Atmosfair Airline Index

Documentation of the methodology

The Atmosfair Airline Index at a glance

The Airline Index compares aviation companies based on their climate efficiency when transporting payload (passengers and coloaded freight) and assigns them a global ranking.

Scope

- 150 of the biggest passenger airlines of the world
- 113 types of aircraft (global coverage of 95%)
- 368 engine types (global coverage 97%)
- 4 market segments (100% coverage)
- 92% coverage of all worldwide flights

Method

- Basis: CO_2 per payload kilometer, averaged over all city pairs of an airline
- Precisely analyzed parameters:
  - city pair and distance
  - type of aircraft
  - engine
  - winglets
  - seating
  - cargo capacity
  - passenger capacity utilization
  - coloaded freight capacity utilization
- Data source year 2012 for Index 2014
- The AAI method is based on key elements of the emissions calculation method of the ICAO.

Quality

- Scientific: inclusion of only physical factors, no normative requirements, etc.
- Data sources: independently and internationally established, among other things, ICAO, IATA, OAG, JP Airline, etc.
- Accuracy and capacity: The ranking is significant with a confidence interval of 95%.
- Review: The Airline index has been reviewed by university professors from different scientific areas, listed in the index brochure.

Word of Greeting of atmosfair Patrons

Flying is an indispensable tool in modern society but at the same time it contributes to global warming. Extremes come to light in few other sectors as abruptly as in air traffic. While we normally fly in an airplane only about once a year, in the few hours we spend flying we easily contribute to the Earth's warming as much as driving a car in one year. And those who suffer and will suffer the most from global warming are those who fly the least: people from many economically undeveloped countries in Africa and Asia.

If flying is unavoidable, we can influence how much climate-changing emissions arise through our choice of airline. In contrast to a still flying old model, a new type of aircraft usually consumes less fuel and hence emits less CO_2. A narrowly configured and full airplane also flies more efficiently than one where only a few seat rows are available and where most seats are empty. Now for a normal passenger these factors are not measurable. What is even worse is that, beside these differences which at first glance clarify the situation, there is an entire series of other factors which remain hidden to the passenger but which are no less important in terms of climate. Passengers can at least influence these factors so long as they have no access to any pertinent information when choosing the airline.

The Atmosfair Airline Index (AAI) now closes these loopholes. It takes the differences between airline companies as the motive for analyzing, evaluating and comparing their carbon footprint scientifically. The AAI depicts the results in different rankings in an illustrative manner, thereby making it equally useful to private and corporate clients[1]. It is our goal to have carbon footprint, in addition to ticket price and service, be incorporated more and more in the competition among airline companies. This can only be helpful for climate protection and ultimately for the entire aviation industry on their path towards sustainability if their customers increase their demand for flights with less CO_2 emissions.

We wish atmosfair a lot of success in this contribution to climate protection and a lot of fun to you readers!

Prof. Dr. Hartmut Graßl
Prof. Dr. Mojib Latif

[1] Corporate clients can also obtain the atmosfair Airline Index for individual routes from atmosfair gGmbH . It allows cost-conscious and environmentally aware companies that have many business aircraft on individual routes to adopt carbon footprint as an added criterion in bid invitations when searching for the airline for the respective route.

Author's Preface

Company rankings based on environmental criteria are widely used. The german VCD auto environment list compares individual cars every year. For years electrical appliance makers have been attaching the EU label for energy efficiency on their products. This also makes environmental friendliness a component of business valuations such as the Dow Jones Sustainability Indexes or the Nature Stock Index which, in turn, are decisive factors for those financiers and investors who pay special attention to the sustainability of their financial investment, especially large institutional investors. Legislators and consumer organizations agree that product labeling provides a significant contribution to environmental protection due to the power of consumers.

For air traffic up until now there has not been any ranking of airlines based on their climate efficiency. Existing emissions calculation standards for flights such as that from the UK ministry of environment DEFRA allow no differentiation among aviation companies. Other approaches such as the emissions calculator of compensation providers or of specialized service providers from the travel industry leave out important factors or, for lack of data, do not represent them precisely enough to allow a ranking of airlines based on climate efficiency[2].

The atmosfair Airline Index fills in these loopholes. This document describes the method, procedure and sources, thus providing the required transparency. For the interested reader it can also serve as a general introduction into the subject of CO_2 emissions of aviation companies.

Our thanks go especially to associate Prof. Paul Peeters, who in his function as aviation engineer has reviewed the methodology, and to Prof. Dr. Hartmut Graßl, who has brought his expertise, among other things, in climate science, as well as to Prof. Dr. Stefan Gössling for the many critical inputs and to Cornelius Joos for his digging into the databases.

Dr. Dietrich Brockhagen,
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and CEO of atmosfair gGmbH

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[2] See Appendix 2 to DEFRA and the vendor TRX.

Summary

The atmosfair Airline Index (AAI) is a ranking of airlines based on their climate efficiency when transporting payload (passengers and coloaded freight) with the following properties:

- Aviation companies receive efficiency points in the ranking. They are assigned to 7 efficiency classes from A to G (similar to the EU energy efficiency label).
- To be awarded efficiency points only greenhouse gas emissions are considered (no noise, no sustainability policy, etc.).
- Within greenhouse gas emissions only CO_2 is considered because the other hazardous materials (soot, particles, water vapor, etc.) show the same effect (e.g. condensation trails) in all airlines. Exception: Oxides of nitrogen (NO_x) are included through an engine factor (through the radiative forcing of ozone formation and methane breakdown).
- Different business models of airlines such as network or low-cost carrier and features such as focus on intercontinental, regional or domestic flights are not evaluated.
- Examination of the 150 largest passenger airlines of the world (arranged according to transport service, pure cargo flights are not included).
- Data source year: 2012 for Index 2014.
- Airline categories considered: network, low-cost, charter and regional carriers.

The AAI is based on atmosfair's own new methodology, which builds on the CO_2 calculation method of the ICAO. Its main data sources are: ICAO TFS (Traffic Flight By Stage), IATA WATS, OAG, Piano-x, JP-Airline Fleets (chapter 9).

The comparison of airlines in the AAI follows the procedure below:

1. Calculation of CO_2 per payload kilometer (on a route or city pair), taking account of type of aircraft, engine, seating, coloaded freight capacity, cargo and passenger capacity utilization factors, winglets. NO_x emissions are included through the engine factor.
2. The CO_2 per payload kilometer for a city pair is compared with the best physically possible case (best case) and with the three times less efficient worst case (chapter 6.1).
3. The airline which realizes the best case on a city pair gets 100 efficiency points. The airline that reaches the worst case gets 0 efficiency points for this one city pair. All other airlines get their points on this city pair by linear interpolation between the two extremes (chapter 6.2).
4. The efficiency points on all city pairs are averaged to arrive at the global efficiency points of an airline.

5. Classification of airlines based on their global efficiency points in a ranking with 7 efficiency classes (similar to the color codes of the EU Ordinance for Energy Efficiency of Refrigerators, Houses, etc.).

The following comparisons are possible using this AAI method:

- An airline with only a few routes flown can be compared to another airline that operates hundreds of city pairs worldwide.
- An airline that flies only short routes can be compared to another that flies only long routes.
- A charter carrier can be compared to a network carrier.
- An airline that flies a city pair alone without competition can be evaluated objectively.

The AAI takes the following into consideration:

- type of aircraft, engine, winglets, seating, freight capacity, passenger and cargo capacity utilizations (chapter 5).
- 113 types of aircraft and 368 engines
- 92% of worldwide passenger air traffic (number of flights)

Content

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Constants und Variables

Variable	Description
C_C	Available Cargo Capacity
CLF	Cargo Load Factor
C_P	Available Passenger Capacity
C_T	Total Payload Available
D_{CP}	City Pair Distance [km]
D_O	Distance [km] of the individual flights needed for the interpolation
D_U	Distance [km] of the individual flights needed for the interpolation
F_{EF}	Fuel consumption of an AAI flight
F_{EF1-6}	Fuel consumption of the individual flights needed for the interpolation
P_C	Cargo transported
P_{FL}	Total payload of an AAI flight
PLF	Passenger Load Factor,
P_P	Passenger Payload transported

Part I

The Airline Index Method

from Beginning to Illustration of Results

1. Objective and principles of the atmosfair Airline Index

1.1. Objective

The objective of the atmosfair Airline Index (AAI) is to offer passengers a means of orientation when selecting a climate-efficient airline for a flight. The Airline Index merges into the classic procedure for environmental protection whereby prevention ranks before reduction before compensation.
For the index to make sense, the passenger needs to have already checked whether the flight is unavoidable and the most direct flight connection has already been selected[3]. The Airline Index then helps in the second "reduction" step and so comes before the possible last step - compensation of greenhouse gas.

With this index atmosfair offers passengers support in all three steps:

- Prevention: atmosfair has developed an optimization software for the travel booking process in companies that wish to replace business trips with video conferences, thereby saving on greenhouse gases and money[4].
- Reduction: With the index atmosfair supports individual passengers and companies in finding a climate-efficient airline.
- Offset: atmosfair offers passengers voluntary offsets of CO_2 emissions by making a contribution towards offset projects building up renewable energies.

1.2. Principles

The atmosfair Airline Index is structured according to the following principles:

Demand perspective
The AAI is for the demand side of the market. It adopts the point of view of a passenger who is not interested in what is going behind the scene in the aviation industry but only in the carbon footprint of his or her flight, regardless of where the passenger wants to fly and which airlines are offering this route.

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[3] The rule of thumb states that a transfer flight in efficiency class C generates more CO_2 than a direct flight in efficiency class E.
[4] ELECTROLUX 2007, p. 12

Physical basis

The AAI evaluates only factors that are objectively detectable. It is based on CO_2 per payload kilometer. In addition, no value judgments are made and there are no normative requirements. The company and environmental policy of individual airlines, airports and aircraft manufacturers also play no role in the AAI.

Methodological completeness and accuracy

The AAI method and the parameters used are enough to create a resilient ranking of airlines. The accuracy of data sources and methods are sufficient for a significant ranking. This is proven by the error analysis (chapter 13). Larger deviations are noted individually in the ranking.

Principle used by the international civil aviation organization ICAO

The AAI method is based on key elements of the emissions calculation method of the ICAO. However, it takes account of more factors, has a wider database, and is further developed more precisely and with significant detail.

Completeness of data

Global civilian air traffic can be ranked using AAI data. This is fully depicted in the AAI. There are no prescribed omissions. For reasons of clarity only a subordinated selection (the 150 largest airlines of the world) is found.

Data independence and data quality

The AAI uses only internationally renowned and recognized sources. AAI data comes from specialized data providers whose principal activity is collecting aviation industry data and who are responsible for quality and independence. The few exceptions are described individually in this article.

2. How do flights affect the climate?

The volume of emissions from a flight and their climate impact depend on a series of factors. These factors are listed in this chapter and discussed in depth in chapter 4.

Air traffic contributes to global warming due to the emission of greenhouse gases such as carbon dioxide (CO_2), oxides of nitrogen (NO_x) and other pollutants. Research has been focused on this issue around the world since around the mid-1980s. The research was compiled in 1999 by the IPCC in a special comprehensive volume called "Aviation and the Global Atmosphere"[5]. The atmospheric effects of air traffic, especially at high flight altitudes, and the existing technology and potential for fuel savings are investigated in this book. As a consequence, international research moved forward and significantly expanded, modified and gave depth to prior knowledge. The findings are published regularly in special sections of the IPCC report.

We now know that air traffic contributes directly to global warming through its emissions in the border zone between the upper troposphere and lower stratosphere. This is more than just pure CO_2 emissions which always arise when fossil fuels are burned and which have global effects. Effects such as the composition of the greenhouse gas, ozone, reacting with oxides of nitrogen from aircraft engines, the formation of line-shaped condensation trails or the emission of water vapor and particles which, in turn, can lead to the formation of cirrus clouds are local or regional and also depend, apart from airplanes, on the current condition of the surrounding atmosphere.

Beside these effects there are still those that depend exclusively on the aviation company - the type of aircraft used and its seating, engine, winglets, etc. Apart from pure technology, this also includes the operation of the airplane. This encompasses not only passenger and cargo capacity utilization but also the actual flight, the airspeed and the landing approach.

All these factors potentially come into consideration so that they can play a role and be ranked when comparing airlines from the standpoint of climate efficiency. The following table lists the possible factors. We will then examine them in more detail in chapter 4 and ask whether they should be included in a ranking.

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[5] IPCC 1999

Factor	Description
Atmospheric Condition	Describes the current local physical properties of the atmosphere around the airplane during the flight, among other things. humidity, background NO_x concentrations and temperature. These quantities influence the effect on ozone, cloud formation, etc.
Time of Day	Flights during the day or at night have, among other things, an effect on the potency of condensation trails.
Weather & Wind	Includes locally changing winds, local weather anomalies as well as regular weather factors such as west wind drift or monsoon.
Flight Route	Route which the airplane flies on a city pair. The route depends on the great route distance, the airspace, the territories of the respective countries, etc.
Detours & Holding Patterns	Detours are deviations from the great route distance between two airports due to limitations in the flight route. Holding patterns are flight maneuvers where the airplane circles above a certain point in a prescribed route and waits for further clearance
Distance	Distance between the airports (city pair)
Flight Profile (Altitude depending on Distance)	Depending on the distance, the prescribed altitude and the flight route, the climb, cruise and approach relationships change with respect to each other and hence affect a flight's fuel consumption.
Airport Operation	Length of taxiing on the ground, push service, ground power supply, etc.
operation	Effects of the piloting of the airplane on fuel consumption of a flight, e.g. continuous descent approach, slower flying, etc.
Type of Aircraft	Airplane used
Winglets	Aerodynamic extensions on the wing tips; reduce air resistance and fuel consumption
Age of Aircraft	Age of the airplane and technological status of a model
Maintenance	Effect of maintenance on airframe and engines
Engine	Affects fuel consumption as well as the emission of NO_x, etc.
Seating, Seat Capacity	Number of seats offered on board divided into different seat classes
Coloaded Freight Capacity	Capacity to carry coloaded freight
Coloaded Freight	Payload in the form of cargo and mail that is transported in addition to passengers
Capacity Utilization	Number of actually transported passengers and amount of coloaded freight of a flight in relation to the possible payload capacity
Operating Empty Weight	Operating weight of an airplane, which depends, among other things, on configuration with screens, various seat comfort classes, etc.
Other Hazardous Materials	Includes harmful emissions that the aircraft engine emits during operation apart from CO_2 emissions, e.g. oxides of nitrogen (NO_x), soot, particles, water vapor.

Table 1: Factors that can influence a flight's climate impact

3. Introduction: How is a climate-based comparison of airlines possible?

3.1. Differences between aviation companies

In theory airlines can be compared on many levels where the climate factor plays a role. First of all, this is the absolute quantity of generated CO_2 emissions and other greenhouse gas pollutants. The airline's business model and the weight of sustainability and the environment generally come into play in the company policy (e.g. when weighting flight noise against airplane costs, the frequency of aircraft maintenance, the procurement of raw materials, etc.). All these points are concentrated in the atmosfair Airline Index in a central parameter that is used as a guide index for the airline's climate efficiency: CO_2 per passenger kilometer (or more precisely per payload kilometer). This approach represents the issue of climate efficiency of airlines comprehensively and exactly enough as we will show in this article.

Aviation companies differ in many ways. The following categories are directly or indirectly related to CO_2 emissions and hence to the issue of climate protection:

1. Business model:
   We distinguish, as is commonplace in the industry, four main business models of aviation companies: network carrier, charter carrier, low-cost carrier and regional carrier. These differ, among others, in terms of their areas of application, distances and company histories (see below). The direct effect of the business model on the climate impact lies in the fact that charter companies acquire demand over a long period and could cancel flights in an emergency, while commercial airlines always have to maintain capacities even when the worst scenario occurs with the airplane flying almost empty. This difference is however no more relevant in practice, since differences between charter carriers and net carriers regarding crucial criteria such as public access, regularity of flights, and conveyance obligation are clearing away. Especially the conveyance obligation is e.g. in Germany in practice existent by means of the tour operator law[6]. Furthermore, from a pure economic perspective conveyance obligation is a kind of self obligation from the charter carriers[7]. Moreover, low-cost carriers play a special role since they induce flights and hence CO_2 emissions (see chapter 3.4).

[6] § 651 a, Abs. 1 german Civil Code, cited in Pompl, 2007, p. 37.

[7] Bachmann, K.: Charterflugverkehr, S.27, cited in Pompl, 2007, p. 37.

2. Areas of application:

   Demand is greater on certain circuits like the North Atlantic than on secondary regional routes. From the climate point of view, this has at least two effects: first, the time-dependent fluctuation of demand is greater on the small routes and hence the risk of not being able to sell capacities and having to fly with less capacity utilization. Second, aviation companies can fly circuits using bigger airplanes that consume less fuel per passenger and hence generate specifically less CO_2.

3. Distances:

   The specific fuel consumption per passenger kilometer depends on the flight distance: If fuel consumption per kilometer of payload transport on short routes is the highest, then it drops with growing distance up to an optimal value on the middle route before it again rises slightly with further increasing distance. This relationship applies to all airplanes and is based on the interaction of aircraft weight empty and fuel weight. From the climate point of view, therefore, aviation companies are in the advantage if they operate mainly middle routes. Nonetheless, competitors who fly mainly short or long routes must also be rated fairly.

4. History:

   While many of the former national carriers were exposed to competition only upon the liberalization of air travel first in the US and later in the EU, younger aviation companies were founded only later in the already increasingly deregulated and competitive market. On the other hand, younger airlines can buy modern and hence mostly fuel-saving planes from the very onset while older aviation companies take advantage of the long service life of purchased jets until the end in order to avoid taking losses due to early depreciations.

The question is how can airlines be compared at all in a meaningful manner from the climate point of view given these basic differences. Meaningful here means the orientation options available to a passenger if the passenger wishes to include climate efficiency in the decision when selecting the airline for a flight (see chapter 1, Objective of the AAI and Demand Perspective). The answer to the question is that a comparison of airlines is possible if three fundamental bases of assessment are present:

1. Demand perspective (chapter 1)
2. Ranking based on CO_2 per payload kilometer
3. Ranking on a city pair as basis

Let us now discuss the last two points.

3.2. Basis of assessment I: CO_2 per payload kilometer

The pure climate impact of a flight is not sufficient for the objective of giving passengers an orientation option. Not only for the reason that climate impact is mostly indicated in physical units of radiative forcing (W/m2) or temperature increase (ΔC°), which would be difficult to calculate for individual flights. Primarily however this absolute parameter lacks a frame of reference which relates the climate impact that automatically accumulated during each flight to the passenger's objective, namely transport to his or her flight destination (since otherwise the airlines that fly the least would perform the best).

This type of cost-to-benefit ratio has proven successful in many cases as an efficiency unit (e.g. EUR per liter of milk with food products, CO_2 per kilometer in cars). For this reason, the AAI makes climate impact per payload kilometer as the first basis. The application of such a ratio as basis of assessment is mostly similar to CO_2 per payload kilometer since besides CO_2 only NO_x has to be included in the AAI even with the requested completeness (see chapter 4.12). For this reason, this article always talks in a simplified manner about CO_2 per payload kilometer instead of climate impact per payload kilometer.

With payload the AAI does not differentiate between coloaded freight (mail and cargo) and passengers but rather uses only the total transported payload in the unit of transported mass. This is justifiable because without normative specifications we cannot make comparisons between the benefits to passengers during their flight and the benefits to cargo recipients upon shipment of their cargo. Moreover, in practice aviation companies optimize transported passengers and cargo according to their own preferences. To be able to compare the efficiency of this optimization in something that makes sense, we must be able to add up passengers and cargo. Since climate impact depends on fuel consumption and the latter on payload, this adding up of cargo and passengers is done via the payload mass.

The principle of CO_2 emissions per payload kilometer resolves the above-mentioned challenges of the business model and history of airlines: Just like in ticket price it is irrelevant to the passenger whether the aviation company is young or old, or what history and business model it has. Similar to when purchasing a ticket, the passenger decides on one of the airlines that offers the desired flight. The market regulates competition between airlines, leading to a situation where several airlines offer a flight for some time, then stop offering them, then use another airplane, new airlines come into play, etc. All aviation companies, regardless of business model, have access to the same aircraft manufacturers and hence the same technology. Aviation companies can therefore incorporate CO_2 as well into their product calculation without this causing an aviation company disadvantages that could not be attributed to its own self-selected business model. The CO_2 per passenger here is also integrated in the competition. It does not represent any fundamental problem but only adds another element in the competition between aviation companies.

3.3. Basis of assessment II: Comparison on city pairs

The ranking is based on the comparison of airlines on an offered city pair. The individual ratings of airlines on the different city pairs they fly are later averaged for the total ranking but the actual efficiency points are given individually to city pairs on which every airline meets exactly the same physical ancillary conditions.

The principle of the city pair as the basis resolves all physical challenges of an airline ranking. The physical and central economic ancillary conditions on a city pair are the same for all airlines: distance, air space structure, wind, airports, demand, etc. If an airline therefore decides to offer a certain airplane with a certain seat configuration and technical setup at a certain frequency for a city pair, then it makes fully independent decisions which represent its answer to these central ancillary conditions on this city pair. Another airline will create the same, another or no offer at all for this city pair. So CO_2 per passenger kilometer (more precisely: payload kilometer) also becomes the result of the freely made decisions of an aviation company in competition with other aviation companies. If an aviation company cannot make an offer on a certain city pair, for example, because it is not considered in the slot policy of the affected airports, then it does not accrue in the Airline Index any disadvantage since an aviation company is rated only on a city pair that it also operates.

Another basic problem which the comparison based on city pairs resolves is the following: the specific consumption per payload kilometer depends heavily on the flight profile or the distance. From the standpoint of climate, middle-haul flights, in particular, are more efficient than short-haul or long-haul flights given otherwise similar ancillary conditions (same airplane, same capacity utilization, etc.). In a pure examination based on CO_2 per payload kilometer, airlines with many middle-haul flights would be at an advantage and airlines that do not offer these routes at all at a disadvantage. Even from the point of view of demand this would be deceptive. The AAI user is not served if the user is considering a long-haul flight and concludes from the AAI that it should rather book a middle-haul flight from the climate point of view. Comparing airlines on the level of city pairs eliminates this problem since distance and flight profile of flights of airlines to be compared are the same on a city pair at all times.

3.4. Special low-cost airlines

Climate is heated by absolute emissions, that is, tons of CO_2 that people generate. This depends first of all on the distance of the travel destination and the selected means of transportation. From the consumer perspective the passenger first makes the decision to travel and so becomes responsible for the associated absolute CO_2 emissions. The airline is then responsible for minimizing the specific CO_2 emissions on the customer's flight. The AAI ranking is based on this principle of demand perspective and the specific CO_2 emissions per payload kilometer of an airline.

We have shown up to this point that in the demand perspective of a passenger and based on two fundamental principles (CO_2 per payload kilometer and per city pair) all differences between airlines are eliminated so comprehensively that they become comparable in the AAI without financial difficulties from the climate point of view. A governing notion on this score was that, given all the diversity of their products, airlines make significant distinctions only in those factors that are invisible to customers. The prerequisites, conditions and objectives of a charter carrier, low-cost carrier or network carrier may still be so different; they are visible to the customer only on whether an airline offers flights or not on the city pair the customer wants at the conditions the customer desires (flight time, flexibility, class, price, etc.).

However, while the factors of flight schedule and flight class are neutral from the climate point of view, it is not the price, and here lies a difference between low-cost airlines and other airlines. The low ticket prices elicit only the trip in many passengers. It is a known fact that low-cost airlines induce demand with their price policy and hence cause additional absolute CO_2 emissions[8]. The European Low Fares Airline Association (ELFAA) found in a study that just under two thirds of all passengers of low-cost airlines in the EU would not have flown without the offerings of these airlines[9] and Nilsson concludes based on a comparison of three studies that the greater part of low-cost flights is "new" traffic[10]. About three-fourths of the passengers polled in the ELFAA study stated that they would also not have traveled with another means of transportation. The growth rates too differ significantly. Low-cost carriers are growing quicker by a multiple than other airlines[11] and with them their absolute CO_2 emissions.

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[8] Nilsson, 2009: "Low-cost aviation influences demand both directly and indirectly. Lower Fares encourage the public to travel more. They also divert consumers away from … other forms of transport. These effects are in line with standard micro-economic models; if the price of a service decreases, the demand will increase."

[9] ELFAA 2004.

[10] NILSSON 2009, p. 122; citing ELFAA 2004, DOGANIS 2006 und KNORR 2007.

[11] In 2007 (2006) low-cost carriers worldwide grew by 20% (14%), whereas the remaining air traffic worldwide increased only by 4% (2%). Between 2001 and 2005 low-cost carriers have doubled their market share from 6% to 12%. Source: OAG press reports, 2005 to 2010.

Economically there is no difference here between airlines. As commercial enterprises all of them maximize their gains. A path towards this end leads through cost reduction. Low-cost carriers are successful in reducing their operating costs, for example, by flying from low-priced regional airports, offering only one booking class, having a few types of aircraft in the fleet, having low turnaround times, generating low marketing costs through direct sales, omitting unnecessary service, etc. In general, a company can gain a cost advantage vis-à-vis competitors either by selling their products at similar prices as the competition at better margins or by attaining higher production capacities at a lower price and lower margins. Both are popular strategies for profit maximization and neutral from the micro-economic standpoint since market processes which ensure optimal allocation of resources are running here.

Low-cost carriers select the path to profit maximization by reducing prices and increasing production capacities. They do this to an extent that leads to flights which otherwise would not have arisen. Low-cost airlines thus change the sequence of "demand of passengers brings about supply from airlines", which in turn leads to additional CO_2. However, as long as law makers do not interfere through climate policy or other policy tools and an airline complies with existing legal framework, this effect cannot be counted towards the airline.

The crucial point is here that the Airline Index addresses passengers, not airlines. The bigger part of the passengers would not fly without the Low-cost carrier. Since avoidance comes before optimisation in an perspective of environmental economics, these passengers would need to avoid these flights in the first place. It is hence difficult to compare Low-cost and other carriers on one level in the Airline Index, without distorting the desired steering effect.

3.4.1. Subsidies

Another possible difference between traditional and low-cost airlines is in financial support from the public sector. Aviation companies generally profit from special regulations such as the non-taxation of international tickets and kerosene, support from aircraft manufacturers, etc. But this applies to all aviation companies and is therefore irrelevant in a ranking.

The relevant difference could be in the direct financial support from the public sector for individual airlines, which are described here for the two classes of network carriers and low-cost airlines:

- Network carriers: They can profit from the public sector through subsidies and public interventions in favor of national (ex) flag carriers (e.g. government subsidies to Air France, rescue of Alitalia, debt release of AUA before takeover by Lufthansa, etc.).

- Low-cost airlines: They often profit from low landing fees and "marketing support" which is provided by public airports not in the form of a benefit-in-kind but which can go directly as money to the airline[12]. With the example of Ryanair it was estimated that direct payments per passenger were between approximately 10 and 30 EUR per flight, hence making a significant part of the low ticket price possible[13]. Moreover, low-cost airlines prefer to fly from small regional airports where the public sector has the highest stake in the financing in comparison to other airports[14].

From the standpoint of environmental economics, subsidies mean external costs since they influence the optimal allocation of resources. But since subsidies to airlines as described above are widespread, there is no basic difference here between low-cost and other airlines. However, these subsidies among low-cost carriers additionally lead to market distortion and to external costs in the form of global warming with more CO_2.

This effect can be large, which we show easily in a back of the envelope calculation: We take as a conservative example the lower bound of 10 EUR of the above cited 10 – 30 EUR subsidies per passenger for a flight of Ryanair. 10 EUR correspond currently to the price of about 600kg CO_2 in the EU emission trading scheme. Hence, whoever subsidies the airline, could instead of subsidizing Ryanair having about 600kg CO_2 saved within the European energy intensive industry. These 600 kg CO_2 exceed however the amount of CO_2 released per passenger even in the least efficient airline class G (chapter 11.3) on an entire short distance return flight. And 600kg CO_2 correspond to the difference between the AAI efficiency class A and E per passenger on a medium range return flight Frankfurt – canary islands. The subsidies are hence of an order of magnitude, which easily could put an airline from a top ranking down to the bottom, if they were included in the climate ranking. Since these data are however not available for all carriers, they cannot be considered in the AAI at this time.

3.4.2. Detours

Low cost carrier offer flights form and to regional airports[15]. This creates detours for the travellers, since it can be assumed that more passengers come from the centres and therefore create a detour

[12]In current quarrel between established network carriers and low-cost airlines this essentially boils down to the question of whether the subsidies according to EU law constitute an act of unauthorized aid or not. The EU Commission has adopted its own guidelines here in 2005. That the public sector supports several low-cost carriers financially is also not disputed by low-cost carriers.

[13] LE FIGARO 2010

[14] Deutsche Bank, 2005.

[15] Pompl 2007, p. 115

when travelling from centre to centre via a regional airport, compared to travels from and to central airports. These detours generate additional CO_2, depending on the distance and means of ground transport used, which would need to be added to the carbon balance of the flight. Since this effect depends on a variety of parameters for which no comparable data are available, the Airline Index cannot capture this effect quantitatively.

3.4.3. Classification of low-cost airlines

Just like with other types of aviation companies, the boundaries between low-cost airlines and other airlines is not clearly drawn. Other aviation companies sometimes create demand which otherwise would not have arisen through ads, frequent flyer programs, special deals, etc. It is known that, on many routes where low-cost carriers compete with network carriers, network or charter carriers also lower prices to low-cost carrier level[16] or spin off their own low-cost affiliates. In addition, the differences between the various low-cost carriers are significant. The Low Cost Monitor of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt or DLR) shows the differences and demarcations between airlines in the German market[17]:

"Airlines operating in the low-cost area in part create their product offerings in various ways. Because of this inhomogeneity only a few explicit classification criteria for the low-cost market segment can be defined: low price, general availability of low prices and direct sales via the Internet. Therefore, in some cases there is a specific latitude of judgment in the assignment of an aviation company to the LCC segment. In some aviation companies there is also an amalgamation of business models which further complicates an explicit assignment to the low-cost market. For this edition the authors of the monitor currently classify 19 of the airlines which operate in German airports and provide low -cost products fully or partially".[18]

Aviation companies are classified as low-cost carriers in the DLR based on criteria similar to those of the ICAO's data service provider, ATI (see chapter 9.2.3). Low-cost airlines are defined there as follows:

“Precise definition of a low-cost carrier is difficult given the evolution of the model and increasing common ground with network carriers, but we specify a low-cost carrier as a point-to-point scheduled operator which largely adheres to the core principles of the low-cost carrier model. The airline will have a stand-alone management team and will market itself on price, mostly with a single class

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[16] VERBRAUCHERZENTRALE NIEDERSACHSEN 2010

[17] DLR Low Cost Monitor 2/2010

[18] The DLR Low Cost Monitor discusses in some cases the classification of airlines.

offering. Carriers will sell most of their tickets through direct sales via the Internet, and onboard frills will be available only for a fee.” [19]

3.4.4. Consideration of low-cost airlines in the AAI

The so-called budget airlines have to be considered separately, since they raise methodological problems in CO2 calculation and representation which atmosfair has not yet solved. As soon as atmosfair arrives at a methodological solution, the budget airlines can be incorporated into future rankings. These problems include:

- Subsidies: Many, though not all, budget airlines receive subsidies, and hence generate flights which they could not otherwise have offered at such low prices. These subsidies cause the emission of CO_2, which must also be assigned to the climate account of the subsidized airlines.

- Detours: Many budget airlines fly to and from regional airports. However, the ground travel required to get to and from these airports is generally longer than in the case of hub to hub flights. These longer ground transport distances cause additional CO_2, which must be incorporated into the ranking.

Representation in the AAI

As shown above, it is currently impossible to compare low-cost airlines without distortions in a climate ranking with other airlines based only on specific CO_2 emissions. For this reason Low cost airlines are currently included in a separate class the AAI. The classification as a Low cost carrier is here taken from ATI, who classifies the bigger airlines of the world in different categories.

[19] ATI, personal communication, February 2011.

4. What factors determine the CO_2 per payload kilometer?

This chapter discusses all factors from chapter 2 which can affect the CO_2 per payload kilometer. This chapter only examines whether a factor is included or not and describes the approach for method selection. The exact method is then discussed in chapter 5.

4.1. Criteria for the inclusion of factors in the calculation of the AAI

This chapter discusses each factor as to whether:

1. an airline can altogether affect the factor,
2. airlines differ in the treatment of this factor,
3. the weight of the factor is large enough to consider it in the AAI (relevance criterion). The threshold is defined so that a factor must affect CO_2 emissions per payload kilometer by at least 1%.

Only if all three criteria are met the AAI will include the respective factor in the calculations.

4.2. Flight distance

Flight distance influences a flight's fuel consumption directly. The farther the flight, the more fuel an airplane consumes. Every airline determines how far it wants to fly, hence establishing the absolute fuel consumption and CO_2 emissions.

However, all airlines usually follow the same route between the respective city pairs where the distance is the same for all and therefore there is no distinguishing characteristic. Since the rating in the AAI is based on individual ratings on identical city pairs (see chapter 6), then distance is not included separately in the AAI.

Furthermore, there is an interrelationship between distance and altitude. It is a known fact that short-haul flights consume more fuel per kilometer than middle-haul flights, for example, because the energy-intensive climb carries more weight. This aspect is discussed in the next section separately.

Flight distance	
Controllable by the airline	Yes, but not on a given city pair
Differences possible between airlines	No, not on a city pair
Inclusion in the AAI	Only indirectly via the flight profile

Table 2: Summary of the factor of flight distance

4.3. Flight profile (climb and cruising altitude depending on distance)

The flight profile is the two-dimensional progression of a flight, where the associated altitude is assigned to every point on the Earth's surface along the flight path from the takeoff airport to the destination airport. The flight profile of every flight consists of the following stages:

1. Takeoff to lift-off
2. Climbing stage when the airplane rises to cruising altitude after takeoff
3. Cruising stage when the airplane covers a certain distance at a relatively constant altitude. It is carried out in different altitudes: in short-haul flights in the range of about 5 to 7 kilometers, in long-haul flights often at about 10 kilometers to about 13 kilometers.
4. Descent stage when the airplane descends from the cruising altitude until landing
5. Landing

The flight profile depends on the distance of the city pair as well as the selected type of aircraft. Flight altitudes are specified partly by air traffic control. There are no specifications (especially in long hauls outside national territories), airplanes ascend to altitudes where total fuel consumption becomes minimal or interfering weather factors are minimized.

The flight profile determines the airplane's fuel consumption to the extent that the fuel-intensive stage of the climb in short routes carries more weight than in middle or long routes.

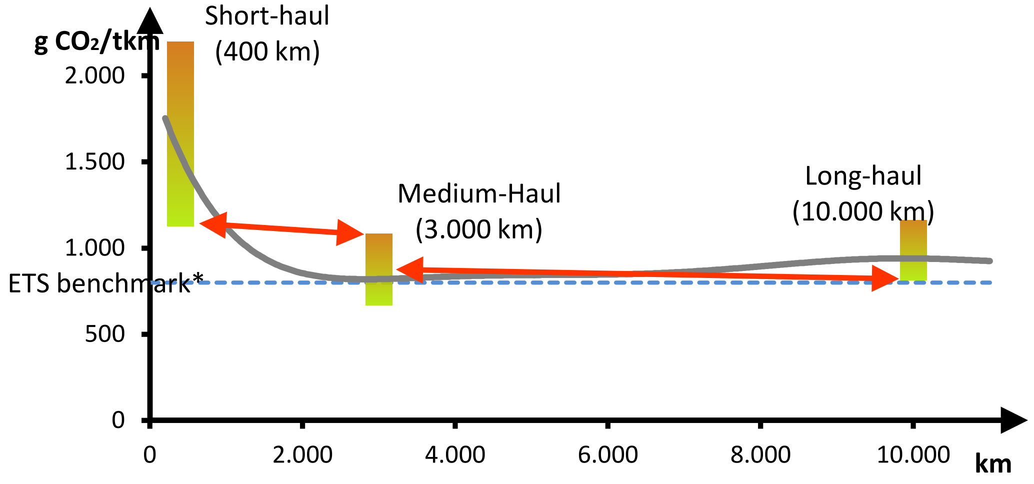

Figure 1: CO_2 emissions of an airplane depending on the route

An aviation company that flies only on short routes and therefore has higher CO_2 emissions per kilometer than another aviation company that optimally operates only middle routes even with an optimal fleet would perform worse in the AAI because the AAI employs specific CO_2 emissions as basis of assessment. However, this result would be undesirable since the information as to whether this or that airline flies on the middle route more efficiently is of little help to a passenger who has decided to fly a short route.

The AAI hence avoids this undesirable effect by comparing airlines only on the same city pairs (see also chapters 3 and 6) and only afterwards averages the efficiency points over all flights. The comparison then becomes meaningful for passengers from whom only a purchasing decision is expected in each flight independently of the distance.

The fuel-optimal flight profile for a given city pair depends directly on the airplane used. The aviation company can control the choice directly and it can also differ here from other aviation companies. The respective type of aircraft used is precisely depicted in the AAI with the flight profile flown by this aircraft on a city pair. The AAI calculates fuel consumption and CO_2 emissions individually for every distance and for every type of aircraft. In this sense the flight profile is incorporated into the AAI in detail.

Flight profile (climb, cruising and landing approach)	
Controllable by the airline	Yes, by means of aircraft choice
Differences possible between airlines	Yes, by means of aircraft choice
Effect on fuel consumption	see type of aircraft
Inclusion in the AAI	Yes, via the rating on city pairs and the selected types of aircraft

Table 3: Summary of the factor of flight profile

4.4. Atmospheric condition

The climate impact of emissions and their effects depend on the altitude and the condition of the atmosphere at the time when the airplane flies through it and emits pollutants. The condition of the atmosphere, among other things, includes temperature, air humidity, concentration of oxides of nitrogen, vertical flow components, etc. These have repercussions on the emergence and duration as well as the radiative properties of condensation trails, the formation or breakdown of ozone, the breakdown of methane, etc., which, in turn, directly change the Earth's radiation budget, leading to a warming or cooling[20].
The instantaneous local condition of the atmosphere is beyond the influence of airlines. Therefore, this factor remains omitted in the AAI even if it significantly influences the climate impact of a flight through the formation of condensation trails, for example.

Atmospheric condition	
Controllable by the airline	No
Differences possible between airlines	No
Inclusion in the AAI	No

Table 4: Summary of the factor of atmospheric condition

4.5. Meteorology

Winds represent a non-negligible effect on the flight stage and fuel consumption. They appear either irregularly during the course of current weather conditions or as regular regional phenomena. Aviation companies can allow for known winds when defining the flight route since they either prove to be obstructive or affect the flight positively by shortening the effective flight time and reducing fuel consumption.

[20] IPCC 1999 and Lee et al 2009.

However, flight routes and flight altitudes are often prescribed especially over land. Local weather and wind effects cannot be bypassed here, that is, an unexpected headwind which increases fuel consumption cannot be avoided. Airlines therefore have little to no possibility to elude locally restricted and variable winds. The wind is not considered further in the Airline Index due to the lack of influence.

Weather & wind	
Controllable by the airline	No
Differences possible between airlines	No
Inclusion in the AAI	No

Table 5: Summary of the factor of weather & wind

4.6. Flight routes and detours

Flight routes are the paths that airplanes cover. For economic reasons the airlines try to fly the shortest possible connection between two points (great circle distance). However, this is not always possible due to a series of limitations.

- Airspace within national territories

Air traffic control assigns flight routes as well as flight altitudes in the airspace inside the territories of the respective country. Deviation from it is allowed only by way of exception or in emergencies. Even in the airspace within the European region, which in spite of harmonization is further split up because of the incompatibility of air traffic control systems, airplanes often have to fly around different regions. To some extent this lengthens the route significantly.

However, in airspace outside territories pilots have the discretion to choose the flight route. However, there are limitations here as well.

- ETOPS

ETOPS (**E**xtended-range **T**win-engine **O**perational **P**erformance **S**tandards) are ICAO regulations that limit the choice of flight routes for twin-engine airplanes. They may fly only routes where it is ensured that in case of engine failure the next permissible airport for the airplane is accessible within a certain time. This limits the discretionary choice of flight route. Out of cost considerations airlines are increasingly relying on twin-engine airplanes so that the ETOPS are playing a role for more and more long-haul flights. This does not affect three-engine or four-engine aircraft models.

Flight route	
Controllable by the airline	sometimes
Differences possible between airlines	No
Effect on fuel consumption	Depending on the detour
Inclusion in the AAI	No

Table 6: Summary of the factor of flight route

4.7. Holding patterns

Air traffic control also prescribes holding patterns. Influence of one airline at the expense of another airline is thereby impossible.

Detours and holding patterns	
Controllable by the airline	No
Differences possible between airlines	No
Inclusion in the AAI	No

Table 7: Summary of the factor of holding patterns

4.8. Ground handling on airport territory

The equipment, dimensions and operation of the airport affect an airplane's fuel consumption on the ground. The following points play a role:

- Taxiing on the ground

Before takeoff airplanes must still taxi from the terminal to the takeoff runway and hence consume fuel that is not recorded in the flight profile. The same applies to taxiing to the terminal after landing. The taxiing can last various times depending on the dimension of the airport, that is, the distance from the terminal to the runway. The scope or duration of taxiing is beyond the control of airlines.

Depending on the setup of an airport, taxi time may vary among airports. The kerosene used on the ground before and after a flight amounts to about 2,5 kg per passenger in Germany on average[21]. Since all airlines need to taxi the same distance, the AAI assumes that differences between the airlines e.g. due to differences in operation of the aircraft is one order of magnitude smaller, i.e. 0,3 kg kerosene per passenger. This is less than 1% of the total fuel consumption even on a short distance flight of 400 km. Thus taxiing will be neglected in the AAI.

[21] Brockhagen, 1995

Moreover, everyone is affected equally. However, aviation companies can influence one thing: during taxiing all engines are running on minimum power. Particularly in the case of twin-engine airplanes, taxiing can be done with one engine while the other is switched off and saves fuel. The consumption of kerosene by taxiing on the ground even in very short flights can be over 1% of the total consumption of the actual flight. But since all airplanes have to taxi for takeoff and at best the relative differences between airlines have an effect on this score, it can be assumed here that the difference in fuel consumption is < 1%.

- Push service

Pushback service may be needed depending on the airport layout. This is done by airplane tractors. It is needed if the airplane is standing with its nose towards the terminal before the flight since most turbojet airplanes cannot taxi backwards and change position on its own. Airlines are therefore subjected to the necessities of airport operation.

Regardless of whether the respective airplane is moved using its own engines or by airplane tractor, the proportion of fuel consumption (it takes a maximum of a few minutes from the parking position to the beginning of taxiing) is so small that it is not considered by the AAI for lack of relevance.

- APU

The auxiliary power unit (APU) is a power unit which supplies electrical energy to operate the aircraft if it is on the ground and has switched off its engines. Moreover, the APU is used as starter for the main engines. While the APU consumes fuel, ground power supply can be possible or be prescribed depending on airport. The fuel consumption of the APU is therefore not applicable. This affects all airlines equally.

The three points described above are mostly beyond the influence of airlines. Airlines must meet the requirements of the respective airport. Since all airlines are affected equally, the consumption of the aircraft in the airport is not considered in the AAI.

Ground handling on airport territory	
Controllable by the airline	hardly
Differences between airlines	No
Effect on fuel consumption	< 1%
Inclusion in the AAI	No

Table 8: Summary of the factor of airport

4.9. Operation: continuous descent approach (CDA), slow flight

4.9.1. Operation

The concept of operation refers to the operation of an airplane and can have several meanings. The meaning of operation in the context of the AAI includes certain forms of airplane piloting which systematically affect fuel consumption and hence CO_2 emissions. The two forms which have the most effect on a flight's fuel consumption are discussed below.

4.9.2. Continuous Descent Approach (CDA)

The CDA is a special approach-to-land procedure which has several characteristics in comparison to the conventional step-down. In the CDA the pilot switches the engines to idle at a certain altitude and lets the airplane drop in continuous glide towards the lqanding. In contrast, the conventional approach-to-land procedure is characterized by changes in acceleration and descent stages which are not present during CDA[22].

But the CDA also has disadvantages: The descent speed of every type of aircraft when gliding with engines at idle is different and cannot be changed. Consequently, changes are necessary during the pre-flight inspection carried out by airports. The conventional lateral and vertical separation, which places as many airplanes as possible behind each other on the final approach line, is no longer possible in the CDA. Therefore, the CDA is currently possible only at low-traffic times (e.g. overnight).

According to a study, kerosene savings of up to 430 kg for a Boeing 747 and up to 434 kg for an Airbus A330 are possible during a flight because of CDA[23]. In a sensitivity analysis the AAI incorporated these values into the ratio to total fuel consumption of different flights. Depending on distance (middle-haul or long-haul flight) and type of aircraft, it established a reduction in fuel consumption by 0.5% – 1.5%.

If an airline were to implement this savings potential on all its flights, it could improve its overall result in the AAI Global Ranking accordingly. Due to the above-mentioned limitations of the continuous descent approach the AAI assumes that CDA landing is currently possible only on a small minority of airports. Therefore, in reality the kerosene savings potential of an airline that flies to many airports amounts to an order of magnitude of less than 1%. Hence the CDA does not meet the relevance criterion and is not considered in the AAI

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[22] DFS Continuous Descent Approach, 2010

[23] CAO, SUN, DELAURENTIS

Operation: Continuous Descent Approach (CDA)	
Controllable by the airline	yes, but restrictions by airport operation
Differences between airlines	Yes
Effect on fuel consumption	< 1%
Inclusion in the AAI	No

Table 9: Summary of the CDA factor

4.9.3. Reduced airspeed

A reduction of speed while cruising reduces the fuel consumption of an airplane and thus its CO_2 emissions. Aviation companies therefore follow this approach to reduce their fuel costs.

However, slower flying on a flight route also has consequences. Lower speed means an extended flight time. Even in commuter flights or flights between hubs airlines must adjust flight schedules to allow passengers to reach their connecting flights. Furthermore, speed cannot be reduced arbitrarily. If the speed of engines is too widely throttled, they may no longer operate in the optimal range. This can lead to an increase in fuel consumption. The savings potential is hence subject to limits.

Using the piano-x program (see chapter 9.1) the AAI has calculated fuel consumption twice respectively for different flights (short-haul, medium-haul and long-haul flights with different types of aircraft): once with the typical cruising speed of the respective type of aircraft and a second time with a speed reduced by 50 km/h[24]. The other parameters (seat configuration, passenger load factor, etc.) remained the same. The difference between the two results forms the fuel savings which can be attained by flying slower. This is between 0.4% and 1.4%. The AAI assumes that an airline will or can reduce the cruising speed only on a fraction of all flights due to the above restrictions and disadvantages. Therefore in reality the reduction potential is much smaller than 1%. The factor of slower flying therefore does not meet the relevance criterion and is not considered by the AAI.

Operation: slower flying	
Controllable by the airline	Yes
Differences between airlines	Yes
Effect on fuel consumption	< 1%
Inclusion in the AAI	No

Table 10: Summary of the factor of slower flying

24 The 50 km/h here are an example chosen for a sensitivity analysis.

4.10. Aircraft

The fuel consumption of a flight depends on a series of factors which are discussed below. This includes type of aircraft, winglets, age of aircraft and servicing, engines, seat configuration, cargo capacity and capacity utilization, as well as the operating empty weight (OEW).

4.10.1. Type of aircraft

Fuel consumption depends on the airplane used. In general, one differentiates between propeller airplanes and airplanes with jet engines. Each airplane is optimized to a certain distance as well as a cargo and passenger transport capacity. Operation outside this optimum is possible but this increases the specific fuel consumption.

Every flight connection has a passenger potential which airlines take advantage of. The airline can use various aircraft models depending on the required transport service, the flight frequency (how often is the connection between cities operated within a certain period) and the distance to be flown.

The type of aircraft used on a city pair can therefore be influenced directly by airlines. They differ directly from each other in the aircraft choice. Different types of aircraft can differ in fuel consumption by up to approximately 10% – 50% (see also Factor Analysis, chapter 12). For these reasons, the type of aircraft is included in the AAI.

Airplane: type of aircraft	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	>10%
Inclusion in the AAI	Yes

Table 11: Summary of the factor of type of aircraft

4.10.2. Engine

In general, aircraft engines are often built directly for one or more special types of aircraft, and are adapted to their structural properties and performance requirements; or the other way around – for every type of aircraft there is either exactly one or, in most cases, a few appropriate engines.

Engines can affect the carbon footprint of a flight in two ways:

1. Through the specific fuel consumption and hence CO_2 emissions
2. Through other pollutant emissions (NO_x, UHC etc.)

We will discuss these two issues below.

Specific fuel consumption

Specific fuel consumption (SFC) expresses how much fuel an engine consumes per thrust unit generated and per time. The SFC reached by the airplane, in turn, depends on a series of factors, among other things:

1. Pressure and temperature in the combustion chamber
2. Bypass ratio, that is, the ratio of the inner (to the actual turbine) to the outer air current in turbofan engines
3. Weight of the engine
4. Air resistance of the engine, including integration into the airframe
5. Airspeed and thrust

Airlines act in accordance with these factors and with purely economic factors when selecting the engines for their airplanes. So heavier and simpler engines with higher SFC exhibit less wear and tear and hence tolerate higher numbers of cycles, which would make these engines economically appealing for frequently flown short routes in spite of the higher SFC[25]. The differences in SFC can clearly reach 1%, as we will show later (see chapter 8.1.4). Therefore, the SFC must also be included in the AAI.

Other pollutant emissions

The optimization of engines for ever larger pressures, temperatures and bypass ratios in the past has led to a situation where the SFC could be decreased but emissions of oxides of nitrogen (NO_x) simultaneously increased. NO_x causes the build-up of ozone in the upper troposphere and lower stratosphere. The interrelationship is approximately linear, that is, the more NO_x is emitted, the more O_3 is formed[26]. Since ozone in these atmospheric layers acts as a greenhouse gas, the NO_x emissions must also be considered as an penalty effect to the SFC if the SFC is also included in the AAI.

A further effect is induced by means contrails (see section 4.12). There is a trade off between contrail formation and the specific fuel consumption: the more efficient an engine is, the more frequent contrail will form[27]. Sine, however, there is not yet an established relation which would allow a quantitative contribution of contrail formation toward engine efficiency and since the formation itself depends strongly also from other external parameters, this effect is not considered in the AAI. There are other pollutants beside NO_x but they will be discussed elsewhere (see 4.12).

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[25] CFM INTERNATIONAL 2007

[26] Lee et al. 2009

[27] Gierens et al., 1999

Airplane: engine	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	>1% and indirect effect via NO_x emissions
Inclusion in the AAI	Yes

Table 12: Summary of the engine factor

4.10.3. Winglets

Winglets are wing tips attached to wings. They improve the aerodynamic properties of the flight vehicle and lead to fuel savings. The shape and size of winglets (raked winglets, blended winglets, etc.) conform to the structural properties of a type of aircraft and are customized individually. Airplanes are either retrofitted or by default are equipped with winglets. There are therefore many airplanes that come in a version with winglets or without winglets.
The use of winglets allows fuel savings of 3% - 5%[28]. Since airlines themselves have the discretion to decide on the use of winglets, the AAI differentiates according to flights on airplanes with or without winglets.

Airplane: winglets	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	3% – 5%
Inclusion in the AAI	Yes

Table 13: Summary of the winglet factor

4.10.4. Seat capacity

The number of seats on board the aircraft has a great effect on the actually transported payload and thus on the flight's fuel consumption. Seat configuration can turn out in different ways. Business and first-class seats are bigger and heavier than economy seats. The former therefore take up more space and hence squeeze out economy seats.
However, aviation companies also differ in the issue of how many seats are placed in one row. Every aviation company attempts to configure the seating of their airplanes so that they optimally take advantage of their customer profile with respect to willingness to pay and comfort requirement.
Seat configuration must be incorporated as a factor in the AAI since airlines differ from each other in this respect and airlines have a direct influence on it. Moreover, the factor analysis shows (chapter 12) that the weight in the ranking is large enough to be considered in the rating.

[28] Boeing, 2000

Airplane: seat capacity	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	5% – 40%
Inclusion in the AAI	Yes

Table 14: Summary of the seat capacity factor

4.10.5. Cargo capacity

For every airplane make, regardless of the aviation company, there are specifications for the maximum permissible weight for takeoff, landing, loading and refueling. The "maximum zero fuel weight" (MZFW) is the maximum permissible weight of an aircraft with load (passengers and cargo) and without fuel. There is an upper limit for cargo payload depending on the seat configuration and passenger load factor. However, this is seldom reached because of two reasons.

1. The volume of the cargo compartment is limited. Before the maximum possible cargo mass is reached, the cargo compartment in the lower deck is often completely filled.
2. If you include the kerosene, the maximum takeoff weight (MTOW) - the maximum permissible total weight during takeoff - may not be exceeded. Therefore, in longer flights and with appropriate refueling the available cargo capacity according to the MZFW cannot be exploited since the total weight would exceed the MTOW.

The cargo capacity of a flight is hence not constant but depends on other factors such as distance, seat configuration and airplane. These can be controlled directly by the airline. Consideration as an influencing variable on the actual payload is also necessary since airlines differ significantly in the handling of cargo capacity.

Lastly the factor analysis (chapter 12) shows that the weight of the cargo capacity factor in the total rating is large enough for it to have to be considered.

Airplane: cargo capacity	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	up to 10%
Inclusion in the AAI	Yes

Table 15: Summary of the cargo capacity factor

4.10.6. Operating Empty Weight (OEW)

The operating empty weight is the empty weight of the aircraft supplemented by the permanent built-in equipment (seats, galley, TV screens, stairways, life jackets, etc.). As a rule, airlines equip their airplanes themselves. There are vendors for passenger-related equipment such as seats. Every airline has an interest in weight-reduced equipment to decrease fuel consumption. Ultimately lighter seats, for example, mean a lower OEW, which decreases the takeoff weight and fuel consumption. The OEW can therefore be influenced by airlines but is limited to interior equipment such as galleys, seats, display screens, toilets, stairways. The OEW of an aircraft can be modified by an airline in two ways:

1.Available seats and coverage of furnishings

Airlines determine the number of seats offered with a certain airplane and the kind and coverage of furnishing as a function of their business planning and customer profiles. Trade literature has evidence to the effect that the OEW increases for every seat offered since, apart from the seat, additional equipment must be retained for every passenger such as overhead bins, galleys, toilets, life jackets, food, etc. For this reason, instead of 100 kg for one passenger, including baggage, airline companies use values between 140 kg and 200 kg per passenger, depending on airline and route length[29]. For the seat alone on average about 20 kg of additional OEW accrue per passenger if the airline offers an additional seat.

2. Specification of furnishing

Furthermore there can be differences regarding the specification of furnishing. In a sensitivity analysis the AAI analysed the potential fuel savings resulting from differences in furnishing weight. On different distances (1000km, 5000km, 10000km) and different aircraft types we calculated the fuel consumption with piano-x. One example result for an A340-600 is shown in Table 16.

[29] WIT et al. 2002, p. 30

OEW reducing measure	savings	Ø fuel reduction
Installation of lighter economy seats (savings of 5 kilos per seat)	1.900 kg (at 380 Economy – seats)	1%
Installation of lighter galleys (per galley 100 kg - 2 for narrow body, 4 for wide-body jets)	400 kg	0,2%
Installation of water-saving toilets (approx. 200 l less water on board)	200 kg	0,1%
Retrofitting to paperless flight deck (up to 50 kg saved)	up to 50 kg savings	0,02%
Drinking glasses made of lighter plastic, lighter plastic spoons, paperless passenger cabin	ca. 150 kg	0,06%
Lighter display screens	ca. 50 kg	0,02%
Total savings	**2.750kg**	**1,4%**

Table 16: Results of the OEW sensitivity analysis (example A340-600)

If an airline fully takes advantage of the savings potential of almost three tons shown in the table, it could save a total of up to about 1,5% on fuel by carrying out the underlying reduction of the OEW. From the report of one airline it shows however that for this example of an A340-600 a much less weight saving is stated as saving objective[30]. However, the weight savings brought about by lighter equipment (in Table 16 summing up to about 7 kg per seat), is smaller than the above discussed absolute effect, according to which the OEW increases by around 20kg with every additional seat offered. Thus, the AAI takes into account this reduction or increase of the OEW by 20kg per seat and neglects the effects of lighter forms of equipment.

Airplane: operating empty weight	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	> 1%
Inclusion in the AAI	Yes, through seat capacity

Table 17: Summary of the OEW factor

4.10.7. Age of aircraft and maintenance

Airplanes are subject to material fatigue as well as wear and tear due to constant usage. Depositions or the smallest surface changes on the flight vehicle affect aerodynamic properties. The consequence, among other things, is higher fuel consumption. An airline can counteract this by means of proper maintenance. Based on an airline's specifications, regular maintenance of the airframe can yield fuel savings of up to 2% in comparison to the unexpected condition[31].

[30] Virgin Atlantic, 2007

[31] LUFTHANSA 2002

Intervals, quality and scope of maintenance are strictly regulated in the interest of safety (in the EU by VO 2042/2003 [32]). Intervals and scope are specified in maintenance programs which the respective airline must have approved by the appropriate air safety authorities.

It is therefore assumed that wear and tear, material fatigue and maintenance cause no noteworthy difference in fuel consumption among airlines. Since fuel consumption reduction is already the focus of airlines for economic reasons, it must also be expected that maintenance, performed more frequently than prescribed, is carried out by all airlines if this leads to significant improvements and hence differences between airlines remain small.

The AAI therefore assumes that the real differences between airlines are clearly smaller than the maximum 2% in the cell (as mentioned above). Therefore the age of a given aircraft in contrast to the type of aircraft is not considered in the AAI.

Airplane: age and maintenance	
Controllable by the airline	Yes
Differences possible between airlines	Yes, but restricted to minimum by legislation on maintenance
Effect on fuel consumption	< 1%
Inclusion in the AAI	No

Table 18: Summary of the age & maintenance factor

4.11. Passenger and cargo load factor

Capacity utilization multiplied by the passenger (seat configuration) as well as cargo capacity yields the actually transported payload. Capacity utilization is therefore a key factor for payload and hence for kerosene consumption.

The capacity utilization attained by aviation companies (passengers and freight) depends on different factors: among others, on ticket prices, type of flight and flight region with respect to passenger load factor, and on prices and capacities with respect to cargo. With respect to the latter, airlines can increase the volume of transported freight with lower passenger numbers.

Capacity utilization is the most weighty factor in fuel consumption (see chapter 12, Factor Analysis). Moreover, since airlines fully control capacity utilization and thereby differ from each other in this score, capacity utilization must be considered in the AAI.

[32] COMMISSION REGULATION (EC) No 2042/2003

Airplane: passenger and cargo capacity utilization	
Controllable by the airline	Yes
Differences possible between airlines	Yes
Effect on fuel consumption	Passengers: 30% – 60% Cargo: 2% – 10%
Inclusion in the AAI	Yes

Table 19: Summary of the capacity utilization factor

4.12. Other pollutants beside CO_2

Aircraft engines emit other pollutants beside CO_2. Among other things, these include NO_x, particulates, sulfur, UHC and water vapor. All have a direct or indirect climate impact.

NO_x causes a net production of ozone in the upper troposphere and lower stratosphere. The interrelationship is direct, that is, the more NO_x is emitted, the more O_3 it forms. Since ozone acts as a greenhouse gas in these atmospheric layers, NO_x emissions are considered in the AAI by means of an engine factor (chapter 5.3).

Particulates, sulfur and water vapor, among other things, affect cloud formation. Moreover, sulfur and particulates have a cooling effect since they shield incoming solar radiation. The clouds induced by air traffic (line-shaped condensation trails and flat cirrus clouds) have an overall climate-warming effect[33]. Therefore the source pollutants would have to be included in the AAI.

However, the processes in cloud formation are not only complex, they also depend on a multitude of external parameters such as temperature and environmental moisture. Therefore for these pollutants there are no direct relationships between pollutant emission and radiative forcing and hence global warming. For this reason, the AAI here cannot establish any correlation expressed as: the more pollutants an airline causes, the greater the global warming. Such a relationship could be produced only for the global sum over all aviation companies.

Taken together these non-CO_2 pollutants have a warming effect on the climate. Consideration in the AAI requires that one factor be handled differently by airlines. Indeed, one airline can affect these other pollutants (for example, by means of engine choice). However, the effect of this measure cannot be verified due to the missing direct correlation between pollutants and global warming on the level of a flight. Therefore, other pollutants apart from CO_2 and NO_x remain discounted from the AAI.

[33] Lee et al., 2009

Airplane: other pollutants	
Controllable by the airline	Yes
Differences possible between airlines	Yes, but climate impact not clear
Inclusion in the AAI	No, only NO_x via the engine factor

Table 20: Summary of the other pollutants factor

4.13. Conclusion: classification of relevant factors

All the factors that are considered in the AAI for the ranking are listed below. The effect of every individual factor on fuel consumption is also indicated. The weight of factors in the AAI is discussed more precisely in chapter 12 (Factor Analysis)

Factor	Effect on specific fuel consumption
Type of aircraft	>10%
Winglets	3% – 5%
Engines (NO_x)	as engine factor
Seat configuration	5% – 40%
Cargo capacity	up to 10%
Passenger load factor	30% – 60%
Cargo load factor	up to 10%

Table 21: Factors considered in the AAI

The AAI considers these seven factors when calculating the CO_2 emissions per payload kilometer. The procedure on how the AAI evaluates these factors is described in the next chapter.

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5. Calculation of the CO_2 per payload kilometer on a city pair

This chapter describes the procedure for calculating the CO_2 per payload kilometer on a city pair. The approach and structure of the method are mentioned and the data sources named for each of the seven factors that were considered relevant in the previous chapter. A detailed description, including formulas, can be found in chapter 8.

5.1. Starting basis of ICAO method

The AAI methodology is based in significant parts on the CO_2 calculation method of the ICAO[34]. However, the AAI method is not only far more detailed but also considers additional factors not found in the ICAO. The significant improvements of the AAI in comparison to the ICAO method are:

- inclusion of all aircraft families and aircraft models
- detailed types of aircraft
- inclusion of precise seat configuration
- three times higher resolution in flight distance
- precise examination of freight
- inclusion of engines
- inclusion of winglets

The method on how the AAI uses the factors to calculate the CO_2 per payload kilometer of a flight on a city pair is described below. The weight of the factor is also given, indicating how strongly this factor affects the global efficiency points of an airline and hence its place in the ranking (chapter 12, Factor Analysis). An airline can strive to get these efficiency points on a city pair (maximum 100, minimum 0, see chapter 6).
The accuracy of calculation of the efficiency points is also given. This accuracy is later discussed in detail (chapter 13, Error Analysis). Only the results are shown in this chapter. Confidence limits are indicated for the respective accuracy. This indicates by how many efficiency points the true result can vary from the one calculated in the AAI. The data sources used are described in chapter 9, and the exact calculation formulas in chapter 8.

[34] ICAO Carbon Emissions Calculator (Version 3) 2010

5.2. 113 types of aircraft

The AAI differentiates 113 types of aircraft. These include not only aircraft families but also individual models as well as their subvariants. Furthermore, the larger turboprops as well as the models with/without winglets are included in detail. The types of aircraft identified by the AAI thus cover more than 95% of the types of aircraft used in global aviation. The fuel consumption or CO_2 emissions of 113 types of aircraft are calculated in the AAI using piano-x (chapter 5.9).

Inclusion coverage of types of aircraft in the AAI	
Data sources	Piano-x, JP Fleet Airline (chapter 9)
Scope of data	113 types of aircraft
Data coverage	95% of all commercial flights of commercial airplanes worldwide
Data formats	IATA & ICAO codes, plain text (e.g.: B767-400)
Average weight in the ranking	31% (chapter 12)
Method	Detailed inclusion coverage of payload-dependent and distance-dependent fuel consumptions and flight profiles except the subvariant of a type of aircraft, e.g. • Boeing 767-400ER • Airbus A320-200
Confidence limit	±0.2 efficiency points (chapter 13.2.3)

Table 22: Inclusion coverage of the type of aircraft factor in the AAI

5.3. Engines

The AAI differentiates engines using a so-called engine factor. This depicts the two central parameters of specific fuel consumption (SFC) and ozone formation or methane lifetime reduction through NO_x emissions. The engine factor is smaller, equal or greater than one, depending on whether the engine, plus the NO_x correction, consumes more or less fuel in comparison to other engines which can be used on a type of aircraft.

The JP Fleet Catalog contains the aircraft fleets of the airlines considered, including the engines used. If the engine of an airplane is determined, the AAI calculates the effective SFC and the NO_x correction.

Calculating the effective SFC

The effective SFC is the SFC of an engine in combination with a certain type of aircraft. The effective SFC is calculated in three steps:

1. Calculation of the isolated engine SFC using Boeing fuel flow method 2 (see chapter 8.1.4)
2. Correction of the isolated SFC by the air resistance of the engine
3. Correction of the isolated SFC by the weight of the engine

This method considers the significant compromises which airlines use in practice with engines, namely that lower SFC is often gained with higher weight and greater diameter of an engine. The pure SFCs of different engines can differ by up to about 10% or more. The correction by air resistance then turns out to be an order of magnitude smaller and the correction by engine weight is on average even smaller.

NO_x correction

Apart from the formation of ozone, NO_x also has the effect of shortening the lifetime of the greenhouse gas methane (cooling effect). Both effects are short-lived in comparison to the lifetime of CO_2. To be able to compare the effects of NO_x over ozone and methane with the effect of the SFC and hence CO_2, the AAI uses by approximation absolute global warming potentials (AGWPs) of CO_2, CH_4 and O_3. The timeframe is set to 100 years, an international convention as part of the UNFCCC climate talks. In the application of the AGWPs the AAI uses averages for every pollutant based on the current status of research[35].

Due to the long timeframe of 100 years where only CO_2 has significant weight, the NO_x correction factor becomes so small and usually does not turn out to be greater than the weight correction factor. For this reason, it is sufficient that the AAI takes the NO_x emissions in g/kg kerosene for the climbout thrust settings from the ICAO Engine Emission Database[36].

Coverage

The AAI includes 368 engines, which include all the important engines from major manufacturers. Hence 97% of all flights can be entered in detail in the AAI in terms of engine. The remaining 3% are divided into two groups:

1. Unknown turboprop engines (2.5% of all flights)

   The turboprop airplanes in the AAI are determined in terms of engine as described above. However, there are also turboprop engines that are known to the AAI from JP Airline Fleets but are not in the ICAO database. The engine factor of one will be applied to these. The resulting error here is small and is discussed in chapter 13.2.8.
2. Engines of types of aircraft of Russian manufacture (0.5%)

   Engines of Russian types of aircraft (Illyushin, Tupolev) are not contained in the ICAO Engine Emission Database so no engine factor can be calculated for these engines and hence for the associated flights. In contrast, the AAI includes engines of airplanes that were developed and were in service at the same time as the Russian models. The AAI has determined the engine factor for

[35] PEETERS, WILLIAMS 2009.

[36] CAA (2010), ICAO Engine Emission Database (12/2010)

them and applies this factor to the Russian models. This procedure brings about an error which is discussed in chapter 13.2.7.

Inclusion coverage of engines in the AAI	
Data sources	JP Fleet Airline, ICAO Engine Emission Database
Scope of data	368 engines
Data coverage	97% of all engines of commercial airplanes worldwide
Coverage method	Detailed inclusion coverage of all engines which the airlines in the AAI use, including their NO_x emissions at different thrust settings, conversion to an engine factor of <1, 1 or >1.
Data format	Abbreviation of engine manufacturer as well as plain text
Average weight in the ranking	3% (chapter 12)
Confidence limit	± 0.15 efficiency points (see chapter 13.2.7)

Table 23: Inclusion coverage of the engine factor in the AAI

5.4. Winglets

The AAI differentiates airplanes with and without winglet, that is, in the context of the AAI there two different aircraft models (e.g. B737-800 and B737-800 winglets). The JP Fleet Catalog specifies whether the relevant aircraft model in the fleet is equipped with winglets or not. The OAG also indicates whether a model is used on a certain flight with or without winglets. With these sources it is therefore possible to establish for every airline and every individual flight on a city pair whether the airplane flies with winglets or not.

Inclusion coverage of winglets in the AAI	
Data sources	JP Fleet Airline, piano-x
Scope of data	39 of the 113 types of aircraft with winglets
Data coverage	Almost 100% of all commercial airplanes with winglets worldwide
Coverage method	Inclusion coverage of all airplanes with winglets in the fleet of airlines (all Boeing and Airbus models)
Data format	ICAO & IATA codes as well as plain text
Average weight in the ranking	2% (chapter 12)
Confidence limit	±0.1 efficiency points (chapter 13.2.9)

Table 24: Inclusion coverage of the winglets factor in the AAI

5.5. Seat capacity

Apart from the passenger load factor, seat capacity is the basis for calculating passenger payload. The distribution of seats within the classes can vary between airlines depending on the customer segment operating an airline. Up to three sources provide the number of seats offered in a flight (see chapter 9). The amount is included in the calculation of the AAI. The overall seat configuration of the aircraft corresponds to 100% of the passenger capacity of a flight.

The AAI does not differentiate according to seat classes. Nonetheless, seat classes are included in the calculation of CO_2 per payload kilometer. If an airline retrofits an airplane from a one-class to a multiple-class seat configuration, the now existing business or first-class seats then take up more space, thus reducing the total number of existing seats due to the limited space inside the aircraft. Different airlines which differ from each other in relation to the seats per class (number of seats in economy to business to first class) as well as in the distance of seat rows are therefore correctly included in the AAI automatically via the seat capacity factor.

The AAI calculates the total number of existing seats for every flight of aviation companies under consideration. This seat configuration is offset by the passenger load factor of the respective flight in order to determine the number of passengers transported.

Inclusion coverage of seat capacity in the AAI	
Data sources	OAG, ICAO TFS, Airline Data T100I (see chapter 9)
Scope of data	All seat configurations of an airline on all flights and types of aircraft they offer
Data coverage	approx. 92% of all worldwide passenger flights identified by the IATA
Coverage method	Detailed coverage of seat configuration per airline, city pair, type of aircraft and flight
Data format and units	Absolute values, dimensionless
Average weight in the ranking	8% (chapter 12)
Confidence limit	±0.6 efficiency points (chapter 13.2.5)

Table 25: Inclusion coverage of the seat capacity factor in the AAI

5.6. Cargo capacity

Many airplanes have space for cargo in the lower deck. In contrast to the passenger area, which can have various equipment from airline to airline, the dimensions of cargo compartments per type of aircraft usually do not differ from each other. In principle, cargo in a type of aircraft is limited. The limits are extracted from the volume of the cargo compartment as well as the MTOW of the aircraft and depend, among other things, on two parameters:

- Distance: The greater the distance to be flown, the more fuel needed and the lesser cargo capacity available.
- Passengers: The more passengers are on board the aircraft, the less cargo capacity available until the MTOW is reached.

Airlines and logistics companies have user manuals which specify the maximum mass cargo that may be loaded in the lower deck of an aircraft. Except for small differences (approx. 5%), these values are

the same per aircraft model (e.g. B737-800 5,000 kg; A319 2,000 kg). These maximum air cargo capacities per type of aircraft are included in the AAI for plausibility tests on the payload of a flight.
The AAI takes the offered cargo capacity of every flight from up to four data sources (see chapter 9). In contrast to the offered seats, details on this score can be incomplete. The reason for this is the data gaps in the sources, resulting from insufficient details during the inquiry. This is the case in under 10% of all flights. The gaps are filled by case-specific averages. The resulting inaccuracy is discussed in chapter 13.2.6.

Inclusion coverage of cargo capacity in the AAI	
Data sources	OAG, ICAO TFS, Airline Data T100I, IATA WATS
Scope of data	All cargo capacities of an airline on all flights and types of aircraft they offer
Data coverage	approx. 92% of all worldwide flights identified by the IATA
Coverage method	Detailed coverage of the offered cargo capacity per flight, subjected to a plausibility check.
Data format and units	Absolute values in kilogram
Average weight in the ranking	4% (chapter 12)
Confidence limit	±0.1 efficiency points (chapter 13.2.6)

Table 26: Inclusion coverage of the cargo capacity factor in the AAI

5.7. Passenger load factor

The passenger load factor essentially determines the volume of payload and thereby the absolute fuel consumption of a flight. Each one of the flights contained in the AAI has individual capacity utilization. The passenger load factor (PLF) for all flights is subdivided in the AAI into three accuracy levels:

- Level 1: one PLF per airline per city pair and per type of aircraft
- Level 2: one PLF per airline per city pair
- Level 3: one PLF per airline in various markets (international, domestic).

The capacity utilization factors themselves were taken from the following data sources: ICAO TFS, Airline Data T100I and IATA WATS. For flights inside the US or from and to the US the PLFs from Airline Data had priority since this has the highest degree of completeness among all the data sources. ICAO TFS was considered the leading data source for all other flights. The calculation of the PLF followed a method in which level two is chosen if data from level one is unavailable, etc.
For all flights not identified in Airline Data and ICAO, the passenger load factors from IATA WATS were used (level 3). Domestic flights were distinguished from international flights since WATS collects this data separately.

No PLFs could be calculated for approximately less than 5% of all flights so these were not in the AAI. This has a negligible effect on the results and is later discussed in the error calculation (chapter 13.2.1).

Inclusion coverage of the passenger load factor in the AAI	
Data sources	ICAO TFS, Airline Data T100I, IATA WATS
Scope of data	Capacity utilization factors on three different accuracy levels
Data coverage	approx. 87% of all worldwide flights identified by the IATA
Coverage method	Coverage of the passenger load factor on the level of airline and/or city pairs and/or type of aircraft
Data format and units	Absolute values (comparable with capacities) and relative values (in percentage)
Average weight in the ranking	48% (see chapter 12)
Confidence limit	±0.7 efficiency points (see chapter 13.2.10)

Table 27: Inclusion coverage of the passenger load factor in the AAI

5.8. Cargo load factor

The actually transported payload also depends, apart from passengers, on the cargo load factor. Cargo in the context of the AAI is goods and mail. The capacity utilization factors for cargo in the Airline Index come from the same sources as the passenger load factors: Airline Data T100I, ICAO TFS, IATA WATS. Just like with the PLF the latter source also differentiates between domestic flights and international flights. The accuracy levels are identical to those of the PLF:

- Level 1: one CLF per airline per city pair and per type of aircraft
- Level 2: one CLF per airline per city pair
- Level 3: one CLF per airline

There is no CLF in the data source in less than 9% of all flights. The AAI uses the following method here:

1. With cargo capacity of zero: no coloaded freight, that is, the AAI automatically calculates here with 0 kg coloaded freight (2% of all flights in the AAI).
2. With cargo capacity greater than zero: this data set does not reach the AAI and is also not included in the calculation of efficiency points. This is the case in 7% of all flights in the AAI. The associated error is negligible and is discussed in chapter 13.2.1.

Inclusion coverage of the cargo load factor in the AAI	
Data source	IATA WATS, ICAO TFS and Airline Data T100I
Scope of data	Capacity utilization factors on three different accuracy levels
Data coverage	approx. 85% of all worldwide flights identified by the IATA
Coverage method	Coverage of the cargo load factor on the level of airline, city pair and type of aircraft
Data format and units	Absolute values (comparable with the capacities) and relative values (in percentage)
Average weight in the ranking	4% (see chapter 12)
Confidence limit	±0.8 efficiency points (see chapter 13.2.10)

Table 28: Inclusion coverage of the cargo load factor in the AAI

5.9. Flight profiles & distance, combination with types of aircraft in individual flights

The flight profile determines the airplane's fuel consumption to the extent that the fuel-intensive stage of the climb in short routes carries more weight than in middle or long routes. Therefore, the flight profile acts so that the CO_2 per payload kilometer on short-haul flights with otherwise the same parameters (airplane, seat capacity, etc.) is higher than on medium-haul or long-haul flights (cf. chapter 4.2). The flight profile depends on the type of aircraft used and is therefore depicted by the AAI through this parameter. A detailed fuel calculation is thus needed for every type of aircraft.

The calculation is done using the piano-x program (chapter 9.1). This program considers the specific flight profile of every type of aircraft (climb, climbing speed, etc.) on a preselectable distance in the fuel calculation. Using piano-x the AAI yields exact fuel and hence CO_2 results for a series of individual flights. To create these individual flights the AAI varies all 113 airplanes with up to 30 distances, depending on the maximum range of the type of aircraft.

Clearances between the individual flights in km	Distances of the individual flights in km
250	0, 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000
500	3500, 4000, 4500, 5000, 5500, 6000, 6500, 7000
1000	8000, 9000, 10000, 11000, 12000, 13000, 14000, 15000, 16000

Table 29: Distances of the individual flights in the AAI

Not every airplane can cover all distances. If one determines the possible airplane-distance pairs from the 113 types of aircraft as well as the 29 possible distances, the AAI yields 1745 possible type of aircraft/distance pairs. For every individual the AAI can vary the other six factors as follows:

- maximum seat capacity as well as the manufacturer-recommended standard seat capacity per type of aircraft
- maximum and average cargo capacity
- passengers: capacity utilization of 20% and 100%
- freight: capacity utilization of 20% and 100%
- engine of the type of aircraft
- airplane equipped with winglets/not equipped with winglets

This yields up to 3400 different individual flights, determined by all possible combinations of these factors. The AAI determines fuel consumption for each one of these individual flights using piano-x. The fuel consumption is additionally corrected by the engine factor. The AAI interpolates the fuel consumption of the respective flight in a linear fashion from the individual flights (see chapter 8.1.2). The error arising here is virtually zero (chapter 13.2.3).

Inclusion coverage of flight profiles and distances, combined with types of aircraft to individual flights in the AAI	
Data sources	Piano-x, as well as sources for seat and cargo capacities
Scope of data	3390 individual flights
Coverage method	Calculation of fuel consumption of an individual flight using established parameters of distance, type of aircraft, etc. using piano-x
Data format and units	Kilogram of kerosene and kilometer
Average weight in the ranking	Not applicable since already included via the factors of type of aircraft, capacities, etc.
Accuracy	±0.05 efficiency points through interpolation

Table 30: Inclusion overage of the flight profile and distance factors in the AAI

The following Figure 2 gives an overview of the number of flights in the AAI, distributed over the different distance classes.

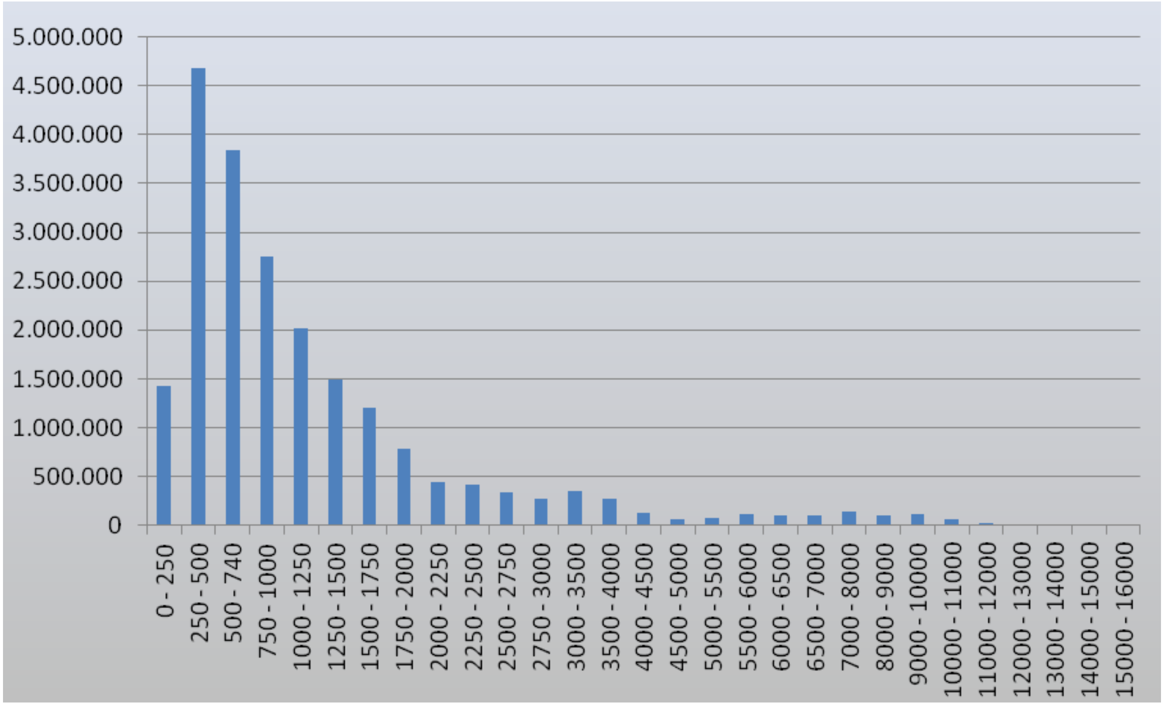

Figure 3: Number of flights depending on their distance

5.10. Results of the chapter at a glance

The factors discussed above allow the calculation of the CO_2 per payload kilometer for every flight in the AAI. The methods and data sources are summarized in the table below.

	Data source	Scope of data	Coverage method	Weight in the ranking	Data coverage
Type of aircraft	OAG, JP Fleet Airlines, piano-x	113 types of aircraft	Detailed inclusion coverage of payload-dependent and distance-dependent consumptions and flight profiles except for subvariant of a type of aircraft	31%	95% of all commercial flights of commercial airplanes worldwide
Engine	JP Fleet Airline, ICAO Engine Emission Database	368 engines	Detailed inclusion coverage of all engines which the airlines in the AAI use, including their NOx emissions at different thrust settings, conversion to an engine factor of <1, 1 or >1.	3%	97% of all engines of commercial airplanes worldwide
Winglets	JP Fleet Airline, piano-x	37 of the 113 types of aircraft with winglets	Inclusion coverage of all airplanes with winglets in the fleet of airlines (all Boeing and Airbus models)	2%	Almost 100% of all commercial airplanes with winglets worldwide
Seat capacity	OAG, ICAO TFS, Airline Data T100I	Seats offered per flight	Detailed coverage of seat configuration per airline, city pair, type of aircraft and flight	8%	approx. 92% of all worldwide passenger flights identified by the IATA
Cargo capacity	OAG, ICAO TFS, Airline Data T100I, IATA WATS	Cargo capacity offered per flight	Detailed coverage of the offered cargo capacity per flight, subjected to a plausibility check.	4%	approx. 92% of all worldwide flights identified by the IATA
passenger load factor	IATA WATS, ICAO TFS and Airline Data T100I	Capacity utilization factors on three different accuracy levels	Coverage of the passenger load factor on the level of airline and/or city pairs and/or type of aircraft	48%	approx. 87% of all worldwide flights identified by the IATA
Cargo load factor	IATA WATS, ICAO TFS and Airline Data T100I	Capacity utilization factors on three different accuracy levels	Coverage of the cargo load factor on the level of airline, city pair and type of aircraft	4%	approx. 85% of all worldwide flights identified by the IATA
Flight profile & distance	Calculated by the AAI	3.390 individual flights	Calculation of fuel consumption of an individual flight using established parameters of distance, type of aircraft, etc. using piano-x	n.a.	Via the seven factors

Table 31: Summary, calculation of CO_2 per payload kilometer

6. From CO_2 per payload kilometer to city-pair efficiency points

The method with which the AAI calculated CO_2 in kilogram per payload kilometer was described in chapter 5. The next step now is to classify these values and make them comparable. A neutral parameter independent of airlines is added in the best case and worst case. As the result of this step the AAI converts the CO_2 per payload kilometer into efficiency points on a city pair for every flight of an airline.

This approach allows you to compare airlines that fly in various distances since every airline gets its points on a city pair based on absolute standards and independently of other airlines. At the same time, this approach also allows you to rate flights of airlines that operate a city pair alone without competition.

6.1. Best case & worst case

To rate the climate efficiency of aviation companies, the AAI introduces a theoretical best case or worst case on each city pair. The best case or worst case corresponds to the most efficient or most inefficient flight possible with today's material on the city pair considered in relation to the CO_2 emissions per payload kilometer. Both values are therefore emissions per payload kilometer for a certain city pair. The CO_2 emissions per payload kilometer of an airline on this city pair are compared to these two values, with the involvement of the engine factor.

Best case

To determine the best case on a certain city pair, the AAI calculates the CO_2 per payload kilometer for all airplanes in the AAI with the following assumptions:

1. Flight distance of the city pair
2. Seat configuration based on ICAO method (all economy)
3. Full passenger load factor (100%)
4. If additional cargo capacity is then possible, this is likewise fully utilized.
5. The most efficient engine (least NOx output) for the respective aircraft model

The type of aircraft that has the lowest values of CO_2 emissions per payload in this comparison defines the best case with its value of CO_2/payload kilometer.

The best case is therefore a best practice standard with which the performance of an airline can always be measured. It develops with new types of aircraft that come into the market and sets the "measuring staff" ever higher without prescribing technology which does not yet exist.

Worst case

400% of the best case (CO_2 per payload kilometer) form the worst case. Overall with the definition of the worst case as 400% of the best case a good 98% of all flights in the AAI lie between the best case and worst case. The other 2% which fall under the worst case of a flight receive negative efficiency points (see below). But strictly speaking, the definition on a value such as 400% is altogether unnecessary since the ranking after city-pair efficiency points (see below) would not have otherwise arisen if another value were selected for the worst case (for example, 200% or 150%). In these cases, only more flights which have worse consumption values than the worst case would simply receive negative points. However, these would have again resulted in the same end result in the ranking order in the total rating (chapter 7) over all city pairs of an airline.

6.2. City-pair efficiency points

The AAI yields city-pair efficiency points per airline and per city pair. It compares the calculated CO_2 emissions per payload kilometer of an airline with the best case and worst case of the city pair. Since an airline can use several types of aircraft on a city pair, all CO_2 emissions per payload kilometer of an airline on a city pair are calculated in the first step and weight averaged to one value.

Then the AAI adjusts this value in linear fashion with the best case and worst case and also incorporates the engine factor. The best case corresponds to 100 city pair efficiency points, the worst case to zero city-pair points. Aviation companies hence receive between 0 and 100 city pair points for each city pair on which they fly.

In just under 2% of all flights where the CO_2 emissions per payload kilometer is worse than the worst case, the airline gets for this city pair a corresponding number of negative efficiency points which are offset in the total ranking of this airline over all city pairs.

7. From city pair to global efficiency points for all airlines

For the global ranking the AAI averages the efficiency points that an aviation company has reached on the city pairs it operates over the number of rated city pairs of the airline into global efficiency points. These also move automatically from 0 to 100 points. Negative point values on individual city pairs where an airline has higher emissions than the worst case go one-to-one into the average over all city pairs (chapter 6.2). 100 global efficiency points correspond to the maximum attainable climate efficiency, that is, an airline reaching the 100 points has always used the best possible airplanes, has fully configured their seats and fully utilized capacity. Global efficiency points are absolute points. They include and transport all factors that were mentioned in the previous chapters (e.g. type of aircraft, winglets, engines, cf. chapter 5).

In the calculation of total efficiency points, the city-pair efficiency points on a city pair are weighted against the payload kilometer. This is needed because CO_2 always arises per payload kilometer and hence on long flights more than on short flights, which is relevant from the climate point of view. This means that in an airline with many long-haul flights they carry more weight and the weight acts in both directions: If the airline company is better on the long haul than on the short haul, it will greatly improve; but vice versa it will significantly worsen. The weighting against payload kilometers is neutral in terms of competition. Every airline company flying its city pairs efficiently can get a ranking, regardless of whether it flies only on long haul or only on short haul.

Part II

The Airline Index Method in Detail

8. The calculations step by step

8.1. CO_2 emissions of a flight in the AAI

8.1.1. Overview

The AAI compiles a tightly woven set of single flights for which it ascertains absolute fuel consumption using possible combinations of the flight parameters relevant for fuel consumption – aircraft type, route distance and net load (Chapter 8.1.2). For the actual route of an airline for which the AAI calculates CO_2 per net load kilometre, the AAI identifies particular routes like parameters of which are as close as possible to the actual flight, and which contain the absolute fuel consumption of the route in question by means of interpolation. Using the net load carried, the flight distance and the engine factors, the AAI ascertains the CO_2 heard that load kilometre flight in question.

The AAI uses the following procedure for this process:

1. Selecting a certain flight first of all establishes the city pair and hence the flight distance in question.
2. The AAI ascertains the exact aircraft type, including engine type and winglets, with which the flight is to be carried out.
3. From the seating capacity, the freight capacity passenger occupancy and load utilization, the AAI ascertains the net load carried on the flight, and the correction of the Operating Empty Weight (OEW; Chapter 8.1.3).
4. The absolute fuel consumption figures of four single flights can thus be assigned to the ascertained parameters aircraft type, flight distance and net load of the flight in question – two pairs of flight distances and net loads, which bracket those of the flight (Chapter 8.1.5).
5. From these four values, the AAI interpolates the exact absolute fuel consumption of the flight in question (Chapter 8.1.5).
6. In addition, the AAI factors the engine and its engine factor into its correction factor for this flight (Chapter 8.1.4).
7. The AAI calculates the CO_2 per net load kilometre via the ratio between absolute fuel use, net load and flight distance (Chapter 8.1.5).

8.1.2. Fuel consumption of individual flights

The kerosene consumption of a flight in the AAI is determined from the specifically calculated consumptions of individual flights. The AAI determines the fuel consumption of every individual flight using the piano-x computing program. Applying all possible variations of the parameters, the AAI disposes thus of 3.248 individual flights.

- 113 types of aircraft (aircraft with winglets are considered as extra models)
- 29 individual flight distances per type of aircraft (can be less, depending on the range of the aircraft type, see chapter 5.9)
- 2 payloads, resulting from assumptions, spanning well the real range:
    - High payload: derived from standard seating (pre-selected in piano-x) in combination with 100% passenger occupancy.
    - Low payload: derived from standard seating (pre-selected in piano-x) in combination with 20% passenger occupancy.

The weight equivalent of a passenger is 100 kg. This corresponds to the weight of the person plus baggage. These 100kg per passenger is a value used internationally by the aviation industry[37].

From these parameters the AAI calculates the kerosene consumption of an individual flight F_{EF} using piano-x. Since the web of individual flights serving as basis for the interpolation is tightly woven, the error resulting from interpolation can be neglected (chapter 13). For the linear interpolation of the actual payload the two payloads cited above are sufficient, since total fuel consumption within the range of possible payloads depends almost linearly on the aircraft weight.

8.1.3. Calculation of payload and OEW-correction

The payload of a flight (Payload) consists of the mass of transported passengers P_P and the mass of freight on-board P_C:

$$P_{FL} = P_P + P_C$$

The weight equivalent of a passenger amounts to 100 kg (section 8.1.2). The real passenger load factor (PLF) taken together with the weight equivalent of a passenger and the number of available seats (passenger capacity or C_{PAX}) of the flight delivers the mass of the transported passengers.

$$P_P = C_P * 100 \text{ kg} * PLF$$

The cargo capacity C_C is defined in the AAI as

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[37] Wit et al., 2002

$$C_C = C_T - C_P$$

where C_t denotes the maximum payload. Combining the cargo load factor CLF and the cargo capacity C_{CARGO} of a flight one obtains the payload cargo as

$$P_C = C_C * CLF.$$

8.1.4. Engine Factor

The engine factor has various components:

1. SFC of the isolated engine
2. SFC correction by air resistance
3. SFC correction by engine weight
4. Correction factor of the CO_2 effect of the SFC through NO_x emissions and then O_3 and CH_4 effects

To calculate the engine factor the SFC factor of the isolated engine is first calculated (step 1). This is then corrected in steps 2-4 by air resistance, weight and NO_x emissions. The end result is the engine factor, an SFC correction factor incorporated with piano-x into the calculation of fuel consumption.

1. SFC of the isolated engine

The SFC of the isolated engine, first of all, depends on the design of the engine itself and thus on its thermodynamic cyclic process data, bypass ratio and combustion chamber design, etc. [38]. During flight this includes the dependence of temperature, pressure and speed. These factors are depicted fully and in detail over all flight conditions (takeoff, climb out, cruise, etc.) in piano-x using a representative engine for every type of aircraft and every distance. Nonetheless, the fluctuation between different engines, which can be great especially in older airplanes and engines, is not considered here.

For this reason, the AAI calculates for the SFC of the isolated engine a dimensionless SFC correction factor, which assumes values >1 for engines with high SFC and <1 for engines with low SFC. This factor can be entered in piano-x. It then lets the relative quality of the engine over the entire flight be incorporated with all stages. We will see that in practice the differences between modern airplane-engine combinations are negligibly small but can definitely have an effect in older airplanes.

To calculate the SFC factor, the AAI in the first step determines the SFCs from the ICAO database at 85% thrust and the associated fuel flow and converts this to SFC for cruising using Boeing fuel flow

[38] GMELIN et al. 2008

method 2[39]. The AAI uses the specifications for cruising altitude and speed from piano-x for the respective type of aircraft and distance and takes the corresponding values for pressure and temperature from the ICAO-defined ISA standard atmosphere. This procedure is not accurate enough to calculate absolute SFC or current fuel flow. This is due to the fact that every engine reaches the optimal SFC at its own optimal airspeed and, in addition, the thrust of 85% used here does not apply during the entire flight. However, the goal of the AAI is not to determine absolute fuel consumption (piano-x does this already) but only to incorporate the differences between engines per factor. The approach in Boeing fuel flow method 2 and the ICAO engine database are sufficient for this purpose.

The AAI repeats this step for each type of aircraft on all individual flight distances and for all engines coming into question for the respective type of aircraft. The AAI in a detailed analysis studied 70 types of aircraft which appeared in practice in combinations with up to 10 different engines. It was shown that the calculated SFC differences between the engines in 47 types of aircraft reached a maximum of 3% but were usually <1%. In the other 20 types of aircraft (including the older B737 200-500, B747 100 and B757) the SFC difference reached 10%. Only in three obsolete types of aircraft (B727 and DC9) were there extreme values of over 10% deviation.

2. SFC correction by engine air resistance

Higher bypass ratios have significantly decreased the SFC of turbofan engines in the past. However, as an undesirable side effect of the bypass ratio increase, the diameter of the engine and hence its air resistance also increase. This effect reduces the gain in SFC caused by higher bypass ratios. This effect is depicted in the AAI by the fact that piano-x incorporates the increase in air resistance as a factor in the fuel calculation. Piano-x determines the change in proportion in the overall resistance which causes the enlargement of the engine used vis-à-vis the average engine. Only the front of the engine and not the outer skin and the embedding of the engine into the pod (which are disregarded) are considered by means of approximation over the diameter of the engine. This is sufficient as a simple approximation[40]. The AAI, in turn, completes this step for all airplane-engine combinations and distances. The AAI takes the engine diameter values from pertinent industry directories[41].

3. SFC correction by engine weight

Higher bypass ratios also increase the weight of an engine. In the AAI this relates directly through an increase of the OEW vis-à-vis the standard OEW, which is already assigned in piano-x. The weight disadvantage is thus depicted in detail.

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[39] BAUGHCUM et al. 1996, Appendix D

[40] GREENER BY DESIGN 2005

[41] UBM AVIATION. ENGINE YEARBOOKS 2006-2011

The AAI also completes this step for all airplane-engine combinations and distances. The AAI takes the values for engine weights from industry directories[42].

Evaluation of steps 1-3

The preceding steps are combined into one engine factor as correction factor for every aircraft-engine combination on all individual flight distances. The following points are highlighted:

- The differences in SFC of the isolated engine are mostly negligible in modern airplanes and engines. This coincides with statements of experts to the effect that engine manufacturers have been in very close competition with regard to SFC due to ongoing development over the last years and decades. However, in old airplanes and engines the difference can exceed 10% only in a few extreme cases. Averaged over all flights and engines the engine has only one weight of about 3% when calculating the global efficiency points of an airline (see also chapter 12, Factor Analysis).
- The analysis shows that the air resistance correction factor is indeed noticeable but with the increase in bypass ratio in the past it has not offset the advantage of the SFC. The correction by the weight factor turns out to be even less as it has a stronger effect only in long-haul flights.

4. Correction factor of the CO_2 effect of the SFC over NO_x emissions and then O_3 and CH_4 effects (NO_x correction factor for SFC)

The NO_x correction factor evaluates the emissions of oxides of nitrogen of engines. Since it is based on NO_x and their effect, it cannot be offset directly with an engine's SFC which, in turn, is based on fuel consumption and hence CO_2. For this reason, it is applied to the SFC as a dimensionless factor, where the result is not a purely quantitative change in the SFC but rather a quantitative-qualitative conversion of the SFC into a climate-equivalent SFC. But since the NO_x correction factor will turn out to be small, we will continue to speak easily of the SFC in this article. The NO_x correction factor is calculated in two steps.

Step 1: Calculating NO_x emissions while cruising

The AAI differentiates below between a globally averaged engine (with about 14.3g NO_x / kg kerosene[43]) and the respective engine which the AAI obtains for a flight from the data sources. To determine the NO_x correction factor, the absolute NO_x output for every engine is first calculated at 65% thrust setting (approximately corresponding to the cruise mode[44]) using values from the ICAO

[42] UBM AVIATION. ENGINE YEARBOOKS 2006-2011

[43] KIM et al. 2007, p. 331

[44] TORENBEEK 1982

database. The NO_x emissions of the engines in the AAI at 85% (climbout) or 30% (approach) thrust are interpolated on the 65% thrust value. Table 32 shows extreme values of NO_x emissions of different engines with different thrust settings. The value for 65% thrust is already interpolated here. It shows that in this extreme case the NO_x emissions can deviate by about ±100% from an average value.

NO_x emissions per thrust	**NO_x emissions per kerosene consumption (EI-NO_x) [g/kg] maximum**	**NO_x emissions per kerosene consumption (EI-NO_x) [g [g/kg] minimum**
30%	16.59*	3.4***
65%	33.2**	5.6***
85%	46.31**	6.8***
*GE90-94B **RB211-524H ***Pratt & Whitney JT15D-1		

Table 32: Minimum and maximum NO_x emissions of extreme engines depending on thrust, on sea level height[45]

Every engine is thus assigned an NO_x emissions index (EI-$NO_{x\ engine}$). At the same time, a global average (EI-$NO_{x\ global}$) can thus be calculated, where the individual EI-$NO_{x\ TW}$ is weighted in the averaging based on flight kilometers covered by the engines.

Step 2: AGWP comparison of engine to global average

The absolute emitted NOx causes a temporally variable net radiative forcing. To be able to compare this with that of the emitted CO2, both radiative forcing values are integrated in their temporal progression over an internationally (UNFCCC) established timeframe of 100 years. For every pollutant we get absolute global warming potentials which are shown in Table 33 for air traffic of the year 2005.

Pollutant	**AGWP [10^{-14} Wm^{-2} $kgCO_2^{-1}$ year]**	**Application in the AAI**
CO_2	9.15	Considered directly in the AAI
O_3 and CH_4 net	-0.038	Considered via NO_x correction of the engine factor in the AAI
Condensation trails	1.8	Same for all airlines, therefore not considered in the AAI
AIC	5.6 (0-14.4)	Same for all airlines, therefore not considered in the AAI

Table 33: AGWPs and EWF of 2005 global air traffic, as per Peeters and Williams[46]

[45] CAA (2010). ICAO Engine Emission Database

[46] PEETERS, WILLIAMS 2009

To then work out the NO_x correction factor of a certain engine, the net AGWP of O_3 and CH_4 is weighted with the NO_x-EI of the engine (see step 1) and compared to the AGWPs of all pollutants of the global average engine. AP stands for AGWP in the formula.

$$NO_x - CorrectionFactor\_SFC = \frac{AP_{CO_2} + AP_{O_3+CH_4}net \frac{EI - NO_{x\,TW}}{EI - NO_x global} + AP_{contrails} + AP_{AIC}}{AP_{CO_2} + AP_{O_3+CH_4}net + AP_{contrails} + AP_{AIC}}$$

It is shown that the NO_x correction factor even in extreme engines (see Table 32) is only <1.01 or >0.99. The correction effect of the SFC is therefore less than one percent and is smaller by an order of magnitude than the correction factor which accrues in engine air resistance (see above). This is primarily due to the fact that CO_2 has a significantly stronger effect than the net effect of O_3 and CH_4 over the timeframe of 100 years.

Because of the small dimension, the NO_x correction factor for the SFC could actually be disregarded. But since the increase in NO_x emissions occurs as an opposite effect to the reduction of the SFC at higher pressures and temperatures in the combustion chamber, for reasons of systematic completeness it is included when calculating the engine factor.

8.1.5. Payload and distance to kerosene consumption

The consumption of a flight in the AAI over the distance of the city pair and with the transported payload is interpolated in a linear fashion between the values of the consumption matrix. The AAI interpolates kerosene consumption from the associated individual flights using the real city-pair distance (D_{CP}) and the calculated payload (P_{FL}) (chapter 8.1.2). For this the AAI needs both adjacent pairs of payloads and distances on individual flights, where only those individual flights whose material (type of aircraft, winglets) corresponds to that of the flight are considered. The fuel consumption of the flight is interpolated as follows, where D stands for distance, o and u for upper and lower values of the individual flights:

$$F_{EF5} = \left(\frac{(F_{EF1} - F_{EF2})}{(D_O - D_U)} * (D_{CP} - D_U)\right) + F_{EF2}$$

$$F_{EF6} = \left(\frac{(F_{EF3} - F_{EF4})}{(D_O - D_U)} * (D_{CP} - uD)\right) + F_{EF4}$$

The second step then interpolates the kerosene consumption of the flight from the two previously calculated values.

$$F_{EF} = \left(\frac{(F_{EF5} - F_{EF6})}{(P_O - P_U)} * (P_{FL} - P_U)\right) + F_{EF6}$$

The total resulting error in the interpolation is negligibly small (< 0.05% of consumption) because close-meshed values of individual flights in the consumption matrix are selected (see chapter 5.9).

8.1.6. CO_2 per payload kilometer, specific emissions

The CO_2 output is directly proportional to the kerosene consumption of the flight. The conversion factor is 3.16 kg CO_2 / kg kerosene. The AAI then obtains conclusively from the above-calculated absolute fuel consumption of the flight, the payload and the city-pair distance the designated CO_2 per payload kilometer on a flight. In this document we call these CO_2 emissions per payload kilometer "specific CO_2 emissions".

8.2. CO_2 emissions per payload kilometer on a city pair per airline

Up to this point the AAI has calculated the specific CO_2 emissions of a specific flight. As an intermediary step to the city-pair efficiency points (8.3.2) the AAI now combines the specific CO_2 emissions on the level of a city pair for an airline. This step is necessary since an airline can use several aircraft models on a city pair and can operate them with different operating parameters. The specific CO_2 emissions of an airline on a city pair is averaged by the AAI for an airline over all these different flights, weighted according to frequency of occurrence. The result is a representative value for the specific CO_2 emissions of an airline on this city pair.

8.3. Efficiency points on a city pair

8.3.1. Calculation of the best case and worst case

The AAI yields efficiency points for every city pair as the basis for the global ranking: Airline companies flying on a city pair receive between 0 and 100 efficiency points for this purpose.
As described in section 6.1, as reference points for every city pair a best case and a worst case is calculated for the specific CO_2 emissions. To determine these values, the calculation steps of 8.1.3 – 8.1.6 are repeated but with modified starting parameters:

Best case:

- Type of aircraft: The calculation is done for all possible airplanes that can fly the city pair physically. A short-haul jet such as the A318 therefore cannot be considered for the best-case calculation of a long haul.
- Engine: The engine factor (see 8.1.4) of the best engine for the respective type of aircraft is considered here.
- Payload: This is 100% capacity utilization at maximum seat capacity (ICAO Full Economy Method) per type of aircraft as well as 100% capacity utilization of the maximum possible cargo capacity per type of aircraft. If the calculated payload of the best case flight exceeds the MTOW, it is limited in the MTOW.

The calculation of kerosene consumption for the best case flight is similar to that in section 8.1.6, with all types of aircraft that can cover the distance of the respective city pair (that is, up to 113 types of aircraft), including the engine factor. As a result there is a series of specific CO_2 emissions for every city pair: one value per type of aircraft. The type of aircraft with the least specific CO_2 emissions then defines, in conjunction with the best possible engine factor, the best case on this city pair. The best case therefore represents the most efficient flight possible today on this city pair using existing flight material.

Worst case:
The AAI defines this as 400% of the specific CO_2 emissions of the best case. It could also have another value without this changing the results (see chapter 6.1).

8.3.2. Calculating city-pair efficiency points

The specific CO_2 emissions per payload kilometer of all airlines on this city pair are compared to the best case or worst case. The following rules then apply to the calculation of city-pair efficiency points:

- Best case corresponds to 100 efficiency points
- Worst case corresponds to 0 efficiency point

The efficiency points of an airline on this city pair are now calculated in a linear fashion between worst case and best case.
The approach using the most efficient flight possible as best case has the advantage in that the city-pair efficiency points of an airline are independent of the flights of other airlines on the same city pair. The best case is a best practice standard with which the performance of an airline can always be measured. It remains germane in the sense that it develops at the same time as new types of aircraft come into the

market come and thus sets the measuring staff ever higher without prescribing technology which does not yet exist.

8.4. Efficiency points in the global AAI ranking

The global AAI ranking averages the efficiency points of city pairs flown by an airline and therefore determines the global efficiency points between 0 and 100 for every airline company. One hundred points here mark the highest climate efficiency.

9. Data sources

Data sources lie in the heart of the AAI. The AAI demands a lot from them in terms of quality, depth, being up-to-date and independence of information. The AAI uses only high-ranking sources from international organizations or long established, specialized service providers. The AAI never utilizes data published by airlines in their websites, business reports or own statistics, etc. To ensure the quality of data, the AAI covers every factor with at least two independent sources and subjects them to consistency checks.

9.1. Piano-x (Lissys Ltd)

The Piano-x database and software from Lissys Ltd is used for calculating fuel and emissions of airplanes. Lissys Ltd is a company with headquarters in Great Britain. Aircraft manufacturers, aviation authorites, universities and research institutions use Piano-x (see Appendix 1). The ICAO uses Piano-x too for its emissions calculator[47].

Piano-x from Lissys Ltd calculates fuel consumption for all types of aircraft depending on flight distance and transported payload. The program maps all the specific design-inherent flight parameters (e.g. air resistance and lift depending on flap settings, thrust, etc.). The flight profile in a given flight distance is programmed in. The consumption and emission values underlying the fuel calculation correspond to those of a standard engine typical for the respective airplane. Piano-x calculates the refueling quantity automatically if it is not chosen separately. The program applies a standard calculation identical over all types of aircraft for the reserve fuel.

9.2. ICAO data

The ICAO is the International Civil Aviation Organization based in Montreal. The ICAO offers access to various operational and technical data on global air traffic. This data is collected as part of the ICAO statistics program which has been in existence since 1947. This program collects and then analyzes and processes, among other things, data on airline companies through the member states of the ICAO, that is, through their government agencies.

[47] ICAO (Carbon Emissions Calculator, Version 3) 2010

9.2.1. ICAO TFS

The ICAO Traffic By Flight Stage Database (TFS) supplies the passenger and cargo capacity as well as the capacity utilization on the level of city pair, airline company and type of aircraft for international scheduled flights. Since this data source is incomplete, the AAI also resorts to other sources when it comes to data on capacity and capacity utilization (see below, OAG, Airline Data, IATA WATS).

ICAO TFS	
Number of airlines considered	168
Scope	scheduled flights,, no charters
Number of flights	4.3 million
Number of passengers	approx. 470 million
Passenger load factors	Specified more precisely (offered and actually in demand seat capacities), per city pair per airline per aircraft model
Transported cargo	Specified more precisely (offered and actually in demand cargo capacities), per city pair per airline per aircraft model, itemized under cargo and mail

Table 34: Scope of ICAO TFS

9.2.2. ICAO Engine Emission Database

The ICAO Engine Emission Database contains, among other things, NO_x emission values of all 368 conventional aircraft engines in many different standard thrust settings[48] (August 2012 issue).

9.2.3. ATI – Air Transport Intelligence

ATI is an online data service of Flight Global. It offers, among other things, formatted ICAO air traffic data. The AAI uses, among others, the following data from ATI:

- number of passengers of an airline
- passenger load factors of an airline
- offered and in demand passenger kilometer of an airline
- 200 largest airlines of the world (respectively arranged according to financial result or transport service)
- catalog of the 25 largest low-cost airlines worldwide

[48] CAA - ICAO Engine Emission Database (12/2010)

9.3. OAG - UBM

The Official Airline Guide (OAG) is a business branch of United Business Media Limited, a media company based in the UK. OAG has been publishing the Official Aviation Guide since 1929 (available in the past only in the US and with 35 airline companies) [49]. OAG is at the interface between airline companies and flight ticket selling systems. The OAG database contains the flight schedules of all airline companies that submit their schedules to OAG. This flight database contains current and detailed information about past and planned flights, especially types of aircraft and cargo or seat capacities. The process for acceptance of schedules in the database is as follows: Airlines send their flight schedules to OAG in intervals that they determine (daily, weekly or monthly, etc.). Data undergoes quality control at OAG and is then accepted in the database captured in standardized format, and distributed worldwide to global computer reservation systems of travel agencies and airlines, online booking platforms, industry analysts, publishers, government agencies and service providers of the aviation industry[50]. The service is free of charge for airlines. The enticement for the airline companies to submit their flight schedules comes from the associated marketing vehicle for their flight capacities.

OAG	
Number of airlines considered	approx. 800
Scope	Scheduled flights, charter flights, low-cost flights, cargo flights, flights of government airplanes
Basis	Flight schedules, worldwide
Number of flights	approx. 33 million
Passenger capacity	approx. 3 billion
Seat capacity	Offered seats per city pair per airline per aircraft model
Cargo capacity	Offered cargo capacity per city pair per airline per aircraft model

Table 35: Summary of OAG

OAG itself states on its website that it is the most trusted source of global flight schedules. If you compare worldwide passenger numbers from 2009 from OAG (2031 million passengers) with IATA data of 2228 million passengers[51] then you get approx. 92% coverage of the entire worldwide air traffic by OAG. The missing passengers are most probably ascribed to small regional airline companies that do not wish to participate in ticket booking systems. To determine participation in the AAI, the AAI utilizes ATI information about passenger numbers of an airline independently of OAG. These airline companies report their flight schedules to OAG without exception so that the AAI coverage relevant for our purposes is 100%.

[49] OAG-UBM History

[50] Vgl. OAG DATA 2003

[51] Vgl. IATA FACT SHEET 2010

9.4. Airline Data T100 International

Database Products Inc. (Airline Data) is a company based in the US. Airline Data offers flight data on the US market which the company obtains from the United States Department of Transportation (DOT).

The product called Airline Data T100I contains detailed data for the US market segment (flights within as well as from and to the US) - among others, passenger capacity and passenger capacity utilization as well as cargo capacity and capacity utilization[52].

Airline Data T100 International	
Number of airlines considered	221
Scope	Scheduled flights, charter flights, cargo flights
	Data on flights from, to and inside the US
Number of flights	approx. 10 million
Number of passengers	1,022 million
Passenger load factors	Specified more precisely per city pair per airline per aircraft model
Transported cargo	Specified more precisely per city pair per airline per aircraft model, itemized under cargo and mail

Table 36: Summary of Airline Data T100 International

9.5. JP Airline Fleets International

The JP Airline Fleets International (JP) catalog has been published for over 40 years by BUCHair (USA) Inc. [53]. The catalog contains detailed information about the fleets of global airline companies, including more precise aircraft type names and their engines. Airplanes with winglets are also noted in the catalog.

9.6. IATA WATS

The World Air Transport Statistics (WATS) catalog has been published for over 50 years by the International Air Transport Association (IATA). WATS catalogs the capacity utilization factors for passenger and cargo volumes of the largest airline companies worldwide, subdivided by domestic/international flights respectively.

[52] DATA BASE PRODUCTS 2011

[53] Refer to the homepage of buchair.com

IATA WATS	
Number of airlines considered	approx. 300
Scope	Scheduled flights, charter flights, subdivided into domestic and international
Passenger load factors	Per airline, differentiated according to domestic/international
Cargo load factors	Per airline, itemized to cargo & mail, differentiated according to domestic/international

Table 37: Summary of IATA WATS

9.7. AeroSecure

Aerosecure is a commercial database service provider which claims to have databases on safety information from several hundred large airlines and this data is offered by customers from the media and travel industry.

Aerosecure subdivides airlines into different classes which have been partially accepted (cf. chapter 10.2).

9.8. Coverage of factors by data sources, consistency checks

The seven relevant factors of the AAI are fed from the following data sources:

	Type of aircraft	Seat capacity	Cargo capacity	Passenger capacity utilization	Cargo capacity utilization	Engines	Winglets
ICAO TFS	x	x	x	x	x		
IATA WATS				x	x		
AD T100I	x	x	x	x			
ICAO Engine Emission Database						x	
OAG	x	x	x			x	x
Piano-x							
JP Airline Fleets	x					x	x
consistency check possible	yes	yes	yes	yes	yes	yes	yes

Table 38: Overview of factors of the AAI and the associated data sources

Every factor can be based on data from more than one data source. It is possible to do a consistency check of sources with each other.

The consistency checks completed for this article compare the same data from various sources in randomly taken samples. Information from the different sources usually coincided. The error analysis (chapter 13) discusses individual deviations and their repercussions in detail.

10. Acceptance and classification of airlines

In this chapter we discuss the selection of airlines for the AAI as well as the classification of airlines into the four categories of network, charter, regional and low-cost, and then later special cases such as code sharing, leasing, etc.

10.1. Selection of airlines for the AAI

The AAI ranks the 150 largest airlines of the world. Transport service is the decisive factor for admission here, in which case the parameter in terms of passenger kilometers flown is measured. The procedure is as follows:

1. Using ATI (see chapter 9.2.3) the AAI selects from all airlines worldwide the 150 that fly the most passenger kilometers, regardless of their business model and markets.
2. The AAI checks the data for these airlines. Airlines whose data is insufficient to depict all factors in adequate detail are not admitted into the AAI. The number then decreases from 20 airlines to 130.
3. Several of the 130 airlines offer domestic and commuter flights under their own brand (e.g. Continental Airlines with Continental Connection). Sometimes the airline uses its own airplanes, and sometimes commissions subcarriers (cf. 10.3.3), in which case the airplanes of several airlines can hide behind the brand. The AAI identifies the airplanes that the subcarrier uses for the regional division of the respective airline and assigns them to the parent brand. The AAI regards the brand as an independent "airline" and assigns the airplanes of the subcarrier to it (Colgan Air to Continenatal Connection). Using this method the number of airlines increases to about 150. Behind each of the 25 brands are one or more subcarriers (total 54), so that the number of airlines considered in the AAI increases to a total of just under 200.

As a result, the AAI calculates the global efficiency points for significantly more than 100 airlines. Due to space limitations, only the 125 largest are included in the results brochure.

10.2. Categorization of airlines in the AAI using specialized service providers

The AAI classifies civil airline companies into four categories which are described below. This classification is customary to the industry and so can also be found in the literature[54]. However, later

[54] Pompl, Air Traffic, chapter 4.2, 2006

with the liberalization of the air traffic market and the emergence of low-cost airlines, the traditional class divisions have become more difficult because the properties of the classes are still theoretically exact but many airline companies follow several business models simultaneously and exhibit different characteristics in different flights or in different markets.

For this reason, the division of airlines into categories in the AAI serves the user only upon first orientation. It is not the objective of the AAI to create new criteria or independent divisions of airlines into categories, or even to evaluate these categories per se. The AAI therefore adopts the respective classification of an airline into a category used by service providers in the airline industry. The most important sources here are ATI, AeroSecure and the DLR Low Cost Monitor. ATI includes low-cost carriers. AeroSecure also includes (ex) domestic airlines, classified here as network carriers, as well as regional and charter carriers. The DLR Low Cost Monitor uses the low-cost airline classification for airline companies. The classifications of airlines into the respective categories by these sources did not conflict with each other in any airline.

We give below a short overview of the criteria used in the literature[55] and by ATI or AeroSecure to categorize airlines.

- Commercial airlines (network carriers)

Many airline companies developed from state-owned or state-subsidized companies and were afterwards increasingly privatized. If the state most is the majority shareholder, then we can also speak of a flag or national carrier in this instance. On a certain market – for example, international, domestic, continental – network carriers cover possible flight routes with a network-like product which includes connection flights. They have scheduled flights, that is, flights on established days and times which are not only seasonally offered. As a rule, these flights must also then be offered if bookings are small. Departure and arrival times for flights are laid down over a longer period in a published flight schedule.

- Charter airlines

This is how the AAI designates those airline companies which mostly offer charter flights. In contrast to scheduled flights, flights are offered only at times when the airline companies expect high demand. Charter airlines have no legal obligation to carry out inadequately booked flights. However, in practice many seats in these airlines are booked through tour operators in a package with the entire vacation trip, for which travel contract law often establishes the de facto obligation to transport. In practice, the boundary between charter carriers and network carriers blurs even with the announcement of summer and winter flight schedules.

The separation established by traffic law between scheduled and charter traffic has been abolished in Germany since 1993. However, the prior differences continue to exist in execution and in sales.

[55] Pompl, Air Traffic, 2006

Scheduled air service is network-oriented and tickets are sold mainly to end users. In contrast, charter traffic is predominantly point-to-point traffic and more than 80% are sold through tour operators as part of tour packages.

What is seen in the development of charter airlines is that they are becoming more and more tourist package-oriented commercial airlines. This means that many destinations are flown with one fixed flight schedule over the entire year.

- Low-cost airline companies

The concept of low-cost flights have experienced a rapid upturn since the mid-1990s. Low-cost carriers start from different points to lower the prices for airplane tickets. The reduction or complete elimination of comfort (no frills) or comfort and flexibility against a surcharge, one-class configuration, use of to some extent remote regional airports, restriction to a few flight routes in the short-haul and middle-haul range without transfers and the reduction of maintenance costs by means of uniform fleets are typical business characteristics. However, since commercial airlines also often significantly lower their prices on routes where they fly in direct competition with low-cost airlines, it is increasingly becoming difficult here to draw a clear boundary between low-cost airlines and commercial airlines.

The AAI uses the definition of low-cost carrier of ATI: "Precise definition of a low-cost carrier is difficult given the evolution of the model and increasing common ground with network carriers, but we specify a low-cost carrier as a point-to-point scheduled operator which largely adheres to the core principles of the low-cost carrier model. The airline will have a stand-alone management team and will market itself on price, mostly with a single class offering. Carriers will sell most of their tickets through direct sales via the Internet, and onboard frills will be available only for a fee. Carriers will have simplified fleet structures and fast turnarounds." [56]

This definition corresponds to the approach of atmosfair of viewing low-cost carriers as a special case (see chapter 3.4) because even ATI with the above-mentioned "core principles of the low-cost model" places low prices in the center, making them a special case from the climate point of view due to their flight-induced effect. But since network carriers can also lower their prices on routes flown in competition with low-cost carriers to a similar level as low-cost carriers, the AAI advises the passenger in its results illustration to examine this circumstance before booking a flight.

[56] ATI, personal communication, February 2010

- Regional airline companies

These are airline companies that carry out commuter flights to the large hubs (flights from small regional airports to hubs and vice versa). They use predominantly regional airplanes or commuter airplanes, sporadically short-haul jets as well (e.g. Embraer ERJ).

10.3. Code sharing, low-cost affiliates and leasing

As indicated above, the AAI examines the 150 largest airlines of the world. In spite of the clear sources for the categorization of airlines, additional delimitations are discussed in special cases since some flights can overlap. The following cases are possible:

1. Code sharing
2. Majority stakes
3. Subcarriers
4. Leasing

10.3.1. Code sharing

In this arrangement an airline offers a flight under its own flight number but the flight itself is carried out by another airline. The latter likewise sells tickets for this flight using its own flight number. Therefore, at least two flight numbers exist for one and the same flight. However, in most cases both airlines belong to a larger economic consolidation of airline companies (alliances). This allows airline companies to increase their offer of flights without using their own airplanes. Potentially this also improves the capacity utilization of a flight.

Treatment in the AAI: The data sources of the AAI allow in code sharing a differentiation as to which of the participating airlines sells only ticket quotas sold and which has actually carried out the flight actual using its own airplanes. Since all airlines have access to flight capacities, all of them are responsible for the CO_2 emissions of the flight. Nonetheless, the AAI assigns them to the airline which actually carries out the flight using its airplane because they alone can affect all factors of the AAI (cf. chapter 12) and because of the passenger point of view of the AAI. Passengers can know from the fact that their flight is a code-sharing flight and choose the airline transporting them. For these reasons, the AAI in code sharing assigns CO_2 emissions to the airline that actually carries out the flight.

10.3.2. Majority stakes

Many airlines have equity interests in other airlines (in the form of partner interest or shares). A majority stake of airline A in another airline B theoretically allows A to interfere directly in the transactions of B. In the most unfavorable case, B cannot independently affect the factors that go into the ranking (e.g. the type of aircraft used or the seat capacity offered) but must comply with the requirements of A.

Treatment in the AAI: The AAI does not consider majority stakes. It does this for two reasons. First in this instance as well the passenger perceives the airline only in its external impact. The respective ownership structures here are also unknown to the passenger. Passengers usually will not know whether the airline flying them has its transactions imposed from outside.
Secondly, consideration of majority stakes could distort the ranking as spelled out by the following hypothetical example:

Three airlines fly on a city pair:

- airline A with 16.8 kg CO_2 / 100,000 km
- airline B with 17.0 kg CO_2 / 100,000 km
- airline C with 25.2 kg CO_2 / 100,000 km.

A holds the majority stake in C and controls its transactions (selection of types of aircraft, number and distribution of seat classes, etc.). If the AAI considers the majority stake and assigns the CO_2 per payload kilometer of flights of C on this city pair to airline A, two problems emerge:

1. Passengers flying with C will not come across this airline in the ranking. Passengers themselves must make the assignment from C to A in the AAI ranking.
2. The merging of flights of A and C changes the ranking, for example, as follows:

    - Airline A: 21 kg CO_2 / 100,000 km
    - Airline B: 17 kg CO_2 per 100,000 km

An environmentally conscious passenger could using this ranking switch from airline A to airline B, without knowing that A, without the addition of C, would be more efficient than the airline B selected by the passenger. Finally, based on the AAI the passenger would cause more CO_2 on this city pair, which is in conflict with the objective of the AAI.

Regardless of whether the majority of shareholders' equity in an airline is in the hands of another airline and thereby its transactions are imposed from outside, the AAI assigns the flights of an airline and hence the efficiency points to this airline as well.

10.3.3. Subcarriers

Some airlines offer flights under their own flight numbers but they themselves do not carry out these flights but commission smaller airlines (subcarriers) for this purpose. The subcarriers use airplanes with the paint colors and flight number of the client. However, beyond the contractual agreement on the provision of flight service, there is no economic or legal connection between airline and subcarrier.

Treatment in the AAI: The flights carried out by the subcarrier take place by order of an airline using its flight number. It is not clear to passengers that the airline transporting them is some other airline different from that indicated in their ticket. Therefore these flights are assigned to the commissioning airline.

10.3.4. Leasing and chartered airplanes

Airlines carry out many flights not with their own aircraft but rather charter carrier or lease aircraft from other airline companies.

Treatment in the AAI: The emissions of the flight on a leased or chartered aircraft are attributed to the leasing airline company and not to the owner. Passengers in this instance are also unaware of the actual ownership structure. Moreover, the chartering or leasing airline company is also free to choose the respective airplanes based on environmental concerns.

11. Results illustration in the AAI

This chapter describes the illustration of results in the AAI.

11.1. Efficiency points

The AAI ranking is shown in the results illustration based on efficiency points. The linguistic use is based on the description of efficiency labels in EU Directive 2002/91/EC.

11.2. Illustration in various airline categories

The AAI shows network, regional, and charter carriers in one ranking, noting also their classification (see chapter 10.2). Regardless of their category, all airline companies have the same basis for calculating their efficiency points.

11.3. Division into efficiency classes

The illustration of the AAI ranking follows the model of the EU Energy Efficiency Directive[57]. For this purpose the AAI adopts the EU approach of seven efficiency classes A-F. The width of the seven efficiency classes is not specified in the EU Directive. The AAI follows a British energy efficiency label and adopts its class width distribution which is also based on a scale of 0 to 100 points. The approach selected here by the AAI to define classes with increasing efficiency in narrower, that is, more discriminating fashion corresponds to the EU Labeling Scheme for cars and buildings.

The illustration in the AAI also adopts this choice of form of classes from the energy efficiency directive.

Class	AAI Efficiency Points
Efficiency Class A	100 – 90
Efficiency Class B	89 – 78
Efficiency Class C	77 – 65
Efficiency Class D	64 – 51
Efficiency Class E	50 – 36
Efficiency Class F	35 – 20
Efficiency Class G	20 - 0

[57] Directive 92/75/EEC, 1992.

11.4. Error illustration

The inaccuracies quantified in the error analysis are transparently shown in the AAI as signatures in the respective graphics (see chapter 13.4).

12. Factor analysis

This chapter describes the weight that factors described in chapter 5 have in the CO_2 result of an airline. This was determined as part of a factor analysis which investigates the effect that a change in a factor has on the CO_2 per payload kilometer of a flight, assuming that all other factors remain the same and are incorporated into the flight with their mean value.

The AAI incorporates the following factors on each city pair (see chapter 5):

- type of aircraft
- seat capacity
- coloaded freight capacity
- passenger load factor
- cargo load factor
- winglets
- engines

12.1. Step I: mean value and standard deviations of factors

Mean value and standard deviation are calculated for every factor.

Factor	Mean Value	Standard Deviation
type of aircraft	Mean value of CO_2 emissions of all possible types of aircraft over a distance	1 sigma within the series of discrete CO_2 values (per airplane)
Seat capacity	per type of aircraft: mean value of all actually existing seats	1 sigma
Coloaded freight capacity	per type of aircraft: mean value of all actually existing capacities	1 sigma
PLF	mean value of PLF of all flights in the AAI	1 sigma
CLF	mean value of CLF of all flights in the AAI	1 sigma
Winglets	Not meaningful since only two real values are possible	airplane with/without winglets
Engine	per type of aircraft: median of all NO_x emissions of the possible engines	Lower value: the most inefficient engine, upper value: the most efficient engine

Table 39: Factors of the AAI, their mean values and standard deviations

This step proceeds differently for the individual factors:

- Type of aircraft: A mean value cannot be directly established for the type of aircraft because it is not a continuous parameter but only has discrete values (e.g. Boeing 757-200 or Boeing 767-300, but no values between these two). Nonetheless, the type of aircraft is important for CO_2 emissions and is considered in the factor analysis in the AAI as follows: For a selected distance of, say, 1000 kilometers flights with all the types of aircraft possible over this distance are calculated, with the other six factors (seats to engine) always having fixed values. Factors that depend on the type of aircraft such as seating are thereby scaled with mean values together with the type of aircraft so that they have no effect on the result. So, for example, with all things equal, with 85 types of aircraft we get a total of 85 different CO_2 emissions, which depend here only on the type of aircraft since all other factors are fixed. We then obtain a series of 85 discrete CO_2 values, from which mean value and standard deviation can be determined. This method is used separately for the most important distances.
- Passenger load factor (PLF) and cargo load factor (CLF): Here the procedure is simple since both quantities in the AAI represent sets of continuous values. Conventional mean values and standard deviations are calculated for these over all types of aircraft and over all airlines.
- Seat capacity and cargo capacity: Mean value and standard deviation of all existing seats are calculated over all flights in the AAI per type of aircraft but over all airlines.
- Winglets: A mean value calculation for this factor does not make sense since it gives only two values: airplane with winglets and airplane without winglets. They form the "standard deviation".
- Engines: The mean value is not calculated here. Since in many cases no more than three engines are available for every type of aircraft, the median of engines is calculated as the mean value. We define the standard deviation with a small error as the most efficient or the most inefficient engine (in relation to the NO_x emission per kg of kerosene).

12.2. Step II: Determining the CO_2 differentials in case of variation of the factor by a standard deviation

For a flight the CO_2 per payload kilometer is calculated twice for each of the seven factors. The factor under consideration is included once with its above-mentioned mean value, and a second time with its above-mentioned standard deviation from the mean value. The remaining six factors remain constant in their values in both calculations (with all things equal). The result is seven factor-dependent CO_2 differentials (one differential per factor).

The CO_2 differential (hereinafter referred to as "**factor-dependent CO_2 differential"**) between the two calculations (mean value – standard deviation) is then further processed in the third step.

Factor	Mean Value	Standard Deviation	Factor-Dependent CO_2 Differential
Type of aircraft	e.g. McDonnell Douglas MD-87	In this example represented by Boeing 737-400	10% to 45%
Winglets	e.g. B737-800 without winglets	B737-800 with winglets	3%
Engine	1	±0,03	3%
Seat capacity	e.g. 268 for A340-300	e.g. ±21 for A340-300	2% - 19%
Cargo capacity	e.g. 6,650 kg for A340-300	e.g. ±2,300 kg for A340-300	0% - 7%
Passenger load factor	74%	±20%	10% - 19%
Cargo load factor	17%	±15%	0% - 6%

Table 40: Factor-dependent CO_2 differentials of factors over distances of 1000 to 8000 kilometers

Table 40shows the factor-dependent CO_2 differentials of the seven factors as well as the elasticity of these factors. The dimensionless elasticity is defined here as the ratio of change in the CO_2 per payload to change in the causative factor (both in the unit %change). It is shown that hardware such as type of aircraft, etc. obviously has the greatest elasticity and factors such as cargo capacity, which form only a small part of the main factor of payload, are accordingly poorly elastic. We will later use the elasticities in the error analysis (chapter 13).

12.3. Step III: The weight of factors relative to each other

The seven factor-dependent CO_2 differentials are summed up in the third step and then their percentage share in the sum is determined for every differential. This is the result of the factor analysis. It indicates the weight by which a factor changes the result (CO_2 per payload kilometer) relative to the other factors in case of a change by one standard deviation. The factor weights shift with the flight distances relative to each other. Figure 3 gives shows a mean value over all distances.

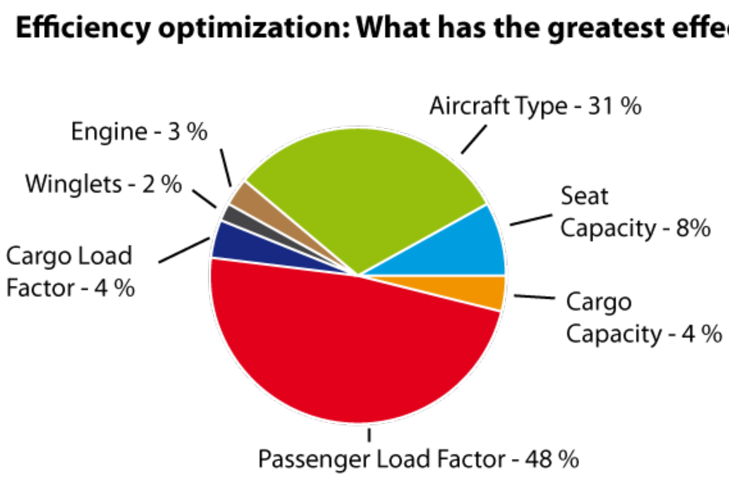

Figure 4: Average effect of factors in the AAI Global Ranking

13. Error analysis

13.1. Introduction

How exact is the AAI? Is the ranking applicable? This chapter answers these questions. The AAI is based on CO_2 per payload kilometer and NO_x and hence on physical quantities. Like all physical quantities these are subject to errors during their calculation. For this reason, this chapter determines the accuracy of the AAI using the error calculation method from physics.

For each of the factors that are included in the AAI the errors are calculated and the repercussions of the total error in the ranking are analyzed. Moreover, we clarify how the calculated inaccuracies go into the depiction of the AAI.

13.1.1. Types of error

The error calculation differentiates between the following types of error:

- gross error (e.g. improper handling of a measuring device)
- constant error (e.g. wrong calibrated measuring instruments)
- systematic error (e.g. preceding dial indicator)
- random error (uncontrollable error, the in positive how negative direction arise)

Gross, constant and systematic errors do not appear in the AAI because it is based on calculations and not direct measurements. The data could be faulty but we impute this to random errors because we have no information about the fact that data from a source deviates systematically in one direction. We distinguish three categories of random errors:

- Operating data error (capacity utilization, seat configuration, type of aircraft etc.): The commercially obtained data for the AAI (see chapter 9) can contain errors which are discussed in chapter 13.2.2.
- Incompleteness of operating data: Individual data records are missing, hence there are data gaps. In the error analysis we treat this as sample and calculate the error resulting from it.
- Uncertainty of operating data: The data set in this case is available and correct but unclear. This error only applies to the airplanes if instead of the type of aircraft only aircraft model or aircraft family is known (see chapter 13.2.4 and the following).
- Inaccuracy of physical data. This pertains to the following factors:
    - Fuel consumption of a type of aircraft that is calculated in the AAI with piano-x (chapter 8.1.2).
    - Winglets and the associated fuel savings.

- Engines and their SFC (chapter 8.1.4) and the associated engine factor.

Since all these errors fall under the category of random errors, normal distribution with symmetrical deviations in both directions is assumed for them unless otherwise indicated below.

13.1.2. Error propagation

The end result of the AAI is the efficiency points (EP) for an airline. These are calculated depending on the factors F_i

$$(1) \quad EP = f(F_1, F_2, \dots, F_i)$$

Since the errors of the factors are random and mutually independent, for the total error ΔEP, we can estimate the Gaussian error propagation:

$$(2) \quad \Delta EP = \sqrt{\sum_{i=1}^{k} \left(\frac{\partial f}{\partial F_i}\right)^2 (\sigma F_i)^2}$$

13.1.3. Significance

With the AAI airlines receive absolute efficiency points by which they take their place in the ranking. If the ranking is significant, the extreme values, which mark the opposite confidence limits of the efficiency points of two adjacent airlines in a confidence interval of 95% around the mean values of the efficiency points, usually may not overlap. For this reason, in the error calculation we will calculate the confidence limits which apply to this confidence interval (95%, associated with the double standard deviation) for every single error and subsequently for the total error as well.

13.1.4. Progress of error calculation

The fundamentals of error calculation in the AAI are thus created. For each of the seven factors this follows the steps in this chapter:

1. What causes error in a factor? The error and its source are discussed here.
2. How large is the error of a factor on the source? Here we discussed how large the error of a factor is in extreme case and in a standard deviation of two 1 sigma.
3. Single error: How does the error affect the efficiency points of airlines? The AAI calculates the efficiency points twice: Once with the original source value and once with the source value

which deviates by the two above-mentioned errors in step 2. The difference of the results signifies the maximum error and the confidence limit for every factor given a double standard deviation. We call these errors for every individual factor "single error".

4. Total error: The single errors of all seven factors are added up according to the Gaussian error propagation formula. We then get the maximum total error (extreme case) and the error which at 95% confidence interval determines the significant difference of the two airlines in the ranking (confidence limit).

13.2. Single error

We will discuss single error below before it is offset against total error in section 13.3

13.2.1. Data gaps

The AAI with its sources covers approx. 95% of all flights of the 150 largest airlines of the world. While the flights of these airlines are 100% recorded by the OAG, with further processing it comes down to a situation where the OAG data cannot be assigned and augmented with data for capacity utilization factors, etc. from other databases. These flights are completely omitted in the AAI. An error resulting from gaps occurs in the following cases:

1. omission of about 5% of all flights due to absent capacity utilization factors
2. Elimination of flights where the sum of cargo and passenger capacity is implausible (exceeding the maximum payload, approx. 3% of all flights).
3. Elimination of flights with small airplanes which cannot be identified by piano–x (approx. 2% of all flights).

This results in only a negligible error for the AAI. This occurs as follows: We considered the flights of an airline which are available without data gaps as a sample from the population of all flights of this airline, of which several are unknown to the AAI (data gap). The mean value of the efficiency points over all flights of the airline is calculated. Since we cannot know which flights are missing, the sample of flight known to the AAI is randomly taken. This then results in the standard error of the mean values of sample S over a selection of N flights (sample parameter):

$$\Delta S = \frac{\sigma}{\sqrt{N}}$$

σ is the standard deviation of the mean value of the efficiency points. Since a sample parameter of N > 1000 is regularly available in the large airlines of the AAI, as a consequence the standard error of the sample of the average efficiency points is smaller by more than a order of magnitude than the standard deviation of the efficiency points and is therefore negligible.

13.2.2. Error in the sources for operating data

The data sources of the AAI for operating data such as type of aircraft used, seat configuration, capacity utilization, etc. can have errors. These can be caused by transmission error on the part of airlines, as well as by analysis error in the reading and processing of data by the data service providers. All operating data included in the calculation of the CO_2 per payload kilometer comes from at least two sources (chapter 9.8). This makes plausibility and deviation tests possible. They usually lead a situation where the biggest part of data can be assumed to be error-free, while errors can occur at a smaller scale. These errors will be discussed below individually for each factor.

13.2.3. Fuel consumption of a type of aircraft

13.2.3.1. What causes the error?

The AAI calculates the fuel consumption of a type of aircraft on an individual flight using piano-x. Inaccuracies within the software therefore affect the AAI directly. Since the software has assigned separate databases to every type of aircraft, it is assumed that errors might arise only up to a specified upper limit. No more errors are then expected on the other side of this limit. For this reason, outliers themselves should not arise and conservatively are assumed to occur at most in one per thousand.

13.2.3.2. How large is the error?

The maker of Piano-x, Lissy limits, indicates an accuracy of more than one percent in the calculation of fuel consumption. A maximum of 1% error in fuel consumption can then arise if two airlines respectively use only one type of aircraft that differs from that of the other airline. This case will occur only in the direct comparison of two low-cost airlines since a significant narrowing of the variety of types of aircraft is observed only in these airlines. Because of the greater heterogeneity of the fleets of other airlines, the maximum error in fuel consumption when these carriers are compared to each other is about 0.2%, and when a network carrier is compared to a low-cost carrier the maximum error is about 0.3%.

The error arising from the linear interpolation of consumption of the individual flights (see chapter 8.1.1) is an approximation error which then appears if the underlying function is not linear and hence the linear interpolation incorrectly depicts this function. Using individually completed comparisons between values interpolated with piano-x and values precisely calculated with piano-x, it is shown that the interpolation error of 0.05% is smaller by an order of magnitude than the error of piano-x. For this reason, it is further disregarded.

13.2.3.3. Repercussions on efficiency points

Since separate outliers can at best be assumed in the software piano-x, a confidence limit of 3σ can be assigned to the above-mentioned errors in fuel consumption (99.7% of all errors lie within the said margins of error). If the AAI compares the extreme case of 1% point in the fuel consumption described for low-cost carriers to an assumed fuel consumption without error, then the deviation in the AAI result is one efficiency point. A narrower confidence limit of 2σ (95% of all errors lie within the margins of error), which is adequate for the significance of the AAI results, corresponds to a lower result deviation of about 0.7 efficiency points. In the same manner, when comparing all other airlines with each other and given a confidence limit of 2σ, the possible result deviation can be calculated to 0.2 efficiency points.

13.2.4. Uncertainty of the type of aircraft

13.2.4.1. What causes the error?

The OAG supplies information about which type of aircraft was used on a flight in the AAI. In some data sets the name of the aircraft is unclear, that is, the AAI cannot identify the type of aircraft directly without undertaking further steps. The data sets from OAG include three accuracy levels for the type of aircraft:

	Accuracy Level I	Accuracy Level II	Accuracy Level III
Description	Type of aircraft clearly named	Only aircraft family named	Several aircraft families named
Sample data set from OAG	• Boeing 747-400 • Boeing 737-300	• Airbus A330 • Boeing 737 passenger • Boeing 747 (passenger)	• Airbus A318 /319 /320 /321 • ATR42 /ATR72
Share in the AAI	83%	15%	2%

Table 41: Accuracy levels of aircraft names

The uncertainty affects accuracy levels II and III, so overall about 17% of all flights in the AAI are affected by this.

13.2.4.2. How large is the error?

This question is answered for the different accuracy levels.

Type of aircraft level I

The aircraft names of level I identify exact types of aircraft, that is, the AAI can assign the respective flight profile of the individual flight for the fuel calculation (cf. 8.1.2). This yields no error in the context of the AAI. Only the physical inaccuracy from 13.2.3 has an effect.

Type of aircraft level II

The aircraft name at this level does not indicate the type of aircraft used but rather the aircraft family to which the airplane used belongs. The AAI can assign different types of aircraft, as shown in the table below:

Aircraft Name Level II	Possible Types of Aircraft of Level I
Airbus A330	A330-200, A330-300
Airbus A340	A340-200, A340-300, A340-500, A340-600
ATR 72	ATR 72-200, ATR72-500
Boeing 737 Passenger	737-200, 737-300, 737-400, 737-500, 737-600, 737-700, 737-800, 737-900

Table 42: Examples of possible aircraft names of level I and those of level II

The inexact aircraft name allows no unique assignment to an individual flight profile (cf. 8.1.2) since, according to the example, up to 8 types of aircraft are possible. Since every single one of these types of aircraft has a different seat capacity, cargo capacity, winglets as well as engine, more errors emerge in addition to the type of aircraft. These errors are discussed separately in the sections below. All specifications in this subchapter are to be understood in such a way that the isolated error, which is traced back only to the type of aircraft, is examined. This means that the other factors were assumed to remain constant. In reality this is impossible since, for example, a change in the type of aircraft usually also involves a change in aircraft size and hence in seat configuration. For this reason, the respective seat and cargo capacity were scaled together with the aircraft size for the calculation and winglets and engines were adjusted against correction factors so that the effect of these factors on the change in type of aircraft was again calculated. Therefore, with all others remaining the same, the designated change in fuel consumption due to the inaccuracy-laden change in type of aircraft could then be calculated.

Error minimization through fleet approximation

This uncertainty affects 15% of all flights in the AAI. In the extreme case, depending on the respective type of aircraft, the error would result in 20% difference in fuel consumption but would usually amount to about 3%-5% if the error were not corrected. However, the AAI at level II has data which allows a reduction of the error. For these flights the AAI uses an allocation table in which all possible types of aircraft of level I are assigned to the aircraft names from level II (Table 42). If one of the flights in the AAI contains an unclear type of aircraft from level II, the calculation of the specific CO_2 emissions (chapter 8.1) of the flight in the AAI for all types of aircraft of level I, which can hide behind the name from level II, is done in parallel to the parameters of the flight (seat capacity, cargo capacity, passenger and cargo capacity utilization). For the example of the A330, the result of this step would be two values for CO_2 per payload kilometer, one for the A330-200 and one for the A330-300. The AAI then averages the specific CO_2 emissions of this model, weighted according to its occurrence in the fleet of the airline under consideration. For the above-mentioned example this means the following: If there are 20 Airbus A330-200 and 5 Airbus A320-200330-300 in the fleet of an airlines, the AAI calculates for the "A330" aircraft type specification from the OAG a CO_2 value, one fifth of which consists of the CO_2 value of the A330-300 and one fifth of the CO_2 value of the A330-200. In contrast, if there is no Airbus A330-300, the CO_2 value consists only of that of the A330-200. Thus the error is not applicable.

This method reduces the maximum error of fuel consumption to 0.5%. This is possible in 13% of all flights. The large error reduction is also possible for this reason because in many cases the fleet of the respective airline consists only of one type of aircraft which matches the family mentioned in the OAG. The remaining error in several types of aircraft within one family and airline is now statistical in nature and would then be completely eliminated in practice if, given the large number of flights, all airplanes of the fleet all fly the same, since the fleet approximation error in an individual flight is offset by those of the other flights. However, since the number the flights with individual airplanes from level II is unknown and statistical sampling should not be used here, the AAI calculates conservatively and in this case yields a confidence limit of 0.4% of fuel consumption with double standard deviation.

Aircraft name level III

The aircraft name at this level does not indicate the type of aircraft used or the family (just like in level II) but rather several aircraft families. Here too the AAI can assign different types of aircraft (see Table 43).

In addition, the affected data sets exhibit an additional uncertainty with regard to seat capacity, cargo capacity, winglets and engines, which once again exceeds those from level II. The types of aircraft that can hide behind the names from level III admit a greater margin of values for the above-mentioned factors than those from level II. The respective data set therefore contains an average seat configuration, cargo capacity etc. (e.g. 150 seats Airbus A318 /319 /320 /321).

This affects 2% of flights in the AAI. In the extreme case, the resulting error, depending on the respective type of aircraft, would amount to an approximately 25% difference in absolute fuel consumption if the error were not corrected.

Here too the AAI reduces the error through parallel calculation of all types of aircraft from level I, which can hide behind the names from level III, and averages the CO_2 per payload kilometer, weighted as per occurrence of the individual aircraft in the respective fleet. This yields the following maximum and mean Δ in fuel consumption:

Aircraft name level III	**Possible types of aircraft of level I**	**Δ fuel consumption maximum**
Airbus A318 /319 /320 /321	Airbus A318, Airbus A319, Airbus A320-100/200, Airbus A321-100/200	5%
Avro RJ70 /rj85 /rj100	Avro RJ70, Avro RJ85, Avro RJ100	13%
Embraer RJ 135 /140 /145	Embraer RJ135, Embraer RJ140. Embraer RJ145	16%

Table 43: Deviations in fuel consumption at level III after correction

This method reduces the maximum error of the fuel consumption to 16%. In half of the cases (about 1% of all flights in the AAI) the error in fuel consumption decreases to 4%. In this case, the confidence limit is around 3% of fuel consumption given double standard deviation.

13.2.4.3. Repercussions on efficiency points

As described in 13.1.4, the AAI compares error-free fuel consumption of a flight with one which deviates by the error and compares the results in efficiency points:

Level	**Frequency, uncorrected values**	**Error after correction [efficiency points]**	**Frequency, corrected values**
Level I	83%	0	83%
Level II	15%	0.4	13%
Level III	2%	3	1%
Rest	0%	>3	3%

Table 44: Effect of error in the type of aircraft on efficiency points

The values in the table show that an ensuing error in the AAI result of 0.4 efficiency points lies within the confidence interval of 96% necessary for the significance of results (sum of level I and level II).

The inexact aircraft name brings with it further inaccuracies in relation to seat capacity, cargo capacity, engine used as well as winglets. This does not happen if the inaccuracy of the type of aircraft is not applicable. The errors are described individually in the following chapters.

13.2.5. Seat capacity

13.2.5.1. What causes the error?

The AAI also calculates seat capacity using a multi-level method (chapter 5.5). Errors can arise here because data with the highest resolution does not exist for all flights. The AAI has several data sources available for the capacities and carries out consistency checks. An unclear type of aircraft (see 13.2.3.1) can lead to errors in level II if the classification process, with which the fleet of the airline is weighed based on its composition, depicts the relevant airplane of the respective flight (see fleet approximation 13.2.4.2) combined with one from the source of precisely known seat configuration.

At level III the seat configurations are indicated in the source only as standard values which are likewise unclear in reality.

13.2.5.2. How large is the error?

At level I (83% of all flights in the AAI) seat capacity is precisely known and the data can be assumed to be error-free. At level II (15% of all flights in the AAI) seat capacity is precisely indicated in the data source but the type of aircraft is only imprecisely known. The maximum error before correction in seat configuration is about ±4% points. This was shown when comparing the data sources where one source had the precise value and the other had the imprecise value for types of aircraft. The error at level II for seat configuration can then be reduced to ±1% point through the fleet approximation described for the error in the type of aircraft factor. This is applicable to 13% of all flights of the AAI. Given an assumed normal distribution of errors, 95% of all flights lie within a confidence limit of ±0.7% points in passenger capacity. This ± 0.7% point error in seat configuration coincides with the 0.6% error in fuel consumption (95% confidence interval) in the given elasticity of the seat configuration factor (see chapter 12).

At level III (2% of all flights in the AAI) special cases occur in the A320, A318-321, Embraer 135/140 and Avro 70 - 100 aircraft families (see Table 42). The maximum error arising here when these families are combined with unclear standard seat configuration was not calculated more precisely in this analysis. However, the resulting maximum error in fuel consumption should be around 20% and should decrease to about 10% in 1% of all flights in the AAI. The confidence limit at two σ standard deviations should then be around 6% in fuel consumption.

13.2.5.3. Repercussions on efficiency points

There is no error at level I, therefore there is also no repercussion on efficiency points. The errors in fuel consumption at levels II and III are translated directly to efficiency points. This is shown in Table 45.

Level	Frequency, uncorrected values	Error after correction [efficiency points]	Frequency, corrected values
Level I	83%	0	83%
Level II	15%	0.6	13%
Level III	2%	6	1%
Rest	0%	>6	3%

Table 45: Effect of error in seat capacity on the efficiency points

In the sum of levels I and II, the error then lies in a confidence interval of about 96% within a confidence limit of ± 0.6 efficiency points.

13.2.6. Cargo capacity

13.2.6.1. What causes the error?

Similar to seat capacities, cargo capacities in the AAI can also have errors. Since the data is the same, the procedure in this chapter to a large extent follows the one in chapter 13.2.5.

Consistency check with passenger capacity

The novelty here is that further consistency checks could be carried out based on existing data for cargo and passenger capacity: The AAI checks whether the given cargo and passenger capacity for each flight exceeds the maximum payload of the respective aircraft on this flight at hypothetical full utilization. If this were the case, the data set was removed from the AAI. This was the case in about 3% of all flights. The error arising from the removal of these data sets is negligible (see chapter 13.2.1)

Furthermore, it is possible to weed out more flights at level III since the data sources had the implausible value of zero in about 25% of all cases, that is, about 0.5% of all flights in the AAI.

13.2.6.2. How large is the error?

Similar to passenger capacity, the error at level I can be assumed to be zero. At level II (15% all cases in the AAI) the error before correction is around 5% and this decreases after correction to about 2% points in cargo capacity. This is possible in 12% of all flights in the AAI. The confidence limit, associated with the confidence interval of 95%, is around 1.6% points of cargo capacity. This 1.6% point error in cargo capacity translates to around 0.1% error in fuel consumption. This small error in consumption given the high input error in cargo capacity is due to the low elasticity of this factor (see chapter 12).

The errors of level III, in turn, were estimated using only incomplete analyses, thereby yielding values of ±10% in fuel consumption.

13.2.6.3. Repercussions on efficiency points

There is no error at level I, therefore there is also no repercussion on efficiency points. The errors in fuel consumption at levels II and III are translated directly to efficiency points. This is shown in Table 46.

In the sum of levels I and II, the error then lies in a confidence interval of about 96% within a confidence limit of ± 0.6 efficiency points.

Level	Frequency, uncorrected values	Error after correction [efficiency points]	Frequency, corrected values
Level I	83%	0	83%
Level II	15%	0.1	13%
Level III	2%	10	1%
Rest	0%	>10	3%

Table 46: Effect of error in cargo capacity on efficiency points

In the sum of levels I and II, the error then lies in a confidence interval of about 96% within a confidence limit of ± 0.1 efficiency points.

13.2.7. Operating Empty Weight (OEW)

13.2.7.1. What causes the error?

For OEW correction, the AAI uses a weight equivalent of 60 kg per available seat (4.10.6; not to be confused with the assumed average passenger weight of 100 kg). This average weight is error-prone from the outset, since the quantity and quality of cabin equipment involved (seating, toilets, galley, etc., as well as of such service items as food, media etc.) are the design responsibility of the airline.

13.2.7.2. How great is the error?

The AAI estimates the error in OEW correction at ± 30 kg, an estimate based on its own experience and on the literature.[58] Moreover, the AAI assumes a normal distribution of error of approx. 60 kg, with a standard deviation Σ of 15 kg. Thus, the error of ± 30 kg is in accord with the generally accepted confidence coefficient of 2Σ, or 95%. The underlying Gaussian error distribution thus takes into account both high and low outliers. For instance, it is hence conceivable that an airline could use the cabin space made available by reducing the seating to install additional interior equipment and furnishings, which could in extreme cases even result in a higher total weight than that of a cabin configuration with standard seating.

13.2.7.3. Effect on efficiency points

The error-prone weight equivalent of a seat of 60 ±30 kg translates into an approximately normal error distribution of efficiency points, a distribution which the AAI approximates by means of repeated calculation of efficiency points, varying the original error. The confidence limit of a confidence coefficient of 95% corresponds to ± 0.2 efficiency points, and is taken into account for every flight for which the AAI calculates the CO_2 per net load kilometre.

13.2.8. Engines

13.2.8.1. What causes the error?

The data source JP Airline Fleets gives detailed information about engines with which airplanes of airline fleets are equipped. The AAI determines the engine factor of every flight through fleet approximation (13.2.4.2), which can result in an error if the engine in the fleet of an airline cannot be assigned precisely. Another error occurs if the engine per se is unknown. This applies to a few engines of Russian airplanes (see chapter 5.3), and appears in 0.5% of all flights in the AAI.

The engine factor covers two components: SSC and NO_x emissions. Miscalculation is also corrected by the factors air resistance and engine weight. Since these, and also the NO_x component, are small compared with the SFC component, we will ignore these error factors in the following, and only discuss the error in determining the SSC of an engine.

The AAI determines the engine factor for an engine (see 8.1.4) on the basis of the ICAO engine emissions database. This contains, among other things, the data for the fuel flow and various thrust settings for each engine. These data have been documented by the industry for many years, and are constantly being updated. The AAI assumes that these data contain only minimal error. Since however such errors affect equally all airlines which choose the respective engine, all that remains is the

[58] Wit, R.N.C. & Dings, J.M.W., 2002

theoretical error that the various airlines use various engines with SFC errors in different directions and at different frequencies. Since however the number of combination possibilities is great, and no systematic error need be assumed here, the resulting possible error can be assumed to be negligible.

13.2.8.2. How large is the error in the source?

The Boeing Fuel flow method 2, which is used in the AAI to determine the engine factor, projects potentially not accurately the fuel flow during cruise, which would lead to an error of the efficiency points. Since this potential methodical error is however the same for all engines and subsequently for all airlines, it would not change the relative position of the airlines and will thus not be considered further in the following.

The maximum error in the engine factor could occur if the engine assumed for the calculation deviates to a maximum degree from the actual engine of the flight. From the engine factor mentioned in chapter 8.1.4 it can easily be calculated that the maximum deviation in the engine factor can be around 30%. The standard deviation of the engine factor from the airplane-engine combination precisely known in the AAI is around 3%. Since we can assume that the error is normally distributed, we take those 3% standard deviation also for the remaining 3% of the flights. We also assume that this deviation is also valid for those aircraft engine combinations not exactly known from the data source.

The AAI can reduce the error significantly by means of fleet approximation (13.2.4.1). In practice, each type of aircraft is equipped only with a few different engine types. Fleet approximation reduces the maximum error of the engine factor to 0.2%. This applies to all flights in the AAI, regardless of identification class I, II or III, inclusive of the error arising from the lack of knowledge for several Russian engines. The large error reduction is therefore possible because in many cases the fleet of the respective airline only has one type of aircraft which matches the family indicated in the OAG. In addition, this type of aircraft is equipped with only one engine type as per JP Airline Fleets so that the engine is clearly determined in this instance. The remaining error in several aircraft-engine combinations in the fleet of an airline is statistical in nature and would be fully eliminated in practice if, given the large number of flights, all airplanes of the fleet fly with the same frequency since the errors in engine calculation in an individual flight would then balance out with those of other flights. However, since the AAI has no data on the distribution of flights with different airplane-engine combination within the fleet of an airline, the AAI determines the confidence limit associated with the confidence interval of 95% conservatively at around 0.15% of the engine factor.

13.2.8.3. Repercussions on efficiency points

The conservatively calculated error above for the engine factor of 0.15% translates to a confidence limit of ±0.15 efficiency points in a confidence interval of 95%.

13.2.9. Winglets

13.2.9.1. What causes the error?

The same problem occurs for winglets as that for seat and cargo capacity. If the type of aircraft is unclear, the AAI also cannot clearly determine whether the airplane on the respective flight was equipped with winglets or not. In contrast, if the type of aircraft is precise, the AAI can clearly distinguish airplanes with winglets from airplanes without winglets.

13.2.9.2. How large is the error in the source?

At level I the accuracy of the type of aircraft (13.2.4.1) is due to the above explicit assignment of error in the fuel consumption of 0. At levels II and III the maximum error in fuel consumption which can arise in winglets is 3%. Using the fleet approximation correction (cf. 13.2.4.2) the error in fuel consumption decreases by a maximum to 0.2% in 13% of flights. The confidence limit, associated here with the confidence interval of 95%, is around 0.1% point, thereby yielding an approximate 0.1% error in fuel consumption.

13.2.9.3. Repercussions on efficiency points

There is no error at level I, therefore there is also no repercussion on efficiency points. The errors in fuel consumption at levels II and III are translated directly to efficiency points. This is shown in Table 47.

Level	Frequency, uncorrected values	Error in fuel consumption after correction	Error after correction (efficiency points)	Frequency, corrected values
Level I	83%	0%	0	83%
Level II	15%	0.1%	0.1	12%
Level III	2%	3%	3	1%
Rest	0%	>3%	>3	4%

Table 47: Repercussions of winglet error on efficiency points

In the sum of levels I and II, the error then lies in a confidence interval of about 96% within a confidence limit of ± 0.1 efficiency points.

13.2.10. Capacity utilization factors for passengers and cargo

13.2.10.1. What causes the error?

The AAI calculates the passenger and cargo load factors of all flights using a multi-level method (chapter 0). Errors can theoretically arise because data with the highest resolution does not exist for all flights and uncertainties arise in type of aircraft or city pair. However, the airline is precisely determined in all cases. The AAI has several data sources available for the capacity utilization factors (as for all other factors as well) so that consistency checks could be carried out. Since the analysis for both the passenger and cargo load factor is similar given the same data structure, it will be discussed jointly below.

In general, it is shown that there are deviations between all three data sources in terms of capacity utilization (Airline Data, ICAO TFS and IATA WATS). These are probably caused by transmission error on the part of airlines as well as by analysis error when data service providers read and process data. We will consider here only the deviations for the average value of an airline over a complete reporting year over all city pairs. Since the capacity utilization of individual flights (in conjunction with the cargo load factors) are included as linear factors in the city-pair efficiency points only to the first degree and are averaged without being weighed against the global efficiency points of an airline, in the examination of the global annual average instead of individual flights no other errors occur for the global efficiency points of an airline.

13.2.10.2. How large is the error in the source?

A statistical analysis of the three data sources shows that there are systematic deviations in capacity utilization between all three sources, with an upper limit of 5% points in passengers and 6% points in cargo. The double standard deviation is 1.5% points for the passenger load factor and 1.8% points for the cargo load factor. This applies only to differences between the various sources. To reduce the possible error, the AAI uses for every city pair only one source for capacity utilization. This means that a possible error of one source probably has the same has effect for all airlines since differences between the sources no longer apply. The scope of the error here obviously cannot be calculated since we have no other information about the deviations within one data source. Nonetheless, a reduction of error to zero cannot be expected. However, since the number of data sources per city pair is at least halved and with them the number of possible error sources, we assume that upon first approximation the resulting error in capacity utilization is also halved. For this reason, at the double standard deviation it is estimated to have a value of 0.8% points for passengers and 0.9% points for cargo. The approach of combining different data sources for different city pairs for an airline in the final tally of city-pair points yields only a negligible additional error due to the large number of flights and because the standard error of a sample (in this instance, the city pairs of an airline where capacity utilization comes from a certain data source) corresponds to the standard deviation of the sample divided by the root of the number of flights N. At $N > 1000$ the resulting error will then be below the derived errors in capacity utilization by an order of magnitude.

13.2.10.3. Repercussions on efficiency points

The 0.8% points in the passenger load factor calculated above translate to about 0.7% points in fuel consumption and then to 0.7 efficiency points for an airline. What happens here is that an increase in both the passenger and cargo load factor increases the payload to the full extent but lowers the CO_2 emissions per payload kilometer only to a somewhat lesser extent since more payload also requires more fuel. In the same manner, the error in efficiency points is calculated through the error in the cargo load factor to about 0.8 efficiency points. Both errors mark the confidence limits at a confidence interval of 95%, which was used to estimate the error in capacity utilization in the previous section.

13.3. Total error

The single errors from the sections above are summarized in the table below. Using the Gaussian error propagation formula (see 13.1.2) they are added up in the last line to arrive at the total error.

Error	Confidence limit, [efficiency points]
Fuel consumption of type of aircraft	±0.2
Uncertainty in type of aircraft	±0.4
Uncertainty in passenger capacity	±0.6
Uncertainty in cargo capacity	±0.1
Uncertainty in winglets	±0.1
Uncertainty in OEW	±0.2
Uncertainty in engine	±0.15
Error in passenger load factor	±0.7
Error in cargo load factor	±0.8
Total (Gaussian error formula)	**±1.3**

Table 48: Confidence limits given a confidence interval of 95%

Based on the analysis above, the calculations of the AAI for the airlines are subject to an average total error of ±1.3 efficiency points at a confidence interval of 95%. To this we still need to add the errors from the factors not included in the calculations of the AAI because they do not cause any sufficiently large difference between the airlines (see chapter 4). These are the factors of CDA and slower flying, age and maintenance as well as OEW. For these factors we carefully and altogether estimate the error in efficiency points to be about 0.2% points. Since we do not know whether they are coincidental and independent, we must compute them into the other errors conservatively using their absolute values.
This yields a total error of ±1.5 efficiency points for the AAI ranking. Since we used a confidence interval of 95% in our calculation, the AAI can significantly distinguish and hence rank airlines whose efficiency points differ from each other by more than 1.5 efficiency points.

13.4. Error depiction in the AAI

The errors calculated in the previous sections are clearly shown in the AAI. The guiding principle here is that all errors, which can be specifically assigned to an airline and which exceed the normal total error, are individually shown by means of marking.

The AAI uses the following approach here:

Error (ranking points)	**Depiction in the AAI results graphic**
$\leq \pm 1.5$	General reference for all airlines in graphic text
$> \pm 1.5 \leq \pm 3$	Special reference to affected airlines using one asterisk (*)
$> \pm 3$	Special reference to affected airlines using two asterisks (**)

Table 49: Depiction of errors in the AAI global ranking

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Annexes

Appendix 1: Piano X

From the piano x website and user guide[59]:

Piano-X is a new version of Piano, the aircraft analysis tool used by many airframe and engine manufacturers worldwide.

Piano-X provides unprecedented analytical power to anyone involved in the science of aircraft emissions, in airline fleet planning, or in the assessment of both existing and projected aircraft.

With a uniquely simple interface, Piano-X lets you see results within moments of downloading. To get you started, several free aircraft models are provided. You will have instant access to fuel consumption, environmental emissions (NOx, HC, CO, CO2), drag and performance characteristics at any range and payload combination. If you find Piano-X useful, you will be able to purchase other individual aircraft models, or the entire Piano database of more than 250 files covering a huge variety of commercial aircraft types.

Piano-X is much more than a database - it is a full-strength performance program incorporating precisely the same analytical routines as Piano. Unlike Piano, you will not be able to define completely new aircraft 'from scratch' with Piano-X: Instead, you purchase predefined models. But you will then be able to adjust these models exactly as you want:

What are the effects of changing Flight Levels in an A380? What happens if the empty weight of the Boeing 787-9 goes up by 1000 pounds? What if the sfc is 0.5% better, or the drag improves, or there is less climb thrust, or the NOx and hydrocarbon emissions must reflect the latest engine certification results? Piano-X does not expect you to rely solely on current estimates - you can change all of the above for yourself at anytime, to match changing realities, today and tomorrow, or to understand the impact of missed promises and guarantees. And you won't need a PhD in computer science or aeronautics to get the information you need out of Piano-X.

The Piano-X database is precisely the same as supplied with Piano. Aircraft models do not imply the approval or cooperation of any manufacturers or represent guaranteed performance. They do constitute the best and truly independent estimates of aircraft characteristics available to Lissys and are

[59] PIANOX, 2008

underpinned by two decades of expertise in analysing commercial aircraft, with global contacts and a customer list that speaks for itself.

You can Google 'piano aircraft emissions' to find several major environmental studies (some at intergovernmental level) that reference Piano. It is mentioned in ICAO's annual environmental report (large pdf).

Lissys is constantly reviewing future projected aircraft and can provide consultancy related to Piano or Piano-X models. If you are an aeronautical engineer and interested in generating your own aircraft models entirely from scratch, take a look at the full Piano, which lets you do precisely that, and is now available on Windows.

Reference List of piano users

- Rolls Royce plc (Derby)
- Airbus Industrie (Toulouse)
- Boeing (Seattle)
- U.S. Environmental Protection Agency (National Vehicle and Fuel Emissions Laboratory)
- U.S. Department of Transportation (Volpe National Transportation Systems Center)
- Bombardier Aerospace (Montreal)
- Ilyushin Aviation Complex (Moscow)
- ATR Regional Aircraft (Toulouse)
- International Council on Clean Transportation
- JAXA - Japan Aerospace Exploration Agency
- McDonnell Douglas (Long Beach, pre-Boeing merger)
- UK Department of Trade and Industry
- UK Ministry of Defence
- Allison Engines (now RR USA)
- BMW Rolls-Royce GmbH (now RR Deutschland)
- de Havilland Canada (pre-Bombardier)
- SHORTS (pre-Bombardier)
- SNECMA (SAFRAN group)
- Korean Aerospace Research Institute (KARI)
- MTU - Motoren und Turbinen Union
- Samsung Aerospace
- Daewoo Heavy Industries
- IPTN (PT. Industri Pesawat Terbang Nusantara)

- EUROCONTROL (Bretigny sur Orge)
- Fairchild Dornier
- FFA (now FOI), the Aeronautical Research Institute of Sweden
- Centre for Air Transport and the Environment, Manchester Metropolitan University
- QinetiQ (ex DERA)
- AVIC 1 (Aviation Industries of China)
- First Aircraft Institute of AVIC 1 (Shanghai)
- Pratt & Whitney Canada
- Northrop Grumman Corporation
- University of Cambridge, Institute for Aviation and the Environment – AIM
- MIT Department of Aeronautics and Astronautics - PARTNER

Appendix 2: TRX and DEFRA

DEFRA is the English Department for Environment, Food and Rural Affairs. It has developed a methodology for calculating the CO_2 emissions of flights[60]. TRX is a private company from the US which specializes in data service and IT for the travel market[61]. It has developed a CO_2 calculator which can compare airlines.

The table shows the factors needed to calculate the CO_2 of a flight, classified under the various methods which deal with CO_2 emissions accounting in air traffic.

Factor	Coverage of TRX	Coverage of DEFRA	Coverage of atmosfair Airline Index
Type of aircraft	40 representative airplanes, for Boeing and Airbus mostly only aircraft family, not type of aircraft (for example, A340), Corinair data from 2006, new types of aircraft such as A380 not included	-	113, all models up until type level; for example, A340-300, data from 2009, including new developments
Number of distance classes	8	3 Domestic, short haul and long haul	18
Engines	-	-	368 engines
Winglets	-	-	detailed
Coverage of airlines	Only scheduled flights	n/a	Scheduled flights and charter flights
Passenger load factor	Only through ICAO data (about 30% of all global flights, see chapter 9.2)	Standard value	From various sources, about 92% of all global flights
Coloaded freight capacity	Detailed data only for flights that concern the US, therefore differentiation into two classes: domestic and international flights	-	Detailed data for all worldwide flights at city-pair level
Accuracy*	± 25%	± 40%	± 1.5%

* The accuracy of DEFRA and TRX were estimated using the factor and error analysis presented in the AAI (chapter 12 and 13). The accuracy of the AAI is calculated in this article in chapter 13.

The comparison shows that none of the hitherto existing systems considers all the factors that affect CO_2 emissions. The identified factors do not have the needed accuracy in order to allow a comparison of airlines.

[60] DEFRA 2009: Guidelines to Defra / DECC's GHG Conversion Factors: Methodology Paper for Emission Factors.
[61] TRX 2009

Appendix 3: ICAO TFS

Excerpts from the Economic Analysis and policy (EAP) Section of ICAO FTS

The Economic Analysis and Policy (EAP) Section is responsible for functions related to Strategic Objectives A (Safety), C (Environment) and D (Efficiency), articulated around three areas of expertise, namely statistics, economic analyses and forecasts.

The Statistics Programme

This programme, initiated in 1947, collects, processes, analyzes and disseminates civil aviation statistics as required by States and the Organization for an efficient, safe and secure development of civil aviation. This web-enabled database covers historical time-series on air carrier traffic, on-flight origin and destination (OFOD), traffic by flight stage (TFS), air carrier fleet and personnel, air carrier finances, airport traffic, airport finances, en-route facility traffic, en-route facility finances and civil aircraft on register.

What is ICAOData?

ICAOData.com is a new website that increases the availability and visibility of the ICAO statistical data on the air transport industry. The website delivers ICAO's air transport statistics in a user-friendly interface allowing for easy access and analysis. The database contains detailed financial, traffic, personnel and fleet information for commercial air carriers. It also holds Traffic by Flight Stage (TFS) information and On-flight Origin/Destination statistics for air carriers. Additionally financial and traffic data for airports are available.

What data will be available?

Through its regular statistics programme, ICAO collects information from its Contracting States, which is then compiled into multiple data series. These cover information on civil aviation subjects relating to commercial air carriers (traffic, on-flight origin and destination, traffic by flight stage, fleet-personnel and financial data), airports (airport traffic and financial data), air navigation service providers (financial and traffic data), as well as data on civil aircraft on register. While these data series have traditionally been offered in the form of hard copy publications they will now be offered only online. The data are updated in real time and change, often daily, depending on the nature of the series. Some of these statistical series contain historical data of 20 years or more.

Commercial Air Carriers - Traffic

Contains, either on a monthly or annual basis, operational, traffic and capacity statistics of both international and domestic scheduled airlines as well as non-scheduled operators. Where applicable, the data are for all services (passenger, freight and mail) with separate figures for domestic and international services, for scheduled and non-scheduled services, and for all-freight services. There are two sample images which give an idea of the data included: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

On-Flight Origin and Destination - OFOD

Shows on an aggregate basis the number of passengers, freight and mail tonnes carried between all international city-pairs on scheduled services. These data are collected on a quarterly basis, but due to confidentiality restrictions can only be shown 12 months after the end of each reporting period, and only where there are at least two air carriers from at least two states.There are two sample images which give an idea of the data included: annual data and quarterly data. (Please make sure you enlarge the images to be able to view them properly).

Traffic by Flight Stage - TFS

Contains traffic on-board aircraft on flight stages of international scheduled services. The data are classified by international flight stage for each air carrier and aircraft type used, the number of flights operated, the aircraft capacity offered and the traffic (passengers, freight and mail) carried. There are two sample images which give an idea of the data included: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

Commercial Air Carriers – Fleet

Covers the fleet data of international and domestic scheduled airlines as well as non-scheduled operators. The data consist of statistics on the number and types of aircraft operated, their capacity and their utilization. There are two sample images which give an idea of the data included: average aircraft utilisation and total fleet numbers per air carrier. (Please make sure you enlarge the images to be able to view them properly).

Commercial Air Carriers – Personnel

Covers the personnel data of international and domestic scheduled airlines as well as non-scheduled operators. The data consist of statistics on the number of airline personnel by job category and the annual expenditures for these personnel. For examples: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

Commercial Air Carriers – Financial data

Shows the financial data for international scheduled airlines giving revenues and expenditures for the year (calendar or fiscal), assets and liabilities at the end of the year and retained earnings as well as summary traffic data. There are two sample images which give an idea of the data included: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

Airport - Traffic

Covers monthly or annual traffic data for major international airports. The data consists of aircraft movements, number of passengers embarked and disembarked and tons of freight and mail loaded and unloaded. There are two sample images which give an idea of the data included: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

Airport - Financial Data

Covers on an annual basis (calendar or fiscal year), income, expenses and investments for major international airports. There are two sample images which give an idea of the data included: overview and detailed results. (Please make sure you enlarge the images to be able to view them properly).

Appendix 4: JP Airline Fleets international

"The Bible of Civil Aviation", 44th edition. The world's most comprehensive yearly fleets reference book provides administrative information for all known commercial aircraft operators, plus technical information on every aircraft over 3,000 lbs (1,361 kgs) (Including current registration, type, serial number, previous identity, date of manufacture, date of delivery, engine type and number, maximum take off weight, configuration, Sel-cal, fleet number, name, remarks, etc.). Covers more than 6,000 operators and over 50,000 aircraft.