough. Fly Green seems to acknowledge the fact, that not every person can afford the cleanest flight. Their “best offer” consists of flights with the lowest emissions (50 %), flight time (30 %), and price (20 %). This approach balances the most important criteria with an emphasis on environmental impact. The best option could be described as the flight with the best **Multimodal Trip Score**, as it combines the three main evaluation criteria. This feature could be enhanced if users could customize the weighting of each criterion. For instance, a user who prioritizes price over time might set the weighting to 30 % for emissions, 50 % for price, and 20 % for time.

Further reductions in environmental impact could be achieved if flight search engines displayed alternatives from multiple regional airports, as Sanguinetti (2021) suggested. Google Flights offers the option to search for flights to an entire country, such as from Hamburg to Italy, showing the prices on a map. However, this feature is not available for departure airports. Route Rank offers both options but does not perform well, while Fly Green does not provide this functionality. Google Flights does allow users to select up to five locations for departure or arrival, but this is limited to one direction. Route Rank and Fly Green restrict users to a single departure and arrival airport.

A multimodal trip score should help users find the best travel option based on chosen criteria (environmental impact, time, price), with an individual rating attached to each. Since train travel is much more environmentally friendly, a travel search engine should include this option as well. Google Flights does suggest train travel for trips like Berlin to Hamburg, marked by a green leaf indicating a "green option", though no further environmental information is provided (see Figure 5.7). A direct comparison between transportation methods might encourage more consumers to travel by train. Such comparisons of environmental impact between train, car, and aircraft for specific trips can be made using platforms like Eco Passenger (www.ecopassenger.de).

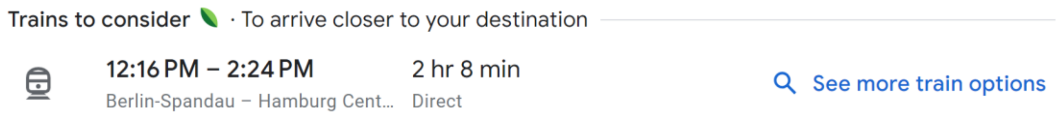


**Figure 5.7** The train as an alternative for short-haul flights (Google Flights)

Google Flights does not display the price for train options in its search results, which highlights a limitation in combining different modes of transport in one search. Although Google Flights suggests taking the train for not only short-haul flights but also night train connections for specific routes, it falls short in providing a comprehensive solution. For users interested in traveling by train, Google Flights merely performs a basic search for trains on a specific day from the chosen departure and arrival airports, without linking to specific train connections. In contrast, platforms like Omio (www.omio.com) allow users to compare journeys by train, bus, flight, and ferry, displaying the price and duration of each trip, though they do not provide environmental information.

A multimodal trip score would only be complete if all means of transport are considered. Even if flying covers most of the distance between two locations, the journey to and from the airport must be factored in to find the best option based on the personal preferences for environmental impact, time, and price. For example, certain flight connections between airports are only offered on specific days of the week, which may require a multi-leg journey. However, there might be a direct flight available from a nearby airport that could be reached by train, bus, or ferry. Because of the higher energy consumption of the aircraft, this option should be better for the environment and could be even more favorable in duration and price. Without entering regional airports along with the preferred arrival airport in the search, such an option would not be suggested by most, if not by any flight booking engine. A first step to implement this feature would be the option to add a radius around the arrival and departure location. Such a radius could be a distance in km or the duration of the journey – both of which could deliver quite different results of travel options.

Each of the flight booking engines discussed has its strengths and limitations. Unlike most search engines, all the presented platforms provide information about the environmental impact of a flight. Fly Green, for example, excels in calculating environmental information using Atmosfair. Their ranking system is particularly strong, as it defaults to listing the cleanest flight first, considering the environmental burden, time, and price in a transparent, weighted manner. However, Google Flights offers additional user-friendly features, such as the ability to search for flights to an entire country or to add multiple arrival and departure airports to the search. Furthermore, Google Flights also includes train options on certain routes, which adds another dimension to its search capabilities.

Ideally, a multimodal trip score would combine the best features of all three flight booking engines. To achieve this, the limitations of incorporating all modes of transport in a single search engine must be addressed. Additionally, offering users the option to personally weight the importance of different criteria – environmental impact, time, and price – would create a more tailored and effective travel planning tool.

# 6 Flight Label

A significant challenge in developing a multimodal trip score is ensuring seamless and efficient connections between different modes of transportation, as discussed in the previous chapter. One potential solution to this issue is the construction of city airports directly above existing train stations. This concept has been explored by the research institution Bauhaus Luftfahrt, with the conceptual design illustrated in Figure 6.1. While the advantages of reduced transfer times between train and aircraft in such a setup are evident, there are also substantial challenges that must be addressed.

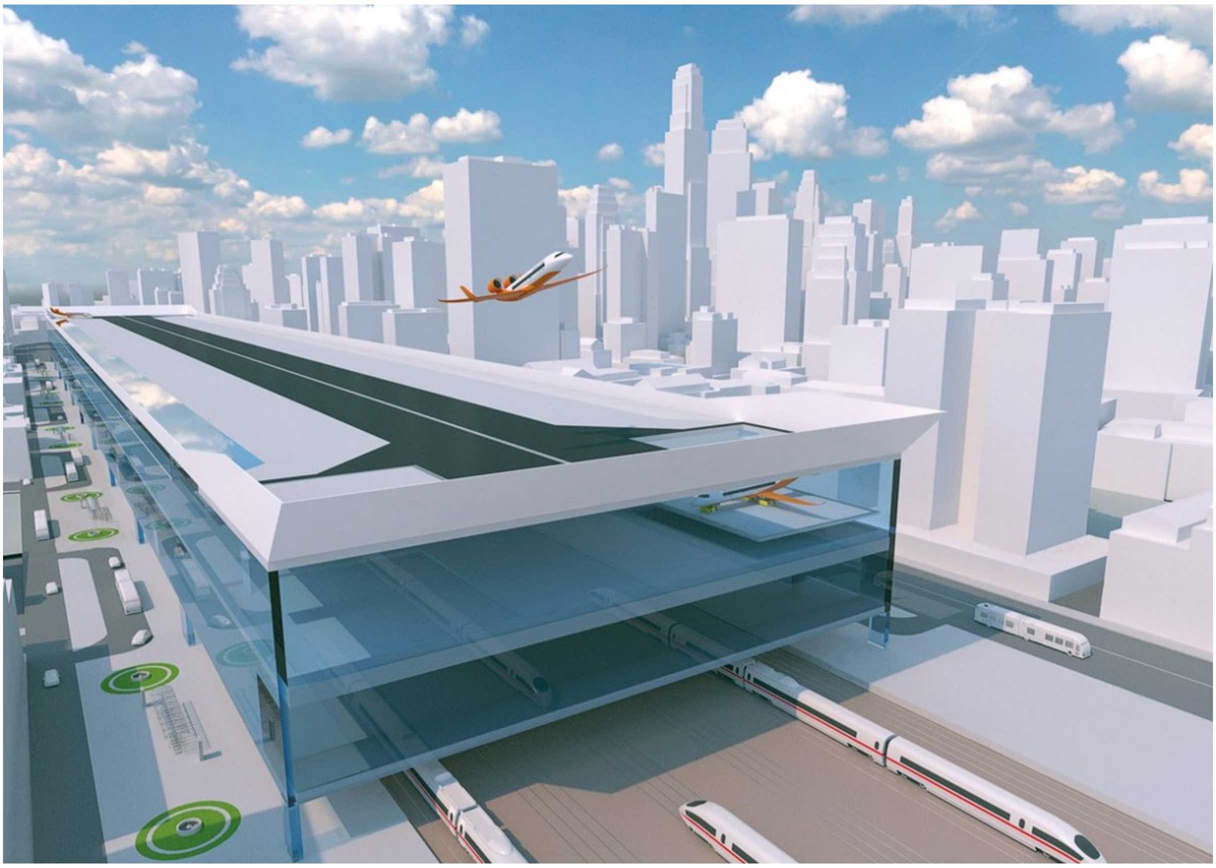

**Figure 6.1** “CentAirStation” airport concept and “CityBird” aircraft concept (Bauhaus Luftfahrt 2024)

The "CentAirStation" concept highlights the significance of local noise emissions and air pollution, factors that are accounted for by the aircraft and airline label but not by the flight booking engines discussed earlier. While these FBE´s do consider emissions from the LTO cycle, they do not offer a comparative analysis of emissions produced during the LTO cycle by different aircraft or flights.

In the case of direct flights, the aircraft label effectively functions as a flight label, providing crucial information on fuel performance, $CO_2$-equivalent emissions, local air pollution, and noise levels. However, the challenge arises when determining the environmental impact of a flight with multiple legs. One initial approach might be to assign each leg an individual aircraft label and rating. The overall rating of the flight could then be derived from a weighted score based on the duration of each leg. However, this approach is not ideal for comparing direct flights with those involving multiple stopovers. Since flights with multiple legs involve several LTO cycles, the associated local noise levels and air pollution should be cumulative rather than averaged. Additionally, non-direct flights typically cover more distance than direct flights, which should be reflected in the environmental burden assessed by a flight label. Averaging multiple aircraft labels fails to account for this, making it unsuitable for use in flight booking engines. To address this, modifications to the existing equations in the aircraft label, as defined in Chapter 2, are necessary to develop a flight label that can be effectively implemented in a flight booking engine.

The fuel performance only depends on the MTOW, MZFW, the harmonic range and the number of seats of an aircraft as can be seen in (3.1). This metric is intentionally independent of the actual distance flown, allowing for comparisons between different aircraft models. It measures the potential efficiency of an aircraft rather than its performance on a specific flight. However, to effectively compare the environmental impact of different flights, it is essential to evaluate how airlines utilize this potential. Specifically, the distance flown and the total fuel consumed must be considered to accurately assess the environmental burden of each flight.

The calculation of fuel consumption is straightforward, as shown in (7.1), which multiplies fuel consumption by stage length. This approach is based on the trip emission calculator developed by Hurtecant (2021). The same methodology applies to determining the total $CO_2$-equivalent emissions for all legs of a flight, as described in (7.2). The individual stage lengths $R_n$ are calculated using great circle distances. To account for inefficiencies in flight paths, an additional 50 km is added to each leg, consistent with the methodology used by the Atmosfair Flight Emissions Calculator (Atmosfair 2021).

$$FP = FP_1 \cdot R_1 + FP_2 \cdot R_2 + \cdots + FP_n \cdot R_n \quad \text{[kg/seat]} \tag{7.1}$$

$$CO_2\ eq. = CO_2\ eq._{\cdot 1} \cdot R_1 + CO_2\ eq._{\cdot 2} \cdot R_2 + \cdots + CO_2\ eq._{\cdot n} \cdot R_n \quad \text{[kg/seat]} \tag{7.2}$$

Local noise levels and air pollution require a slightly different approach when calculating their environmental impact. The total environmental burden from local noise during each LTO cycle can be determined by summing the noise levels from each cycle, as shown in (7.3). The local air pollution has to be considered in relation to the thrust of the engine $T$ and the number of passengers $n_{airline,n}$ which is leading to (7.4).

$$LNL = LNL_1 + LNL_2 + \cdots + LNL_n \ \text{[EPNdB/EPNdB]} \tag{7.3}$$

$$LAP = \frac{LAP_1 \cdot T_1}{n_{airline,1}} + \frac{LAP_2 \cdot T_2}{n_{airline,2}} + \cdots + \frac{LAP_n \cdot T_n}{n_{airline,n}} \quad \text{[g/seat]} \tag{7.4}$$

Calculating the absolute values for each category introduces the challenge of ranking flights. To determine which flight is the best, the worst, and where a specific flight falls within the spectrum, it is necessary to establish a reference point. One approach is to use the average performance of all search results as a reference, a method currently implemented by platforms like Google Flights and Fly Green. While effective, this method cannot be fully explored without collaboration with a flight booking engine. Alternatively, a reference point could be established by using a direct flight with a hypothetical aircraft between the departure and arrival airports, with an average environmental burden in each category. In Appendix E, a reference fuel consumption value has already been calculated. However, other categories account for different engine options, requiring that each engine be linked to its respective aircraft type. Given that the calculation of the local air pollution alone involves over 800 different engines, this approach may be too complex for simply determining a reference point.

In the trip emission calculator defined by Hurtecant (2021), a Boeing 737-800 was used as a reference due to its prevalence in the World Airliner Census 2020, representing over 16 % of the active global aircraft fleet. A comparison between the fuel consumption of this aircraft and the reference value calculated in Appendix E shows that they are closely aligned, confirming the suitability of the Boeing 737-800 as a reference point.

In the previous version of the aircraft label, $CO_2$ equivalent emissions were not dependent on the engine type, an issue addressed in Chapter 2.3.2. In the latest version of the aircraft label developed in this thesis, a reference engine must also be selected. The engine configurations used by the 50 most prominent airlines serve as a reference group. Among the 27 airlines operating the Boeing 737-800, all are equipped with a CFMI CFM56 variant. The most commonly used engine is the CFM56-7B26E, with a thrust of 117 kN, employed by ten airlines. This engine is thus selected as the reference. Most airlines operate the Boeing 737-800 with a one-class seating layout, similar to TUIfly. The aircraft label for the reference aircraft is shown in Figure 6.2. The overall rating of 7.38 is strong, earning an "A" rating. The average overall rating across all aircraft operated by the 50 leading airlines is 6.8, with the highest at 8.65 (Airbus A320 Neo, various airlines) and the lowest at 3.55 (Airbus A380, Korean Air). This places the Boeing 737-800 in the upper mid-range of aircraft, close to the top. However, the ratings across categories are inconsistent: while fuel performance and $CO_2$ equivalent emissions receive an "A," local noise levels score an "F," and local air pollution rates a "C."

The average length of a flight is around 2400 km (DLR 2008). A comparison with a standard flight with a Boeing 737-800 over 2400 km is interesting, but problematic with shorter flights. The user could be under the impression, that it does not matter for a shorter flight if they have multiple stopovers as long the environmental burden of the shorter flight is lower than that of the standard flight. It is therefore proposed, that the comparison with this standard flight should not be given in case of a shorter flight with a lower environmental impact, because it does raise the wrong incentive.

A comparison of the environmental impact of an average flight, particularly a long-haul flight, is of paramount importance as it prompts the question of whether such a lengthy journey is truly necessary. In the absence of such a comparison, a flight with the least environmental impact could be presented as a "green option," which it is not. It would be erroneous to encourage the user who has elected to undertake the longer flight with the impression that it is environmentally friendly. Nevertheless, should the trip in question be deemed indispensable, it is imperative to ascertain the optimal course of action.

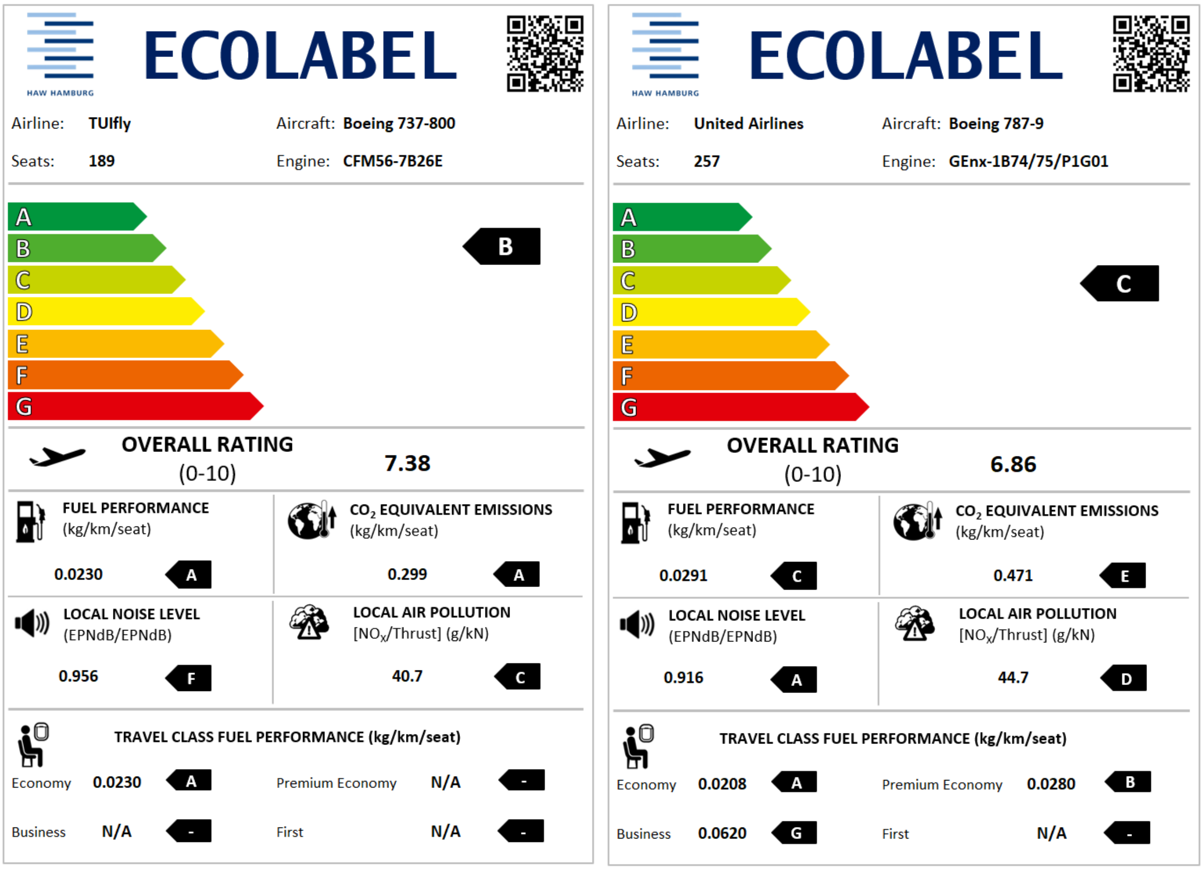


**Figure 6.2** Aircraft label of the reference aircraft Boeing 737-800 equipped with a CFM56-7B26E from TUIfly with a one class seating configuration and aircraft label of a Boeing 787-9 of United Airlines equipped with a GEnx-1B74/75

An exemplary flight from San Francisco to Singapore is chosen to demonstrate the method. To compare the overall rating of a specific flight, the environmental score has to be calculated via (7.7). But first, a reference point has to be chosen via (7.5). This methodology is identical to the trip emission calculator defined by Hurtecant (2021).

$$Comparison_{standard\ flight} = \frac{Indicator_{flight}}{Indicator_{ref}} \tag{7.5}$$

For the comparison of a specific flight with a standard flight, the total amount of emissions in the categories *FP*, $CO_2$ *eq*., *LNL* and *LAP* for both flights have to be determined via (7.1) to (7.4), which is described by the $Indicator_{flight}$.

For instance, one of the direct flights from San Francisco to Singapore operated by United Airlines utilizes a Boeing 787-9 equipped with GEnx-1B74/75 engines (341.2 kN). According to Google Flights, this is the flight with the lowest emissions on this route. The total flight distance is 13643 km (7367 nautical miles), which includes the great circle distance between San Francisco and Singapore plus an additional 50 km to account for flight inefficiencies. The environmental performance of this flight in each category is presented through the aircraft label in Figure 6.2.

To provide a meaningful comparison, this specific flight is measured against the standard flight using a Boeing 737-800 over a distance of 2400 km. The results of this comparison are summarized in Table 6.1, offering insights into the relative environmental burdens of these two flights.

**Table 6.1** Comparison of environmental performance of a standard flight with a Boeing 737-800 over 2400 km and a scheduled flight from San Francisco to Singapore with a Boeing 787-9 over the great circle distance of 13643 km

| | **Reference flight**<br>**Boeing 737-800**<br>$\boldsymbol{Indicator_{737}}$ | **Flight SFO-SIN**<br>**Boeing 787-9**<br>$\boldsymbol{Indicator_{SFO\text{-}SIN,787\text{-}9}}$ |
|---|---|---|
| Fuel Performance (*FP*) | 55.2 [kg/seat] | 397 [kg/seat] |
| $CO_2$ equivalent emissions ($CO_2$ *eq.*) | 717.6 [kg/seat] | 6425.9 [kg/seat] |
| Local Noise Level (*LNL*) | 0.956 [EPNdB/EPNdB] | 0.916 [EPNdB/EPNdB] |
| Local Air Pollution (*LAP*) | 25.2 [g/seat] | 59.4 [g/seat] |

The comparison between the reference flight and a specific flight can now be expressed with the environmental score defined in (7.7). The values for $FP_{comp.}$, $CO_2$ eq.$_{comp.}$, $LNL_{comp}$ and $LAP_{comp.}$ are given by the ratio of $Indicator_{SFO\text{-}SIN,787\text{-}9}$ and $Indicator_{737}$ in each category displayed in Table 6.1 calculated via (7.5). An example is given in (7.6). The environmental score of a flight from San Francisco to Singapore is calculated in (7.8).

$$FP_{comp.} = \frac{397}{2400 \cdot 0.0230} = 7.2 \tag{7.6}$$

$$\begin{aligned} &Environmental\ score \\ &\quad = 0.2 \cdot FP_{comp.} + 0.4 \cdot CO_2\ eq. + 0.2 \cdot LNL_{comp.} + 0.2 \cdot LAP_{comp.} \end{aligned} \tag{7.7}$$

$$\begin{aligned} Environmental\ score_{SFO-SIN,787-9} &= 0.2 \cdot 7.2 + 0.4 \cdot 9 + 0.2 \cdot 1 + 0.2 \cdot 2.4 \\ &= 5.7 \end{aligned} \tag{7.8}$$

The long-distance flight from San Francisco to Singapore imposes a 5.7 times greater environmental burden than an average flight. This significant impact could be effectively communicated in a flight search engine, similar to how Google Flights or Fly Green present environmental data. For instance, on the San Francisco to Singapore route, Google Flights identifies the best flight as emitting 24% fewer emissions than the average flight., which is a very different order of magnitude compared to 540 % and should be acknowledged by the user.

Fly Green's analysis of the same route (SFO-SIN) identifies an indirect flight with stops in Tokyo and Osaka, operated by ANA Airlines, as the cleanest option, producing 1.8 tons of $CO_2$ equivalent emissions. In comparison, the direct flight by United Airlines, previously discussed, generates 2.47 tons of $CO_2$ equivalent emissions – 27 % more than the ANA flight.

To validate the proposed method for calculating a flight's environmental score, it's essential to determine whether it aligns with Fly Green's conclusions. The environmental scores of these flights are compared using the aircraft labels found in Appendix L, with their environmental performances summarized in Table 6.2. This comparison will help determine if the proposed scoring method accurately reflects the environmental impacts, consistent with other tools like Fly Green.

**Table 6.2** Environmental performance of each leg of the flight from San Francisco to Singapore via Tokyo and Osaka

| | **Flight SFO-HND B777-300ER GE90-115B** | **Flight HND-KIX A320 Neo PW1127G-JM** | **Flight KIX-SIN B787-10 Trent 1000** | **Sum of flight SFO-SIN** |
|---|---|---|---|---|
| Thrust [kN] | 513.9 | 120.44 | 324.1 | |
| Flight distance [km] | 8355 | 482 | 4943 | |
| Number of passengers | 212 | 146 | 294 | |
| Fuel Performance (*FP*) [kg/seat] | 432.8 | 11.8 | 133.5 | 578.1 |
| $CO_2$ equivalent emissions ($CO_2$ *eq.*) [kg/seat] | 7168.6 | 148.5 | 2728.5 | 10045.6 |
| Local Noise Level (*LNL*) [EPNdB/EPNdB] | 0.946 | 0.9 | 0.9 | 2.8 |
| Local Air Pollution (*LAP*) [g/seat] | 164.6 | 22.2 | 66.6 | 253.4 |

The environmental performance in each category is determined via (7.1) - (7.4) and the environmental score via (7.9) in comparison with the reference flight and the direct flight on the same route.

$$\begin{aligned} &Environmental\ score_{SFO-HND-KIX-SIN} \\ &\quad = 0.2 \cdot 10.5 + 0.4 \cdot 14 + 0.2 \cdot 2.9 + 0.2 \cdot 10.1 = 10.3 \end{aligned} \tag{7.9}$$

The alternative flight from San Francisco to Singapore with multiple stopovers does have ten times the environmental impact compared to a reference flight. It also causes almost twice the environmental burden compared to a direct flight on the same route.

The flight distance and the choice of aircraft are obviously responsible for the huge difference in the environmental performance of the two flights. The question remains, which of those factors is more relevant for this flight. An average aircraft label can be used to determine the environmental score, if this flight would be a direct flight. This is done by (7.10) – (7.13) derived from the trip emission calculator defined by Hurtecant (2021).

$$FP_{avg} = \frac{FP_1 \cdot R_1 + FP_2 \cdot R_2 + \cdots + FP_n \cdot R_n}{R_1 + R_2 + \cdots + R_n} \quad \text{[kg/seat]} \tag{7.10}$$

$$CO_2\ eq._{avg} = \frac{CO_2\ eq._1 \cdot R_1 + CO_2\ eq._2 \cdot R_2 + \cdots + CO_2\ eq._n \cdot R_n}{R_1 + R_2 + \cdots + R_n} \quad \text{[kg/seat]} \tag{7.11}$$

$$LNL_{avg} = \frac{LNL_1 + LNL_2 + \cdots + LNL_n}{n_{flights}} \quad \text{[EPNdB/EPNdB]} \tag{7.12}$$

$$LAP_{avg} = \frac{LAP_1 + LAP_2 + \cdots + LAP_n}{n_{flights}} \quad \text{[g/seat]} \tag{7.13}$$

The fuel performance and equivalent $CO_2$ emissions than have to be divided by the great circle distance of the departure and arrival airport of the direct flight, which is described by (7.14) and (7.15).

$$FP_{direct} = FP_{avg} \cdot R_{direct} \quad \text{[kg/seat]} \tag{7.14}$$

$$CO_2\ eq._{direct} = CO_2\ eq._{avg} \cdot R_{direct} \quad \text{[kg/seat]} \tag{7.15}$$

The average environmental performance of each category is showed in (7.16) – (7.19). The fuel performance along with the $CO_2$ equivalent emissions of the potential direct flight are displayed in (7.20) and (7.21). The environmental score can be determined in the usual manner via (7.7).

$$FP_{avg} = 0.0418 \quad \text{[kg/seat]} \tag{7.16}$$

$$CO_2\ eq._{avg} = 0.726 \quad \text{[kg/seat]} \tag{7.17}$$

$$LNL_{avg} = 0.916 \ \text{[EPNdB/EPNdB]} \tag{7.18}$$

$$LAP_{avg} = 51.73 \quad [\text{g/seat}] \tag{7.19}$$

The fuel performance and equivalent $CO_2$ emissions than have to be divided by the great circle distance of the departure and arrival airport of the direct flight, which is described by (7.14) and (7.15).

$$FP_{direct} = 570.2 \quad [\text{kg/seat}] \tag{7.20}$$

$$CO_2\ eq._{direct} = 9909 \quad [\text{kg/seat}] \tag{7.21}$$

$$\begin{aligned} &Environmental\ score_{SFO-HND-KIX-SIN,direct} \\ &= 0.2 \cdot 10.3 + 0.4 \cdot 13.8 + 0.2 \cdot 1 + 0.2 \cdot 2.1 = 8.2 \end{aligned} \tag{7.22}$$

The reduction in the environmental score from 10.3 to 8.2 is primarily due to significantly lower local noise levels ($LNL_{avg}$) and local air pollution ($LAP_{avg}$) values, resulting from only one LTO cycle. Despite the two stops, the flight distance of 1380 km remains relatively short compared to the 13643 km of the direct flight, leading to only minor improvements in fuel performance and $CO_2$ equivalent emissions. This highlights the substantial environmental impact of multiple LTO cycles. In this instance, the flight distance does not contribute significantly to the flight's poor performance. The Boeing 777-300ER, used for the longest segment of the flight by ANA Airlines, is rated poorly with an environmental score of only 3.91 (see Appendix L), reflecting its overall poor environmental performance.

Comparing this to a direct flight with an average aircraft label helps evaluate the efficiency of the aircraft used on the route. It also provides a reference point for users when a nonstop flight is not available on their chosen route or time. This comparison encourages users to consider alternative options such as direct flights between different departure and arrival airports, integrating other modes of transport, or searching for direct flights at different times. Ideally, these alternatives should be factored into the multimodal trip score.

To effectively implement a flight label, a reference group of flights on a specific route is necessary, similar to the search results of a flight booking engine. Flights could be categorized into classes from A to G based on their environmental performance, with Class A representing the best and Class G the worst. The environmental score could also be presented. While displaying environmental performance as a percentage compared to an average reference flight – similar to Google Flights or Fly Green – can be informative, it may not immediately convey the quality of a flight if the search results are not sorted by emissions. Sorting flights into distinct classes addresses this issue by clearly showing users which flights are the best and worst, and how a specific flight compares to these benchmarks.

# 7 Summary and Conclusions

## 7.1 Summary

The aircraft label considers four key environmental criteria: *resource depletion*, *climate change*, *air quality*, and *noise pollution*. The environmental impact of an aircraft is determined through four ratings: *fuel performance*, *$CO_2$ equivalent emissions*, *local air pollution*, and *local noise levels*. These ratings are derived using the Ecolabel Calculator, which has undergone thorough validation and revision.

To ensure a fair comparison across different manufacturers, data on fuel consumption has been updated with information on various weight variants of aircraft types (see Chapter 2.1). The need for a standardized measure of fuel consumption in the airline industry remains crucial. In the absence of such a standard, using the extended payload range diagram with comparable data remains the best approach for this application.

$CO_2$ *equivalent emissions* are calculated by considering the contributions from $CO_2$, $NO_x$, and AIC (Aviation-Induced Cloudiness) for each aircraft. The contribution of $NO_x$ is now dependent on the specific engine used, rather than just the aircraft type. As detailed in Chapters 2.5.2 and 2.8, the chemical composition of exhaust gases is highly influenced by the engine type. The calculation methodology for determining the impact of AIC has also been revised. The environmental impact of AIC is now a function of fuel consumption per passenger and kilometer, rather than being solely distance-based as before. Inefficient aircraft with spacious multi-class seating configurations are expected to perform worse and produce more AIC, which is now recognized through a reference fuel consumption average derived from the World Airliner Census 2020 (see Appendix E).

Local air quality around airports is influenced by aviation-related emissions nitrogen oxides ($NO_x$), hydrocarbons (HC), methane ($CH_4$), carbon monoxide (CO), sulfur oxides ($SO_x$) and particulate matter (PM) (FAA 2015). An investigation was conducted to assess the health impacts of each substance and to develop a suitable metric for the aircraft label. According to the ReCiPe 2016 methodology, local air quality can be assessed based on *fine particulate matter formation*, which depends on the emission of primary aerosols (PM) and secondary aerosols from $SO_2$, $NH_3$, and $NO_x$, as well as *photochemical ozone formation*, primarily driven by $NO_x$. The analysis revealed that nearly all the impact of fine particulate matter is attributable to the secondary aerosol $NO_x$, due to its significantly higher emission mass compared to primary aerosols or other secondary aerosols. Consequently, the criteria for determining local air quality are largely dependent on $NO_x$ emissions, which are used to calculate the local air pollution of an aircraft.

A systematic literature review of emission-based airline rankings was conducted to provide an overview of existing research and summarize its findings. The review aimed to assess the current state of emission-based airline rankings and the methodologies they employ. It was found that most airline rankings are based on some form of Data Envelopment Analysis (DEA). This method was originally developed to evaluate the performance of airlines from technical, operational, and especially financial perspectives, with environmental impact considerations being added later. Since $CO_2$ emissions are now linked to an airline's financial performance, it could be argued that financial performance remains the primary focus of these rankings, with environmental impact being treated as a secondary factor. However, it's important to note that DEA-based airline rankings are already quite complex, incorporating multiple inputs, outputs, intermediate products, and stages, making it challenging to include additional parameters like $NO_x$ or noise.

Other airline labels tend to focus on specific aspects of environmental impact, such as the aircraft-engine combination, passengers' perceptions of airlines' environmental practices, or political influences. Few studies consider more than $CO_2$ emissions in evaluating environmental performance, and those that do often struggle with obtaining reliable, up-to-date, and comparable data for other environmental impacts. Several airline rankings with varying levels of complexity were reviewed. The AAI, for example, considers many efficiency aspects of airlines but only accounts for $CO_2$ and $NO_x$ emissions. Another ranking that attempted to include AIC, noise, and other environmental impacts was unable to produce a comprehensive airline ranking due to data limitations.

To bridge the gap between the complexity of DEA-based airline rankings and the need to consider more than just $CO_2$ emissions, a new airline label was developed. This label is based on the methodology of the aircraft label and considers the aforementioned criteria: *fuel performance, $CO_2$ equivalent emissions*, *local air pollution*, and *local noise levels*. A reference group of the 50 most significant airlines was established, and an airline ranking was created and discussed.

Additionally, a selection of flight booking engines was compared and analyzed regarding their environmental impact information. It was found that while their interfaces appear similar, the methodologies used to determine the environmental impact of flights vary significantly. Some key features are also setting them apart like the possibility offered by Fly Green to sort the search results in regard to the *best offer*, which considers not only price, duration, and number of stops of a flight, but also the environmental burden. The possibility of a multimodal trip score, incorporating an individual weighting of criteria like *emissions*, *flight time*, and *price* across all modes of transport, was also discussed. Different approaches to calculating the environmental burden of multi-stop flights using an aircraft label-based flight label were explored in the final chapter, which could be integrated into such a multimodal trip score.

## 7.2 Conclusions

There are numerous approaches to measuring emissions in the aviation sector, highlighting the complexity and variability of environmental impact assessments. To address this, the European Commission plans to introduce the "Count Emissions EU" initiative, aimed at standardizing emission measurements and preventing greenwashing. The rules for calculating equivalent $CO_2$ emissions are defined in ISO Standard 14083-2023, which seeks to encompass the entire mobility chain in its assessments and create incentives for reducing greenhouse gas emissions (EASA 2023a). While this is a commendable effort and a significant step towards greener aviation, the exact methodology for calculating the environmental burden of an aircraft or flight remains to be clarified.

Initiatives like the environmental labeling scheme within the *ReFuelEU Aviation* project highlights the growing importance of environmental labels in the aviation industry. Although the EU's labeling scheme is still under development, the environmental burden of an aircraft, airline, or flight can already be calculated using the labels presented in this thesis. While the limitations of each label have been discussed, these labels could still guide the public in making more environmentally conscious choices based on scientific and rigorously reviewed methods.

Most travelers intuitively understand that a modern, fuel-efficient aircraft with a dense single-class seating configuration is likely the best environmental choice. However, these labels now make it possible to quantify the environmental differences between various travel options, potentially influencing some travelers to opt for slightly more expensive flights to reduce their ecological footprint. Short-haul flights, in particular, may be more frequently substituted with train travel, and long-haul flights might be chosen only when absolutely necessary.

Ultimately, while environmental labels are a step in the right direction, they alone cannot resolve the aviation industry's environmental challenges. For instance, flying at lower altitudes and reduced airspeeds could significantly cut environmental impact by up to 70%, with only a marginal increase in fuel consumption and direct operating costs (Caers 2020). This could be implemented even with aircraft designed for higher altitudes.

Additionally, hydrogen-powered aircraft hold potential for reducing aviation's environmental burden, although this has yet to be conclusively demonstrated. Given these considerations, achieving truly green aviation remains a formidable challenge, even in the distant future. Until then, it is crucial for travelers to make the most environmentally responsible choices possible, aided by the aircraft, airline, and flight labels proposed in this thesis.

# 8 Recommendations

Determining the fuel consumption of an aircraft is a significant challenge in establishing accurate aircraft, airline, or flight labels. The point performance method based on Specific Air Range (SAR) provides a reasonable indication, particularly when considering the purpose and limitations of an environmental label. However, this method does not account for the variations in fuel consumption between different engines on the same aircraft type. Additionally, finding comparable data across manufacturers is difficult due to the lack of standardized data in corporate documents, such as Airbus's Airport Operations and Aircraft Characteristics. Addressing these issues would require a standardized measure of fuel consumption in the aviation industry, which seems unlikely to be implemented in the near future.

While the contribution of $NO_x$ to $CO_2$ equivalent emissions depends on the aircraft-engine combination, $CO_2$ emissions are primarily influenced by overall fuel consumption, which, as mentioned, is not engine-specific. The recent adjustment to make the environmental impact of aircraft-induced cloudiness (AIC) dependent on fuel consumption is a step forward. However, it is reasonable to assume that different aircraft-engine combinations would also produce varying intensities of AIC due to the unique chemical composition of exhaust specific to each engine. Future iterations of aircraft, airline, and flight labels could consider incorporating the amount and impact of different pollutants on AIC formation for a more sophisticated assessment.

In Chapter 2.8, a brief comparison was provided between the contribution to equivalent $CO_2$ emissions of the turboprop ATR 72 and other turbofan aircraft. Due to the lower flight levels at which turboprops operate, the environmental impact of turboprop engines was shown to differ significantly from that of turbofan engines. Unfortunately, it remains challenging to calculate local air pollution for turboprop aircraft due to a lack of publicly available data and restricted access to the Swedish Defense Research Agency (FOI) database, which contains emission indices for $NO_x$, hydrocarbons (HCs), and carbon monoxide (CO) for turboprop engines.

The aircraft database used in the Ecolabel Calculator has been expanded to include more aircraft types. Given that airlines continuously update their fleets, this effort must be ongoing. Additionally, the reference group of aircraft used to calculate the aircraft label rating must be updated regularly to maintain accuracy and relevance.

Finally, the methodologies for a multimodal trip score and a flight label should be further refined. Investigating the implementation of a time-based approach as opposed to a distance-based one could be beneficial. Flight duration and emissions can vary significantly depending on the direction of travel, and a time-based approach would more accurately capture these variations. For example, flights between North America and Europe typically take longer when traveling westward, and emissions estimates should reflect this difference.

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All online resources have been accessed on 2024-08-30 or later.

# Appendix A – Reference Group of Aircraft

**Table A.1** List of reference aircraft

| Ranking | Aircraft type | Accumulated number of passenger A/C | Accumulated percentage of passenger A/C |
|---|---|---|---|
| 1 | Boeing 737-800 | 4788 | 16.39 |
| 2 | Airbus A320 | 8920 | 30.53 |
| 3 | Airbus A321-200 | 10557 | 36.13 |
| 4 | Airbus A319 | 11800 | 40.39 |
| 5 | Airbus A320neo | 12809 | 43.84 |
| 6 | Boeing 737-700 | 13788 | 47.19 |
| 7 | Boeing 777-300ER | 14593 | 49.95 |
| 8 | ATR 72 | 15388 | 52.67 |
| 9 | Airbus A330-300 | 16095 | 55.09 |
| 10 | Embraer E175 | 16719 | 57.22 |
| 11 | Bombardier CRJ100/200 | 17320 | 59.28 |
| 12 | Boeing 737-900 | 17876 | 61.18 |
| 13 | Boeing 787-9 | 18416 | 63.03 |
| 14 | Airbus A330-200 | 18918 | 64.75 |
| 15 | Embraer E190 | 19419 | 66.46 |
| 16 | Embraer ERJ-145 | 19898 | 68.10 |
| 17 | Bombardier CRJ900 | 20369 | 69.72 |
| 18 | De Havilland Canada Dash 8 Q400 | 20831 | 71.30 |
| 19 | Boeing 777-200/200ER | 21222 | 72.64 |
| 20 | Boeing 767-300 | 21587 | 73.89 |
| 21 | Boeing 787-8 | 21950 | 75.13 |
| 22 | Airbus A321neo | 22305 | 76.34 |
| 23 | Boeing 737 MAX 8 | 22652 | 77.53 |
| 24 | Airbus A350-900 | 22973 | 78.63 |
| 25 | Boeing 757-200 | 23275 | 79.66 |
| 26 | Bombardier CRJ700ER | 23566 | 80.66 |
| 27 | Airbus A380-800 | 23803 | 81.47 |
| 28 | Boeing MD-80 | 24035 | 82.26 |
| 29 | Beechcraft 1900D | 24255 | 83.02 |
| 30 | Boeing 737-300 | 24469 | 83.75 |
| 31 | ATR 42 | 24677 | 84.46 |
| 32 | Saab 340 | 24865 | 85.10 |
| 33 | Boeing 737-500 | 25026 | 85.66 |
| 34 | Embraer E195 | 25187 | 86.21 |
| 35 | De Havilland Canada Dash 8 Q300 | 25344 | 86.74 |
| 36 | Embraer E170 | 25501 | 87.28 |
| 37 | De Havilland Canada Dash 8 Q100 | 25653 | 87.80 |
| 38 | Boeing 717-200 | 25798 | 88.30 |
| 39 | Boeing 747-400 | 25940 | 88.78 |
| 40 | Boeing 737-400 | 26081 | 89.27 |

| | | | |
|---|---|---|---|
| 41 | Sukhoi Superjet 100 | 26222 | 89.75 |
| 42 | Embraer EMB-120 Brasilia | 26349 | 90.18 |
| 43 | Fokker 100 | 26458 | 90.56 |
| 44 | Fokker 50 | 26544 | 90.85 |
| 45 | Airbus A340-300 | 26622 | 91.12 |
| 46 | Airbus A220-300 | 26694 | 91.36 |
| 47 | Embraer ERJ-140 | 26764 | 91.60 |
| 48 | Bombardier CRJ1000 | 26827 | 91.82 |
| 49 | Embraer ERJ-135 | 26888 | 92.03 |
| 50 | Boeing 787-10 | 26946 | 92.23 |
| 51 | Airbus A340-600 | 27003 | 92.42 |
| 52 | Boeing 757-300 | 27056 | 92.60 |
| 53 | Dornier 228 | 27109 | 92.79 |
| 54 | Boeing 777-200LR | 27159 | 92.96 |
| 55 | Boeing 777-300 | 27209 | 93.13 |
| 56 | Airbus A330-900 | 27256 | 93.29 |
| 57 | Airbus A350-1000 | 27299 | 93.44 |
| 58 | De Havilland Canada Dash 8 Q200 | 27341 | 93.58 |
| 59 | Airbus A220-100 | 27381 | 93.72 |
| 60 | Boeing 767-400ER | 27418 | 93.84 |
| 61 | Airbus A300 | 27453 | 93.96 |
| 62 | Boeing 747-8 | 27488 | 94.08 |
| 63 | Fokker 70 | 27523 | 94.20 |
| 64 | Comac ARJ21-700 | 27554 | 94.31 |
| 65 | Boeing 737 MAX 9 | 27582 | 94.40 |
| 66 | Boeing MD-90 | 27608 | 94.49 |
| 67 | Airbus A318 | 27632 | 94.58 |
| 68 | Airbus A310 | 27654 | 94.65 |
| 69 | Dornier 328JET-300 | 27672 | 94.71 |
| 70 | Embraer E190-E2 | 27687 | 94.76 |
| 71 | Embraer E195-E2 | 27695 | 94.79 |
| 72 | Airbus A319neo | 27695 | 94.79 |
| 73 | Airbus A321-100 | 27695 | 94.79 |
| 74 | Airbus A350-900ULR | 27695 | 94.79 |
| 75 | Boeing 737-900ER | 27695 | 94.79 |
| 76 | Boeing 767-300ER | 27695 | 94.79 |
| 77 | Boeing MD-11 | 27695 | 94.79 |
| 78 | Bombardier CRJ200ER | 27695 | 94.79 |
| 79 | Bombardier CRJ200LR | 27695 | 94.79 |
| 80 | COMAC C919 | 27695 | 94.79 |
| 81 | Embraer E170LR | 27695 | 94.79 |
| 82 | Embraer E175LR | 27695 | 94.79 |
| 83 | Embraer E190AR | 27695 | 94.79 |
| 84 | Embraer E190LR | 27695 | 94.79 |
| 85 | Embraer E195AR | 27695 | 94.79 |
| 86 | Embraer E195LR | 27695 | 94.79 |

# Appendix B – Fuel Consumption for Reference Group of Aircraft

**Table B.1** List of fuel consumption for reference group of aircraft

| Ranking | Aircraft type | Normalized fuel consumption (kg/km/seat) for calculated standard seating capacity |
|---|---|---|
| 1 | Boeing 737 MAX 9 | 0.0220 |
| 2 | Boeing 737 MAX 8 | 0.0228 |
| 3 | Airbus A320neo | 0.0234 |
| 4 | Airbus A321neo | 0.0234 |
| 5 | Airbus A330-900 | 0.0239 |
| 6 | Boeing 787-8 | 0.0240 |
| 7 | Airbus A220-300 | 0.0245 |
| 8 | Airbus A350-900 | 0.0246 |
| 9 | Airbus A321-100 | 0.0247 |
| 10 | Boeing 787-10 | 0.0250 |
| 11 | Boeing 787-9 | 0.0252 |
| 12 | Airbus A220-100 | 0.0256 |
| 13 | Airbus A350-900ULR | 0.0257 |
| 14 | Airbus A319neo | 0.0260 |
| 15 | Embraer E195-E2 | 0.0262 |
| 16 | Airbus A321-200 | 0.0262 |
| 17 | COMAC C919 | 0.0267 |
| 18 | Airbus A330-300 | 0.0273 |
| 19 | Boeing 767-300ER | 0.0275 |
| 20 | Boeing 777-300ER | 0.0281 |
| 21 | Embraer E190-E2 | 0.0281 |
| 22 | Boeing 777-300 | 0.0283 |
| 23 | Airbus A330-200 | 0.0285 |
| 24 | Airbus A380-800 | 0.0286 |
| 25 | Boeing 777-200 | 0.0286 |
| 26 | Airbus A319 | 0.0288 |
| 27 | Boeing 767-400ER | 0.0289 |
| 28 | Boeing 757-300 | 0.0291 |
| 29 | Airbus A350-1000 | 0.0292 |
| 30 | ATR 72 | 0.0292 |
| 31 | Airbus A320 | 0.0293 |
| 32 | Boeing 737-800 | 0.0297 |
| 33 | Boeing 737-900 | 0.0302 |
| 34 | De Havilland Canada Dash 8 Q400 | 0.0303 |
| 35 | Boeing 737-300 | 0.0307 |
| 36 | Fokker 50 | 0.0309 |
| 37 | Boeing 737-700 | 0.0309 |
| 38 | Boeing 777-200LR | 0.0310 |

| | | |
|---|---|---|
| 39 | Boeing 777-200ER | 0.0312 |
| 40 | Boeing 757-200 | 0.0321 |
| 41 | Airbus A340-300 | 0.0323 |
| 42 | Boeing 747-400 | 0.0324 |
| 43 | Airbus A318 | 0.0328 |
| 44 | Boeing MD-11 | 0.0329 |
| 45 | Airbus A310 | 0.0333 |
| 46 | Airbus A340-600 | 0.0335 |
| 47 | Boeing 737-400 | 0.0339 |
| 48 | Bombardier CRJ1000 | 0.0341 |
| 49 | Embraer E195AR | 0.0342 |
| 50 | Embraer E190AR | 0.0345 |
| 51 | Saab 340 | 0.0349 |
| 52 | Boeing MD-80 | 0.0351 |
| 53 | Embraer E190LR | 0.0353 |
| 54 | Boeing 767-300 | 0.0353 |
| 55 | Boeing 737-900ER | 0.0358 |
| 56 | Bombardier CRJ200LR | 0.0360 |
| 57 | Embraer E195LR | 0.0363 |
| 58 | Bombardier CRJ900 | 0.0368 |
| 59 | Boeing MD-90 | 0.0375 |
| 60 | Embraer E170LR | 0.0377 |
| 61 | Boeing 747-8 | 0.0380 |
| 62 | Bombardier CRJ700ER | 0.0386 |
| 63 | De Havilland Canada Dash 8 Q200 | 0.0387 |
| 64 | ATR 42 | 0.0392 |
| 65 | De Havilland Canada Dash 8 Q300 | 0.0395 |
| 66 | Fokker 100 | 0.0395 |
| 67 | Embraer E175LR | 0.0397 |
| 68 | Embraer ERJ-145 | 0.0398 |
| 69 | Embraer E190 | 0.0402 |
| 70 | Airbus A300 | 0.0405 |
| 71 | Comac ARJ21-700 | 0.0408 |
| 72 | Embraer E195 | 0.0412 |
| 73 | Embraer E175 | 0.0417 |
| 74 | Fokker 70 | 0.0421 |
| 75 | Sukhoi Superjet 100 | 0.0428 |
| 76 | Bombardier CRJ200ER | 0.0428 |
| 77 | Embraer E170 | 0.0434 |
| 78 | Boeing 737-500 | 0.0434 |
| 79 | De Havilland Canada Dash 8 Q100 | 0.0440 |
| 80 | Boeing 717-200 | 0.0453 |
| 81 | Dornier 328JET-300 | 0.0456 |
| 82 | Bombardier CRJ100 | 0.0467 |
| 83 | Embraer ERJ-140 | 0.0491 |
| 84 | Embraer ERJ-135 | 0.0496 |

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|---|---|---|
| 85 | Dornier 228 | 0.0611 |
| 86 | Embraer EMB-120 Brasilia | 0.0621 |
| 87 | Beechcraft 1900D | 0.0798 |

# Appendix C – Local Air Pollution for a Selection of Aircraft Engines

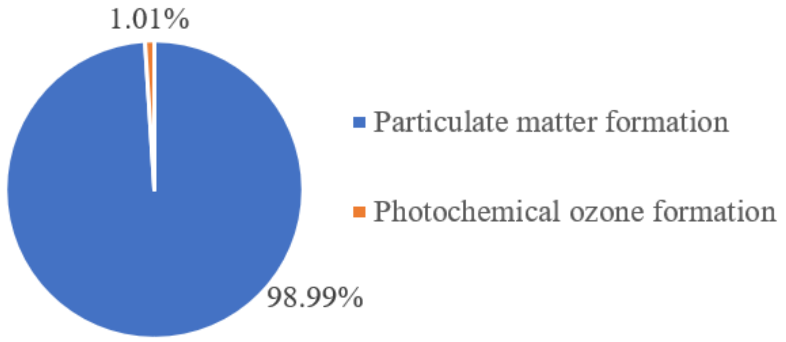


**Figure C.1** Impact of particulate Matter formation and ozone formation on human health of a V2527-A5

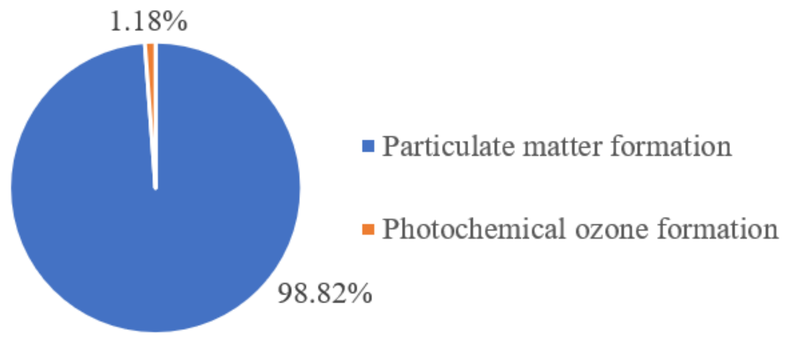


**Figure C.2** Impact of Particulate Matter Formation and Ozone Formation on Human Health of a Trent 1000-J3

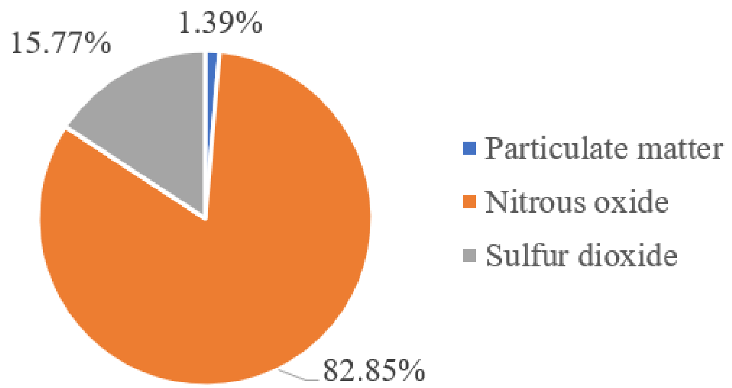


**Figure C.3** Contribution of Aerosols to the Impact of Particulate Matter Formation on Human Health of a CFM56-5B4/3

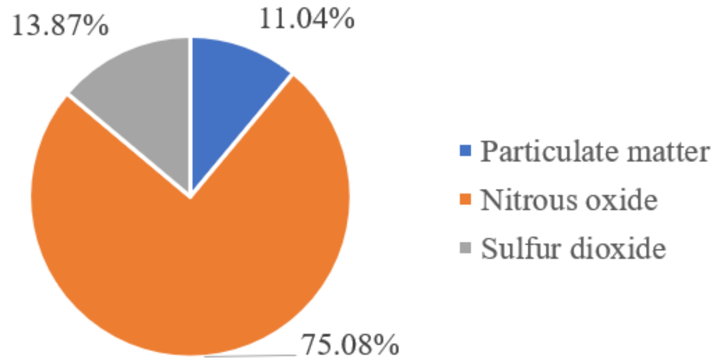


**Figure C.4** Contribution of Aerosols to the Impact of Particulate Matter Formation on Human Health of a V2527-A5

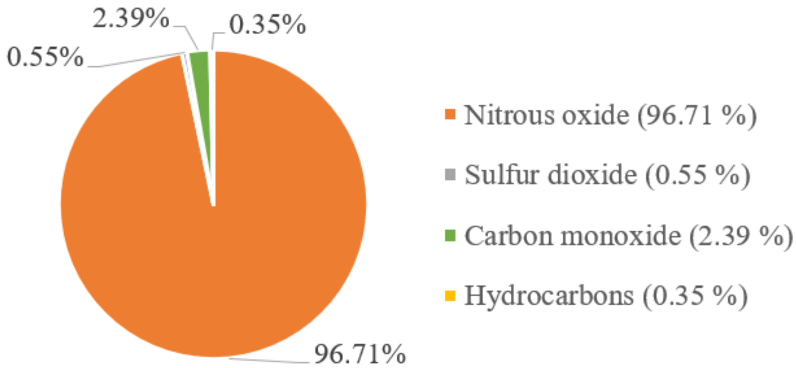


**Figure C.5** Contribution of Pollutants to the Impact of Ozone Formation on Human Health of a V2527-A5

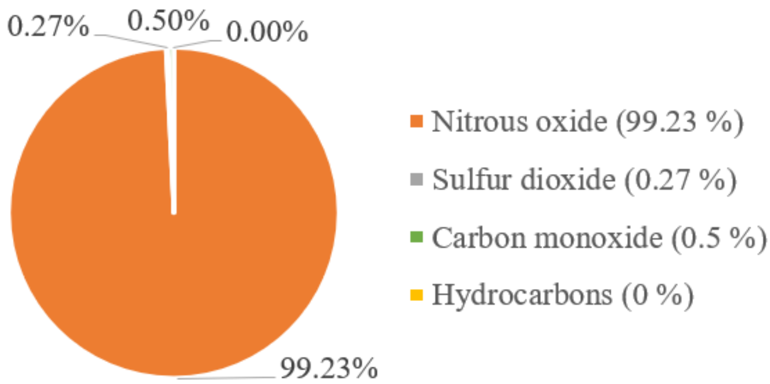


**Figure C.6** Contribution of Pollutants to the Impact of Ozone Formation on Human Health of a Trent 1000-J3

# Appendix D – $CO_2$ Equivalent Emissions of Aircraft Engine Combinations

**Table D.1** $CO_2$ equivalent emissions mass of different aircraft engine combinations

| Rank-ing | Aircraft type | Engine | Equivalent mass of $CO_2$ (kg/km/seat) |
|---|---|---|---|
| 1 | ATR 72 | PW 127 | 0.0976 |
| 2 | Fokker 50 | PW 125B | 0.1125 |
| 3 | Saab 340 | GE C7-5A2 | 0.1306 |
| 4 | ATR 42 | PW127E/M | 0.1329 |
| 5 | De Havilland Canada Dash 8 Q300 | PW123 | 0.1438 |
| 6 | Embraer EMB-120 Brasilia | PW118A | 0.2020 |
| 7 | Airbus A318 | PW6122A | 0.2162 |
| 8 | Airbus A318 | PW6124A | 0.2214 |
| 9 | Airbus A318 | CFM56-5B8/3 | 0.2224 |
| 10 | Airbus A318 | CFM56-5B9/3 | 0.2227 |
| 11 | Airbus A318 | CFM56-5B9/P | 0.2354 |
| 12 | Airbus A318 | CFM56-5B8/P | 0.2354 |
| 13 | Airbus A320neo | LEAP-1A26 | 0.2478 |
| 14 | Airbus A320neo | LEAP-1A24 | 0.2494 |
| 15 | Airbus A321neo | PW1130G-JM | 0.2507 |
| 16 | Airbus A320neo | PW1127G1-JM | 0.2519 |
| 17 | Airbus A320neo | PW1127G-JM | 0.2519 |
| 18 | Airbus A320neo | PW1129G-JM | 0.2554 |
| 19 | Airbus A320neo | PW1124G1-JM | 0.2581 |
| 20 | Airbus A321neo | PW1133G1-JM | 0.2592 |
| 21 | Airbus A321neo | PW1133G-JM | 0.2592 |
| 22 | Beechcraft 1900D | PT6A-67 | 0.2597 |
| 23 | Airbus A320 | CFM56-5B4/2 | 0.2606 |
| 24 | Airbus A319 | CFM56-5B6/2P | 0.2712 |
| 25 | Airbus A320 | CFM56-5B4/2P | 0.2713 |
| 26 | Airbus A320 | CFM56-5B5/3 | 0.2827 |
| 27 | Airbus A320 | CFM56-5B6/3 | 0.2835 |
| 28 | Airbus A320 | CFM56-5B4/3 | 0.2875 |
| 29 | Airbus A319 | CFM56-5B5/3 | 0.2931 |
| 30 | Airbus A319 | CFM56-5B6/3 | 0.2939 |
| 31 | Airbus A320neo | LEAP-1A26CJ | 0.2951 |
| 32 | Airbus A320neo | LEAP-1A26E1 | 0.2951 |
| 33 | Airbus A319neo | LEAP-1A26 | 0.2978 |
| 34 | Airbus A319 | CFM56-5B7/3 | 0.2978 |
| 35 | Airbus A321-200 | CFM56-5B5/3 | 0.3001 |
| 36 | Embraer E195-E2 | PW1921G | 0.3052 |
| 37 | Airbus A321-200 | CFM56-5B1/2P | 0.3073 |
| 38 | Embraer E195-E2 | PW1900G_mean | 0.3073 |
| 39 | Embraer E195-E2 | PW1923G | 0.3079 |

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|---|---|---|---|
| 40 | Embraer E195-E2 | PW1923G-A | 0.3079 |
| 41 | Airbus A320 | CFM56-5A3 | 0.3135 |
| 42 | Airbus A321-200 | CFM56-5B4/3 | 0.3156 |
| 43 | Embraer E190-E2 | PW1919G | 0.3157 |
| 44 | Airbus A220-100 | PW1519G | 0.3168 |
| 45 | Airbus A320 | CFM56-5B6/P | 0.3183 |
| 46 | Airbus A320 | CFM56-5B5/P | 0.3186 |
| 47 | Airbus A320 | CFM56-5B4 | 0.3206 |
| 48 | Embraer E190-E2 | PW1922G | 0.3208 |
| 49 | Airbus A320 | CFM56-5B4/P | 0.3216 |
| 50 | Airbus A321-200 | CFM56-5B1/3 | 0.3226 |
| 51 | Airbus A320 | V2527-A5 | 0.3247 |
| 52 | Airbus A320 | V2527E-A5 | 0.3247 |
| 53 | Airbus A321-200 | CFM56-5B2/3 | 0.3260 |
| 54 | Airbus A319 | CFM56-5B6/P | 0.3276 |
| 55 | Airbus A319 | CFM56-5B5/P | 0.3279 |
| 56 | Airbus A321-200 | CFM56-5B3/2P | 0.3281 |
| 57 | Airbus A220-300 | PW1524G-3 | 0.3296 |
| 58 | Airbus A321-200 | CFM56-5B3/3 | 0.3302 |
| 59 | Airbus A319 | CFM56-5B7/P | 0.3308 |
| 60 | Airbus A319 | CFM56-5A5 | 0.3319 |
| 61 | Airbus A319 | CFM56-5A4 | 0.3319 |
| 62 | Airbus A319 | V2522-A5 | 0.3332 |
| 63 | Airbus A319 | V2524-A5 | 0.3332 |
| 64 | Airbus A319 | V2527-A5 | 0.3336 |
| 65 | Boeing 737-900 | CFM56-7B24/3 | 0.3336 |
| 66 | Boeing 737-900 | CFM56-7B24E/B1 | 0.3336 |
| 67 | Boeing 737-800 | CFM56-7B24/2 | 0.3349 |
| 68 | Boeing 737-900 | CFM56-7B26/3 | 0.3382 |
| 69 | Boeing 737-900 | CFM56-7B26E | 0.3382 |
| 70 | Boeing 737-900 | CFM56-7B26E/F | 0.3382 |
| 71 | Boeing 737-700 | CFM56-7B20/2 | 0.3393 |
| 72 | Boeing 737-800 | CFM56-7B26/2 | 0.3406 |
| 73 | Airbus A321neo | LEAP-1A32 | 0.3414 |
| 74 | Boeing 737-900 | CFM56-7B27/3 | 0.3421 |
| 75 | Boeing 737-900 | CFM56-7B27E/B1 | 0.3421 |
| 76 | Boeing 737-900 | CFM56-7B27E/B1F | 0.3421 |
| 77 | Boeing 737-900 | CFM56-7B27E/B3 | 0.3421 |
| 78 | Boeing 737-900 | CFM56-7B27E/F | 0.3421 |
| 79 | Boeing 737-800 | CFM56-7B27/2 | 0.3442 |
| 80 | Airbus A321-100 | CFM56-5B1/P | 0.3444 |
| 81 | Airbus A220-100 | PW1524G | 0.3471 |
| 82 | Boeing 737-700 | CFM56-7B22/2 | 0.3477 |
| 83 | Airbus A321-100 | V2530-A5 | 0.3490 |
| 84 | Boeing 787-8 | GEnx-1B64/P1G01 | 0.3505 |
| 85 | Boeing 737-700 | CFM56-7B24/2 | 0.3507 |

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|---|---|---|---|
| 86 | Boeing 737-800 | CFM56-7B24/3 | 0.3514 |
| 87 | Boeing 737-800 | CFM56-7B24E | 0.3514 |
| 88 | Boeing 737-800 | CFM56-7B24E/B1 | 0.3514 |
| 89 | Fokker 70 | TAY 620-15 | 0.3521 |
| 90 | Airbus A321-200 | CFM56-5B4/P | 0.3556 |
| 91 | Boeing 737-800 | CFM56-7B26/3 | 0.3560 |
| 92 | Boeing 737-800 | CFM56-7B26E | 0.3560 |
| 93 | Boeing 737-800 | CFM56-7B26E/F | 0.3560 |
| 94 | Boeing 737-700 | CFM56-7B26/2 | 0.3560 |
| 95 | Comac C919 | LEAP-1C_mean | 0.3568 |
| 96 | Airbus A320neo | LEAP-1A29 | 0.3592 |
| 97 | Boeing 737-700 | CFM56-7B27/2 | 0.3594 |
| 98 | Boeing 787-8 | GEnx-1B64/P2G01 | 0.3595 |
| 99 | Boeing 737-800 | CFM56-7B27/3 | 0.3600 |
| 100 | Boeing 737-800 | CFM56-7B27E | 0.3600 |
| 101 | Boeing 737-800 | CFM56-7B27E/B1 | 0.3600 |
| 102 | Boeing 737-800 | CFM56-7B27E/B1F | 0.3600 |
| 103 | Boeing 737-800 | CFM56-7B27E/B3 | 0.3600 |
| 104 | Boeing 737-800 | CFM56-7B27E/F | 0.3600 |
| 105 | Airbus A321-200 | CFM56-5B1/P | 0.3604 |
| 106 | Airbus A321-200 | V2530-A5 | 0.3622 |
| 107 | Boeing 767-400ER | CF6-80C2B8F | 0.3626 |
| 108 | Airbus A321-200 | CFM56-5B2/P | 0.3626 |
| 109 | Airbus A321-200 | V2533-A5 | 0.3627 |
| 110 | Boeing 767-300ER | CF6-80C2B2 | 0.3630 |
| 111 | Boeing 787-8 | GEnx-1B67/P1G01 | 0.3637 |
| 112 | Boeing 737-700 | CFM56-7B20E | 0.3639 |
| 113 | Boeing 737-700 | CFM56-7B20/3 | 0.3642 |
| 114 | Airbus A321-200 | CFM56-5B3/P | 0.3644 |
| 115 | Boeing 767-300ER | CF6-80C2B2F | 0.3649 |
| 116 | Boeing 737-700 | CFM56-7B22/3 | 0.3649 |
| 117 | Boeing 737-700 | CFM56-7B22E | 0.3649 |
| 118 | Airbus A321-200 | CFM56-5B2 | 0.3655 |
| 119 | Boeing 737-700 | CFM56-7B24/3 | 0.3665 |
| 120 | Boeing 737-700 | CFM56-7B24E | 0.3665 |
| 121 | Boeing 737-700 | CFM56-7B24E/B1 | 0.3665 |
| 122 | Boeing 737-300 | CFM56-3C1 | 0.3672 |
| 123 | Airbus A320 | V2500-A1 | 0.3677 |
| 124 | Boeing 737-300 | CFM56-3B2 | 0.3684 |
| 125 | Boeing 737-300 | CFM56-3B1 | 0.3694 |
| 126 | Boeing 787-9 | GEnx-1B67/P2G01 | 0.3708 |
| 127 | Boeing 737-700 | CFM56-7B26/3 | 0.3708 |
| 128 | Boeing 737-700 | CFM56-7B26E | 0.3708 |
| 129 | Boeing 737-700 | CFM56-7B26E/B2 | 0.3708 |
| 130 | Boeing 737-700 | CFM56-7B26E/B2F | 0.3708 |
| 131 | Boeing 737-700 | CFM56-7B26E/F | 0.3708 |

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|---|---|---|---|
| 132 | Boeing 787-8 | GEnx-1B67/P2G01 | 0.3709 |
| 133 | Boeing 787-8 | Genx-1B_mean | 0.3724 |
| 134 | Boeing 737-900 | CFM56-7B24 | 0.3736 |
| 135 | Boeing 767-300ER | CF6-80C2B4 | 0.3738 |
| 136 | Boeing 767-300ER | CF6-80C2B6 | 0.3739 |
| 137 | Boeing 737-700 | CFM56-7B27E | 0.3745 |
| 138 | Boeing 737-700 | CFM56-7B27E/B3 | 0.3745 |
| 139 | Boeing 737-700 | CFM56-7B27E/F | 0.3745 |
| 140 | Boeing 767-300ER | CF6-80C2B4F | 0.3755 |
| 141 | Airbus A220-300 | PW1521G-3 | 0.3764 |
| 142 | Boeing 737-900 | CFM56-7B26 | 0.3781 |
| 143 | Boeing 767-300ER | PW4060 | 0.3803 |
| 144 | Airbus A321neo | LEAP-1A30 | 0.3814 |
| 145 | Airbus A321neo | LEAP-1A33 | 0.3814 |
| 146 | Airbus A321neo | LEAP-1A35A | 0.3814 |
| 147 | Boeing 767-300ER | CF6-80C2B6F | 0.3816 |
| 148 | Boeing 767-300ER | CF6-80C2B7F | 0.3816 |
| 149 | Boeing 787-8 | GEnx-1B70/75/P1G01 | 0.3818 |
| 150 | Boeing 787-8 | GEnx-1B70/P1G01 | 0.3818 |
| 151 | Boeing 737-900 | CFM56-7B27 | 0.3818 |
| 152 | Boeing 767-300ER | PW4062 | 0.3853 |
| 153 | Boeing 787-8 | GEnx-1B70/75/P2G01 | 0.3857 |
| 154 | Boeing 787-8 | GEnx-1B70/P2G01 | 0.3857 |
| 155 | Boeing 787-9 | GEnx-1B70/75/P2G01 | 0.3871 |
| 156 | Boeing 767-300ER | PW4056 | 0.3884 |
| 157 | Boeing 767-400ER | CF6-80C2B7F | 0.3890 |
| 158 | Boeing MD-80 | JT8D-217C | 0.3893 |
| 159 | Boeing MD-80 | JT8D-217 | 0.3920 |
| 160 | Boeing MD-80 | JT8D-217A | 0.3920 |
| 161 | Boeing 737 MAX 8 | LEAP-1B25 | 0.3923 |
| 162 | Boeing 737-800 | CFM56-7B24 | 0.3923 |
| 163 | Boeing 767-300ER | CF6-80A2 | 0.3965 |
| 164 | Boeing 737-800 | CFM56-7B26 | 0.3969 |
| 165 | Bombardier CRJ200LR | CF34-3B1 | 0.3973 |
| 166 | Boeing 787-9 | Genx-1B_mean | 0.3978 |
| 167 | Boeing 737-700 | CFM56-7B20 | 0.3988 |
| 168 | Boeing 737-800 | CFM56-7B27 | 0.4007 |
| 169 | Boeing 737-700 | CFM56-7B22 | 0.4011 |
| 170 | Airbus A330-300 | PW4164-1D | 0.4025 |
| 171 | Boeing 767-300ER | CF6-80A | 0.4029 |
| 172 | Boeing 767-300 | CF6-80C2B2 | 0.4048 |
| 173 | Boeing 737-700 | CFM56-7B24 | 0.4049 |
| 174 | Boeing 767-300 | CF6-80C2B2F | 0.4070 |
| 175 | Boeing 737-700 | CFM56-7B26 | 0.4092 |
| 176 | Airbus A330-300 | PW4168-1D | 0.4104 |

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|---|---|---|---|
| 177 | Airbus A310 | PW4152 | 0.4123 |
| 178 | Airbus A330-300 | PW4170 | 0.4126 |
| 179 | Boeing 737-700 | CFM56-7B27 | 0.4127 |
| 180 | Boeing 787-10 | GEnx-1B76/P2G01 | 0.4128 |
| 181 | Boeing 787-10 | GEnx-1B76A/P2G01 | 0.4128 |
| 182 | Boeing 787-9 | GEnx-1B74/75/P2G01 | 0.4140 |
| 183 | Boeing 737-400 | CFM56-3C1 | 0.4151 |
| 184 | Boeing 737-400 | CFM56-3B2 | 0.4169 |
| 185 | Boeing 767-300 | CF6-80C2B4 | 0.4178 |
| 186 | Airbus A310 | CF6-80C2A2 | 0.4178 |
| 187 | Boeing 767-300 | CF6-80C2B6 | 0.4180 |
| 188 | Boeing 737-400 | CFM56-3B1 | 0.4182 |
| 189 | Boeing 787-9 | GEnx-1B74/75/P1G01 | 0.4193 |
| 190 | Boeing 767-300 | CF6-80C2B4F | 0.4197 |
| 191 | Boeing 737 MAX 8 | LEAP-1B_mean | 0.4198 |
| 192 | Airbus A310 | CF6-80C2A8 | 0.4202 |
| 193 | Boeing 737 MAX 9 | LEAP-1B27 | 0.4213 |
| 194 | Airbus A350-900 | Trent XWB-75 | 0.4217 |
| 195 | Boeing 737 MAX 8 | LEAP-1B27 | 0.4222 |
| 196 | Boeing 767-300 | PW4060 | 0.4247 |
| 197 | Boeing 767-300 | CF6-80C2B6F | 0.4270 |
| 198 | Boeing 767-300 | CF6-80C2B7F | 0.4270 |
| 199 | Boeing 777-200 | GE90-110B1 | 0.4302 |
| 200 | Airbus A310 | CF6-80A3 | 0.4303 |
| 201 | Boeing 767-300 | PW4062 | 0.4309 |
| 202 | Boeing 737-900ER | CFM56-7B26E | 0.4309 |
| 203 | Boeing 737 MAX 9 | LEAP-1B_mean | 0.4332 |
| 204 | Boeing 757-300 | PW2040 | 0.4342 |
| 205 | Boeing 767-300 | PW4056 | 0.4343 |
| 206 | Airbus A350-900 | Trent XWB-84 | 0.4352 |
| 207 | Boeing 737-900ER | CFM56-7B27E | 0.4378 |
| 208 | Boeing 757-300 | PW2037 | 0.4382 |
| 209 | Boeing 767-300 | CF6-80A2 | 0.4442 |
| 210 | Embraer E190AR | CF34-10E7-B | 0.4442 |
| 211 | Boeing 737 MAX 8 | LEAP-1B28 | 0.4449 |
| 212 | Boeing 737 MAX 9 | LEAP-1B28 | 0.4451 |
| 213 | Embraer E190AR | CF34-10E2A1 | 0.4485 |
| 214 | Embraer E170LR | CF34-8E5 | 0.4490 |
| 215 | Embraer E190AR | CF34-10E5 | 0.4498 |
| 216 | Embraer E190AR | CF34-10E6 | 0.4498 |
| 217 | Boeing MD-80 | JT8D-209 | 0.4500 |
| 218 | Embraer E170LR | CF34-8E5A1 | 0.4515 |
| 219 | Boeing 767-300 | CF6-80A | 0.4519 |
| 220 | Embraer E190AR | CF34-10E5A1 | 0.4531 |
| 221 | Embraer E190AR | CF34-10E6A1 | 0.4531 |

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|---|---|---|---|
| 222 | Embraer E190AR | CF34-10E7 | 0.4531 |
| 223 | Boeing 777-200 | RB211 Trent 875 | 0.4532 |
| 224 | Bombardier CRJ700ER | CF34-8C5B1 | 0.4547 |
| 225 | Boeing 777-200 | RB211 Trent 877 | 0.4549 |
| 226 | Boeing MD-80 | JT8D-219 | 0.4558 |
| 227 | Embraer E195AR | CF34-10E2A1 | 0.4563 |
| 228 | Embraer E195AR | CF34-10E5 | 0.4577 |
| 229 | Embraer E195AR | CF34-10E6 | 0.4577 |
| 230 | Embraer E190LR | CF34-10E7-B | 0.4578 |
| 231 | Embraer E195AR | CF34-10E5A1 | 0.4611 |
| 232 | Embraer E195AR | CF34-10E6A1 | 0.4611 |
| 233 | Embraer E195AR | CF34-10E7 | 0.4611 |
| 234 | Embraer E190LR | CF34-10E2A1 | 0.4623 |
| 235 | Boeing 767-300ER | JT9D-7R4D | 0.4626 |
| 236 | Boeing 777-200 | RB211 Trent 884 | 0.4636 |
| 237 | Embraer E190LR | CF34-10E5 | 0.4637 |
| 238 | Embraer E190LR | CF34-10E6 | 0.4637 |
| 239 | Bombardier CRJ700ER | CF34-8C1 | 0.4642 |
| 240 | Airbus A330-300 | Trent 768-60 | 0.4659 |
| 241 | Embraer E190LR | CF34-10E5A1 | 0.4671 |
| 242 | Embraer E190LR | CF34-10E6A1 | 0.4671 |
| 243 | Embraer E190LR | CF34-10E7 | 0.4671 |
| 244 | Boeing 777-200 | RB211 Trent 892 | 0.4710 |
| 245 | Boeing 777-200 | RB211 Trent 895 | 0.4741 |
| 246 | Airbus A330-300 | Trent 772B-60 | 0.4746 |
| 247 | Airbus A330-200 | PW4168A-1D | 0.4759 |
| 248 | Airbus A330-300 | CF6-80E1A2 | 0.4775 |
| 249 | Airbus A330-200 | PW4170 | 0.4783 |
| 250 | Boeing 787-8 | Trent 1000-H2 | 0.4786 |
| 251 | Embraer E175LR | CF34-8E5 | 0.4797 |
| 252 | Boeing 767-300ER | JT9D-7R4E | 0.4801 |
| 253 | Boeing 787-8 | Trent 1000-H3 | 0.4808 |
| 254 | Embraer E175LR | CF34-8E5A1 | 0.4826 |
| 255 | Airbus A350-1000 | Trent XWB-97 | 0.4830 |
| 256 | Bombardier CRJ200ER | CF34-3B1 | 0.4880 |
| 257 | Boeing 787-8 | Trent 1000-A2 | 0.4887 |
| 258 | Airbus A330-300 | CF6-80E1A4 | 0.4889 |
| 259 | Boeing 787-8 | Trent 1000-AE3 | 0.4894 |
| 260 | Bombardier CRJ1000 | CF34-8C5 | 0.4906 |
| 261 | Boeing 757-200 | RB211-535C-37 | 0.4914 |
| 262 | Bombardier CRJ1000 | CF34-8C5A1 | 0.4919 |
| 263 | Boeing 787-8 | Trent 1000-A | 0.4923 |
| 264 | Boeing 787-8 | Trent 1000_mean | 0.4929 |
| 265 | Embraer E195LR | CF34-10E2A1 | 0.4934 |
| 266 | Boeing 777-300ER | GE90-115B | 0.4941 |
| 267 | Boeing MD-11 | PW4460 | 0.4941 |

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|---|---|---|---|
| 268 | Boeing 787-8 | Trent 1000-G3 | 0.4944 |
| 269 | Airbus A330-300 | PW4164 | 0.4944 |
| 270 | Boeing 787-8 | Trent 1000-G2 | 0.4946 |
| 271 | Bombardier CRJ1000 | CF34-8C5A2 | 0.4947 |
| 272 | Embraer E195LR | CF34-10E5 | 0.4949 |
| 273 | Embraer E195LR | CF34-10E6 | 0.4949 |
| 274 | Airbus A330-300 | CF6-80E1A3 | 0.4961 |
| 275 | Boeing 787-8 | Trent 1000-CE3 | 0.4985 |
| 276 | Boeing 787-8 | Trent 1000-D3 | 0.4985 |
| 277 | Embraer E195LR | CF34-10E5A1 | 0.4988 |
| 278 | Embraer E195LR | CF34-10E6A1 | 0.4988 |
| 279 | Embraer E195LR | CF34-10E7 | 0.4988 |
| 280 | Airbus A330-300 | PW4168 | 0.4989 |
| 281 | Airbus A330-300 | PW4168A | 0.4989 |
| 282 | Boeing 757-200 | PW2040 | 0.4991 |
| 283 | Boeing 787-9 | Trent 1000-A2 | 0.4992 |
| 284 | Boeing 737-900ER | CFM56-7B27 | 0.4992 |
| 285 | Boeing 787-9 | Trent 1000-AE3 | 0.4997 |
| 286 | Boeing 787-8 | Trent 1000-C2 | 0.4998 |
| 287 | Boeing 787-8 | Trent 1000-D2 | 0.4998 |
| 288 | Boeing 787-8 | Trent 1000-L2 | 0.4998 |
| 289 | Boeing MD-11 | CF6-80C2D1F | 0.5009 |
| 290 | Boeing 767-300ER | RB211-524G | 0.5010 |
| 291 | Boeing 787-10 | Trent 1000-J3 | 0.5013 |
| 292 | Boeing 757-200 | PW2037 | 0.5039 |
| 293 | Comac ARJ21-700 | CF34-8E5 | 0.5045 |
| 294 | Boeing 757-300 | RB211-535E4B-37 | 0.5055 |
| 295 | Boeing 777-200 | PW4074 | 0.5076 |
| 296 | Boeing 777-200 | PW4077 | 0.5082 |
| 297 | Boeing 777-200LR | GE90-110B1 | 0.5086 |
| 298 | Boeing 787-9 | Trent 1000-D3 | 0.5097 |
| 299 | Boeing 787-9 | Trent 1000-D2 | 0.5115 |
| 300 | Boeing 787-9 | Trent 1000_mean | 0.5121 |
| 301 | Embraer E175 | CF34-8E5 | 0.5138 |
| 302 | Boeing 777-200ER | RB211 Trent 875 | 0.5150 |
| 303 | Boeing 787-9 | Trent 1000-J3 | 0.5163 |
| 304 | Boeing 787-9 | Trent 1000-K3 | 0.5163 |
| 305 | Boeing 777-300 | RB211 Trent 884 | 0.5164 |
| 306 | Boeing 777-200ER | RB211 Trent 877 | 0.5170 |
| 307 | Embraer E175 | CF34-8E5A1 | 0.5174 |
| 308 | Boeing 777-200LR | GE90-115B | 0.5175 |
| 309 | Boeing 787-9 | Trent 1000-J2 | 0.5219 |
| 310 | Boeing 787-9 | Trent 1000-K2 | 0.5219 |
| 311 | Boeing 777-200 | PW4074D | 0.5224 |
| 312 | Boeing 767-300ER | RB211-524H | 0.5228 |
| 313 | Boeing MD-90 | V2525-D5 | 0.5230 |

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|---|---|---|---|
| 314 | Boeing 767-300 | JT9D-7R4D | 0.5231 |
| 315 | Boeing 777-200 | PW4077D | 0.5246 |
| 316 | Boeing MD-90 | V2528-D5 | 0.5249 |
| 317 | Airbus A330-900 | Trent 7000-72 | 0.5249 |
| 318 | Boeing 777-300 | RB211 Trent 892 | 0.5255 |
| 319 | Bombardier CRJ900 | CF34-8C5 | 0.5277 |
| 320 | Boeing 777-200ER | RB211 Trent 884 | 0.5277 |
| 321 | Bombardier CRJ900 | CF34-8C5A1 | 0.5289 |
| 322 | Boeing 757-300 | RB211-535E4-37 | 0.5294 |
| 323 | Boeing 777-200 | PW4084D | 0.5305 |
| 324 | Embraer E170 | CF34-8E5 | 0.5331 |
| 325 | Boeing 777-200 | PW4090 | 0.5349 |
| 326 | Boeing 777-200ER | RB211 Trent 892 | 0.5365 |
| 327 | Embraer E170 | CF34-8E5A1 | 0.5369 |
| 328 | Boeing 777-200ER | RB211 Trent 895 | 0.5405 |
| 329 | Bombardier CRJ200 | CF34-3B1 | 0.5416 |
| 330 | Boeing 747-8 | GEnx-2B67 | 0.5433 |
| 331 | Boeing 747-8 | GEnx-2B67B | 0.5433 |
| 332 | Boeing 767-300 | JT9D-7R4E | 0.5438 |
| 333 | Embraer E190 | CF34-10E7-B | 0.5444 |
| 334 | Airbus A330-200 | Trent 772B-60 | 0.5484 |
| 335 | Fokker 100 | TAY 620-15 | 0.5500 |
| 336 | Embraer E190 | CF34-10E2A1 | 0.5502 |
| 337 | Airbus A330-200 | CF6-80E1A2 | 0.5516 |
| 338 | Embraer E190 | CF34-10E5 | 0.5520 |
| 339 | Embraer E190 | CF34-10E6 | 0.5520 |
| 340 | Boeing 747-8 | GEnx-2B67_mean | 0.5552 |
| 341 | Boeing 777-200 | GE90-94B | 0.5557 |
| 342 | Sukhoi Superjet 100 | SaM146-1S17 | 0.5559 |
| 343 | Embraer E190 | CF34-10E5A1 | 0.5564 |
| 344 | Embraer E190 | CF34-10E6A1 | 0.5564 |
| 345 | Embraer E190 | CF34-10E7 | 0.5564 |
| 346 | Boeing 777-200 | GE90-76B | 0.5568 |
| 347 | Bombardier CRJ100 | CF34-3A1 | 0.5597 |
| 348 | Bombardier CRJ200 | CF34-3A1 | 0.5597 |
| 349 | Boeing 777-200 | GE90-77B | 0.5614 |
| 350 | Airbus A330-200 | CF6-80E1A4 | 0.5645 |
| 351 | Airbus A300 | CF6-80C2A5F | 0.5655 |
| 352 | Embraer ERJ-145 | AE3007 A1 | 0.5684 |
| 353 | Embraer ERJ-145 | AE3007 A1/1 | 0.5685 |
| 354 | Embraer ERJ-145 | AE3007 A1P | 0.5685 |
| 355 | Boeing 777-200 | GE90-85B | 0.5685 |
| 356 | Boeing 767-300 | RB211-524G | 0.5693 |
| 357 | Dornier 328JET-300 | PW306B | 0.5714 |
| 358 | Airbus A330-200 | CF6-80E1A3 | 0.5726 |
| 359 | Boeing 757-200 | RB211-535E4B-37 | 0.5749 |

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|---|---|---|---|
| 360 | Airbus A330-200 | PW4168A | 0.5761 |
| 361 | Boeing 777-200 | GE90-90B | 0.5785 |
| 362 | Boeing 747-8 | GEnx-2B67/P | 0.5788 |
| 363 | Boeing 777-200ER | PW4074 | 0.5801 |
| 364 | Embraer ERJ-145 | AE3007 A | 0.5808 |
| 365 | Boeing 777-200ER | PW4077 | 0.5808 |
| 366 | Embraer E195 | CF34-10E2A1 | 0.5845 |
| 367 | Embraer E195 | CF34-10E5 | 0.5864 |
| 368 | Embraer E195 | CF34-10E6 | 0.5864 |
| 369 | Embraer E195 | CF34-10E5A1 | 0.5914 |
| 370 | Embraer E195 | CF34-10E6A1 | 0.5914 |
| 371 | Embraer E195 | CF34-10E7 | 0.5914 |
| 372 | Boeing 767-300 | RB211-524H | 0.5952 |
| 373 | Boeing 777-200ER | PW4074D | 0.5986 |
| 374 | Boeing 737-500 | CFM56-3C1 | 0.5990 |
| 375 | Boeing 757-200 | RB211-535E4-37 | 0.6008 |
| 376 | Boeing 777-200ER | PW4077D | 0.6013 |
| 377 | Boeing 737-500 | CFM56-3B2 | 0.6017 |
| 378 | Airbus A300 | CF6-80C2A5 | 0.6028 |
| 379 | Boeing 737-500 | CFM56-3B1 | 0.6037 |
| 380 | Boeing 717-200 | BR700-715A1-30 | 0.6050 |
| 381 | Airbus A300 | PW4158 | 0.6052 |
| 382 | Boeing 777-200ER | PW4084D | 0.6085 |
| 383 | Boeing 777-300 | PW4090 | 0.6122 |
| 384 | Boeing 777-200ER | PW4090 | 0.6137 |
| 385 | Airbus A300 | CF6-50C1 | 0.6240 |
| 386 | Airbus A300 | CF6-50C2 | 0.6240 |
| 387 | Airbus A300 | CF6-50A | 0.6253 |
| 388 | Airbus A300 | CF6-80C2A8 | 0.6296 |
| 389 | Embraer ERJ-135 | AE3007 A2 | 0.6311 |
| 390 | Embraer ERJ-135 | AE3007 A1E | 0.6361 |
| 391 | Boeing 777-200ER | GE90-94B | 0.6367 |
| 392 | Boeing 777-200ER | GE90-76B | 0.6387 |
| 393 | Airbus A300 | CF6-80C2A1 | 0.6389 |
| 394 | Airbus A300 | JT9D-59A | 0.6422 |
| 395 | Boeing 777-200ER | GE90-77B | 0.6444 |
| 396 | Airbus A300 | CF6-80C2A3 | 0.6492 |
| 397 | Boeing 777-200ER | GE90-85B | 0.6537 |
| 398 | Boeing 747-400 | CF6-80C2B5F | 0.6553 |
| 399 | Boeing 777-200ER | GE90-90B | 0.6658 |
| 400 | Airbus A300 | CF6-50C | 0.6865 |
| 401 | Airbus A300 | CF6-50C2R | 0.6865 |
| 402 | Embraer ERJ-135 | AE3007 A1P | 0.6890 |
| 403 | Embraer ERJ-135 | AE3007 A1/3 | 0.6896 |
| 404 | Embraer ERJ-135 | AE3007 A3 | 0.6896 |
| 405 | Airbus A340-600 | Trent 556-61 | 0.7001 |

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|---|---|---|---|
| 406 | Embraer ERJ-140 | AE3007 A1/3 | 0.7235 |
| 407 | Embraer ERJ-140 | AE3007 A3 | 0.7235 |
| 408 | Boeing 747-400 | CF6-80C2B1F | 0.7271 |
| 409 | Airbus A300 | JT9D-7R4H1 | 0.7456 |
| 410 | Airbus A340-300 | CFM56-5C3/P | 0.7585 |
| 411 | Boeing 747-400 | PW4056 | 0.7626 |
| 412 | Airbus A340-300 | CFM56-5C4/P | 0.7693 |
| 413 | Airbus A340-300 | CFM56-5C2 | 0.7781 |
| 414 | Airbus A380-800 | Trent 970-84 | 0.7926 |
| 415 | Airbus A340-300 | CFM56-5C4 | 0.8004 |
| 416 | Airbus A380-800 | Trent 972E-84 | 0.8099 |
| 417 | Airbus A350-900ULR | Trent XWB-75 | 0.8204 |
| 418 | Airbus A380-800 | GP7270 | 0.8442 |
| 419 | Airbus A350-900ULR | Trent XWB-84 | 0.8527 |
| 420 | Boeing 747-400 | RB211-524G | 1.1736 |

# Appendix E – Reference Fuel Consumption

**Table E.1** List of fuel consumption in kg/km with frequency of aircraft type (World Airliner Census 2020)

| Aircraft type | Fuel consumption (kg/km) | Total passenger aircraft | Weighting passenger aircraft in percent |
|---|---|---|---|
| Boeing 737-800 | 4.34240 | 4788 | 17.59 |
| Airbus A320 | 4.19753 | 4132 | 15.18 |
| Airbus A321-200 | 4.74699 | 1637 | 6.01 |
| Airbus A319 | 3.67171 | 1243 | 4.57 |
| Airbus A320neo | 3.57774 | 1009 | 3.71 |
| Boeing 737-700 | 3.77136 | 979 | 3.60 |
| Boeing 777-300ER | 10.97802 | 805 | 2.96 |
| ATR 72 | 2.15983 | 795 | 2.92 |
| Airbus A330-300 | 8.67539 | 707 | 2.60 |
| Embraer E175LR | 3.03770 | 624 | 2.29 |
| Bombardier CRJ200LR | 1.79947 | 601 | 2.21 |
| Boeing 737-900 | 4.50955 | 556 | 2.04 |
| Boeing 787-9 | 7.47107 | 540 | 1.98 |
| Airbus A330-200 | 8.38770 | 502 | 1.84 |
| Embraer E190LR | 3.31010 | 501 | 1.84 |
| Embraer ERJ-145 | 1.98977 | 479 | 1.76 |
| De Havilland Canada Dash 8 Q400 | 2.43696 | 462 | 1.70 |
| Boeing 777-200ER | 9.91464 | 391 | 1.44 |
| Boeing 767-300 | 7.66643 | 365 | 1.34 |
| Boeing 787-8 | 6.56833 | 363 | 1.33 |
| Airbus A321neo | 4.36285 | 355 | 1.30 |
| Boeing 737 MAX 8 | 3.40653 | 347 | 1.27 |
| Airbus A350-900 | 7.80772 | 321 | 1.18 |
| Boeing 757-200 | 5.87827 | 302 | 1.11 |
| Bombardier CRJ700ER | 2.69244 | 291 | 1.07 |
| Airbus A380-800 | 16.98129 | 237 | 0.87 |
| Boeing MD-80 | 4.84624 | 232 | 0.85 |
| Beechcraft 1900D | 1.51624 | 220 | 0.81 |
| Boeing 737-300 | 3.75894 | 214 | 0.79 |
| ATR 42 | 1.96078 | 208 | 0.76 |
| Saab 340 | 1.29032 | 188 | 0.69 |
| Boeing 737-500 | 4.83230 | 161 | 0.59 |
| Embraer E195LR | 3.69924 | 161 | 0.59 |
| De Havilland Canada Dash 8 Q300 | 2.20979 | 157 | 0.58 |
| Embraer E170LR | 2.83054 | 157 | 0.58 |
| De Havilland Canada Dash 8 Q100 | 1.71598 | 152 | 0.56 |
| Boeing 717-200 | 4.25538 | 145 | 0.53 |
| Boeing 747-400 | 14.26868 | 142 | 0.52 |
| Boeing 737-400 | 4.59454 | 141 | 0.52 |

| | | | |
|---|---|---|---|
| Sukhoi Superjet 100 | 4.06920 | 141 | 0.52 |
| Embraer EMB-120 Brasilia | 1.86220 | 127 | 0.47 |
| Fokker 100 | 3.78498 | 109 | 0.40 |
| Fokker 50 | 1.72817 | 86 | 0.32 |
| Airbus A340-300 | 10.24816 | 78 | 0.29 |
| Airbus A220-300 | 3.18386 | 72 | 0.26 |
| Embraer ERJ-140 | 2.15983 | 70 | 0.26 |
| Bombardier CRJ1000 | 3.15000 | 63 | 0.23 |
| Embraer ERJ-135 | 1.83585 | 61 | 0.22 |
| Boeing 787-10 | 7.94847 | 58 | 0.21 |
| Airbus A340-600 | 11.41214 | 57 | 0.21 |
| Boeing 757-300 | 6.41594 | 53 | 0.19 |
| Dornier 228 | 1.16162 | 53 | 0.19 |
| Boeing 777-200LR | 9.84879 | 50 | 0.18 |
| Boeing 777-300 | 11.07101 | 50 | 0.18 |
| Airbus A330-900 | 7.89849 | 47 | 0.17 |
| Airbus A350-1000 | 9.25658 | 43 | 0.16 |
| De Havilland Canada Dash 8 Q200 | 1.54885 | 42 | 0.15 |
| Airbus A220-100 | 2.89617 | 40 | 0.15 |
| Boeing 767-400ER | 7.92185 | 37 | 0.14 |
| Airbus A300 | 10.28858 | 35 | 0.13 |
| Boeing 747-8 | 13.98999 | 35 | 0.13 |
| Fokker 70 | 3.21837 | 35 | 0.13 |
| Comac ARJ21-700 | 3.38974 | 31 | 0.11 |
| Boeing 737 MAX 9 | 3.74233 | 28 | 0.10 |
| Boeing MD-90 | 5.17700 | 26 | 0.10 |
| Airbus A318 | 3.64471 | 24 | 0.09 |
| Airbus A310 | 7.00000 | 22 | 0.08 |
| Dornier 328JET-300 | 1.50319 | 18 | 0.07 |
| Embraer E190-E2 | 2.78576 | 15 | 0.06 |
| Embraer E195-E2 | 2.74226 | 8 | 0.03 |
| Airbus A319neo | 3.30693 | 0 | 0.00 |
| Airbus A321-100 | 4.46429 | 0 | 0.00 |
| Airbus A350-900ULR | 8.15041 | 0 | 0.00 |
| Boeing 737-900ER | 5.27818 | 0 | 0.00 |
| Boeing 767-300ER | 7.07274 | 0 | 0.00 |
| Boeing 777-200 | 9.08553 | 0 | 0.00 |
| Boeing MD-11 | 9.77301 | 0 | 0.00 |
| Bombardier CRJ100/200 | 2.33660 | 0 | 1.03 |
| Bombardier CRJ200ER | 2.14238 | 0 | 0.00 |
| Bombardier CRJ900 | 2.95995 | 0 | 0.00 |
| COMAC C919 | 4.03846 | 0 | 0.00 |
| Embraer E170 | 3.25522 | 0 | 0.00 |
| Embraer E175 | 3.29545 | 0 | 0.00 |
| Embraer E190 | 3.77430 | 0 | 0.00 |
| Embraer E190AR | 3.23442 | 0 | 0.00 |

| | | | |
|---|---|---|---|
| Embraer E195 | 4.19333 | 0 | 0.00 |
| Embraer E195AR | 3.48812 | 0 | 0.00 |

| | |
|---|---|
| weighted mean value World Airliner Census 2020: | 4.74 |

# Appendix F – Atmosfair Airline Index 2018

**Table F.1** Atmosfair Airline Index 2018 overall ranking

| Rank[1] | Airline[2] | Country | EP[3] '18 | EP '17 | EK[4] | Type[5] | Passengers (in Mio.)[6] |
|---|---|---|---|---|---|---|---|
| 1 | TUI Airways | UK | 79,3 | 78,9 | B | Charter | 10,9 |
| 2 | LATAM Airlines Brasil[7] | Brasilien | 78,8 | 72,3 | B | Net Carrier | 33,8 |
| 3 | China West Air | China | 77,8 | 78,6 | C | Regional | 7,2 |
| 4 | TUIfly | Deutschland | 77,6 | 78,2 | C | Charter | 4,6 |
| 5 | Transavia.com France | Frankreich | 76,3 | - | C | Charter | 5,1 |
| 6 | SunExpress | Türkei | 74,9 | - | C | Charter | 6,3 |
| 7 | Thomas Cook Airlines | UK | 74,7 | 72,9 | C | Charter | 6,6 |
| 8 | Air Europa Express | Spanien | 73,4 | - | C | Regional | 0,2 |
| 9 | Condor Flugdienst | Deutschland | 71,8 | 72,9 | C | Charter | 7,3 |
| 10 | Juneyao Airlines | China | 70,9 | 61,6 | C | Net Carrier | 13,3 |
| 11 | Jet2.com | UK | 70,8 | 73,8 | C | Charter | 6,7 |
| 12 | Air Europa | Spanien | 70,7 | 65,6 | C | Net Carrier | 10,7 |
| 13 | Air New Zealand | Neuseeland | 70,5 | 60,8 | C | Net Carrier | 15,2 |
| 14 | Vietnam Airlines | Vietnam | 70,4 | 64,3 | C | Net Carrier | 20,6 |
| 15 | Beijing Capital Airlines | China | 69,8 | 58,1 | C | Net Carrier | 13,1 |
| 16 | Siberia Airlines[8] | Russland | 69,2 | 65,6 | C | Net Carrier | 9,5 |
| 17 | KLM | Niederlande | 68,9 | 68,1 | C | Net Carrier | 30,4 |
| 18 | Virgin Australia International | Australien | 68,5 | 67,0 | C | Net Carrier | 19,7 |
| 19 | Air New Zealand Link | Neuseeland | 68,3 | 64,4 | C | Regional | 3,0 |
| 20 | Air Caraibes | Guadeloupe | 68,2 | - | C | Net Carrier | 1,4 |
| 21 | Avianca | Kolumbien | 67,9 | 61,7 | C | Net Carrier | 29,5 |
| 22 | Alaska Airlines | USA | 67,4 | 67,6 | C | Net Carrier | 24,4 |
| 23 | Shandong Airlines | China | 67,4 | 55,8 | C | Net Carrier | 18,6 |
| 24 | Sichuan Airlines | China | 67,4 | 65,6 | C | Net Carrier | 23 |
| 25 | Thai Airways International | Thailand | 67,4 | 65,3 | C | Net Carrier | 18,2 |
| 26 | Air Transat | Kanada | 67,1 | 65,7 | C | Charter | 4,4 |
| 27 | UTair Aviation | Russland | 66,9 | 46,5 | C | Net Carrier | 6,7 |
| 28 | Air India Express | India | 66,8 | - | C | Regional | 3,2 |
| 29 | Hong Kong Airlines | Hong Kong | 66,2 | 61,7 | C | Net Carrier | 6,5 |
| 30 | Shenzhen Airlines | China | 66,1 | 65,7 | C | Net Carrier | 27,6 |
| 31 | Xiamen Airlines Company | China | 66,0 | 53,8 | C | Net Carrier | 24,5 |
| 32 | Air Canada | Kanada | 65,6 | 55,5 | C | Net Carrier | 44,8 |
| 33 | Hainan Airlines | China | 65,6 | 60,6 | C | Net Carrier | 27,4 |
| 34 | Iberia | Spanien | 65,0 | 59,8 | C | Net Carrier | 17,8 |
| 35 | Ural Airlines | Russland | 64,9 | 55,1 | D | Net Carrier | 6,5 |

[1] In the event of ties, airlines are listed alphabetically.
[2] The following airlines were not evaluated due to data gaps: Gol, Anadolu Jet, Travel Service Airlines, Globus.
[3] EP: Efficiency points
[4] EK: Efficiency class
[5] Type: The division of the airlines in categories was based on Air Transport Intelligence and other sources.
[6] Passengers: Number of passengers (data from Air Transport Intelligence, a service of ICAOData.com, IATA WATS, and other sources)
[7] also TAM Linhas Aereas
[8] also S7 Airlines

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 36 | Finnair | Finnland | 64,4 | 57,4 | D | Net Carrier | 10,9 |
| 37 | China Eastern Airlines | China | 64,0 | 59,5 | D | Net Carrier | 80,9 |
| 38 | Japan Airlines | Japan | 63,9 | 53,1 | D | Net Carrier | 32,9 |
| 39 | Air India | Indien | 63,4 | 57,4 | D | Net Carrier | 19,8 |
| 40 | El Al Israel Airlines | Israel | 63,2 | 54,8 | D | Net Carrier | 5,5 |
| 41 | Air China | China | 63,1 | 58,0 | D | Net Carrier | 62,4 |
| 42 | Batik Air | Indonesia | 62,5 | - | D | Net Carrier | 7,6 |
| 43 | Royal Air Maroc Express | Marokko | 62,3 | 57,0 | D | Regional | 0,5 |
| 44 | Garuda Indonesia | Indonesien | 61,9 | 58,8 | D | Net Carrier | 23,9 |
| 45 | Cathay Pacific Airways | Hong Kong | 61,8 | 63,2 | D | Net Carrier | 24,4 |
| 46 | Delta Airlines | USA | 61,8 | 59,7 | D | Net Carrier | 183,7 |
| 47 | Corsair | France | 61,6 | 60,7 | D | Charter | 1,2 |
| 48 | TAP Portugal | Portugal | 61,5 | 61,5 | D | Net Carrier | 11,7 |
| 49 | Qantas Airways | Australien | 61,4 | 58,2 | D | Net Carrier | 28,2 |
| 50 | Aerolineas Argentinas | Argentina | 60,4 | 58 | D | Net Carrier | 8,3 |
| 51 | United Airlines | USA | 60,4 | 59,7 | D | Net Carrier | 143,2 |
| 52 | China Southern Airlines | China | 60,3 | 59,3 | D | Net Carrier | 84,9 |
| 53 | TianJin Airlines | China | 60,0 | 48,9 | D | Regional | 12,1 |
| 54 | Icelandair | Island | 59,9 | 60,4 | D | Net Carrier | 3,7 |
| 55 | Shanghai Airlines | China | 59,8 | 59,0 | D | Net Carrier | 14,3 |
| 56 | Cathay Dragon | Hong Kong | 59,6 | - | D | Net Carrier | 9,9 |
| 57 | Hawaiian Airlines | USA | 59,0 | 57,0 | D | Net Carrier | 11,1 |
| 58 | American Airlines | USA | 58,7 | 55,1 | D | Net Carrier | 198,7 |
| 59 | MASwings | Malaysia | 58,7 | 56,8 | D | Regional | 1,4 |
| 60 | Ukraine Int. Airlines | Ukraine | 58,7 | 55,9 | D | Net Carrier | 6,0 |
| 61 | All Nippon Airways | Japan | 58,4 | 48,1 | D | Net Carrier | 52,1 |
| 61 | Malaysia Airlines | Malaysia | 58,4 | 45,5 | D | Net Carrier | 13,9 |
| 63 | Copa Airlines | Panama | 58,2 | 54,8 | D | Net Carrier | 8,5 |
| 64 | Aeromexico | Mexico | 58,1 | 50,2 | D | Net Carrier | 11,2 |
| 65 | Alitalia | Italien | 57,2 | 57,8 | D | Net Carrier | 23,1 |
| 66 | Lufthansa | Deutschland | 56,9 | 55,2 | D | Net Carrier | 62,4 |
| 67 | Singapore Airlines | Singapore | 56,5 | 35,1 | D | Net Carrier | 19,0 |
| 68 | Aeroflot Russian Airlines | Russland | 56,4 | 55,7 | D | Net Carrier | 39,2 |
| 69 | Turkish Airlines | Türkei | 56,2 | 59,4 | D | Net Carrier | 62,8 |
| 70 | Asiana Airlines | Südkorea | 56,1 | 53,1 | D | Net Carrier | 19,3 |
| 71 | Korean Air | Südkorea of | 55,9 | 49,3 | D | Net Carrier | 26,9 |
| 72 | Srilankan Airlines | Sri Lanka | 55,6 | 56,0 | D | Net Carrier | 4,4 |
| 73 | Air France | Frankreich | 54,5 | 55,0 | D | Net Carrier | 49,8 |
| 74 | British Airways | UK | 54,4 | 51,7 | D | Net Carrier | 44,5 |
| 75 | Iberia Regional | Spanien | 54,3 | 51,3 | D | Regional | 2,2 |
| 76 | Royal Air Maroc | Marokko | 54,0 | 45,3 | D | Net Carrier | 6,8 |
| 77 | QantasLink | Australien | 53,6 | 59,9 | D | Regional | 6,2 |
| 78 | SAS Scandinavian Airlines | Schweden | 53,4 | 52,0 | D | Net Carrier | 29,4 |
| 79 | EVA Airways | Taiwan | 53,2 | 62,1 | D | Net Carrier | 11,2 |
| 79 | SilkAir | Singapore | 53,2 | 56,3 | D | Regional | 4,1 |
| 81 | Austrian Airlines | Österreich | 51,6 | 51,6 | D | Net Carrier | 11,4 |
| 82 | China Airlines | Taiwan | 51,4 | 57,5 | D | Net Carrier | 14,7 |
| 83 | Virgin Atlantic Airways | UK | 51,3 | 40,9 | D | Net Carrier | 5,4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 84 | Brussels Airlines | Belgium | 50,5 | 49,0 | E | Net Carrier | 7,7 |
| 85 | South African Express | Südafrika | 50,3 | 41,6 | E | Regional | 0,3 |
| 86 | Air Algerie | Algerien | 50,2 | - | E | Net Carrier | 6,1 |
| 87 | Pakistan Int. Airlines | Pakistan | 50,1 | 52,5 | E | Net Carrier | 5,5 |
| 87 | Philippine Airlines | Philippinen | 50,1 | 50,1 | E | Net Carrier | 13,4 |
| 89 | Swiss | Schweiz | 49,7 | 46,8 | E | Net Carrier | 18,0 |
| 90 | Alaska Horizon | USA | 49,5 | 48,9 | E | Regional | 7,8 |
| 91 | Jazz Aviation | Kanada | 49,1 | 45,6 | E | Regional | 10,5 |
| 92 | PAL Express | Philippinen | 48,8 | 49,5 | E | Regional | 5,1 |
| 93 | ANA Wings | Japan | 48,6 | 49,6 | E | Regional | 0,2 |
| 94 | Nordic Regional Airlines | Finland | 48,3 | 44,3 | E | Regional | 2,8 |
| 95 | Gulf Air | Bahrain | 47,3 | 44,2 | E | Net Carrier | 5,2 |
| 96 | Etihad Airways | VAE | 47,2 | 49,8 | E | Net Carrier | 18,5 |
| 97 | LOT - Polish Airlines | Polen | 47,0 | 44,2 | E | Net Carrier | 5,5 |
| 98 | Flybe | UK | 46,8 | 48,5 | E | Regional | 8,4 |
| 99 | Lufthansa Regional | Deutschland | 46,7 | 46,8 | E | Regional | 5,1 |
| 100 | Qatar Airways | Qatar | 46,4 | 46,1 | E | Net Carrier | 32 |
| 101 | Egyptair | Ägypten | 44,7 | 41,1 | E | Net Carrier | 8,2 |
| 102 | BA CityFlyer | UK | 43,6 | 39,7 | E | Regional | 2,2 |
| 103 | Oman Air | Oman | 43,4 | 40,5 | E | Net Carrier | 7,7 |
| 104 | HOP! | France | 42,9 | - | E | Regional | 6,0 |
| 104 | Kuwait Airways | Kuwait | 42,9 | 42,2 | E | Net Carrier | 2,9 |
| 106 | Ohana by Hawaiian | USA | 42,8 | 38,8 | E | Regional | 0,4 |
| 107 | J-Air | Japan | 41,1 | 41,3 | E | Regional | 3,5 |
| 108 | Emirates | VAE | 40,7 | 39,6 | E | Net Carrier | 56,1 |
| 109 | Swiss Global Air Lines | Schweiz | 40,3 | 46,8 | E | Regional | 1,1 |
| 110 | Saudi Arabian Airlines | Saudi-Arabien | 40,2 | 40,3 | E | Net Carrier | 28,2 |
| 111 | South African Airways | Südafrika | 39,5 | 41,4 | E | Net Carrier | 6,6 |
| 112 | Aeromexico Connect | Mexico | 38,6 | 30,6 | E | Regional | 8,5 |
| 113 | Austral Lineas Aereas | Argentinien | 37,7 | 33,2 | E | Regional | 3,2 |
| 114 | Royal Jordanian | Jordanien | 37,4 | 34,7 | E | Net Carrier | 3,0 |
| 115 | Ethiopian Airlines | Äthiopien | 36,5 | 26,5 | E | Net Carrier | 8,2 |
| 116 | Virgin Australia Regional | Australien | 36,0 | 40,4 | E | Regional | 4,6 |
| 117 | Air Astana | Kasachstan | 34,8 | 36,0 | F | Net Carrier | 3,7 |
| 118 | Mahan Air | Iran | 33,9 | 39,0 | F | Net Carrier | 5,9 |
| 119 | United Express | USA | 31,1 | 32,0 | F | Regional | 22,0 |
| 120 | TAP Express | Portugal | 30,6 | 37,0 | F | Regional | 1,3 |
| 121 | Delta Connection | USA | 28,5 | 29,5 | F | Regional | 39,0 |
| 122 | Envoy | USA | 28,2 | 32,8 | F | Regional | 11,8 |
| 123 | Kenya Airways | Kenia | 27,6 | 19,5 | F | Net Carrier | 4,5 |
| 124 | Egyptair Express | Ägypten | 25,4 | 22,0 | F | Regional | 1,2 |
| 125 | South African Airlink | Südafrika | 2,3 | 2,6 | G | Regional | 0,5 |

# Appendix G – Atmosfair Airline Index of Airlines with Fleet of at least 100 Aircraft

**Table G.1** List of AAI of Airlines with a fleet of at least 100 aircraft

| Rank | Airline | Country | Efficiency Points '18 | Efficiency Points '17 | Pax (in Mio.) |
|---|---|---|---|---|---|
| 1 | LATAM Airlines Brazil | Brazil | 78.8 | 72.3 | 33.8 |
| 2 | Air New Zealand | New Zealand | 70.5 | 60.8 | 15.2 |
| 3 | Vietnam Airlines | Vietnam | 70.4 | 64.3 | 20.6 |
| 4 | KLM | Netherlands | 68.9 | 68.1 | 30.4 |
| 5 | Avianca | Colombia | 67.9 | 61.7 | 29.5 |
| 6 | Alaska Airlines | USA | 67.4 | 67.6 | 24.4 |
| 7 | Shandong Airlines | China | 67.4 | 55.8 | 18.6 |
| 8 | Sichuan Airlines | China | 67.4 | 65.6 | 23 |
| 9 | Shenzhen Airlines | China | 66.1 | 65.7 | 27.6 |
| 10 | Xiamen Airlines | China | 66 | 53.8 | 24.5 |
| 11 | Air Canada | Canada | 65.6 | 55.5 | 44.8 |
| 12 | Hainan Airlines | China | 65.6 | 55.5 | 27.4 |
| 13 | China Eastern Airlines | China | 64 | 59.5 | 80.9 |
| 14 | Japan Airlines | Japan | 63.9 | 53.1 | 32.9 |
| 15 | Air India | India | 63.4 | 57.4 | 19.8 |
| 16 | Air China | China | 63.1 | 58 | 62.4 |
| 17 | Garuda Indonesia | Indonesia | 61.9 | 58.8 | 23.9 |
| 18 | Cathay Pacific Airways | Hong Kong | 61.8 | 63.2 | 24.4 |
| 19 | Delta Airlines | USA | 61.8 | 59.7 | 183.7 |
| 20 | Qantas Airways | Australia | 61.4 | 58.2 | 28.2 |
| 21 | United Airlines | USA | 60.4 | 59.7 | 143.2 |
| 22 | China Southern Airlines | China | 60.3 | 59.3 | 84.9 |
| 23 | American Airlines | USA | 58.7 | 55.1 | 198.7 |
| 24 | All Nippon Airways | Japan | 58.4 | 48.1 | 52.1 |
| 25 | Lufthansa | Germany | 56.9 | 55.2 | 62.4 |
| 26 | Singapore Airlines | Singapore | 56.5 | 35.1 | 19 |
| 27 | Aeroflot | Russia | 56.4 | 55.7 | 39.2 |
| 28 | Turkish Airlines | Turkey | 56.2 | 59.4 | 62.8 |
| 29 | Korean Airlines | South Korea | 55.9 | 49.3 | 26.9 |
| 30 | Air France | France | 54.5 | 55 | 49.8 |
| 31 | British Airways | UK | 54.4 | 51.7 | 44.5 |
| 32 | SAS Scandinavian Airlines | Sweden | 53.4 | 52 | 29.4 |
| 33 | Qatar Airways | Qatar | 46.4 | 46.1 | 32 |
| 34 | Emirates | UAE | 40.7 | 39.6 | 56.1 |
| 35 | Saudi Arabian Airlines | Saudi Arabia | 40.2 | 40.3 | 28.2 |
| 36 | Ethiopian Airlines | Ethiopia | 36.5 | 26.5 | 8.2 |
| 37 | United Express | USA | 31.1 | 32 | 22 |
| 38 | Delta Connection | USA | 28.5 | 29.5 | 39 |

# Appendix H – The 50 Most Important Airlines Worldwide

**Table H.1** List of the 50 most important airlines with ranking of AAI and AAI over 100 aircraft, daily departures, fleet size, number of passengers, classification of carrier type

| Airline | IOC | AAI ranking | Daily Departures | Fleet Size | Passengers carried | Flag Carrier | Low Cost Carrier |
|---|---|---|---|---|---|---|---|
| Aeroflot | RUS | 68th/125 \| 27th/38 | 25th | 21st | - | ✓ | - |
| Air Canada | CAN | 32nd/125 \| 11th/38 | 15th | 29th | - | - | - |
| Air China | CHN | 41st/125 \| 16th/38 | 10th | 7th | 7th | ✓ | - |
| Air France | FRA | 73rd/125 \| 30th/38 | 23rd | 20th | 22nd | ✓ | - |
| Air India | IND | 39th/125 \| 15th/38 | 46th | 35th | - | ✓ | - |
| Air New Zealand | NZL | 13th/125 \| 2nd/38 | 36th | 43rd | - | ✓ | - |
| Alaska Airlines | USA | 22nd/125 \| 6th/38 | 19th | 8th | - | - | - |
| All Nippon Airways | JPN | 61st/125 \| 24th/38 | 12th | 18th | 21st | - | - |
| American Airlines | USA | 51st/125 \| 23rd/38 | 1st | 1st | 3rd | - | - |
| Avianca | COL | 21st/125 \| 5th/38 | 32nd | 23rd | - | - | - |
| Azul | BRA | n/a | 20th | 31st | - | - | ✓ |
| British Airways | GBR | 74th/125 31st/38 | 30th | 15th | - | ✓ | - |
| Cathay Pacific | HKG | 45th/125 \| 18th/38 | 93rd | 24th | - | - | - |
| China Eastern Air-lines | CHN | 37th/125 \| 13th/38 | 5th | 6th | 4th | - | - |
| China Southern Airlines | CHN | 52nd/125 \| 22nd/38 | 6th | 5th | 2nd | - | - |
| Condor | GER | 9th | - | - | - | - | - |
| Delta Airlines | USA | 45th/125 \| 19th/38 | 3rd | 3rd | 5th | - | - |
| Delta Connection | USA | 121st/125 \| 38th/38 | | | | - | - |
| easyjet (UK) | GBR | n/a | 9th | 9th | 12th | - | ✓ |
| Emirates | UAE | 108th/125 \| 34th/38 | 38th | 13th | - | - | - |
| Eurowings | GER | n/a | 42nd | - | - | - | ✓ |
| Garuda Indonesia | INA | 44th/125 \| 17th/38 | - | 32nd | - | ✓ | - |
| GOL | BRA | n/a | 33rd | 35th | 25th | - | - |
| Hainan Airlines | CHN | 32nd/125 \| 18th/38 | 22nd | 19th | 18th | - | - |
| IndiGo | IND | n/a | 8th | 16th | 9th | - | ✓ |
| Japan Airlines | JPN | 38th/125 \| 14th/38 | 16th | 25th | - | ✓ | - |
| JetBlue Airways | USA | n/a | 17th | 12th | - | - | ✓ |
| KLM | GBR | 17th/125 \| 4th/38 | 26th | 43rd | - | ✓ | - |
| Korean Air | KOR | 71st/125 \| 29th/38 | 68th | 27th | - | ✓ | - |
| LATAM Brasil Air-lines | BRA | 2nd/125 \| 1st/38 | 13th | - | 10th | ✓ | - |
| Lufthansa | GER | 66th/125 \| 25th/38 | 14th | 14th | 24th | ✓ | - |
| Qatar Airways | QAT | 100th/125 \| 33rd/38 | 37th | 17th | - | ✓ | - |
| Qantas | AUS | 49th/125 \| 20th/38 | 21st | 38th | - | ✓ | - |
| Ryanair | IRL | n/a | 4th | 11th | 6th | - | ✓ |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SAS Scandinavian Airlines | SWE | 78th/125 \| 32nd/38 | 34th | 33rd | - | ✓ | - |
| Saudi Arabian Air-lines | KSA | 110th/125 \| 35th/38 | 44th | 28th | - | ✓ | - |
| Shandong Airlines | CHN | 22nd/125 \| 7th/38 | 29th | - | 20th | - | - |
| Shenzhen Airlines | CHN | 30th/125 \| 9th/38 | 18th | 22nd | 14th | - | - |
| Sichuan Airlines | CHN | 22nd/125 \| 8th/38 | 28th | - | 15th | - | - |
| Singapore Airlines | SGP | 67th/125 \| 26th/38 | 78th | 34th | - | - | - |
| Southwest Airlines | USA | n/a | 7th | 4th | 1st | - | ✓ |
| Spirit Airlines | USA | n/a | 27th | 30th | 19th | - | ✓ |
| Spring Airlines | CHN | n/a | 43rd | - | 17th | - | ✓ |
| TUIfly (Germany) | GER | 4th | - | - | - | - | - |
| Turkish Airlines | TUR | 69th/125 \| 28th/38 | 11th | 10th | 11th | ✓ | - |
| United Airlines | USA | 50th/125 \| 21st/38 | 2nd | 2nd | 8th | - | - |
| Vietnam Airlines | VIE | 14th/125 \| 3rd/38 | 53rd | 46th | - | ✓ | - |
| vueling | SPA | n/a | 31st | 38th | - | - | ✓ |
| WestJet | CAN | n/a | 52nd | 25th | - | - | ✓ |
| Xiamen Airlines | CHN | 31th/125 \| 10th/38 | 24th | - | 13th | - | - |

# Appendix I – Airline Fleet Sources

**Table I.1** List of airline fleet sources

| Airline | Aircraft type and number of aircraft in the fleet (Planespotters.net) |
|---|---|
| Aeroflot | https://perma.cc/KXC7-HYXA |
| Air Canada | https://perma.cc/4CGF-DSPR |
| Air China | https://perma.cc/N7SB-LF6N |
| Air France | https://perma.cc/2JWH-EQD9 |
| Air India | https://perma.cc/H22B-ULWH |
| Air New Zealand | https://perma.cc/WF43-YXPK |
| Alaska Airlines | https://perma.cc/T7W6-YRVX |
| All Nippon Airways | https://perma.cc/KR8F-CR4Z |
| American Airlines | https://perma.cc/U8TZ-B4SN |
| Avianca | https://perma.cc/LYV4-VVHK |
| Azul | https://perma.cc/9HJX-WLBW |
| British Airways | https://perma.cc/5AKJ-8MNG |
| Cathay Pacific | https://perma.cc/5Y3A-YNV9 |
| China Eastern Airlines | https://perma.cc/UCH9-48YF |
| China Southern Airlines | https://perma.cc/A5UZ-F47K |
| Condor | https://perma.cc/D9WJ-UEP3 |
| Delta Airlines | https://perma.cc/426L-WFH7 |
| Delta Connection | https://perma.cc/XQW4-8DC4 |
| easyjet | https://perma.cc/Z9KZ-J5AF |
| Emirates | https://perma.cc/2P8H-8D49 |
| Eurowings | https://perma.cc/AX22-R6GB |
| Garuda Indonesia | https://perma.cc/AX22-R6GB |
| GOL | https://perma.cc/PAX6-SBK3 |
| Hainan Airlines | https://perma.cc/96PR-EALZ |
| indiGo | https://perma.cc/KM36-6QRM |
| Japan Airlines | https://perma.cc/PDC8-9R8A |
| JetBlue Airways | https://perma.cc/H4ZU-NXNZ |
| KLM | https://perma.cc/X5NT-YBGB |
| Korean Air | https://perma.cc/8ZWM-EH6E |
| LATAM Brasil Airlines | https://perma.cc/U23D-89DZ |
| Lufthansa | https://perma.cc/C4HJ-KPHT |
| Ryanair | https://perma.cc/8K4J-9GYK |
| SAS Scandinavian Airlines | https://perma.cc/Q8P8-4G3H |
| Saudi Arabian Airlines | https://perma.cc/6YBK-QUZK |
| Shandong Airlines | https://perma.cc/ZX4F-B784 |
| Shenzhen Airlines | https://perma.cc/86E4-2XKJ |
| Sichuan Airlines | https://perma.cc/W3Q4-DSJL |
| Singapore Airlines | https://perma.cc/G3J8-6NWA |
| Southwest Airlines | https://perma.cc/GG98-FDVV |
| Spirit Airlines | https://perma.cc/9DTR-FYM8 |
| Spring Airlines | https://perma.cc/6MDT-QANX |

| | |
|---|---|
| TUI Airways | https://perma.cc/H4ZU-6CP8 |
| TUIfly (Germany) | https://perma.cc/NA6W-F258 |
| Turkish Airlines | https://perma.cc/RXR3-RTQ7 |
| Qatar Airways | https://perma.cc/Q7WM-V3EH |
| Qantas | https://perma.cc/6RH8-N83V |
| United Airlines | https://perma.cc/EC64-M8DT |
| Vietnam Airlines | https://perma.cc/YCA9-DR4Y |
| vueling | https://perma.cc/YE32-DV4T |
| WestJet | https://perma.cc/GR3E-P4CR |
| Xiamen Airlines | https://perma.cc/7GQK-TSEU |

# Appendix J – Sources Airline Engine and Cabin Layout

**Table J.1** List of sources of airline engines and cabin layouts

| Aircraft Type | Airline | Engine | Reference: Engine (Planespotters) | Reference: Cabin Layout (SeatMaps) |
|---|---|---|---|---|
| **Airbus A220-100** | Delta Air Lines | PW1519G | https://perma.cc/5BBV-V54G | https://perma.cc/CJV7-DH2R |
| **Airbus A220-300** | Air France | PW PW1500G Series | https://perma.cc/974J-RBFV | https://perma.cc/DT63-QXND |
| Airbus A220-300 | Air Canada | PW PW1521G-3 | https://perma.cc/E4MJ-DDM9 | https://perma.cc/E4VZ-J7QK |
| Airbus A220-300 | Delta Air Lines | PW PW1521G-3 | https://perma.cc/SPJ8-7QEC | https://perma.cc/W2CH-JEUX |
| Airbus A220-300 | JetBlue Airways | PW PW1524G-3 | https://perma.cc/MRZ7-EWJP | https://perma.cc/X262-U8LF |
| Airbus A220-300 | Korean Air | PW PW1521G-3 | https://perma.cc/7H8Z-4T8J | https://perma.cc/27SE-2X8T |
| **Airbus A318-100** | Air France | CFMI CFM56-5B8/P | https://perma.cc/A37R-PYB5 | https://perma.cc/VKQ8-56G2 |
| **Airbus A319-100** | Air Canada | CFMI CFM56-5A5 | https://perma.cc/3J2S-98HJ | https://perma.cc/87FX-56DJ |
| Airbus A319-100 | Air China | CFMI CFM56-5B7/3 | https://perma.cc/5DQU-NNGN | https://perma.cc/FKA8-E93T |
| Airbus A319-100 | Air France | CFMI CFM56-5B5/P | https://perma.cc/R4ZL-WC48 | https://perma.cc/4YMP-9V8Z |
| Airbus A319-100 | Air India | CFMI CFM56-5B6/3 | https://perma.cc/HNZ2-PZFQ | https://perma.cc/F4MW-7STL |
| Airbus A319-100 | American Airlines | CFM56-5B7/3 | https://perma.cc/4UYN-QGUA | https://perma.cc/M2YL-4TQY |
| Airbus A319-100 | Avianca | CFM56-5B7/3 | https://perma.cc/8W2B-SM3T | https://perma.cc/38UP-RGGZ |
| Airbus A319-100 | British Airways | IAE V2522-A5 | https://perma.cc/SU77-MGV4 | https://perma.cc/UAK7-FAHC |
| Airbus A319-100 | China Eastern Airlines | CFMI CFM56-5B7/P | https://perma.cc/4ANN-JZX3 | https://perma.cc/HH6C-CE8U |
| Airbus A319-100 | China Southern Airlines | CFMI CFM56-5B7/P | https://perma.cc/R5SP-MVTH | https://perma.cc/8P7A-PH5T |
| Airbus A319-100 | Delta Air Lines | CFMI CFM56-5A5 | https://perma.cc/XBY8-PEHN | https://perma.cc/229T-UBAB |
| Airbus A319-100 | easyJet | CFMI CFM56-5B5/P | https://perma.cc/YLW5-WR7B | https://perma.cc/S4E9-SJ8L |
| Airbus A319-100 | Eurowings | IAE V2524-A5 | https://perma.cc/8TU4-SE2X | https://perma.cc/X6ZQ-792F |
| Airbus A319-100 | LATAM Brasil | IAE V2524-A5 | https://perma.cc/NJ48-HU89 | https://perma.cc/5NLF-FUQ8 |
| Airbus A319-100 | Lufthansa | CFM56-5B6/3 | https://perma.cc/5KL4-EEZF | https://perma.cc/44WB-54GZ |
| Airbus A319-100 | SAS Scandinavian Airlines | IAE V2524-A5 | https://perma.cc/Q9B8-RKEZ | https://perma.cc/8CPY-X8HM |
| Airbus A319-100 | Shenzhen Airlines | IAE V2527M-A5 | https://perma.cc/AS3E-UMNJ | https://perma.cc/W8L7-96NT |
| Airbus A319-100 | Sichuan Airlines | IAE V2527M-A5 | https://perma.cc/X5TU-UFU8 | https://perma.cc/829A-95HU |

| | | | | |
|---|---|---|---|---|
| Airbus A319-100 | Spirit Airlines | IAE V2524-A5 | https://perma.cc/2UQ6-XAKK | https://perma.cc/V6NM-QE6S |
| Airbus A319-100 | Turkish Airlines | IAE V2524-A5 | https://perma.cc/99EB-828X | https://perma.cc/6Y2K-HDMD |
| Airbus A319-100 | United Airlines | IAE V2524-A5 | https://perma.cc/3RSK-2HYS | https://perma.cc/27KF-4BYA |
| Airbus A319-100 | vueling Airlines | CFMI CFM56-5B6/P | https://perma.cc/S5M8-7EF4 | https://perma.cc/R836-4Z7B |
| **Airbus A319 Neo** | China Southern Airlines | CFMI LEAP-1A26 | https://perma.cc/V62M-NHEL | https://perma.cc/NX7Y-SPJS |
| **Airbus A320-200** | Aeroflot | CFMI CFM56-5B4/3 | https://perma.cc/SH48-5UE8 | https://perma.cc/8QEL-5K5D |
| Airbus A320-200 | Air Canada | CFMI CFM56-5B4/P | https://perma.cc/YQP4-SYQT | https://perma.cc/VY7R-HG22 |
| Airbus A320-200 | Air China | CFMI CFM56-5B4/3 | https://perma.cc/23GK-RDEK | https://perma.cc/R99M-RLRL |
| Airbus A320-200 | Air France | CFMI CFM56-5B4/P | https://perma.cc/RP6W-P8TC | https://perma.cc/QH8U-G7NZ |
| Airbus A320-200 | Air India | CFMI CFM56-5B4/3 | https://perma.cc/NRH8-JPYR | https://perma.cc/A8AB-HVL8 |
| Airbus A320-200 | Air New Zealand | IAE V2527-A5 | https://perma.cc/2D6R-EGQG | https://perma.cc/MFL9-N9GU |
| Airbus A320-200 | American Airlines | CFM56-5B4/2P | https://perma.cc/D5L8-8DS7 | https://perma.cc/FY87-8MSM |
| Airbus A320-200 | Avianca | CFM56-5B4/3 | https://perma.cc/H9KV-Q3QN | https://perma.cc/78EP-M7HS |
| Airbus A320-200 | British Airways | IAE V2527-A5 | https://perma.cc/63Q3-2SVM | https://perma.cc/YH68-5VGB |
| Airbus A320-200 | China Eastern Airlines | CFMI CFM56-5B4/3 | https://perma.cc/98SW-CXD6 | https://perma.cc/T2J3-3AGE |
| Airbus A320-200 | China Southern Airlines | IAE V2527-A5 | https://perma.cc/SK2A-LNMX | https://perma.cc/ZJE3-XHUN |
| Airbus A320-200 | Delta Air Lines | CFMI CFM56-5A3 | https://perma.cc/FE22-5Y47 | https://perma.cc/9N2Z-55W7 |
| Airbus A320-200 | Condor | CFMI CFM56-5B4/3 | https://perma.cc/2CMY-Z4AF | https://perma.cc/MCE5-UPDD |
| Airbus A320-200 | easyJet | CFMI CFM56-5B4/3 | https://perma.cc/5LYQ-EFY9 | https://perma.cc/H6AX-M5HQ |
| Airbus A320-200 | Eurowings | CFMI CFM56-5B4/P | https://perma.cc/H3EC-JG9K | https://perma.cc/74J5-VTHX |
| Airbus A320-200 | IndiGo | IAE V2527-A5 | https://perma.cc/NSV7-2PGG | https://perma.cc/K5HY-RPPV |
| Airbus A320-200 | JetBlue Airways | IAE V2527-A5 | https://perma.cc/R4HX-F9NR | https://perma.cc/Q97T-XF7C |
| Airbus A320-200 | LATAM Brasil | IAE V2527-A5 | https://perma.cc/Q2K2-UMYR | https://perma.cc/6775-X37X |
| Airbus A320-200 | Lufthansa | CFM56-5B4/3 | https://perma.cc/MQ22-DB43 | https://perma.cc/HCB5-UV9P |
| Airbus A320-200 | SAS Scandinavian Airlines | IAE V2527-A5 | https://perma.cc/Y27A-ME8A | https://perma.cc/X9X4-2EJ2 |
| Airbus A320-200 | Saudia | CFMI CFM56-5B4/3 | https://perma.cc/TV2K-BEPJ | https://perma.cc/N7HZ-FB3X |
| Airbus A320-200 | Shenzhen Airlines | IAE V2527-A5 | https://perma.cc/9SHK-VXTH | https://perma.cc/395S-P2A8 |
| Airbus A320-200 | Sichuan Airlines | CFMI CFM56-5B4/3 | https://perma.cc/S2GA-FAS7 | https://perma.cc/EY4V-9M62 |
| Airbus A320-200 | Spirit Airlines | IAE V2527-A5 | https://perma.cc/38P9-72UE | https://perma.cc/T5PS-YHU7 |
| Airbus A320-200 | Spring Airlines | CFMI CFM56-5B4/3 | https://perma.cc/UL8F-9YRN | https://perma.cc/9BHM-4AMF |

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| Airbus A320-200 | Turkish Airlines | IAE V2527-A5 | https://perma.cc/XE6S-FZBM | https://perma.cc/6QVL-QNK5 |
| Airbus A320-200 | Qatar Airways | IAE V2527-A5 | https://perma.cc/2J4L-95NW | https://perma.cc/24VW-VX3N |
| Airbus A320-200 | United Airlines | IAE V2527-A5 | https://perma.cc/MX8G-K855 | https://perma.cc/W6UF-858J |
| Airbus A320-200 | vueling Airlines | CFMI CFM56-5B4/3 | https://perma.cc/HWL7-SY8W | https://perma.cc/X8GP-E476 |
| **Airbus A320 Neo** | Aeroflot | CFMI LEAP-1A26 | https://perma.cc/65NZ-9KSW | https://perma.cc/4AU7-8QB2 |
| Airbus A320 Neo | Air China | PW PW1127G | https://perma.cc/77QJ-VPQ2 | https://perma.cc/KV8N-GYQJ |
| Airbus A320 Neo | Air India | CFMI LEAP-1A26 | https://perma.cc/NRH8-JPYR | https://perma.cc/SK8G-4GSX |
| Airbus A320 Neo | Air New Zealand | PW PW1127G | https://perma.cc/KU5T-GVYS | https://perma.cc/LKR8-DUBP |
| Airbus A320 Neo | All Nippon Airways | PW1127G-JM | https://perma.cc/HR3D-L74V | https://perma.cc/K8VU-KFNT |
| Airbus A320 Neo | Avianca | LEAP-1A26 | https://perma.cc/8CGG-AY96 | https://perma.cc/6263-6C78 |
| Airbus A320 Neo | Azul | LEAP-1A26 | https://perma.cc/6T63-EX4X | https://perma.cc/5DPZ-YYPF |
| Airbus A320 Neo | British Airways | CFMI LEAP-1A26 | https://perma.cc/63Q3-2SVM | https://perma.cc/K854-Q6A7 |
| Airbus A320 Neo | China Eastern Airlines | CFMI LEAP-1A26 | https://perma.cc/W3V2-NUCV | https://perma.cc/W6EA-MERD |
| Airbus A320 Neo | China Southern Airlines | CFMI LEAP-1A26 | https://perma.cc/649D-ZHDC | https://perma.cc/59B4-WYH7 |
| Airbus A320 Neo | easyJet | CFMI LEAP-1A26 | https://perma.cc/9TFE-9B7T | https://perma.cc/H6AX-M5HQ |
| Airbus A320 Neo | Eurowings | CFMI LEAP-1A26 | https://perma.cc/36MT-ZQTB | https://perma.cc/74J5-VTHX |
| Airbus A320 Neo | IndiGo | CFMI LEAP-1A26 | https://perma.cc/ZYK5-7RYT | https://perma.cc/5CMF-5RN6 |
| Airbus A320 Neo | LATAM Brasil | PW PW1129G-JM | https://perma.cc/K725-6LSF | https://perma.cc/W5J9-A678 |
| Airbus A320 Neo | Lufthansa | PW1127G-JM | https://perma.cc/449F-7NE2 | https://perma.cc/U7LV-V9SL |
| Airbus A320 Neo | SAS Scandinavian Airlines | CFMI LEAP-1A26 | https://perma.cc/3PYM-3K5W | https://perma.cc/LU4C-5T63 |
| Airbus A320 Neo | Shenzhen Airlines | PW PW1127G-JM | https://perma.cc/G44F-7K5U | https://perma.cc/MF6N-49C2 |
| Airbus A320 Neo | Sichuan Airlines | PW PW1127G-JM | https://perma.cc/46S8-4CGX | https://perma.cc/46S8-4CGX |
| Airbus A320 Neo | Spirit Airlines | PW PW1127G-JM | https://perma.cc/BBG6-8EJ4 | https://perma.cc/9PFK-Y99Q |
| Airbus A320 Neo | Spring Airlines | CFMI LEAP-1A26 | https://perma.cc/WEA6-YHQ8 | https://perma.cc/VU6K-Q9KT |
| Airbus A320 Neo | vueling Airlines | PW PW1127G-JM | https://perma.cc/G3NJ-K9WX | https://perma.cc/6TDF-HS6D |
| Airbus A320 Neo | West Air | PW PW1127G-JM | https://perma.cc/X98C-TEUJ | https://perma.cc/76DP-HKFK |
| **Airbus A321-100** | Air France | CFMI CFM56-5B1/P | https://perma.cc/DQY8-WSL8 | https://perma.cc/3YRW-8WMU |
| Airbus A321-100 | Lufthansa | IAE V2530-A5 | https://perma.cc/AC9D-R5F6 | https://perma.cc/EK88-AUX6 |
| Airbus A321-200 | Aeroflot | CFMI CFM56-5B3/3 | https://perma.cc/TZ94-TEGX | https://perma.cc/7TKQ-VH37 |
| **Airbus A321-200** | Air Canada | CFMI CFM56-5B3/P | https://perma.cc/42T5-ZTGR | https://perma.cc/FF48-KB39 |

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| Airbus A321-200 | Air China | CFMI CFM56-5B2/3 | https://perma.cc/X489-GWB9 | https://perma.cc/EW5N-USE4 |
| Airbus A321-200 | Air France | CFMI CFM56-5B1/3 | https://perma.cc/GJ8Q-QLFT | https://perma.cc/3YRW-8WMU |
| Airbus A321-200 | Air India | CFMI CFM56-5B3/3 | https://perma.cc/NRH8-JPYR | https://perma.cc/LV7N-3AWT |
| Airbus A321-200 | All Nippon Airways | CFM56-5B3/3 | https://perma.cc/MK8K-5ZCX | https://perma.cc/YF9Y-K8FB |
| Airbus A321-200 | American Airlines | CFM56-5B5/3 | https://perma.cc/LP2B-E9R7 | https://perma.cc/7GZE-67PH |
| Airbus A321-200 | British Airways | IAE V2533-A5 | https://perma.cc/CU93-9NUA | https://perma.cc/PU3E-L8YR |
| Airbus A321-200 | Cathay Pacific | V2533-A5 | https://perma.cc/GWL2-CSK3 | https://perma.cc/CM28-7A3Q |
| Airbus A321-200 | China Eastern Airlines | CFMI CFM56-5B3/3 | https://perma.cc/P2XP-SYKW | https://perma.cc/MF2V-6BGG |
| Airbus A321-200 | China Southern Airlines | IAE V2533-A5 | https://perma.cc/V6Y2-T5GV | https://perma.cc/4YWN-CBXS |
| Airbus A321-200 | Condor | CFMI CFM56-5B3/3 | https://perma.cc/CGP7-3FJ5 | https://perma.cc/8WY4-2BHT |
| Airbus A321-200 | Delta Air Lines | CFMI CFM56-5B3/3 | https://perma.cc/5HXC-9KVV | https://perma.cc/9LNH-422F |
| Airbus A321-200 | Eurowings | IAE V2533-A5 | https://perma.cc/QV22-VXUC | https://perma.cc/M52W-JSRK |
| Airbus A321-200 | JetBlue Airways | IAE V2533-A5 | https://perma.cc/PKY9-VVCD | https://perma.cc/AF9Y-ZYTT |
| Airbus A321-200 | LATAM Brasil | IAE V2533-A5 | https://perma.cc/HP73-EYQC | https://perma.cc/D43L-Q2TA |
| Airbus A321-200 | Lufthansa | IAE V2533-A5 | https://perma.cc/5SNV-AM8U | https://perma.cc/C5ZM-9KDJ |
| Airbus A321-200 | Saudia | CFMI CFM56-5B3/3 | https://perma.cc/XPH4-G5F9 | https://perma.cc/2AEE-SYB3 |
| Airbus A321-200 | Sichuan Airlines | IAE V2533-A5 | https://perma.cc/MSL6-YJ75 | https://perma.cc/2A79-BAMD |
| Airbus A321-200 | Spirit Airlines | IAE V2533-A5 | https://perma.cc/GLS4-6FWM | https://perma.cc/3JHZ-FDGC |
| Airbus A321-200 | Turkish Airlines | IAE V2533-A5 | https://perma.cc/43YJ-Q37S | https://perma.cc/4WC4-S873 |
| Airbus A321-200 | Vietnam Airlines | IAE V2533-A5 | https://perma.cc/FQW7-UPYZ | https://perma.cc/AYV3-XKP7 |
| Airbus A321-200 | vueling Airlines | IAE V2533-A5 | https://perma.cc/33XG-YTXL | https://perma.cc/4YFT-AS9C |
| Airbus A321-200 | West Air | CFMI CFM56-5B3/3 | https://perma.cc/3QS4-C8BG | https://perma.cc/76DP-HKFK |
| **Airbus A321 Neo** | Aeroflot | CFMI LEAP-1A32 | https://perma.cc/5QL7-NUEA | https://perma.cc/4AU7-8QB2 |
| Airbus A321 Neo | Air China | CFMI LEAP-1A32 | https://perma.cc/E2NS-WZZE | https://perma.cc/HY8Q-6T64 |
| Airbus A321 Neo | Air India | CFMI LEAP-1A32 | https://perma.cc/75VW-N7T8 | https://perma.cc/Y728-6KC8 |
| Airbus A321 Neo | Air New Zealand | PW PW1133G | https://perma.cc/S79Y-KGT5 | https://perma.cc/5CCY-4GM5 |
| Airbus A321 Neo | Alaska Airlines | LEAP-1A33 | https://perma.cc/UAQ5-6944 | https://perma.cc/G6HV-DFPM |
| Airbus A321 Neo | All Nippon Airways | PW1130G-JM | https://perma.cc/XRZ8-FJ6Q | https://perma.cc/2QRR-Y29J |
| Airbus A321 Neo | American Airlines | LEAP-1A33 | https://perma.cc/7GZE-67PH | https://perma.cc/LB3C-FSX5 |
| Airbus A321 Neo | Azul | LEAP-1A32 | https://perma.cc/E5MR-BSZA | https://perma.cc/HW85-954B |

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| Airbus A321 Neo | British Airways | CFMI LEAP-1A32 | https://perma.cc/VAK4-XXUU | https://perma.cc/5U4F-RAG9 |
| Airbus A321 Neo | Cathay Pacific | LEAP-1A32 | https://perma.cc/Y2LC-XGFY | https://perma.cc/YE3R-M69P |
| Airbus A321 Neo | China Southern Airlines | PW PW1133G | https://perma.cc/KF4A-LASD | https://perma.cc/4LCK-MDAS |
| Airbus A321 Neo | Delta Air Lines | PW PW1133G | https://perma.cc/MW3L-5HQL | https://perma.cc/WN8T-CHQW |
| Airbus A321 Neo | easyJet | CFMI LEAP-1A32 | https://perma.cc/X9A7-WJ86 | https://perma.cc/AP9H-L5LA |
| Airbus A321 Neo | IndiGo | CFMI LEAP-1A32 | https://perma.cc/8DU6-J4JE | https://perma.cc/S9UJ-HPHT |
| Airbus A321 Neo | JetBlue Airways | PW PW1133G-JM | https://perma.cc/QL2K-DWWL | https://perma.cc/W9XE-RVSM |
| Airbus A321 Neo | Korean Air | PW PW1130G-JM | https://perma.cc/MVR9-JJU7 | https://perma.cc/EG4U-UKTY |
| Airbus A321 Neo | Lufthansa | PW1133G | https://perma.cc/VY7G-LCGL | https://perma.cc/B88G-UHW5 |
| Airbus A321 Neo | LATAM Brasil | PW1133G | https://perma.cc/KUU8-B3RL | https://perma.cc/5RXJ-STYF |
| Airbus A321 Neo | SAS Scandinavian Airlines | CFMI LEAP-1A33 | https://perma.cc/KN42-YHKP | https://perma.cc/PU68-EGZU |
| Airbus A321 Neo | Saudia | CFMI LEAP-1A32 | https://perma.cc/AF4E-G465 | https://perma.cc/RLK6-NPTN |
| Airbus A321 Neo | Shenzhen Airlines | PW PW1133G-JM | https://perma.cc/9BCR-Y5MS | https://perma.cc/6W45-YZBT |
| Airbus A321 Neo | Sichuan Airlines | PW PW1133G-JM | https://perma.cc/QZS2-4P9J | https://perma.cc/PLJ8-TLRR |
| Airbus A321 Neo | Xiamen Airlines | CFMI LEAP-1A32 | https://perma.cc/Q5PG-F8XY | https://perma.cc/G7RX-NURV |
| Airbus A321 Neo | Spirit Airlines | PW PW1133G-JM | https://perma.cc/3JHZ-FDGC | https://perma.cc/X68T-FVSP |
| Airbus A321 Neo | Spring Airlines | CFMI LEAP-1A33 | https://perma.cc/6K45-44DY | https://perma.cc/2ERU-CPLY |
| Airbus A321 Neo | Turkish Airlines | PW PW1133G-JM | https://perma.cc/6NQS-XYZ6 | https://perma.cc/RD3E-5GBT |
| Airbus A321 Neo | United Airlines | PW PW1133G-JM | https://perma.cc/F99K-SSMT | https://perma.cc/88SD-Q2KL |
| Airbus A321 Neo | Vietnam Airlines | PW PW1130G-JM | https://perma.cc/DB5Y-6DHN | https://perma.cc/AP7K-G4WK |
| Airbus A321 Neo | vueling Airlines | PW PW1133G-JM | https://perma.cc/KZ3U-5DPS | https://perma.cc/4CC6-EF8Z |
| **Airbus A330-200** | Air China | RR Trent 772B-60 | https://perma.cc/7DUV-2ZML | https://perma.cc/NE36-DCZJ |
| Airbus A330-200 | Air France | GE CF6-80E1A3 | https://perma.cc/EXV6-T89L | https://perma.cc/469Q-ZNHV |
| Airbus A330-200 | China Eastern Airlines | RR Trent 772C-60 | https://perma.cc/N3AS-2CYB | https://perma.cc/LRR5-E2GM |
| Airbus A330-200 | China Southern Airlines | RR Trent 772B-60 | https://perma.cc/C7CW-SWQR | https://perma.cc/KVN2-TEVP |
| Airbus A330-200 | Azul | Trent 772B-60 | https://perma.cc/C5U3-PV6V | https://perma.cc/S4AF-SHTZ |
| Airbus A330-200 | Delta Air Lines | PW PW4168A | https://perma.cc/C3W3-DKRZ | https://perma.cc/6TMG-2WYZ |
| Airbus A330-200 | Condor | RR Trent 772B-60 | https://perma.cc/N2FL-A5C3 | https://perma.cc/TW7Q-6C5U |
| Airbus A330-200 | Garuda Indonesia | RR Trent 772B-60 | https://perma.cc/ZLM6-9G5D | https://perma.cc/22VZ-GRPK |
| Airbus A330-200 | Hainan Airlines | RR Trent 772B-60 | https://perma.cc/B8V8-949V | https://perma.cc/7RBS-C6SL |

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| Airbus A330-200 | KLM | GE CF6-80E1A3 | https://perma.cc/RRJ5-UVP4 | https://perma.cc/7BJB-RYKF |
| Airbus A330-200 | Korean Air | PW PW4168A | https://perma.cc/4QAV-5C7Y | https://perma.cc/F9FR-JWPJ |
| Airbus A330-200 | Sichuan Airlines | RR Trent 772C-60 | https://perma.cc/Z6XV-MSE3 | https://perma.cc/Y7NQ-9G6G |
| Airbus A330-200 | Turkish Airlines | GE CF6-80E1A3 | https://perma.cc/E9E5-ANDA | https://perma.cc/D4D8-7NZM |
| Airbus A330-200 | Qatar Airways | GE CF6-80E1A4B | https://perma.cc/F9U7-R36D | https://perma.cc/NZ67-GB9T |
| Airbus A330-200 | Qantas | GE CF6-80E1A4 | https://perma.cc/T4H3-R4DZ | https://perma.cc/LQ3E-NJKF |
| **Airbus A330-300** | Aeroflot | RR Trent 772B-60 | https://perma.cc/U53S-XUZM | https://perma.cc/9HTF-DRS3 |
| Airbus A330-300 | Air Canada | RR Trent 772B-60 | https://perma.cc/3CHD-MKS4 | https://perma.cc/X9Z9-2VJH |
| Airbus A330-300 | Air China | RR Trent 772B-60 | https://perma.cc/EZA4-6KBV | https://perma.cc/P26T-698W |
| Airbus A330-300 | Cathay Pacific | RR Trent 772B-60 | https://perma.cc/5N2K-XEXT | https://perma.cc/52C8-F3PB |
| Airbus A330-300 | China Eastern Airlines | RR Trent 772C-60 | https://perma.cc/53ZM-EVRB | https://perma.cc/5XTV-CE2R |
| Airbus A330-300 | China Southern Airlines | PW PW4170 | https://perma.cc/VPD2-6CM9 | https://perma.cc/75GE-QFSC |
| Airbus A330-300 | Delta Air Lines | GE CF6-80E1A4 | https://perma.cc/877Q-MJ6M | https://perma.cc/4CPU-LZTY |
| Airbus A330-300 | Garuda Indonesia | RR Trent 772B-60 | https://perma.cc/A6FZ-7QDV | https://perma.cc/6TLY-XRNX |
| Airbus A330-300 | Hainan Airlines | RR Trent 772B-60 | https://perma.cc/5YE2-XBMG | https://perma.cc/HF9W-6BU8 |
| Airbus A330-300 | KLM | GE CF6-80E1A3 | https://perma.cc/7EAS-FRUB | https://perma.cc/CU5L-5F6C |
| Airbus A330-300 | Korean Air | PW PW4168A | https://perma.cc/288R-AS5A | https://perma.cc/UNP5-LGVS |
| Airbus A330-300 | Lufthansa | RR Trent 772B-60 | https://perma.cc/NDW2-YNXA | https://perma.cc/U8RC-HVVA |
| Airbus A330-300 | SAS Scandinavian Airlines | RR Trent 772B-60 | https://perma.cc/3R6F-HTTE | https://perma.cc/22JN-L95F |
| Airbus A330-300 | Saudia | RR Trent 772B-60 | https://perma.cc/XZP5-NEBT | https://perma.cc/HN4M-WWE6 |
| Airbus A330-300 | Shenzhen Airlines | RR Trent 772C-60 | https://perma.cc/ZA7N-EPHX | https://perma.cc/X8AE-26D9 |
| Airbus A330-300 | Sichuan Airlines | RR Trent 772C-60 | https://perma.cc/5XXC-J497 | https://perma.cc/5M44-YTNS |
| Airbus A330-300 | Turkish Airlines | RR Trent 772B-60 | https://perma.cc/N8ST-FQDP | https://perma.cc/R9KK-BBHT |
| Airbus A330-300 | Qatar Airways | GE CF6-80E1A4B | https://perma.cc/RBZ7-2L42 | https://perma.cc/9YC7-GX4Y |
| Airbus A330-300 | Qantas | GE CF6-80E1A3 | https://perma.cc/L2DU-ZJGJ | https://perma.cc/BZL6-LQ8N |
| **Airbus A330-900 Neo** | Azul | Trent 7000-72 | https://perma.cc/5HW9-G93P | https://perma.cc/7P9G-BJXR |
| Airbus A330-900 Neo | Condor | RR Trent 7000-72 | https://perma.cc/2EVV-TYJ5 | https://perma.cc/TCT6-RA2K |
| Airbus A330-900 Neo | Delta Air Lines | RR Trent 7000-72 | https://perma.cc/7F9J-ZWM2 | https://perma.cc/D935-QTAK |
| Airbus A330-900 Neo | Garuda Indonesia | RR Trent 7000-72 | https://perma.cc/9XAH-KVG4 | https://perma.cc/G33S-262J |
| **Airbus A340-300** | Lufthansa | CFM56-5C4 | https://perma.cc/Y998-PGVE | https://perma.cc/N5C9-KD4C |

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| **Airbus A340-600** | Lufthansa | RR Trent 556-61 | https://perma.cc/CA9L-LNAN | https://perma.cc/BR55-EMFF |
| **Airbus A350-900** | Aeroflot | RR Trent XWB-84 | https://perma.cc/M5BF-UVQC | https://perma.cc/K3TN-4Z96 |
| Airbus A350-900 | Air China | RR Trent XWB-84 | https://perma.cc/K253-RVD2 | https://perma.cc/8P4S-KHME |
| Airbus A350-900 | Air France | RR Trent XWB-84 | https://perma.cc/T24P-N2VH | https://perma.cc/469Q-ZNHV |
| Airbus A350-900 | Azul | Trent XWB-84 | https://perma.cc/HV7U-SHR3 | https://perma.cc/Q5F3-7PBJ |
| Airbus A350-900 | Cathay Pacific | Trent XWB-84 | https://perma.cc/2W8K-QKPC | https://perma.cc/K9FZ-N4A9 |
| Airbus A350-900 | China Eastern Airlines | RR Trent XWB-84 | https://perma.cc/L4CR-XD6H | https://perma.cc/J4RH-T5GK |
| Airbus A350-900 | China Southern Airlines | RR Trent XWB-84 | https://perma.cc/4H74-5G6M | https://perma.cc/G3MT-MENS |
| Airbus A350-900 | Delta Air Lines | RR Trent XWB-84 | https://perma.cc/5DWA-PLCP | https://perma.cc/NK9J-UAHU |
| Airbus A350-900 | Japan Airlines | RR Trent XWB-75 | https://perma.cc/WUF8-V7DC | https://perma.cc/76RJ-RSTC |
| Airbus A350-900 | Lufthansa | RR Trent XWB-84 | https://perma.cc/SQV5-RDZ9 | https://perma.cc/82AW-H75K |
| Airbus A350-900 | SAS Scandina-vian Airlines | RR Trent XWB-84 | https://perma.cc/4R2Z-KGS2 | https://perma.cc/Y57K-8EB7 |
| Airbus A350-900 | Sichuan Airlines | RR Trent XWB-84 | https://perma.cc/SM8N-JT8W | https://perma.cc/63QM-H7UT |
| Airbus A350-900 | Singapore Air-lines | RR Trent XWB-84 | https://perma.cc/VV7F-ZNX2 | https://perma.cc/K7CP-Y3SM |
| Airbus A350-900 | Turkish Airlines | RR Trent XWB-84 | https://perma.cc/R7KJ-XD6L | https://perma.cc/RBC7-GV6H |
| Airbus A350-900 | Qatar Airways | RR Trent XWB-84 | https://perma.cc/V93V-N6FS | https://perma.cc/ACS3-8P6U |
| Airbus A350-900 | Vietnam Airlines | RR Trent XWB-84 | https://perma.cc/MP3G-J9QY | https://perma.cc/H47U-TC2P |
| **Airbus A350-900ULR** | Singapore Air-lines | RR Trent XWB-84 | https://perma.cc/76EV-NCX2 | https://perma.cc/BD3E-6HQH |
| **Airbus A350-1000** | British Airways | RR Trent XWB-97 | https://perma.cc/FY6E-AUMV | https://perma.cc/Q3YL-93JZ |
| Airbus A350-1000 | Cathay Pacific | Trent XWB-97 | https://perma.cc/4CSF-V67C | https://perma.cc/6TBE-8VU6 |
| Airbus A350-1000 | Qatar Airways | RR Trent XWB-97 | https://perma.cc/P2JE-ZTKX | https://perma.cc/UB3V-KW6F |
| **Airbus A380-800** | All Nippon Air-ways | Trent 970-84 | https://perma.cc/RT2L-WJSM | https://perma.cc/SR25-NLSC |
| Airbus A380-800 | British Airways | 4x RR Trent 970 | https://perma.cc/NM53-627L | https://perma.cc/8GBA-ESVG |
| Airbus A380-800 | Emirates | 4x RR Trent 972 | https://perma.cc/2RT8-ERE3 | https://perma.cc/SUJ8-DD84 |
| Airbus A380-800 | Korean Air | 4x GP7270 | https://perma.cc/Z6Q4-FC42 | https://perma.cc/JFE4-UCXJ |
| Airbus A380-800 | Lufthansa | RR Trent 970 | https://perma.cc/5VGY-SEPJ | https://perma.cc/RZQ7-KUSH |
| Airbus A380-800 | Singapore Air-lines | 4x RR Trent 970 | https://perma.cc/3D79-TGC2 | https://perma.cc/H4NC-WM3U |
| Airbus A380-800 | Qatar Airways | 4x GP7270 | https://perma.cc/ZWL9-V26H | https://perma.cc/D2M6-LRKC |
| Airbus A380-800 | Qantas | 4x RR Trent 972 | https://perma.cc/24F4-4YST | https://perma.cc/D6FD-E32X |
| **ATR 72** | Air New Zealand | PWC PW127M | https://perma.cc/5QCK-Y5HC | https://perma.cc/JS68-YDBY |

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| ATR 72 | Azul | PW127M | https://perma.cc/V9XD-MLRN | https://perma.cc/A2AS-QQLW |
| ATR 72 | IndiGo | PWC PW127M | https://perma.cc/SNX6-F5WS | https://perma.cc/5NLD-NQ4J |
| ATR 72 | SAS Scandinavian Airlines | PWC PW127M | https://perma.cc/6SHQ-XCWD | https://perma.cc/TH8Q-YEB3 |
| **Boeing 717-200** | Delta Air Lines | BMW RR BR715 | https://perma.cc/W5NK-CFYP | https://perma.cc/6YKF-5ESJ |
| **Boeing 737-700** | Air China | CFMI CFM56-7B24 | https://perma.cc/M9J2-5GFK | https://perma.cc/92ZR-JJ9Y |
| Boeing 737-700 | Alaska Airlines | CFM56-7B24 | https://perma.cc/8FF6-283K | https://perma.cc/A7MS-RNXE |
| Boeing 737-700 | China Eastern Airlines | CFMI CFM56-7B24 | https://perma.cc/7DN6-U54F | https://perma.cc/BRW9-TJN4 |
| Boeing 737-700 | China Southern Airlines | CFMI CFM56-7B22 | https://perma.cc/97GA-LA8Z | https://perma.cc/3FTD-QJ6L |
| Boeing 737-700 | GOL Linhas Aereas | CFMI CFM56-7B24 | https://perma.cc/RTL4-HTFJ | https://perma.cc/BG6G-S9DL |
| Boeing 737-700 | KLM | CFMI CFM56-7B22 | https://perma.cc/93EW-PQPB | https://perma.cc/78ZZ-M2SK |
| Boeing 737-700 | SAS Scandinavian Airlines | CFMI CFM56-7B22 | https://perma.cc/WVR9-9QT5 | https://perma.cc/5BRU-4FXH |
| Boeing 737-700 | Southwest Airlines | CFMI CFM56-7B24 | https://perma.cc/J7TA-N736 | https://perma.cc/7SKK-7LNF |
| Boeing 737-700 | United Airlines | CFMI CFM56-7B24 | https://perma.cc/359M-CEHK | https://perma.cc/FES6-CV4Z |
| Boeing 737-700 | WestJet | CFMI CFM56-7B24 | https://perma.cc/K57R-LY6X | https://perma.cc/L4LK-EE58 |
| Boeing 737-700 | Xiamen Airlines | CFMI CFM56-7B22 | https://perma.cc/DAN9-MNAS | https://perma.cc/JZ5D-8N23 |
| **Boeing 737-800** | Aeroflot | CFMI CFM56-7B26E | https://perma.cc/8DF5-FPHS | https://perma.cc/35DD-EJVY |
| Boeing 737-800 | Air China | CFMI CFM56-7B26E | https://perma.cc/7J25-BV3C | https://perma.cc/Z9GD-W9NU |
| Boeing 737-800 | Alaska Airlines | CFM56-7B27 | https://perma.cc/M6VE-DXE7 | https://perma.cc/N2KT-9845 |
| Boeing 737-800 | All Nippon Airways | CFM56-7B24 | https://perma.cc/HL7K-KCN9 | https://perma.cc/J28M-NVZJ |
| Boeing 737-800 | American Airlines | CFM56-7B24E | https://perma.cc/4LA2-4JPJ | https://perma.cc/BS3R-R2RG |
| Boeing 737-800 | China Eastern Airlines | CFMI CFM56-7B26E | https://perma.cc/K59Y-UAPH | https://perma.cc/CAE7-66SA |
| Boeing 737-800 | China Southern Airlines | CFMI CFM56-7B26E | https://perma.cc/6NPE-KKKD | https://perma.cc/JS36-ZSGV |
| Boeing 737-800 | Delta Air Lines | CFMI CFM56-7B26 | https://perma.cc/E9XB-HSJA | https://perma.cc/FP2D-RDGZ |
| Boeing 737-800 | Eurowings | CFMI CFM56-7B26E | https://perma.cc/3J6C-BC59 | https://perma.cc/8GYS-CGBL |
| Boeing 737-800 | Garuda Indonesia | CFMI CFM56-7B26E | https://perma.cc/M7SZ-MZMK | https://perma.cc/9DMM-222A |
| Boeing 737-800 | GOL Linhas Aereas | CFMI CFM56-7B27 | https://perma.cc/F925-S5U8 | https://perma.cc/Q9A4-RJ3M |
| Boeing 737-800 | Hainan Airlines | CFMI CFM56-7B24E | https://perma.cc/6CCR-884K | https://perma.cc/PE3R-PPY6 |
| Boeing 737-800 | Japan Airlines | CFMI CFM56-7B24 | https://perma.cc/R8HT-RX3N | https://perma.cc/QA3A-VD8X |
| Boeing 737-800 | KLM | CFMI CFM56-7B24 | https://perma.cc/T72P-2HCM | https://perma.cc/9GWU-7BNQ |
| Boeing 737-800 | Korean Air | CFMI CFM56-7BE | https://perma.cc/6ZL2-LBMP | https://perma.cc/W9TX-ZQG5 |

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| Boeing 737-800 | Ryanair | CFMI CFM56-7B26 | https://perma.cc/EPE5-7RPN | https://perma.cc/Y2E9-8MTV |
| Boeing 737-800 | Shandong Airlines | CFMI CFM56-7B26E | https://perma.cc/R6EZ-AEYB | https://perma.cc/UA3S-25EN |
| Boeing 737-800 | Shenzhen Airlines | CFMI CFM56-7BE | https://perma.cc/Y5T2-9Q2K | https://perma.cc/PA23-HJXY |
| Boeing 737-800 | Singapore Airlines | CFMI CFM56-7B27E | https://perma.cc/Y3J8-FY3P | https://perma.cc/9BCX-VKJQ |
| Boeing 737-800 | Southwest Airlines | CFMI CFM56-7B27E | https://perma.cc/LP9Q-P9R3 | https://perma.cc/5X7A-ZPDV |
| Boeing 737-800 | TUI Airways | CFMI CFM56-7B27E | https://perma.cc/RKX7-ML7T | https://perma.cc/S7MH-H9CD |
| Boeing 737-800 | TUIfly | CFMI CFM56-7B26 | https://perma.cc/VWC5-G8Q4 | https://perma.cc/5FRV-CLPM |
| Boeing 737-800 | Turkish Airlines | CFMI CFM56-7B26E | https://perma.cc/JPD2-7ST7 | https://perma.cc/VLP6-72R3 |
| Boeing 737-800 | Qantas | CFMI CFM56-7B24 | https://perma.cc/2KCS-4DPH | https://perma.cc/77GM-ALK2 |
| Boeing 737-800 | United Airlines | CFMI CFM56-7B26 | https://perma.cc/N87L-982E | https://perma.cc/HF3S-UH9C |
| Boeing 737-800 | Xiamen Airlines | CFMI CFM56-7B26E | https://perma.cc/5D8C-UDMQ | https://perma.cc/LR9H-N8UF |
| Boeing 737-800 | WestJet | CFMI CFM56-7B27E | https://perma.cc/XGV4-R8WD | https://perma.cc/PZ7V-62GQ |
| **Boeing 737-900** | Alaska Airlines | CFM56-7B26 | https://perma.cc/EUV6-Y7AF | https://perma.cc/63LP-38BL |
| Boeing 737-900 | KLM | CFMI CFM56-7B26 | https://perma.cc/7USL-2QZC | https://perma.cc/P964-BBMN |
| Boeing 737-900 | Korean Air | CFMI CFM56-7B24 | https://perma.cc/SZZ6-7J8Q | https://perma.cc/LL77-LKX8 |
| Boeing 737-900 | United Airlines | CFMI CFM56-7B26 | https://perma.cc/7HX2-DE6W | https://perma.cc/D6E2-W9YM |
| **Boeing 737-900ER** | Alaska Airlines | CFM56-7B27E/B1 | https://perma.cc/9689-KDSN | https://perma.cc/J2XT-52VH |
| Boeing 737-900ER | Delta Air Lines | CFMI CFM56-7B27E | https://perma.cc/V9H8-247Z | https://perma.cc/ED8C-T6TD |
| Boeing 737-900ER | Korean Air | CFMI CFM56-7BE | https://perma.cc/7VCS-3N35 | https://perma.cc/5JV8-8Z4M |
| Boeing 737-900ER | Turkish Airlines | CFMI CFM56-7B27 | https://perma.cc/M3A9-5B66 | https://perma.cc/ZLH8-3PYQ |
| Boeing 737-900ER | United Airlines | CFMI CFM56-7B26E | https://perma.cc/E7C7-ETCP | https://perma.cc/WL4N-NR24 |
| **Boeing 737-8 MAX** | Air Canada | CFMI LEAP-1B | https://perma.cc/UKX4-X32B | https://perma.cc/994H-VFUP |
| Boeing 737-8 MAX | Air China | CFMI LEAP-1B | https://perma.cc/WN7F-Y6YG | https://perma.cc/Q89N-Y9ET |
| Boeing 737-8 MAX | American Airlines | LEAP-1B25 | https://perma.cc/2F74-VVTA | https://perma.cc/TWS3-NCHF |
| Boeing 737-8 MAX | China Eastern Airlines | CFMI LEAP-1B | https://perma.cc/4RMU-LGMZ | https://perma.cc/WW94-6TYQ |
| Boeing 737-8 MAX | China Southern Airlines | CFMI LEAP-1B | https://perma.cc/6WLC-HZ3V | https://perma.cc/9VE6-756Z |
| Boeing 737-8 MAX | GOL Linhas Aereas | LEAP 1B | https://perma.cc/H3LC-M87Nhttps://perma.cc/VQ3R-SGMZ | - |
| Boeing 737-8 MAX | Hainan Airlines | LEAP 1B25 | https://perma.cc/YEU5-9WZN | https://perma.cc/2Z9Z-E286 |
| Boeing 737-8 MAX | Korean Air | CFMI LEAP-1B | https://perma.cc/EC8R-L44J | https://perma.cc/M666-SGX5 |

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| Boeing 737-8 MAX | Ryanair | CFMI LEAP-1B27 | https://perma.cc/G6ZT-M876 | https://perma.cc/THK6-MUAV |
| Boeing 737-8 MAX | Shandong Airlines | CFMI LEAP-1B | https://perma.cc/DU95-KLSR | https://perma.cc/UA3S-25EN |
| Boeing 737-8 MAX | Shenzhen Airlines | CFMI LEAP-1B | https://perma.cc/9EE2-65PQ | https://perma.cc/PA23-HJXY |
| Boeing 737-8 MAX | Singapore Airlines | CFMI LEAP-1B27 | https://perma.cc/6Q6X-GJWB | https://perma.cc/W8Q4-L9DB |
| Boeing 737-8 MAX | Southwest Airlines | CFMI LEAP-1B28 | https://perma.cc/M3PN-KL4J | https://perma.cc/ECF4-2Z84 |
| Boeing 737-8 MAX | TUI Airways | CFMI LEAP-1B27 | https://perma.cc/TC5C-9R4L | https://perma.cc/36MZ-L9JT |
| Boeing 737-8 MAX | TUIfly | CFMI LEAP-1B27 | https://perma.cc/LZN5-5UQU | https://perma.cc/JHA6-WQW6 |
| Boeing 737-8 MAX | Turkish Airlines | CFMI LEAP-1B27 | https://perma.cc/Q7EP-MA7Q | https://perma.cc/QGD4-8HUU |
| Boeing 737-8 MAX | Qatar Airways | CFMI LEAP-1B | https://perma.cc/Y6Y8-TMDX | https://perma.cc/T5TJ-DAYQ |
| Boeing 737-8 MAX | United Airlines | CFMI LEAP-1B28 | https://perma.cc/4BTZ-42CR | https://perma.cc/JB8K-WT8G |
| Boeing 737-8 MAX | WestJet | CFMI LEAP-1B | https://perma.cc/2RPB-Y7Z9 | https://perma.cc/6K54-RUSD |
| Boeing 737-8 MAX | Xiamen Airlines | CFMI LEAP-1B28 | https://perma.cc/E8H7-29NB | https://perma.cc/6Y5Q-QRZD |
| **Boeing 737-9 MAX** | Alaska Airlines | LEAP-1B28 | https://perma.cc/8UZV-E2FB | https://perma.cc/T36U-VA2X |
| Boeing 737-9 MAX | Turkish Airlines | CFMI LEAP-1B | https://perma.cc/KU6P-MW8N | https://perma.cc/RA4Z-4EKD |
| Boeing 737-9 MAX | United Airlines | CFMI LEAP-1B28 | https://perma.cc/W2WB-YGS6 | https://perma.cc/8RBD-P8AT |
| **Boeing 747-400** | Air China | 4x PW PW4056 | https://perma.cc/WN7F-Y6YG | https://perma.cc/VNV2-QVPG |
| Boeing 747-400 | Lufthansa | GE CF6-80C2B1F | https://perma.cc/AC5Y-WVP5 | https://perma.cc/8JM8-NMNY |
| Boeing 747-400 | Saudia | 4x GE CF6-80C2B1F | https://perma.cc/MWY6-C6XZ | https://perma.cc/3ZDN-EPJ7 |
| **Boeing 747-800** | Air China | 4x GEnx-2B67 | https://perma.cc/S4NY-PYFE | https://perma.cc/LB7J-3PBH |
| Boeing 747-800 | Lufthansa | 4x GEnx-2B67 | https://perma.cc/8VEH-2V9U | https://perma.cc/M3G8-KPNX |
| Boeing 747-800 | Korean Air | 4x GEnx-2B67 | https://perma.cc/75PA-WYTW | https://perma.cc/2GMR-XT3D |
| **Boeing 757-200** | Delta Air Lines | PW PW2037 | https://perma.cc/5N2V-H453 | https://perma.cc/Z8QF-P89F |
| Boeing 757-200 | United Airlines | RR RB211-535E4B | https://perma.cc/MP8P-ABSQ | https://perma.cc/4KSN-SX4H |
| **Boeing 757-300** | Condor | RR RB211-535E4B | https://perma.cc/MT6W-LZBM | https://perma.cc/3DSB-599Z |
| Boeing 757-300 | Delta Air Lines | PW PW2043 | https://perma.cc/U3P2-K62R | https://perma.cc/T2AF-UZTV |
| Boeing 757-300 | United Airlines | RR RB211-535E4C | https://perma.cc/LG3P-9NJF | https://perma.cc/B5WX-AU7C |
| **Boeing 767-300ER** | All Nippon Airways | CF6-80C2B6F | https://perma.cc/AN5L-YZWH | https://perma.cc/ZMU3-CYP2 |
| Boeing 767-300ER | Delta Air Lines | GE CF6-80C2B6F | https://perma.cc/4QUJ-UF3Y | https://perma.cc/243L-LM6L |
| Boeing 767-300ER | Condor | PW PW4060 | https://perma.cc/K6FA-JLXR | https://perma.cc/YAP5-W2CD |
| Boeing 767-300ER | Japan Airlines | GE CF6-80C2B7F | https://perma.cc/MY3B-MY23 | https://perma.cc/XU79-T8YM |

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| Boeing 767-300ER | LATAM Brasil | GE CF6-80C2B7F | https://perma.cc/ZJ4L-3WQK | https://perma.cc/WG8V-2N8F |
| Boeing 767-300ER | United Airlines | PW PW4060 | https://perma.cc/LVY7-BJ5T | https://perma.cc/C8Z4-ER8P |
| **Boeing 767-400ER** | Delta Air Lines | GE CF6-80C2B8F | https://perma.cc/83SR-D8KN | https://perma.cc/J3GP-J3TZ |
| Boeing 767-400ER | United Airlines | GE CF6-80C2B8F | https://perma.cc/TV9L-B2RU | https://perma.cc/D2YS-NCWA |
| **Boeing 777-200ER** | Air France | GE GE90-94B | https://perma.cc/C4UE-VPEC | https://perma.cc/U5A9-WHYT |
| Boeing 777-200ER | Air India | GE GE90-110B1 | https://perma.cc/3C4M-HM9M | https://perma.cc/EY7V-EAQU |
| Boeing 777-200ER | All Nippon Airways | PW4084D | https://perma.cc/772D-RRS3 | https://perma.cc/E4ZN-MN9N |
| Boeing 777-200ER | American Airlines | RB211 Trent 892 | https://perma.cc/69RZ-SZRJ | https://perma.cc/XG76-X2JK |
| Boeing 777-200ER | British Airways | RR Trent 895 | https://perma.cc/W9W5-ZH5W | https://perma.cc/5WUE-2VNC |
| Boeing 777-200ER | Japan Airlines | GE GE90-94B | https://perma.cc/NQ62-LZTZ | https://perma.cc/E337-6YH8 |
| Boeing 777-200ER | KLM | GE GE90-94B | https://perma.cc/PC58-DQXA | https://perma.cc/JL5T-J499 |
| Boeing 777-200ER | Korean Air | PW PW4090 | https://perma.cc/27LP-X83D | https://perma.cc/U8PL-4JXE |
| Boeing 777-200ER | United Airlines | PW PW4090 | https://perma.cc/9D42-7YWX | https://perma.cc/PBZ3-7DFE |
| **Boeing 777-200LR** | Air Canada | GE GE90-110B1 | https://perma.cc/4VJ7-RJJU | https://perma.cc/RN6U-3HCB |
| Boeing 777-200LR | Emirates | GE GE90-110B1 | https://perma.cc/UK65-BNUT | https://perma.cc/GU7V-PUFT |
| Boeing 777-200LR | Qatar Airways | GE GE90-110B1 | https://perma.cc/4PS5-4229 | https://perma.cc/V5PD-QF8U |
| **Boeing 777-300** | All Nippon Airways | PW PW4090 | https://perma.cc/N22U-SHH7 | https://perma.cc/HX2P-Z3T6 |
| Boeing 777-300 | Cathay Pacific | Trent 884 | https://perma.cc/U8HJ-XYTG | https://perma.cc/8ZWX-PBY7 |
| Boeing 777-300 | Korean Air | PW PW4090 | https://perma.cc/T99N-NQJS | https://perma.cc/8UA2-5MVU |
| **Boeing 777-300ER** | Aeroflot | GE GE90-115B | https://perma.cc/FTP2-22N9 | https://perma.cc/9S79-CGB9 |
| Boeing 777-300ER | Air Canada | GE GE90-115B | https://perma.cc/QJ3N-2NKJ | https://perma.cc/TXZ4-7Q2Z |
| Boeing 777-300ER | Air China | GE GE90-115B | https://perma.cc/XDA3-SZAF | https://perma.cc/74SM-ZBRP |
| Boeing 777-300ER | Air France | GE GE90-115B | https://perma.cc/YMR7-SFEF | https://perma.cc/6Y7V-A4PV |
| Boeing 777-300ER | Air India | GE GE90-115B | https://perma.cc/C8HC-NWSQ | https://perma.cc/Y5C9-K3TY |
| Boeing 777-300ER | Air New Zealand | GE GE90-115B | https://perma.cc/SX9F-VZFH | https://perma.cc/7MB2-8W5K |
| Boeing 777-300ER | All Nippon Airways | GE90-115B | https://perma.cc/TT59-C4AL | https://perma.cc/V495-8X47 |
| Boeing 777-300ER | American Airlines | GE90-115B | https://perma.cc/DN2Y-FXT5 | https://perma.cc/JG4X-2Y7K |
| Boeing 777-300ER | British Airways | GE GE90-115B | https://perma.cc/2TS2-SBDJ | https://perma.cc/2HG9-HVB3 |
| Boeing 777-300ER | Cathay Pacific | GE GE90-115B | https://perma.cc/CW38-4ZN5 | https://perma.cc/JJ3Z-DPN2 |
| Boeing 777-300ER | China Eastern Airlines | GE GE90-115B | https://perma.cc/AK8K-ZRGG | https://perma.cc/QQ3K-APX3 |

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| Boeing 777-300ER | China Southern Airlines | GE GE90-115B | https://perma.cc/7HYR-RR6C | https://perma.cc/22R4-4NJJ |
| Boeing 777-300ER | Emirates | GE GE90-115B | https://perma.cc/SK6A-H6UN | https://perma.cc/D2Z4-XRK5 |
| Boeing 777-300ER | Garuda Indonesia | GE GE90-115B | https://perma.cc/JNC3-KSBV | https://perma.cc/5KM2-GU4R |
| Boeing 777-300ER | IndiGo | GE GE90-115B | https://perma.cc/77MX-CABA | https://perma.cc/2L8F-Z33M |
| Boeing 777-300ER | Japan Airlines | GE GE90-115B | https://perma.cc/M9DC-54PV | https://perma.cc/J8V3-GT8P |
| Boeing 777-300ER | KLM | GE GE90-115B | https://perma.cc/U5Y5-42LB | https://perma.cc/KUQ9-QKF3 |
| Boeing 777-300ER | Korean Air | GE GE90-115B | https://perma.cc/N4GL-VR96 | https://perma.cc/43Q2-8GTM |
| Boeing 777-300ER | LATAM Brasil | GE GE90-115B | https://perma.cc/D5CN-JVLQ | https://perma.cc/5M6F-YA8V |
| Boeing 777-300ER | Saudia | GE GE90-115B | https://perma.cc/S35A-5D3C | https://perma.cc/4D9Q-2DGE |
| Boeing 777-300ER | Singapore Airlines | GE GE90-115B | https://perma.cc/4ETM-9HR2 | https://perma.cc/TS6D-4E2V |
| Boeing 777-300ER | Turkish Airlines | GE GE90-115B | https://perma.cc/KU6P-MW8N | https://perma.cc/R95U-3M2D |
| Boeing 777-300ER | Qatar Airways | GE GE90-115B | https://perma.cc/YDL3-838N | https://perma.cc/F6Y2-C5WX |
| Boeing 777-300ER | United Airlines | GE GE90-115B | https://perma.cc/EZ3Z-UTUJ | https://perma.cc/6A7G-785F |
| **Boeing 787-8** | Air Canada | GEnx-1B67/P2G01 | https://perma.cc/3H2B-SGMT | https://perma.cc/DFL9-MF27 |
| Boeing 787-8 | Air India | GEnx-1B | https://perma.cc/XSW2-J8D2 | https://perma.cc/9Q3B-Z2TB |
| Boeing 787-8 | All Nippon Airways | Trent 1000 | https://perma.cc/APA7-M7D8 | https://perma.cc/W6FR-7GM5 |
| Boeing 787-8 | American Airlines | GEnx-1B | https://perma.cc/25XL-SJFX | https://perma.cc/VUU2-L56E |
| Boeing 787-8 | Avianca | Trent 1000 | https://perma.cc/E947-9HXG | https://perma.cc/G99J-MG6F |
| Boeing 787-8 | British Airways | RR Trent 1000 | https://perma.cc/4XJQ-WDYK | https://perma.cc/W26R-QLSY |
| Boeing 787-8 | China Southern Airlines | GEnx-1B | https://perma.cc/ZT9B-W8ZQ | https://perma.cc/7M7G-B8Y7 |
| Boeing 787-8 | Hainan Airlines | GEnx-1B | https://perma.cc/Y8AH-93XS | https://perma.cc/6LYC-62PM |
| Boeing 787-8 | Japan Airlines | GEnx-1B | https://perma.cc/8LPL-ZHFA | https://perma.cc/K7MW-MY8X |
| Boeing 787-8 | Qatar Airways | GEnx-1B | https://perma.cc/CH2W-KZGE | https://perma.cc/AC5W-568B |
| Boeing 787-8 | TUI Airways | GEnx-1B70/P1G01 | https://perma.cc/R2T6-CS37 | https://perma.cc/VNN5-6Z35 |
| Boeing 787-8 | United Airlines | GEnx-1B70 | https://perma.cc/JS96-Y48L | https://perma.cc/29MQ-VZAC |
| Boeing 787-8 | Xiamen Airlines | GEnx-1B | https://perma.cc/XT22-YNFU | https://perma.cc/R89G-456R |
| **Boeing 787-9** | Air Canada | GEnx-1B | https://perma.cc/AX4X-NNDZ | https://perma.cc/EN24-H7BA |
| Boeing 787-9 | Air China | RR Trent 1000 | https://perma.cc/M2KA-G4Q6 | https://perma.cc/EFY3-NRMQ |
| Boeing 787-9 | Air France | GEnx-1B | https://perma.cc/G3W3-5ZWL | https://perma.cc/8LKP-GWWN |
| Boeing 787-9 | Air New Zealand | RR Trent 1000 | https://perma.cc/R8UM-UG8K | https://perma.cc/YJM5-75A7 |

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| Boeing 787-9 | All Nippon Airways | Trent 1000 | https://perma.cc/AD5H-N43J | https://perma.cc/4JNU-Y7SQ |
| Boeing 787-9 | American Airlines | GEnx-1B | https://perma.cc/7REV-AASB | https://perma.cc/HC39-278L |
| Boeing 787-9 | British Airways | RR Trent 1000 | https://perma.cc/GLT6-9CR9 | https://perma.cc/Z5LS-RC83 |
| Boeing 787-9 | China Eastern Airlines | GEnx-1B | https://perma.cc/3AR7-3JZV | https://perma.cc/E4SB-Z4KS |
| Boeing 787-9 | China Southern Airlines | GEnx-1B | https://perma.cc/H4M9-7ELR | https://perma.cc/HJG9-PC94 |
| Boeing 787-9 | Hainan Airlines | GEnx-1B | https://perma.cc/MV3M-8ZEH | https://perma.cc/LBL5-5GKS |
| Boeing 787-9 | Japan Airlines | GEnx-1B | https://perma.cc/M9DC-54PV | https://perma.cc/M9D9-3VXS |
| Boeing 787-9 | KLM | GEnx-1B74/75 | https://perma.cc/87QD-AQYG | https://perma.cc/T6C8-AJQJ |
| Boeing 787-9 | Korean Air | GEnx-1B | https://perma.cc/NZE7-DHU6 | https://perma.cc/KUY6-GQ5J |
| Boeing 787-9 | LATAM Brasil | RR Trent 1000 | https://perma.cc/76AC-3R27 | https://perma.cc/M867-QMYS |
| Boeing 787-9 | Lufthansa | GEnx-1B | https://perma.cc/GH76-MU72 | https://perma.cc/2LX5-5K55 |
| Boeing 787-9 | Saudia | GEnx-1B | https://perma.cc/S6GN-Z489 | https://perma.cc/RW79-MVLA |
| Boeing 787-9 | TUI Airways | GEnx-1B70/P2G01 | https://perma.cc/JCB8-CAM7 | https://perma.cc/62T5-C37A |
| Boeing 787-9 | Turkish Airlines | GEnx-1B74/75 | https://perma.cc/Z484-VZW4 | https://perma.cc/D9SZ-BAWS |
| Boeing 787-9 | Qatar Airways | GEnx-1B | https://perma.cc/G5YK-QGU5 | https://perma.cc/A52D-ZYR4 |
| Boeing 787-9 | Qantas | GEnx-1B | https://perma.cc/8T8C-2Q2Y | https://perma.cc/39GN-CQN8 |
| Boeing 787-9 | United Airlines | GEnx-1B74/75 | https://perma.cc/CCC6-NLPM | https://perma.cc/FCB8-QKN7 |
| Boeing 787-9 | Vietnam Airlines | GEnx-1B74/75 | https://perma.cc/Q4GR-XEKJ | https://perma.cc/E9WZ-HXCV |
| Boeing 787-9 | WestJet | GEnx-1B | https://perma.cc/3UWC-FSLU | https://perma.cc/9SGM-E5HD |
| Boeing 787-9 | Xiamen Airlines | GEnx-1B | https://perma.cc/87AR-TPLC | https://perma.cc/2BD7-3FX5 |
| **Boeing 787-10** | All Nippon Airways | Trent 1000 | https://perma.cc/M588-C9TZ | https://perma.cc/39LE-2FXU |
| Boeing 787-10 | British Airways | RR Trent 1000-J3 | https://perma.cc/RJ4D-UP3N | https://perma.cc/UM69-HW9L |
| Boeing 787-10 | KLM | GEnx-1B76 | https://perma.cc/6XKZ-6CE6 | https://perma.cc/9T5W-73N2 |
| Boeing 787-10 | Saudia | GEnx-1B | https://perma.cc/Y7HX-6F3V | https://perma.cc/8WV4-37VF |
| Boeing 787-10 | Singapore Airlines | RR Trent 1000-J3 | https://perma.cc/4TGD-KX9X | https://perma.cc/2LMW-5ZE3 |
| Boeing 787-10 | United Airlines | GEnx-1B | https://perma.cc/83NH-KKU8 | https://perma.cc/47AD-2JEX |
| Boeing 787-10 | Vietnam Airlines | GEnx-1B74/75 | https://perma.cc/WGF3-LKBX | https://perma.cc/N5RM-DT9W |
| **Bombardier CRJ-200LR** | Delta Connection | GE CF34-3B1 | https://perma.cc/EEC8-UR3S | https://perma.cc/4AFH-6ZCD |
| **Bombardier CRJ-700ER** | Delta Connection | GE CF34-8C5B1 | https://perma.cc/D9TA-6EEG | https://perma.cc/Q43S-Q64Y |
| **Bombardier CRJ-900LR** | Delta Connection | GE CF34-8C5 | https://perma.cc/K62A-TEDB | https://perma.cc/H3DT-XKPG |

| | | | | |
|---|---|---|---|---|
| Bombardier CRJ-900LR | Lufthansa | GE CF34-8C5 | https://perma.cc/WG3B-GN96 | https://perma.cc/XPA9-MDNN |
| Bombardier CRJ-900LR | SAS Scandinavian Airlines | GE CF34-8C5 | https://perma.cc/V2JC-STP9 | https://perma.cc/3UD9-WVKD |
| **COMAC ARJ21-700** | Air China | GE CF34-10A | https://perma.cc/M4JQ-4YJD | https://perma.cc/TY43-LES2 |
| COMAC ARJ21-700 | China Southern Airlines | GE CF34-10A | https://perma.cc/CE6C-QB5T | https://perma.cc/YQ9W-M72F |
| **COMAC C919** | China Eastern Airlines | CFMI LEAP-1C | https://perma.cc/5QM3-KUS7 | https://perma.cc/9WSC-YHPR |
| **Dornier 328JET-300** | British Airways | PWC PW306B | https://perma.cc/VL3W-KRE2 | https://perma.cc/Q6B4-STCL |
| **De Havilland Canada DHC-8-300** | Air New Zealand | PWC PW123 | https://perma.cc/A7HY-YGK5 | https://perma.cc/6W3Y-DVKK |
| **Embraer E170LR** | Delta Connection | GE CF34-8E5 | https://perma.cc/5YM4-XZCJ | https://perma.cc/FQ5N-HXZC |
| **Embraer E175LR** | Alaska Airlines | GE CF34-8E5 | https://perma.cc/CWL6-QRAS | https://perma.cc/7K5V-VL4H |
| Embraer E175LR | Delta Connection | GE CF34-8E5 | https://perma.cc/DRU7-X7W7 | https://perma.cc/FJC3-VD3N |
| **Embraer E190LR** | British Airways | GE CF34-10E6 | https://perma.cc/VD23-6JZK | https://perma.cc/6BLG-AX74 |
| **Embraer E190AR** | JetBlue Airways | GE CF34-10E6 | https://perma.cc/BFW5-QM2Q | https://perma.cc/EUB3-97RL |
| **Embraer E190LR** | Lufthansa | GE CF34-10E5 | https://perma.cc/D6WQ-QPSC | https://perma.cc/KK5P-F55J |
| **Embraer E195LR** | Azul | CF34-10E5 | https://perma.cc/V37N-9YAC | https://perma.cc/4ZKU-RDKY |
| **Embraer E195-E2** | Azul | PW1900G_mean | https://perma.cc/7774-5ZQK | https://perma.cc/3VFW-RSV4 |

# Appendix K – Airline Rating Calculation for the 50 Most Important Airlines

**Table K.1** Aeroflot Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 52 | 158 | 7.17 | 8216 | 58908.72 |
| 2 | Airbus A320 Neo | 6 | 156 | 8.33 | 936 | 7796.88 |
| 3 | Airbus A321-200 | 32 | 183 | 6.64 | 5856 | 38883.84 |
| 4 | Airbus A321 Neo | 3 | 196 | 7.31 | 588 | 4298.28 |
| 5 | Airbus A330-300 | 12 | 296 | 6.3 | 3552 | 22377.6 |
| 6 | Airbus A350-900 | 7 | 316 | 7.29 | 2212 | 16125.48 |
| 7 | Boeing 737-800 | 37 | 158 | 6.98 | 5846 | 40805.08 |
| 8 | Boeing 777-300ER | 22 | 402 | 6.42 | 8844 | 56778.48 |
| | Total: | 171 | | ∑: | 36050 | 245974.36 |
| | | | | **Airline Rating:** | | **6.82** |

**Table K.2** Air Canada Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A220-300 | 33 | 137 | 7.83 | 4521 | 35399.43 |
| 2 | Airbus A319-100 | 5 | 120 | 6.61 | 600 | 3966 |
| 3 | Airbus A320-200 | 12 | 146 | 6.75 | 1752 | 11826 |
| 4 | Airbus A321-200 | 16 | 190 | 6.46 | 3040 | 19638.4 |
| 5 | Airbus A330-300 | 18 | 297 | 6.31 | 5346 | 33733.26 |
| 6 | Boeing 737 MAX 8 | 40 | 169 | 7.62 | 6760 | 51511.2 |
| 7 | Boeing 777-200LR | 6 | 300 | 6.09 | 1800 | 10962 |
| 8 | Boeing 777-300ER | 19 | 400 | 6.41 | 7600 | 48716 |
| 9 | Boeing 787-8 Dreamliner | 8 | 255 | 7.76 | 2040 | 15830.4 |
| 10 | Boeing 787-9 Dreamliner | 30 | 298 | 7.57 | 8940 | 67675.8 |
| | Total: | 187 | | ∑: | 42399 | 299258.49 |
| | | | | **Airline Rating:** | | **7.06** |

**Table K.3** Air China Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 32 | 128 | 7.1 | 4096 | 29081.6 |
| 2 | Airbus A320-200 | 38 | 158 | 7.17 | 6004 | 43048.68 |
| 3 | Airbus A320 Neo | 49 | 158 | 8.2 | 7742 | 63484.4 |
| 4 | Airbus A321-200 | 61 | 185 | 6.82 | 11285 | 76963.7 |
| 5 | Airbus A321 Neo | 30 | 180 | 7.08 | 5400 | 38232 |
| 6 | Airbus A330-200 | 22 | 237 | 5.72 | 5214 | 29824.08 |
| 7 | Airbus A330-300 | 28 | 301 | 6.35 | 8428 | 53517.8 |
| 8 | Airbus A350-900 | 29 | 312 | 7.26 | 9048 | 65688.48 |
| 9 | Boeing 737-700 | 18 | 128 | 6.59 | 2304 | 15183.36 |
| 10 | Boeing 737-800 | 88 | 159 | 6.71 | 13992 | 93886.32 |
| 11 | Boeing 737 MAX 8 | 16 | 176 | 7.66 | 2816 | 21570.56 |
| 12 | Boeing 747-400 | 3 | 344 | 4.04 | 1032 | 4169.28 |
| 13 | Boeing 747-800 | 7 | 365 | 5.38 | 2555 | 13745.9 |
| 14 | Boeing 777-300ER | 28 | 311 | 5.6 | 8708 | 48764.8 |
| 15 | Boeing 787-9 Dreamliner | 14 | 293 | 6.83 | 4102 | 28016.66 |
| 16 | COMAC ARJ21-700 | 21 | 90 | 6.29 | 1890 | 11888.1 |
| | Total: | 484 | | ∑: | 94616 | 637065.72 |
| | | | | **Airline Rating:** | | **6.73** |

**Table K.4** Air France Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A220-300 | 32 | 148 | 7.99 | 4736 | 37840.64 |
| 2 | Airbus A318-100 | 6 | 118 | 6.95 | 708 | 4920.6 |
| 3 | Airbus A319-100 | 14 | 143 | 7.27 | 2002 | 14554.54 |
| 4 | Airbus A320-200 | 37 | 174 | 7.19 | 6438 | 46289.22 |
| 5 | Airbus A321-100 | 4 | 212 | 7.14 | 848 | 6054.72 |
| 6 | Airbus A321 200 | 11 | 212 | 7.17 | 2332 | 16720.44 |
| 7 | Airbus A330-200 | 15 | 224 | 5.3 | 3360 | 17808 |
| 8 | Airbus A350-900 | 24 | 324 | 7.36 | 7776 | 57231.36 |
| 9 | Boeing 777-200ER | 18 | 312 | 5.69 | 5616 | 31955.04 |
| 10 | Boeing 777-300ER | 43 | 381 | 6.27 | 16383 | 102721.41 |
| 12 | Boeing 787-9 Dreamliner | 10 | 279 | 7.4 | 2790 | 20646 |
| | Total: | 214 | | ∑: | 52989 | 356741.97 |
| | | | | **Airline Rating:** | | **6.73** |

**Table K.5** Air India Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 18 | 122 | 7.09 | 2196 | 15569.64 |
| 2 | Airbus A320-200 | 9 | 168 | 7.31 | 1512 | 11052.72 |
| 3 | Airbus A320 Neo | 33 | 162 | 8.4 | 5346 | 44906.4 |
| 4 | Airbus A321-200 | 13 | 182 | 6.62 | 2366 | 15662.92 |
| 5 | Airbus A321 Neo | 4 | 172 | 6.95 | 688 | 4781.6 |
| 6 | Boeing 777-200LR | 8 | 238 | 5.25 | 1904 | 9996 |
| 7 | Boeing 777-300ER | 15 | 342 | 5.93 | 5130 | 30420.9 |
| 8 | Boeing 787-8 Dreamliner | 27 | 256 | 7.69 | 6912 | 53153.28 |
| | Total: | 127 | | ∑: | 26054 | 185543.46 |
| | | | | **Airline Rating:** | | **7.12** |

**Table K.6** Air New Zealand Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 17 | 171 | 7.21 | 2907 | 20959.47 |
| 2 | Airbus A320 Neo | 6 | 165 | 8.28 | 990 | 8197.2 |
| 3 | Airbus A321 Neo | 11 | 214 | 8.01 | 2354 | 18855.54 |
| 4 | ATR 72 | 29 | 68 | 8.1 | 1972 | 15973.2 |
| 5 | Boeing 777-300ER | 8 | 342 | 5.93 | 2736 | 16224.48 |
| 6 | Boeing 787-9 Dreamliner | 14 | 302 | 6.91 | 4228 | 29215.48 |
| 7 | De Havilland Canada DHC-8-300 | 23 | 50 | 7.22 | 1150 | 8303 |
| | Total: | 108 | | ∑: | 16337 | 117728.37 |
| | | | | **Airline Rating:** | | **7.21** |

**Table K.7** Alaska Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-700 | 14 | 124 | 6.59 | 1736 | 11440.24 |
| 2 | Boeing 737-800 | 61 | 159 | 6.64 | 9699 | 64401.36 |
| 3 | Boeing 737-900 | 12 | 178 | 6.87 | 2136 | 14674.32 |
| 4 | Boeing 737-900ER | 79 | 178 | 6.67 | 14062 | 93793.54 |
| 5 | Boeing 739 MAX 9 | 63 | 178 | 7.22 | 11214 | 80965.08 |
| 6 | Embraer E175LR | 83 | 76 | 6.03 | 6308 | 38037.24 |
| | Total: | 312 | | ∑: | 45155 | 303311.78 |
| | | | | **Airline Rating:** | | **6.72** |

**Table K.8** All Nippon Airways Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320 Neo | 11 | 146 | 8.04 | 1606 | 12912.24 |
| 2 | Airbus A321-200 | 4 | 194 | 6.77 | 776 | 5253.52 |
| 3 | Airbus A321 Neo | 22 | 194 | 7.89 | 4268 | 33674.52 |
| 4 | Airbus A380-800 | 3 | 520 | 5.13 | 1560 | 8002.8 |
| 5 | Boeing 737-800 | 39 | 166 | 6.9 | 6474 | 44670.6 |
| 6 | Boeing 767-300ER | 24 | 270 | 7.11 | 6480 | 46072.8 |
| 7 | Boeing 777-200 | 10 | 405 | 6.77 | 4050 | 27418.5 |
| 8 | Boeing 777-300 | 5 | 514 | 6.55 | 2570 | 16833.5 |
| 9 | Boeing 777-300ER | 13 | 212 | 3.91 | 2756 | 10775.96 |
| 10 | Boeing 787-8 Dreamliner | 36 | 240 | 6.8 | 8640 | 58752 |
| 11 | Boeing 787-9 Dreamliner | 41 | 246 | 6.26 | 10086 | 63138.36 |
| 12 | Boeing 787-10 Dreamliner | 3 | 294 | 6.58 | 882 | 5803.56 |
| | Total: | 211 | | ∑: | 50148 | 333308.36 |
| | | | | **Airline Rating:** | | **6.65** |

**Table K.9** American Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 133 | 128 | 7.1 | 17024 | 120870.4 |
| 2 | Airbus A320-200 | 48 | 150 | 7.19 | 7200 | 51768 |
| 3 | Airbus A321-200 | 218 | 187 | 7.51 | 40766 | 306152.66 |
| 4 | Airbus A321 Neo | 74 | 196 | 6.96 | 14504 | 100947.84 |
| 5 | Boeing 737-800 | 303 | 172 | 7.26 | 52116 | 378362.16 |
| 6 | Boeing 737 MAX 8 | 56 | 172 | 7.76 | 9632 | 74744.32 |
| 7 | Boeing 777-200ER | 47 | 273 | 5.51 | 12831 | 70698.81 |
| 8 | Boeing 777-300ER | 20 | 304 | 5.52 | 6080 | 33561.6 |
| 9 | Boeing 787-8 Dreamliner | 37 | 234 | 7.47 | 8658 | 64675.26 |
| 10 | Boeing 787-9 Dreamliner | 22 | 285 | 7.46 | 6270 | 46774.2 |
| | Total: | 958 | | ∑: | 175081 | 1248555.25 |
| | | | | **Airline Rating:** | | **7.13** |

**Table K.10** Avianca Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 8 | 120 | 6.93 | 960 | 6652.8 |
| 2 | Airbus A320-200 | 66 | 150 | 7.05 | 9900 | 69795 |
| 3 | Airbus A320 Neo | 33 | 180 | 8.59 | 5940 | 51024.6 |
| 4 | Boeing 787-8 Dreamliner | 13 | 250 | 6.92 | 3250 | 22490 |
| | Total: | 120 | | ∑: | 20050 | 149962.40 |
| | | | | **Airline Rating:** | | **7.48** |

**Table K.11** Azul Brazilian Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320 Neo | 48 | 174 | 8.53 | 8352 | 71242.56 |
| 2 | Airbus A321 Neo | 6 | 214 | 7.52 | 1284 | 9655.68 |
| 3 | Airbus A330-200 | 4 | 271 | 6.17 | 1084 | 6688.28 |
| 4 | Airbus A330-900 | 5 | 298 | 6.37 | 1490 | 9491.3 |
| 5 | Airbus A350-900 | 2 | 334 | 7.43 | 668 | 4963.24 |
| 6 | ATR 72 | 39 | 70 | 8.16 | 2730 | 22276.8 |
| 7 | Embraer E195-E2 | 19 | 136 | 8.32 | 2584 | 21498.88 |
| 8 | Embraer E195LR | 43 | 118 | 6.66 | 5074 | 33792.84 |
| | Total: | 166 | | ∑: | 23266 | 179609.58 |
| | | | | **Airline Rating:** | | **7.72** |

**Table K.12** British Airways Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 30 | 144 | 7.19 | 4320 | 31060.8 |
| 2 | Airbus A320-200 | 66 | 180 | 7.33 | 11880 | 87080.4 |
| 3 | Airbus A320 Neo | 20 | 180 | 8.59 | 3600 | 30924 |
| 4 | Airbus A321-200 | 11 | 205 | 6.85 | 2255 | 15446.75 |
| 5 | Airbus A321 Neo | 11 | 210 | 7.48 | 2310 | 17278.8 |
| 6 | Airbus A350-1000 | 16 | 331 | 6.42 | 5296 | 34000.32 |
| 7 | Airbus A380-800 | 12 | 469 | 4.63 | 5628 | 26057.64 |
| 8 | Boeing 777-200ER | 43 | 275 | 5.48 | 11825 | 64801 |
| 9 | Boeing 777-300ER | 16 | 299 | 5.46 | 4784 | 26120.64 |
| 10 | Boeing 787-8 Dreamliner | 12 | 214 | 6.44 | 2568 | 16537.92 |
| 11 | Boeing 787-9 Dreamliner | 18 | 216 | 5.77 | 3888 | 22433.76 |
| 12 | Boeing 787-10 Dreamliner | 7 | 256 | 5.93 | 1792 | 10626.56 |
| 13 | Dornier 328JET-300 | 4 | 32 | 5.64 | 128 | 721.92 |
| 14 | Embraer E190LR | 20 | 98 | 6.46 | 1960 | 12661.6 |
| | Total: | 286 | | ∑: | 62234 | 395752.11 |
| | | | | **Airline Rating:** | | **6.36** |

**Table K.13** Cathay Pacific Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A321-200 | 1 | 172 | 6.41 | | |
| 2 | Airbus A321 Neo | 12 | 202 | 7.39 | 2424 | 17913.36 |
| 3 | Airbus A330-300 | 42 | 262 | 5.92 | 11004 | 65143.68 |
| 4 | Airbus A350-900 | 29 | 280 | 6.95 | 8120 | 56434 |
| 5 | Airbus A350-1000 | 18 | 334 | 6.45 | 6012 | 38777.4 |
| 6 | Boeing 777-300 | 17 | 438 | 6.62 | 7446 | 49292.52 |
| 7 | Boeing 777-300ER | 39 | 294 | 5.39 | 11466 | 61801.74 |
| | Total: | 158 | | ∑: | 46472 | 289362.70 |
| | | | | **Airline Rating:** | | **6.23** |

**Table K.14** China Eastern Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 35 | 122 | 6.71 | 4270 | 28651.7 |
| 2 | Airbus A320-200 | 165 | 158 | 7.17 | 26070 | 186921.9 |
| 3 | Airbus A320 Neo | 104 | 158 | 8.36 | 16432 | 137371.52 |
| 4 | Airbus A321-200 | 77 | 182 | 6.62 | 14014 | 92772.68 |
| 5 | Airbus A330-200 | 30 | 234 | 5.68 | 7020 | 39873.6 |
| 6 | Airbus A330-300 | 26 | 300 | 6.34 | 7800 | 49452 |
| 7 | Airbus A350-900 | 19 | 288 | 7.03 | 5472 | 38468.16 |
| 8 | Boeing 737-700 | 36 | 134 | 6.8 | 4824 | 32803.2 |
| 9 | Boeing 737-800 | 102 | 170 | 7.15 | 17340 | 123981 |
| 10 | Boeing 737 MAX 8 | 3 | 164 | 7.66 | 492 | 3768.72 |
| 11 | Boeing 777-300ER | 20 | 310 | 5.59 | 6200 | 34658 |
| 12 | Boeing 787-9 Dreamliner | 3 | 285 | 7.46 | 855 | 6378.3 |
| 13 | COMAC C919 | 2 | 164 | 7.47 | 328 | 2450.16 |
| | Total: | 622 | | ∑: | 111117 | 777550.94 |
| | | | | **Airline Rating:** | | **7.00** |

**Table K.15** China Southern Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 9 | 130 | 6.88 | 1170 | 8049.6 |
| 2 | Airbus A319 Neo | 4 | 136 | 8.07 | 544 | 4390.08 |
| 3 | Airbus A320-200 | 103 | 160 | 7.05 | 16480 | 116184 |
| 4 | Airbus A320 Neo | 42 | 166 | 8.45 | 6972 | 58913.4 |
| 5 | Airbus A321-200 | 99 | 179 | 6.52 | 17721 | 115540.92 |
| 6 | Airbus A321 Neo | 56 | 195 | 7.82 | 10920 | 85394.4 |
| 7 | Airbus A330-200 | 10 | 260 | 6.04 | 2600 | 15704 |
| 8 | Airbus A330-300 | 26 | 283 | 6.47 | 7358 | 47606.26 |
| 9 | Airbus A350-900 | 20 | 314 | 7.27 | 6280 | 45655.6 |
| 10 | Boeing 737-700 | 23 | 128 | 6.82 | 2944 | 20078.08 |
| 11 | Boeing 737-800 | 161 | 172 | 7.18 | 27692 | 198828.56 |
| 12 | Boeing 737 MAX 8 | 24 | 178 | 7.68 | 4272 | 32808.96 |
| 13 | Boeing 777-300ER | 15 | 361 | 6.11 | 5415 | 33085.65 |
| 14 | Boeing 787-8 Dreamliner | 10 | 266 | 7.78 | 2660 | 20694.8 |
| 15 | Boeing 787-9 Dreamliner | 17 | 297 | 7.56 | 5049 | 38170.44 |
| 16 | COMAC ARJ21-700 | 23 | 90 | 6.29 | 2070 | 13020.3 |
| | Total: | 642 | | ∑: | 120147 | 854125.05 |
| | | | | **Airline Rating:** | | **7.11** |

**Table K.16** Condor Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 12 | 180 | 7.46 | 2160 | 16113.6 |
| 2 | Airbus A321-200 | 11 | 208 | 6.93 | 2288 | 15855.84 |
| 3 | Airbus A330-200 | 2 | 262 | 6.06 | 524 | 3175.44 |
| 4 | Airbus A330-900 | 11 | 310 | 6.49 | 3410 | 22130.9 |
| 5 | Boeing 757-300 | 9 | 262 | 6.51 | 2358 | 15350.58 |
| 6 | Boeing 767-300ER | 4 | 255 | 6.72 | 1020 | 6854.4 |
| | Total: | 49 | | ∑: | 11760 | 79480.76 |
| | | | | **Airline Rating:** | | **6.76** |

**Table K.17** Delta Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A220-100 | 45 | 109 | 7.69 | 4905 | 37719.45 |
| 2 | Airbus A220-300 | 20 | 130 | 7.72 | 2600 | 20072 |
| 3 | Airbus A319-100 | 57 | 132 | 6.87 | 7524 | 51689.88 |
| 4 | Airbus A320-200 | 61 | 157 | 6.88 | 9577 | 65889.76 |
| 5 | Airbus A321-200 | 127 | 191 | 6.74 | 24257 | 163492.18 |
| 6 | Airbus A321 Neo | 45 | 194 | 7.81 | 8730 | 68181.3 |
| 7 | Airbus A330-200 | 11 | 223 | 5.21 | 2453 | 12780.13 |
| 8 | Airbus A330-300 | 31 | 282 | 6.01 | 8742 | 52539.42 |
| 9 | Airbus A330-900 | 25 | 281 | 6.18 | 7025 | 43414.5 |
| 10 | Airbus A350-900 | 28 | 306 | 7.2 | 8568 | 61689.6 |
| 11 | Boeing 717-200 | 88 | 110 | 5.91 | 9680 | 57208.8 |
| 12 | Boeing 737-800 | 77 | 160 | 6.72 | 12320 | 82790.4 |
| 13 | Boeing 737-900ER | 163 | 180 | 6.7 | 29340 | 196578 |
| 14 | Boeing 757-200 | 111 | 199 | 6.32 | 22089 | 139602.48 |
| 15 | Boeing 757-300 | 16 | 234 | 6.45 | 3744 | 24148.8 |
| 16 | Boeing 767-300ER | 45 | 216 | 6.51 | 9720 | 63277.2 |
| 17 | Boeing 767-400ER | 21 | 238 | 6.42 | 4998 | 32087.16 |
| | Total: | 971 | | ∑: | 176272 | 1173161.06 |
| | | | | **Airline Rating:** | | **6.66** |

**Table K.18** Delta Connection Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Bombardier CRJ-200LR | 9 | 50 | 7.35 | 450 | 3307.5 |
| 2 | Bombardier CRJ-700ER | 22 | 69 | 6.39 | 1518 | 9700.02 |
| 3 | Bombardier CRJ-900 | 163 | 76 | 6.29 | 12388 | 77920.52 |
| 4 | Embraer E170LR | 11 | 69 | 5.96 | 759 | 4523.64 |
| 5 | Embraer E175LR | 129 | 76 | 6.03 | 9804 | 59118.12 |
| | Total: | 334 | | ∑: | 24919 | 154569.80 |
| | | | | **Airline Rating:** | | **6.20** |

**Table K.19** Easyjet (UK) Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 47 | 156 | 7.47 | 7332 | 54770.04 |
| 2 | Airbus A320-200 | 77 | 186 | 7.53 | 14322 | 107844.66 |
| 3 | Airbus A320 Neo | 37 | 186 | 8.65 | 6882 | 59529.3 |
| 4 | Airbus A321 Neo | 10 | 235 | 7.73 | 2350 | 18165.5 |
| | Total: | 171 | | ∑: | 30886 | 240309.50 |
| | | | | **Airline Rating:** | | **7.78** |

**Table K.20** Emirates Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A380-800 | 119 | 519 | 5.04 | 61761 | 311275.44 |
| 2 | Boeing 777-200LR | 10 | 302 | 6.11 | 3020 | 18452.2 |
| 3 | Boieng 777-300ER | 123 | 354 | 6.04 | 43542 | 262993.68 |
| 4 | Airbus A319 | 1 | 19 | -7.09 | 19 | -134.71 |
| | Total: | 253 | | ∑: | 108342 | 592586.61 |
| | | | | **Airline Rating:** | | **5.47** |

**Table K.21** Eurowings Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 29 | 138 | 7.07 | 4002 | 28294.14 |
| 2 | Airbus A320-200 | 35 | 180 | 7.26 | 6300 | 45738 |
| 3 | Airbus A320 Neo | 7 | 180 | 8.59 | 1260 | 10823.4 |
| 4 | Airbus A321-200 | 6 | 230 | 7.1 | 1380 | 9798 |
| 5 | Boeing 737-800 | 3 | 180 | 7.28 | 540 | 3931.2 |
| | Total: | 80 | | ∑: | 13482 | 98584.74 |
| | | | | **Airline Rating:** | | **7.31** |

**Table K.22** Garuda Indonesia Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A330-200 | 5 | 222 | 5.48 | 1110 | 6082.8 |
| 2 | Airbus A330-300 | 17 | 251 | 5.77 | 4267 | 24620.59 |
| 3 | Airbus A330-900 | 3 | 301 | 6.4 | 903 | 5779.2 |
| 4 | Boeing 737-800 | 42 | 162 | 7.04 | 6804 | 47900.16 |
| 5 | Boeing 777-300ER | 8 | 393 | 6.36 | 3144 | 19995.84 |
| | Total: | 75 | | ∑: | 16228 | 104378.59 |
| | | | | **Airline Rating:** | | **6.43** |

**Table K.23** GOL Linhas Aereas Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-700 | 16 | 138 | 6.87 | 2208 | 15168.96 |
| 2 | Boeing 737-800 | 80 | 186 | 7.02 | 14880 | 104457.6 |
| 3 | Boeing 737 MAX 8 | 42 | 186 | 7.82 | 7812 | 61089.84 |
| | Total: | 138 | | ∑: | 24900 | 180716.40 |
| | | | | **Airline Rating:** | | **7.26** |

**Table K.24** Hainan Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A330-200 | 9 | 222 | 5.48 | 1998 | 10949.04 |
| 2 | Airbus A330-300 | 22 | 292 | 6.26 | 6424 | 40214.24 |
| 3 | Boeing 737-800 | 133 | 164 | 7.15 | 21812 | 155955.8 |
| 4 | Boeing 737 MAX 8 | 11 | 176 | 7.81 | 1936 | 15120.16 |
| 5 | Boeing 787-8 Dreamliner | 10 | 213 | 7.22 | 2130 | 15378.6 |
| 6 | Boeing 787-9 Dreamliner | 28 | 292 | 7.52 | 8176 | 61483.52 |
| | Total: | 213 | | ∑: | 42476 | 299101.36 |
| | | | | **Airline Rating:** | | **7.04** |

**Table K.25** IndiGo Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 30 | 180 | 7.33 | 5400 | 39582 |
| 2 | Airbus A320 Neo | 180 | 186 | 8.65 | 33480 | 289602 |
| 3 | Airbus A321 Neo | 94 | 232 | 7.71 | 21808 | 168139.68 |
| 4 | Boeing 777-300ER | 2 | 531 | 7.11 | 1062 | 7550.82 |
| 5 | ATR 72 | 42 | 78 | 8.34 | 3276 | 27321.84 |
| | Total: | 348 | | ∑: | 65026 | 532196.34 |
| | | | | **Airline Rating:** | | **8.18** |

**Table K.26** Japan Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A350-900 | 16 | 369 | 7.79 | 5904 | 45992.16 |
| 2 | Boeing 737-800 | 42 | 165 | 6.89 | 6930 | 47747.7 |
| 3 | Boeing 767-300ER | 27 | 227 | 6.64 | 6129 | 40696.56 |
| 4 | Boeing 777-300ER | 13 | 244 | 4.61 | 3172 | 14622.92 |
| 5 | Boeing 787-8 Dreamliner | 24 | 206 | 7.13 | 4944 | 35250.72 |
| 6 | Boeing 787-9 Dreamliner | 22 | 195 | 6.27 | 4290 | 26898.3 |
| | Total: | 144 | | ∑: | 31369 | 211208.36 |
| | | | | **Airline Rating:** | | **6.73** |

**Table K.27** JetBlue Airways Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A220-300 | 22 | 140 | 7.88 | 3080 | 24270.4 |
| 2 | Airbus A320-200 | 129 | 162 | 7.08 | 20898 | 147957.84 |
| 3 | Airbus A321-200 | 63 | 159 | 6.18 | 10017 | 61905.06 |
| 4 | Airbus A321 Neo | 30 | 200 | 7.87 | 6000 | 47220 |
| 5 | Embraer E190AR | 42 | 100 | 6.65 | 4200 | 27930 |
| | Total: | 286 | | ∑: | 44195 | 309283.30 |
| | | | | **Airline Rating:** | | **7.00** |

**Table K.28** KLM Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A330-200 | 6 | 268 | 5.93 | 1608 | 9535.44 |
| 2 | Airbus A330-300 | 5 | 292 | 6.06 | 1460 | 8847.6 |
| 3 | Boeing 737-700 | 6 | 132 | 6.9 | 792 | 5464.8 |
| 4 | Boeing 737-800 | 31 | 186 | 7.17 | 5766 | 41342.22 |
| 5 | Boeing 737-900 | 5 | 178 | 6.87 | 890 | 6114.3 |
| 6 | Boeing 777-200ER | 15 | 316 | 5.74 | 4740 | 27207.6 |
| 7 | Boeing 777-300ER | 16 | 408 | 6.47 | 6528 | 42236.16 |
| 8 | Boeing 787-9 Dreamliner | 13 | 275 | 7.05 | 3575 | 25203.75 |
| 9 | Boeing 787-10 Dreamliner | 10 | 344 | 7.41 | 3440 | 25490.4 |
| | Total: | 107 | | ∑: | 28799 | 191442.27 |
| | | | | **Airline Rating:** | | **6.65** |

**Table K.29** Korean Air Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A220-300 | 10 | 140 | 7.88 | 1400 | 12694.5 |
| 2 | Airbus A321 Neo | 9 | 182 | 7.75 | 1638 | 6696.96 |
| 3 | Airbus A330-200 | 6 | 218 | 5.12 | 1308 | 33568.8 |
| 4 | Airbus A330-300 | 20 | 284 | 5.91 | 5680 | 33568.8 |
| 5 | Airbus A380-800 | 10 | 407 | 3.55 | 4070 | 14448.5 |
| 6 | Boeing 737-800 | 2 | 138 | 6.71 | 276 | 1851.96 |
| 7 | Boeing 737-900 | 9 | 188 | 7.09 | 1692 | 11996.28 |
| 8 | Boeing 737-900ER | 6 | 173 | 6.23 | 1038 | 6466.74 |
| 9 | Boeing 737 MAX 8 | 5 | 146 | 7.27 | 730 | 5307.1 |
| 11 | Boeing 747-8 | 9 | 368 | 5.41 | 3312 | 17917.92 |
| 12 | Boeing 777-200ER | 8 | 261 | 4.84 | 2088 | 10105.92 |
| 13 | Boeing 777-300 | 4 | 338 | 5.23 | 1352 | 7070.96 |
| 14 | Boieng 777-300ER | 25 | 277 | 5.16 | 6925 | 35733 |
| 16 | Boeing 787-9 | 11 | 269 | 7.3 | 2959 | 21600.7 |
| | Total: | 134 | | ∑: | 34468 | 219028.14 |
| | | | | **Airline Rating:** | | **6.35** |

**Table K.30** LATAM Airlines Brasil

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 19 | 138 | 7.07 | 2622 | 18537.54 |
| 2 | Airbus A320-200 | 58 | 180 | 7.33 | 10440 | 76525.2 |
| 3 | Airbus A320 Neo | 17 | 180 | 8.46 | 3060 | 25887.6 |
| 4 | Airbus A321-200 | 31 | 224 | 7.05 | 6944 | 48955.2 |
| 5 | Airbus A321 Neo | 6 | 224 | 8.09 | 1344 | 10872.96 |
| 6 | Boeing 767-300ER | 2 | 221 | 6.56 | 442 | 2899.52 |
| 7 | Boeing 777-300ER | 10 | 410 | 6.48 | 4100 | 26568 |
| 8 | Boeing 787-9 Dreamliner | 1 | 304 | 6.93 | 304 | 2106.72 |
| | Total: | 144 | | ∑: | 29256 | 212352.74 |
| | | | | **Airline Rating:** | | **7.26** |

**Table K.31** Lufthansa Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 35 | 138 | 7.38 | 4830 | 35645.4 |
| 2 | Airbus A320-200 | 52 | 168 | 7.31 | 8736 | 63860.16 |
| 3 | Airbus A320 Neo | 35 | 180 | 8.44 | 6300 | 53172 |
| 4 | Airbus A321-100 | 20 | 200 | 7.12 | 4000 | 28480 |
| 5 | Airbus A321-200 | 37 | 200 | 6.93 | 7400 | 51282 |
| 6 | Airbus A321 Neo | 17 | 215 | 8.01 | 3655 | 29276.55 |
| 7 | Airbus A330-300 | 10 | 255 | 5.82 | 2550 | 14841 |
| 8 | Airbus A340-300 | 17 | 279 | 4.32 | 4743 | 20489.76 |
| 9 | Airbus A340-600 | 10 | 297 | 4.39 | 2970 | 13038.3 |
| 10 | Airbus A350-900 | 21 | 293 | 7.08 | 6153 | 43563.24 |
| 11 | Airbus A380-800 | 8 | 509 | 5.03 | 4072 | 20482.16 |
| 12 | Boeing 747-400 | 8 | 317 | 4.8 | 2536 | 12172.8 |
| 13 | Boeing 747-800 | 19 | 364 | 5.36 | 6916 | 37069.76 |
| 14 | Boeing 787-9 Dreamliner | 5 | 294 | 7.53 | 1470 | 11069.1 |
| 15 | Bombardier CRJ-900 | 28 | 79 | 6.42 | 2212 | 14201.04 |
| 16 | Embraer E190LR | 7 | 100 | 6.57 | 700 | 4599 |
| | Total: | 329 | | ∑: | 69243 | 453242.27 |
| | | | | **Airline Rating:** | | **6.55** |

**Table K.32** Qatar Airways Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 29 | 144 | 6.77 | 4176 | 28271.52 |
| 2 | Airbus A330-200 | 3 | 260 | 5.89 | 780 | 4594.2 |
| 3 | Airbus A330-300 | 7 | 305 | 6.25 | 2135 | 13343.75 |
| 4 | Airbus A350-900 | 34 | 283 | 6.98 | 9622 | 67161.56 |
| 5 | Airbus A350-1000 | 24 | 327 | 6.38 | 7848 | 50070.24 |
| 6 | Airbus A380-800 | 8 | 517 | 4.86 | 4136 | 20100.96 |
| 7 | Boeing 737 MAX 8 | 9 | 176 | 7.7 | 1584 | 12196.8 |
| 8 | Boeing 777-200LR | 9 | 272 | 5.76 | 2448 | 14100.48 |
| 9 | Boeing 777-300ER | 57 | 354 | 6.04 | 20178 | 121875.12 |
| 10 | Boeing 787-8 Dreamliner | 30 | 254 | 7.67 | 7620 | 58445.4 |
| 11 | Boeing 787-9 Dreamliner | 15 | 311 | 7.67 | 4665 | 35780.55 |
| | Total: | 225 | | ∑: | 65192 | 425940.58 |
| | | | | **Airline Rating:** | | **6.53** |

**Table K.33** Qantas Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A330-200 | 16 | 271 | 6.02 | 4336 | 26102.72 |
| 2 | Airbus A330-300 | 10 | 297 | 6.11 | 2970 | 18146.70 |
| 3 | Airbus A380-800 | 10 | 485 | 4.71 | 4850 | 22843.50 |
| 4 | Boeing 737-800 | 75 | 174 | 7.02 | 13050 | 91611.00 |
| 5 | Boeing 787-9 Dreamliner | 14 | 217 | 6.65 | 3038 | 20202.70 |
| | Total: | 125 | | ∑: | 28244 | 178906.62 |
| | | | | **Airline Rating:** | | **6.33** |

**Table K.34** Ryanair Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-800 | 220 | 189 | 7.12 | 41580 | 296049.6 |
| 2 | Boeing 737 MAX 8 | 80 | 197 | 7.88 | 15760 | 124188.8 |
| | Total: | 300 | | ∑: | 57340 | 420238.40 |
| | | | | **Airline Rating:** | | **7.33** |

**Table K.35** SAS Scandinavian Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 4 | 150 | 7.26 | 600 | 4356 |
| 2 | Airbus A320-200 | 11 | 168 | 7.17 | 1848 | 13250.16 |
| 3 | Airbus A320 Neo | 36 | 180 | 8.59 | 6480 | 55663.2 |
| 4 | Airbus A321 Neo | 3 | 157 | 6.27 | 471 | 2953.17 |
| 5 | Airbus A330-300 | 8 | 5.92 | 5.92 | 47.36 | 280.3712 |
| 6 | Airbus A350-900 | 3 | 300 | 7.15 | 900 | 6435 |
| 7 | ATR 72 | 7 | 70 | 8.16 | 490 | 3998.4 |
| 8 | Boeing 737-700 | 1 | 141 | 7.06 | 141 | 995.46 |
| 9 | Bombardier CRJ-900 | 17 | 90 | 6.8 | 1530 | 10404 |
| | Total: | 90 | | ∑: | 12507.36 | 98335.76 |
| | | | | **Airline Rating:** | | **7.86** |

**Table K.36** Saudi Arabian Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 37 | 144 | 6.94 | 5328 | 36976.32 |
| 2 | Airbus A321-200 | 15 | 165 | 6.37 | 2475 | 15765.75 |
| 3 | Airbus A321 Neo | 4 | 188 | 7.2 | 752 | 5414.4 |
| 4 | Airbus A330-300 | 33 | 330 | 6.61 | 10890 | 71982.9 |
| 5 | Boeing 747-400 | 2 | 434 | 5.46 | 868 | 4739.28 |
| 6 | Boeing 777-300ER | 37 | 413 | 6.5 | 15281 | 99326.5 |
| 7 | Boeing 787-9 Dreamliner | 13 | 298 | 7.57 | 3874 | 29326.18 |
| 8 | Boeing 787-10 Dreamliner | 8 | 357 | 5.74 | 2856 | 16393.44 |
| | Total: | 149 | | ∑: | 42324 | 279924.77 |
| | | | | **Airline Rating:** | | **6.61** |

**Table K.37** Shandong Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-800 | 123 | 176 | 7.23 | 21648 | 156515.04 |
| 2 | Boeing 737 MAX 8 | 7 | 176 | 7.7 | 1232 | 9486.4 |
| | Total: | 130 | | ∑: | 22880 | 166001.44 |
| | | | | **Airline Rating:** | | **7.26** |

**Table K.38** Shenzhen Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 5 | 128 | 6.91 | 640 | 4422.4 |
| 2 | Airbus A320-200 | 76 | 128 | 6.43 | 9728 | 62551.04 |
| 3 | Airbus A320 Neo | 27 | 152 | 8.12 | 4104 | 33324.48 |
| 4 | Airbus A321 Neo | 5 | 199 | 7.86 | 995 | 7820.7 |
| 5 | Airbus A330-300 | 6 | 309 | 6.43 | 1854 | 11921.22 |
| 6 | Boeing 737-800 | 72 | 168 | 7.2 | 12096 | 87091.2 |
| 7 | Boeing 737 MAX 8 | 6 | 168 | 7.56 | 1008 | 7620.48 |
| | Total: | 197 | | ∑: | 30425 | 214751.52 |
| | | | | **Airline Rating:** | | **7.06** |

**Table K.39** Sichuan Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 23 | 132 | 6.99 | 3036 | 21221.64 |
| 2 | Airbus A320-200 | 51 | 164 | 7.26 | 8364 | 60722.64 |
| 3 | Airbus A320 Neo | 27 | 158 | 8.2 | 4266 | 34981.2 |
| 4 | Airbus A321-200 | 43 | 194 | 6.72 | 8342 | 56058.24 |
| 5 | Airbus A321 Neo | 27 | 198 | 7.85 | 5346 | 41966.1 |
| 6 | Airbus A330-200 | 7 | 274 | 6.2 | 1918 | 11891.6 |
| 7 | Airbus A330-300 | 8 | 301 | 6.35 | 2408 | 15290.8 |
| 8 | Airbus A350-900 | 6 | 331 | 7.41 | 1986 | 14716.26 |
| | Total: | 192 | | ∑: | 35666 | 256848.48 |
| | | | | **Airline Rating:** | | **7.20** |

**Table K.40** Singapore Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A350-900 | 56 | 253 | 6.64 | 14168 | 94075.52 |
| 2 | Airbus A350-900ULR | 7 | 161 | 4.42 | 1127 | 4981.34 |
| 3 | Airbus A380-800 | 12 | 471 | 4.65 | 5652 | 26281.8 |
| 4 | Boeing 737-800 | 7 | 162 | 6.98 | 1134 | 7915.32 |
| 5 | Boeing 737 MAX 8 | 16 | 154 | 7.35 | 2464 | 18110.4 |
| 6 | Boeing 777-300ER | 23 | 264 | 4.96 | 6072 | 30117.12 |
| 7 | Boeing 787-10 Dreamliner | 21 | 337 | 6.82 | 7077 | 48265.14 |
| | Total: | 142 | | ∑: | 37694 | 229746.64 |
| | | | | **Airline Rating:** | | **6.10** |

**Table K.41** Southwest Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-700 | 393 | 143 | 6.96 | 56199 | 391145.04 |
| 2 | Boeing 737-800 | 207 | 175 | 7.16 | 36225 | 259371 |
| 3 | Boeing 737 MAX 8 | 215 | 175 | 7.49 | 37625 | 281811.25 |
| | Total: | 815 | | ∑: | 130049 | 932327.29 |
| | | | | **Airline Rating:** | | **7.17** |

**Table K.42** Spirit Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 19 | 145 | 7.19 | 2755 | 19808.45 |
| 2 | Airbus A320-200 | 64 | 182 | 7.36 | 11648 | 85729.28 |
| 3 | Airbus A320 Neo | 84 | 182 | 8.46 | 15288 | 129336.48 |
| 4 | Airbus A321-200 | 30 | 228 | 7.08 | 6840 | 48427.2 |
| 5 | Airbus A321 Neo | 8 | 235 | 8.18 | 1880 | 15378.4 |
| | Total: | 205 | | ∑: | 38411 | 298679.81 |
| | | | | **Airline Rating:** | | **7.78** |

**Table K.43** Spring Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A320-200 | 78 | 180 | 7.46 | 14040 | 104738.4 |
| 2 | Airbus A320 Neo | 34 | 186 | 8.65 | 6324 | 54702.6 |
| 3 | Airbus A321 Neo | 12 | 240 | 7.47 | 2880 | 21513.6 |
| | Total: | 124 | | ∑: | 23244 | 180954.60 |
| | | | | **Airline Rating:** | | **7.79** |

**Table K.44** TUIfly Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-800 | 16 | 189 | 7.38 | 3024 | 22317.12 |
| 2 | Boeing 737 MAX 8 | 7 | 189 | 7.8 | 1323 | 10319.4 |
| | Total: | 23 | | ∑: | 4347 | 32636.52 |
| | | | | **Airline Rating:** | | **7.51** |

**Table K.45** Turkish Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 6 | 132 | 6.96 | 792 | 5512.32 |
| 2 | Airbus A320-200 | 12 | 159 | 7.04 | 1908 | 13432.32 |
| 3 | Airbus A321-200 | 65 | 180 | 6.53 | 11700 | 76401 |
| 4 | Airbus A321 Neo | 41 | 182 | 7.67 | 7462 | 57233.54 |
| 5 | Airbus A330-200 | 21 | 279 | 6.06 | 5859 | 35505.54 |
| 6 | Airbus A330-300 | 36 | 289 | 6.23 | 10404 | 64816.92 |
| 7 | Airbus A350-900 | 15 | 329 | 7.39 | 4935 | 36469.65 |
| 8 | Boeing 737-800 | 40 | 151 | 6.87 | 6040 | 41494.8 |
| 9 | Boeing 737-900ER | 15 | 151 | 5.79 | 2265 | 13114.35 |
| 10 | Boeing 737 MAX 8 | 20 | 151 | 7.31 | 3020 | 22076.2 |
| 11 | Boeing 737 MAX 9 | 5 | 169 | 7.25 | 845 | 6126.25 |
| 12 | Boeing 777-300ER | 35 | 349 | 6 | 12215 | 73290 |
| 13 | Boeing 787-9 Dreamliner | 21 | 300 | 7.28 | 6300 | 45864 |
| | Total: | 332 | | ∑: | 73745 | 491336.89 |
| | | | | **Airline Rating:** | | **6.66** |

**Table K.46** United Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 81 | 126 | 6.83 | 10206 | 69706.98 |
| 2 | Airbus A320-200 | 92 | 150 | 6.89 | 13800 | 95082 |
| 3 | Airbus A321 Neo | 2 | 200 | 7.87 | 400 | 3148 |
| 4 | Boeing 737-700 | 40 | 126 | 6.64 | 5040 | 33465.6 |
| 5 | Boeing 737-800 | 141 | 166 | 6.82 | 23406 | 159628.92 |
| 6 | Boeing 737-900 | 12 | 179 | 6.88 | 2148 | 14778.24 |
| 7 | Boeing 737-900ER | 136 | 179 | 6.75 | 24344 | 164322 |
| 8 | Boeing 737 MAX 8 | 74 | 166 | 7.37 | 12284 | 90533.08 |
| 9 | Boeing 737 MAX 9 | 79 | 179 | 7.24 | 14141 | 102380.84 |
| 10 | Boeing 757-200 | 40 | 176 | 5.63 | 7040 | 39635.2 |
| 11 | Boeing 757-300 | 21 | 234 | 6.07 | 4914 | 29827.98 |
| 12 | Boeing 767-300ER | 37 | 167 | 5.37 | 6179 | 33181.23 |
| 13 | Boeing 767-400ER | 16 | 231 | 6.33 | 3696 | 23395.68 |
| 14 | Boeing 777-200ER | 74 | 276 | 5.07 | 20424 | 103549.68 |
| 15 | Boeing 777-300ER | 22 | 350 | 6.01 | 7700 | 46277 |
| 16 | Boeing 787-8 Dreamliner | 12 | 243 | 7.51 | 2916 | 21899.16 |
| 17 | Boeing 787-9 Dreamliner | 38 | 257 | 6.86 | 9766 | 66994.76 |
| 18 | Boeing 787-10 Dreamliner | 21 | 318 | 5.22 | 6678 | 34859.16 |
| | Total: | 938 | | ∑: | 175082 | 1132665.51 |
| | | | | **Airline Rating:** | | **6.47** |

**Table K.47** Vietnam Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A321-200 | 45 | 184 | 6.59 | 8280 | 54565.20 |
| 2 | Airbus A321 Neo | 20 | 203 | 7.98 | 4060 | 32398.80 |
| 3 | Airbus A350-900 | 14 | 305 | 7.2 | 4270 | 30744.00 |
| 4 | Boeing 787-9 Dreamliner | 11 | 274 | 7.04 | 3014 | 21218.56 |
| 5 | Boeing 787-10 Dreamliner | 4 | 367 | 5.86 | 1468 | 8602.48 |
| | Total: | 94 | | ∑: | 21092 | 147529.04 |
| | | | | **Airline Rating:** | | **6.99** |

**Table K.48** Vueling Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Airbus A319-100 | 6 | 144 | 7.24 | 864 | 6255.36 |
| 2 | Airbus A320-200 | 72 | 180 | 7.26 | 12960 | 94089.6 |
| 3 | Airbus A320 Neo | 25 | 186 | 8.49 | 4650 | 39478.5 |
| 4 | Airbus A321-200 | 18 | 220 | 7.01 | 3960 | 27759.6 |
| 5 | Airbus A321 Neo | 4 | 236 | 8.18 | 944 | 7721.92 |
| | Total: | 125 | | ∑: | 23378 | 175304.98 |
| | | | | **Airline Rating:** | | **7.50** |

**Table K.49** Westjet Airlines Airline Rating Calculation

| ID (I) | Aircraft Type | No. Of A/C (*N*) | Seats per A/C (*S*) | Overall rating (*O*) | *N S* | *N S O* |
|---|---|---|---|---|---|---|
| 1 | Boeing 737-700 | 40 | 120 | 6.5 | 4800 | 31200 |
| 2 | Boeing 737-800 | 50 | 174 | 7.15 | 8700 | 62205 |
| 3 | Boeing 737 MAX 8 | 32 | 174 | 7.68 | 5568 | 42762.24 |
| 4 | Boeing 787-9 Dreamliner | 7 | 320 | 7.74 | 2240 | 17337.6 |
| | Total: | 129 | | ∑: | 21308 | 153504.84 |
| | | | | **Airline Rating:** | | **7.20** |

**Table K.50** Xiamen Airlines Airline Rating Calculation

| **ID (I)** | **Aircraft Type** | **No. Of A/C (*N*)** | **Seats per A/C (*S*)** | **Overall rating (*O*)** | ***N S*** | ***N S O*** |
|---|---|---|---|---|---|---|
| 1 | Airbus A321 Neo | 11 | 208 | 7.46 | 2288 | 17068.48 |
| 2 | Boeing 737-700 | 9 | 128 | 6.82 | 1152 | 7856.64 |
| 3 | Boeing 737-800 | 118 | 170 | 7.15 | 20060 | 143429 |
| 4 | Boeing 737 MAX 8 | 10 | 184 | 7.6 | 1840 | 13984 |
| 5 | Boeing 787-8 Dreamliner | 6 | 237 | 7.5 | 1422 | 10665 |
| 6 | Boeing 787-9 Dreamliner | 6 | 287 | 7.47 | 1722 | 12863.34 |
| | Total: | 160 | | ∑: | 28484 | 205866.46 |
| | | | | **Airline Rating:** | | **7.23** |

# Appendix L – Aircraft Labels of the Flight from San Francisco to Singapore

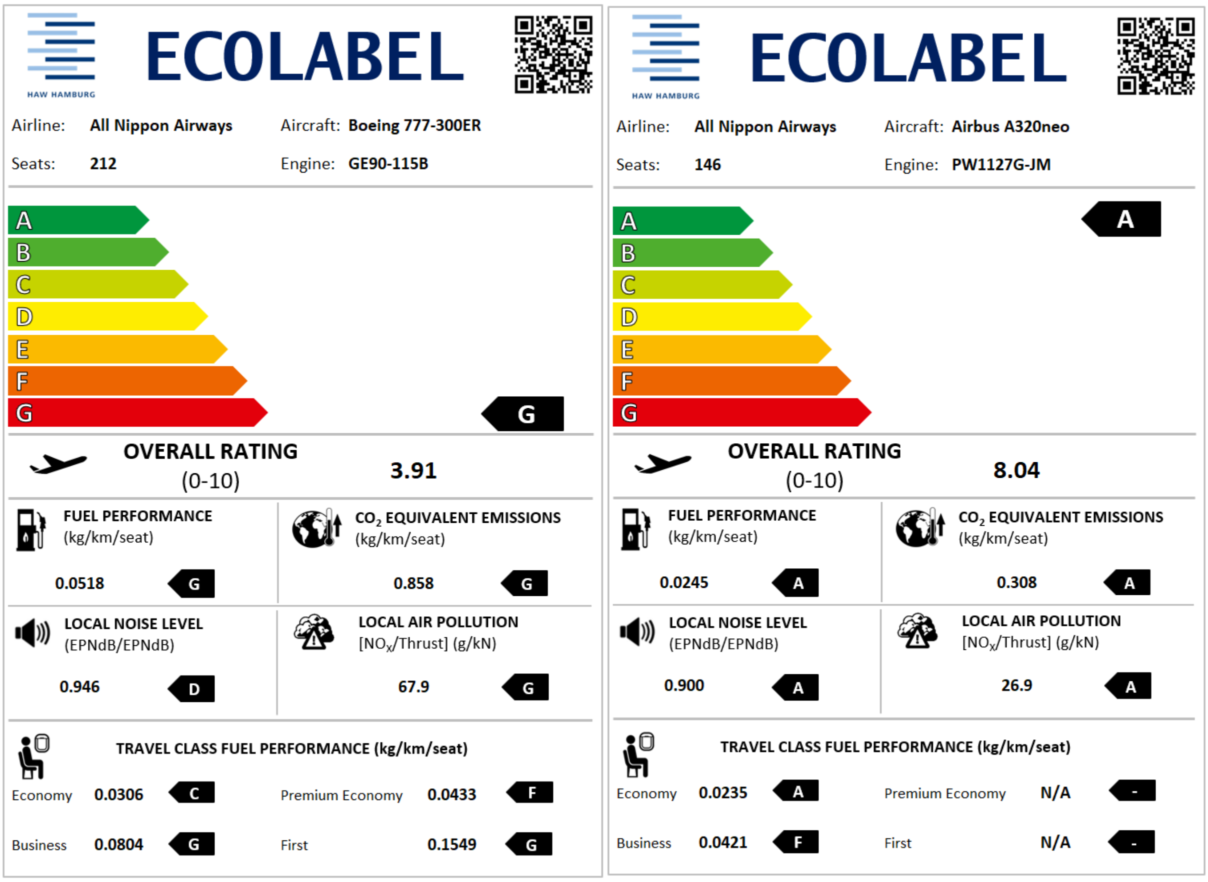


**Figure L.1** Aircraft label of the Boeing 777-300ER operated between SFO-HND and aircraft label of the Airbus A320 Neo operated between HND-KIX

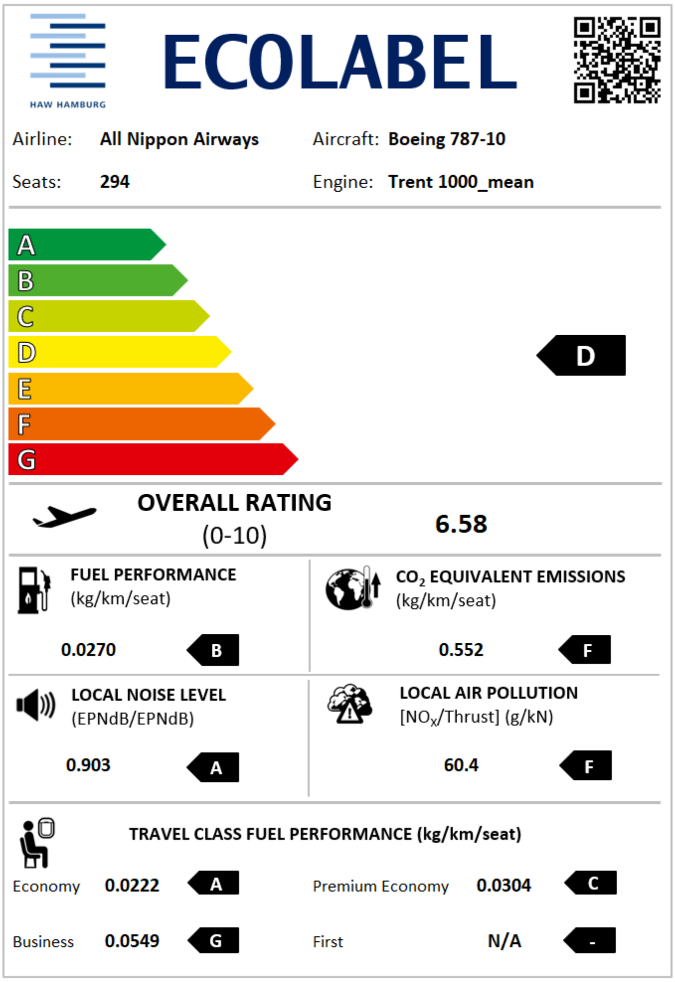


**Figure L.2** Aircraft label of the Boeing 787-10 operated between KIX-SIN

# Appendix M – Add New Aircraft Types in the Eco-label Calculator

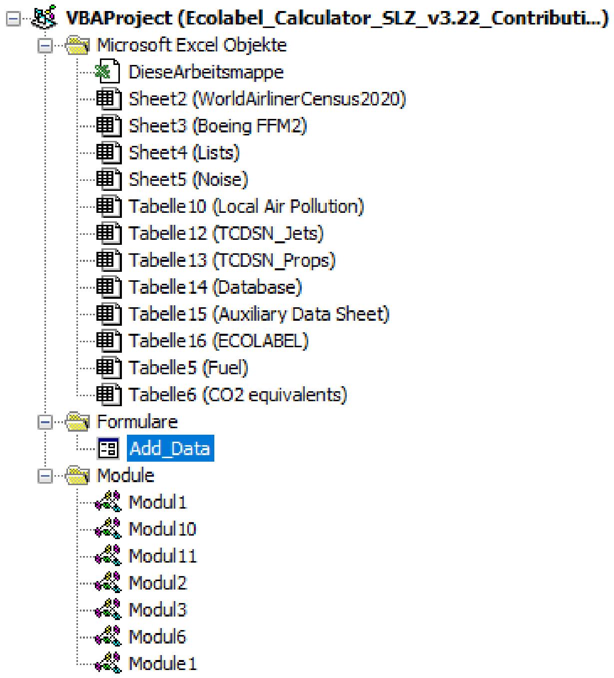


**Figure M.1** Location of the Makro Add_Data, which has to be edited to accept more aircraft types

```
'Add new Aircraft Engine Options here:
    '1. Add a new column with the aircraft model and its engine options in the worksheet "Lists"
    '2. Select the cells with the headline (aircraft name) up to the last engine option and press
    '   CTRL(STRG) + T to create a smart Excel spreadsheet (intelligente Tabelle)
    '3. Give the smart Excel spreadsheet a new name analaog to the existing ones you see below

    Case Is = "COMAC C919"
        Engine.RowSource = "Lists!" & Range("tblC919").Address
    Case Is = "Airbus A319neo"
        Engine.RowSource = "Lists!" & Range("tblA319neo").Address
    Case Is = "Airbus A320neo"
        Engine.RowSource = "Lists!" & Range("tblA320neo").Address
```

**Figure M.2** Instructions to accept more aircraft types