atmosfair Flight Emissions Calculator

Documentation of the Method and Data

atmosfair gGmbH

Berlin, October 2023

Table of Content

1 Introduction

This text documents the details of atmosfair's emissions calculation program for flights. The atmosfair flight Emissions Calculator is available free of charge at www.atmosfair.de/en/

For business clients, atmosfair offers comprehensive CO_2 reports either directly or through partnering business travel agencies, travel credit cards such as AirPlus, or by using special services like Conovum (for SAP travel expense reports). The full version of the atmosfair reporting program includes the flights, rental cars, train travel and hotel stays. The report can be generated for any given time frame and can recognize and outline different business units. The program is available for both the travel industry and business customers. atmosfair offers the CO_2 reporting of business trips according to the VDR standard.

https://www.atmosfair.de/en/corporate_services/business_travel/

For any queries please contact: info@atmosfair.de

2 Guidelines and principles

atmosfair developed its Emissions Calculator according to following principles:

2.1 Data independence

atmosfair obtains its data exclusively from independent scientific research projects or from specialized and independent data service providers. Under no circumstances does atmosfair use data provided by the airlines themselves.

2.2 Annual updates

Aircrafts in world air traffic constantly undergo technical improvements and are becoming more and more fuel-efficient in the process. In particular, new aircraft types that enter the market are often up to 30% more economical than their predecessors and thus ensure important changes (atmosfair, AAI 2013). For this reason, atmosfair constantly updates the data for the CO_2 calculation and can thus, among other things, represent the aircraft fleets of the world's airlines in detail. Aircraft types, engines and load factors are updated annually, while aircraft configurations are updated quarterly and flight schedules every two months.

2.3 Accuracy and displaying of results

The accuracy of the calculations is scientifically appropriate. The factors which the passenger can influence as well as the factors which have the greatest influence on the quantity of emissions caused, are represented by the Emissions Calculator with a high degree of detail. For less relevant factors or for factors that the passenger cannot influence, on the other hand, average values are used for the calculation. Where the user cannot specify queried parameters (e.g. aircraft type), the user is provided with as many results as possible[1].

2.4 Validation

The method and the data basis of the atmosfair Emissions Calculator have been verified by the German Federal Environmental Agency (Umweltbundesamt) and internationally active academics in the fields of physics and aeronautical engineering.

2.5 Methodology

The calculation of the atmosfair flight Emissions Calculator is based on the following methodological principles.

2.5.1 atmosfair Airline Index (AAI) for CO_2 emissions

The CO_2 emissions of a flight are calculated in the atmosfair flight Emissions Calculator using the detailed method of the atmosfair Airline Index (AAI). A short summary of the AAI can be found in chapter 2. For more detailed information please refer to ”atmosfair, AAI 2013“.

The atmosfair Airline Index records:

- 32 million flights
- More than 300 of the world's largest airlines
- More than 22,000 City Pairs worldwide
- 125 aircraft types (97% coverage of the global market)
- 409 engines (96% coverage of the global market)

The index thus covers around 92% of global air traffic. The CO_2 emissions of the remaining flights are calculated using generic values averaged for one of 22 world regions from sources such as IATA or ICAO.

[1] e.g. the emissions of different airlines flying on the same route

2.5.2 Non-CO_2 emissions according to the state of science

In addition to the pure CO_2 emissions there are also non-CO_2 emissions for flights, which are also recorded, calculated and reported with their climate impact in the atmosfair method (Chapter 4). atmosfair uses state of the art of climate science according to IPCC and peer-reviewed literature.

2.5.3 ICAO method and refinement with Piano-x

The AAI is based on a proprietary method, building on the ICAO CO_2 calculation method (ICAO, 2010). In it, CO_2 emissions are simulated via the fuel consumption of a complete aircraft on the entered flight using a special computer model (Piano-x, see chapters 3.2 & 5.1). The CO_2 emissions determined in this way are then divided by the number of passengers, with the additional cargo being deducted beforehand.

Lissys Ltd's "Piano-x" database and software is used for aircraft fuel and emissions calculations. Lissys Ltd is a company based in Great Britain. Aircraft manufacturers, aviation authorities as well as universities and research institutes use Piano-x. The ICAO also uses Piano-x for its Emissions Calculator. Piano-x provides by far the most accurate data on fuel consumption in civil aviation for each individual aircraft in its precise configuration and on the respective flight route.

3 Which factors influence my flight's carbon emissions and how does the Emissions Calculator process them?

3.1 Overview

The following factors influence CO_2 emissions and/or non-CO_2 emissions and thus the climate impact of a flight. They are discussed individually in the following chapters.

Chapter 3: Fuel consumption and CO_2 emissions

- ✓ Flight profile (flight altitude depending on flight distance)
- ✓ Detours and holding patterns
- ✓ Operations: airspeed and landing approach
- ✓ Ground operations and airport conditions
- ✓ Meteorological conditions (high altitude winds, thunderstorms, etc.)
- ✓ Airline (fleet)
- ✓ Aircraft type
- ✓ Engines
- ✓ Travel class (seating)
- ✓ Passenger load
- ✓ Cargo capacity
- ✓ Cargo load

Chapter 4

- ✓ non-CO_2 emissions (ozone build-up, contrails, etc.)

3.2 Fuel consumption and CO_2 emissions

CO_2 emissions are directly related to fuel consumption. Per ton of kerosene, 3.16 tons of CO_2 are emitted. Fuel consumption in turn depends on various factors such as the type of aircraft used and its seating, engine, winglets, etc., which are controlled by the respective airline. In addition to the pure technology, there is also the operation of the aircraft. This includes not only the passenger and cargo load, but also the actual flight, through the airspeed to the landing approach procedure.

The following factors play a decisive role in fuel consumption and thus CO_2 emissions:

3.2.1 Flight profile (flight altitude profile in relation to flight route)

Summary: The fuel consumption of an aircraft strongly depends on the total flight distance. In principle, the longer the flight, the higher the total absolute consumption. On short-haul flights, however, the relative consumption per 100 kilometers flown is higher than on medium-haul flights. This is due to the fact that takeoff and climb are particularly energy-intensive and are more important on short-haul flights. Long-haul flights also consume more fuel per 100 kilometers than medium-haul flights, because fuel has to be carried for a large part of the flight and is not consumed until the end of the flight. The flight profile depends on the distance flown, as well as the performance of the aircraft type and local weather conditions.

The Emissions Calculator proceeds in two steps: In the first step, it calculates the great circle distance of the flight[2] from the geographical coordinates of the departure and destination airports. Additional standard values like detours, holding patterns etc. are also included in the calculation.

In the second step, the Emissions Calculator calculates the fuel consumption of a given aircraft as a function of distance. Here, the calculator works on the basis of so-called flight profiles. The flight profile is the two-dimensional course of a flight in which the associated flight altitude is assigned to each point on the earth's surface along the flight path from the departure airport to the destination airport. The flight profile of each flight consists of the following phases:

1. Departure to takeoff.
2. Climb phase in which the aircraft climbs to cruising altitude after takeoff.
3. Cruise phase, in which the aircraft covers a certain distance at a relatively constant altitude. The cruising altitude varies with the flight distance: for short-haul flights, flying altitude lies between 5 and 7 kilometers, for long-haul flights the altitude lies between 10 and 13 kilometers.
4. Descent phase in which the aircraft descends from the cruising altitude to landing.
5. Landing.

The takeoff and climb phases are comparatively fuel-intensive, as the aircraft increases both speed and altitude during these phases. During the cruise phase, the aircraft flies at constant speed at the highest possible altitudes to benefit from reduced drag and more stable weather conditions.

The flight profile depends on the distance of the city pair as well as on the selected aircraft type and other factors. Flight altitudes are partly specified by air traffic control. If no specifications exist (especially for long-haul flights outside national territories), the aircraft climb to the altitudes that are optimal in terms of fuel efficiency, travel time and flight safety. The flight profile determines the aircraft's fuel consumption in that the fuel-intensive phases of takeoff and climb are more important for short distances than for medium or long distances. The CO_2 emissions per payload transported therefore depend heavily on the flight profile and thus on the flight distance.

Exact calculation with Piano-x

For each type of aircraft, the Piano-x software accurately determines the flight profile depending on the respective payload (passengers and cargo) and the route, and calculates the fuel consumption in detail for each flight phase.

Figure 1 below shows, as an example, the calculated fuel consumption of a fully occupied Airbus A340 with 271 seats as a function of the distance flown. The fuel consumption is given in liters of kerosene per passenger and 100 kilometers. It can clearly be seen that medium-haul flights of around 2,000 kilometers in length consume the least fuel per 100 kilometers, reaching values of around 3.7 liters of kerosene per passenger and 100 kilometers. For short-haul and long-haul flights, on the other hand, consumption is higher. For other aircraft types, the consumption values can differ significantly from this example but the basic dependence of consumption on distance is characteristic of most modern jet transport aircraft.

[2] shortest distance of two points on earth

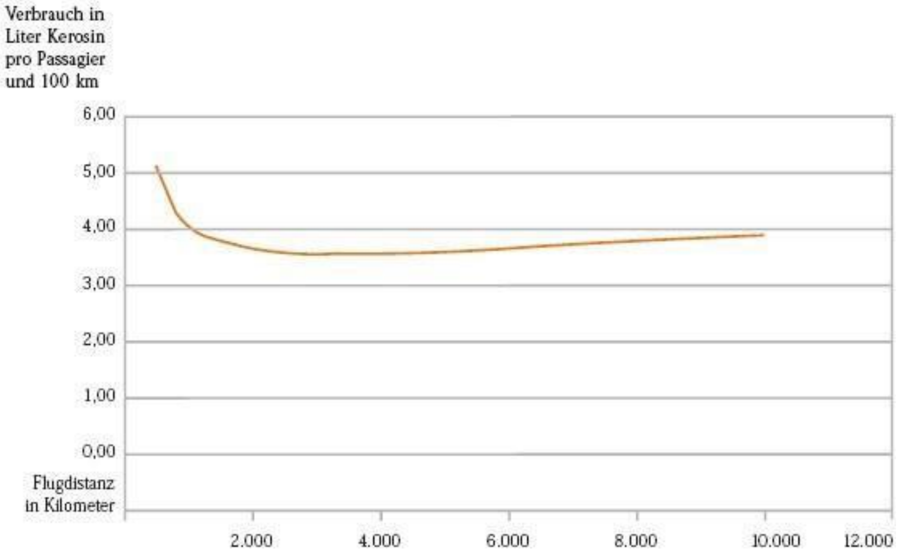

Figure 1: Fuel consumption of a fully occupied Airbus A340 with 271 seats as a function of the flight route (DLR, 2000)

3.2.2 Detours and holding patterns

Detours count the kilometers that an aircraft covers on its way from the departure to the destination airport in addition to the great circle distance (the great circle distance corresponds to the shortest connection between two points on the earth's surface). This excludes holding patterns, which are counted separately (see below). Detours have been statistically recorded. Figure 2 shows the detours on flights in Germany. The detour factor (quotient of real flight distance incl. detour by great circle distance) is shown as a function of great circle distance.

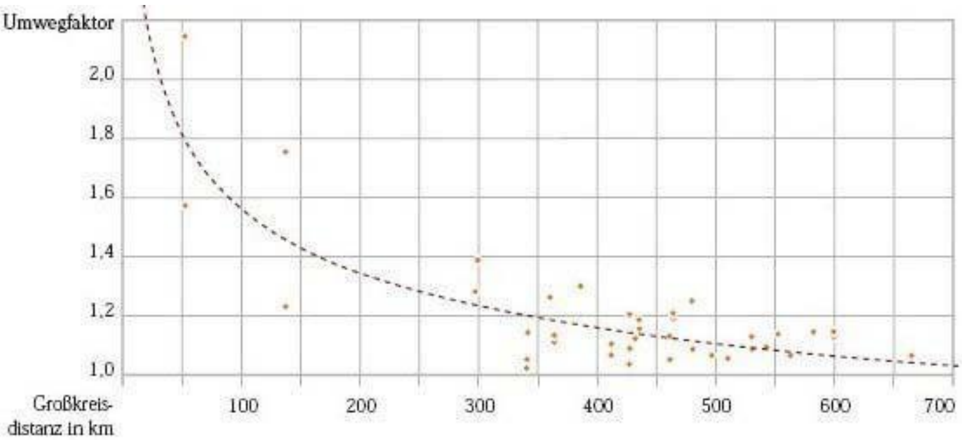

Figure 2: Correlation between detour factor and great circle distance (atmosfair, AAI 2013).

In absolute terms, most detours range to approx. 50 kilometers for any distance. Similar studies on long-haul flights arrive at the same results. The Emissions Calculator takes this empirical result into account by adding the detours as a lump sum to all flights. In light of the overall low significance of this factor, this procedure provides us with sufficient precision. Air traffic control also prescribes holding patterns. An influence of one airline to the detriment of another airline is not possible. Therefore, the atmosfair Emissions Calculator does not consider holding patterns.

3.2.3 Operations: Continuous Descent Approach (CDA), slower flying

The term operation refers to the operation of an aircraft and can be used with several meanings. Here, it includes certain forms of aircraft operation that systematically affect fuel consumption and thus CO_2 emissions. The two forms that have the most influence on the fuel consumption of a flight are discussed below.

Continuous Descent Approach (CDA)

CDA is a special method by which aircrafts approach airports prior to landing differently from other conventional descents. With CDA, the pilot switches the engines to minimum power or, if possible, to idle at a certain predetermined altitude (this can vary depending on the airport and traffic situation) and thus allows the aircraft to descend in a continuous glide until the beginning of the final approach, which can reduce fuel consumption and noise emissions. The conventional approach procedure, on the other hand, is characterized by alternating acceleration and descent phases, resulting in noise-intensive horizontal flight phases that do not exist with CDA.

However, the CDA also has disadvantages: The descent speed while gliding with engines in neutral varies from aircraft to aircraft and cannot be changed. The conventional lateral and vertical staggering of air traffic control, which leads as many aircraft as possible in succession to the final approach route of an airport, is no longer possible with the CDA. CDA might therefore be restricted in some areas or specific times. In Germany for example, some airports only allow CDAs at low traffic times (e.g. at night).

CDA can save up to 430 kg of kerosene for a Boeing 747 and up to 434 kg for an Airbus A330 on a single flight (Cao et al., n.d.). In a sensitivity analysis, the AAI compared these results with the total fuel consumption of different flights. Depending on the distance (medium-haul or long-haul flights) and aircraft type, the AAI identified a reduction in fuel consumption of 0.5 to 1.5%.

If an airline were to implement this savings potential on all of its flights, it could improve its overall AAI Global Ranking result accordingly. However, due to the above-mentioned restrictions of the Continuous Descent Approach, the AAI assumes that landing by means of CDA is currently only possible at a small minority of airports. Therefore, the kerosene savings potential of an airline flying to many airports will in reality be significantly less than 1%. Thus, CDA is not taken into account in the AAI.

Reduced flight speed

Reducing speed in cruise flight reduces an aircraft's fuel consumption and thus its CO_2 emissions. Airlines are therefore pursuing this approach to reduce their fuel costs.

However, flying slower on a flight route can also have consequential effects. Slower speed can result in longer flight times, which may require changes to the flight plan or rescheduling of connecting flights. Furthermore, speed cannot be reduced at will. If the engine speed is reduced too far, it may no longer run in the optimum range. There are therefore limits to the potential savings.

Using the program Piano-x (see chapter 5.1), the AAI calculated the fuel consumption twice for different flights (short-, medium- and long-haul flights with different aircraft types): Once with the typical speed in cruise flight of the respective aircraft type and a second time with a speed reduced by 50 km/h[3].

The other parameters (seating, passenger load factor, etc.) remained the same. The difference between the two results is the fuel savings that can be achieved by flying more slowly. This amounts to between 0.4 and 1.4%. The AAI assumes that an airline will or can reduce cruise speed on only a portion of all flights because of the restrictions and disadvantages mentioned above. Therefore, in reality, the reduction potential will be less than 1%. Thus, slower flying is not considered by the AAI.

3.2.4 Ground operations and airport specifications

The equipment, the dimensioning as well as the operation of the airport have an impact on the fuel consumption of an aircraft on the ground. The following points play a role.

Taxiing

Aircraft have to taxi from the terminal to the runway before takeoff, consuming fuel that is not recorded in the flight profiles. The same applies to taxiing to the terminal after landing. Depending on the distance from the terminal to the runway, taxiing can take different amounts of time. In Germany, the consumption of kerosene due to taxiing on the ground amounts to up to approx. 2.5 kg for taxiing before and after the flight. The extent or duration of taxiing is beyond the airlines' control; moreover, all are affected equally. Therefore, AAI assumes that the differences between the airlines, e.g. due to more efficient operations, are an order of magnitude smaller here than the absolute consumption, i.e. at most approx. 0.3 kg of kerosene per passenger. Even for a short-haul flight of 400 km, this is less than 1% of the fuel consumption per passenger.

Push Service

Depending on the structure of the airport, the pushback service may be necessary. This is performed by aircraft tractors. Pushback services become necessary when the aircraft is nose down to the terminal prior to flight, as most jet aircraft have no way to taxi backwards and change position under their own power. Airlines are thus subject to the constraints of airport operations. Regardless of whether the respective aircraft is moved in the process by means of its own engines or by means of aircraft tractors: the share of fuel consumption (from parking position to the start of taxiing takes a maximum of a few minutes) is so small that it is not considered by AAI for lack of relevance.

APU

The auxiliary power unit (APU) is an auxiliary power unit that supplies electrical power to operate the aircraft when it is on the ground and has shut down its engines. In addition, the APU serves as a starter for the main engines. While the APU consumes fuel, depending on the airport, ground power may be available or mandatory, eliminating the APU's fuel consumption. This affects all airlines equally.

[3] 50 km/h is an example in the sensitivity analysis

In Germany, an aircraft taxis on the ground for an average of just under 15 minutes per flight. During this time, the engines run at low power. A study that examined fuel consumption for taxiing at domestic German airports came to the conclusion that for both taxiing processes together, about 2.5 kilograms of kerosene are consumed per passenger (Brockhagen, 1995). This quantity is also assumed by the Emissions Calculator as a general rule for all other flights to and from or outside Germany. This is certainly not exact, but seems reasonable in view of the overall insignificance of this effect.

3.2.5 Meteorological conditions

Winds represent a non-negligible effect on the flight phase and fuel consumption. They occur either irregularly in the course of momentary weather conditions or as regular, regional phenomena. Airlines may plan for known winds when determining a flight path, as they can either prove to be a hindrance or have a beneficial effect by shortening effective flight time and reducing fuel consumption.

However, especially over land, the flight routes as well as the flight altitudes are often stipulated. Local weather and wind influences cannot be avoided here, i.e. unexpectedly occurring headwinds, which increase fuel consumption, cannot be avoided. The airlines therefore have little to no possibility of avoiding localized as well as changing winds. Due to the lack of influence, wind is not considered further in the Airline Index.

3.2.6 Airline (aircraft fleet and age)

Aircraft age

Aircraft are subject to material fatigue and wear due to continuous operation. Deposits or minute surface changes on the missile affect the aerodynamic properties. The consequence of this is, among other things, increased fuel consumption. Therefore, the age of the aircraft fleet plays a significant role in the fuel and thus CO_2 efficiency of an airline.

This can be counteracted by good maintenance. The intervals, quality and scope of maintenance are strictly regulated for safety reasons[4]. Intervals and scope are specified in maintenance programs, which the respective airline must have approved by the responsible aviation safety authorities.

Thus, it can be assumed that wear and tear, material fatigue and maintenance do not cause any significant difference in fuel consumption between the airlines. Since the reduction of fuel consumption is the focus of the airlines for economic reasons anyway, it can also be expected that more frequent maintenance than prescribed will be carried out by all airlines if this leads to significant improvements and thus differences between airlines remain small.

[4] in the EU, e.g., by Regulation 2042/200332

3.2.7 Aircraft type

Fuel consumption depends on the aircraft used. In general, a distinction is made between propeller-driven aircraft and aircraft with jet engines. Each aircraft is optimized for a specific distance and a cargo and passenger transport capacity. Operation outside these optima is possible, but causes the specific fuel consumption to increase. Each flight connection has a passenger potential, which the airlines serve. Depending on the transport capacity required, the flight frequency (how often the city connection is served within a certain period of time) and the distance to be flown, the airline can use different aircraft models.

The atmosfair Emissions Calculator distinguishes a total of 121 different aircraft types and the associated variants, thus achieving a market coverage of around 97% (as of 2016).

3.2.8 Engines

The atmosfair Emissions Calculator differentiates between engines using a so-called engine factor. This factor reflects the two central parameters of specific fuel consumption (SFC) and ozone formation or methane lifetime reduction due to NO_x emissions. The engine factor is less than, equal to or greater than one, depending on whether the engine, including NO_x correction, consumes more or less fuel compared with other engines that can be used on an aircraft type.

The JP Fleet Catalog (JP Fleet) contains the aircraft fleets of the airlines under consideration, including the engines used. Once the engine of an aircraft has been determined, the atmosfair Emissions Calculator calculates the effective SFC and the NO_x correction.

1. Determination of the actual SFC

"Actual SFC" refers to the SFC of an engine in combination with a specific aircraft type. The determination of the effective SFC proceeds in three steps:

1. Using the Boeing Fuel Flow Method to determine the isolated engine's SFC.
2. Correcting the isolated SFC with the air resistance of the engine.
3. Correcting the isolated SFC with the weight of the engine.

   (atmosfair, AAI 2013)

This method takes into account the main trade-offs that airlines make with engines in practice, namely that lower SFC is often bought with higher weight and larger diameter of an engine. In this context, the pure SFCs of different engines can differ by up to about 10% or more. The correction for drag is then an order of magnitude smaller, and the correction for engine weight is on average even smaller.

2. NO_x correction (heating vs. cooling)

Nitrogen oxides (NO_x), in addition to forming ozone, also have the effect of shortening the lifetime of the greenhouse gas methane (cooling effect). Both effects are short-lived compared to the lifetime of CO_2 . To compare the effects of NO_x via ozone and methane with the effect of SFC and thus CO_2, the AAI uses approximate absolute global warming potentials (AGWPs) of CO_2, CH_4 and O_3 (Lee et al., 2020). The time horizon here is set at 100 years, an international convention under the UNFCCC climate negotiations.

In using the AGWPs, the AAI uses averages for each pollutant based on the current state of research. Due to the long time horizon of 100 years, on which only CO_2 retains significant weight, the NOx correction factor is thus small and usually not greater than the weight correction factor.

In total, the atmosfair Emissions Calculator distinguishes between 408 engines, thus achieving a market coverage of 96%.

3.2.9 Flight class (seating)

In an aircraft fuselage, there is only a limited area available for seating. Seating, however, is in turn directly correlated with fuel consumption, because the aircraft's fuel consumption changes only marginally if a lot or few seats are accommodated. However, since business seats require more space than economy seats, if the total space is fixed, business seats take space away from economy seats. In extreme cases, one business seat can take up more space than two economy seats. Measured against the total number of seats on the aircraft, economy passengers therefore have a below-average impact on fuel consumption, while business passengers have an above-average impact.

The decisive factor for the strength of this effect is the ratio of business to economy seats and the space consumption of a business to an economy seat. These vary from airline to airline and from aircraft type to aircraft type. In order to calculate the fuel consumption per seat in the different travel classes, the atmosfair Emissions Calculator draws on studies regarding the seating plans of the world's 40 largest airlines (Buchner, 2007).

From these studies, the average seat distribution is in the ratio of 74 : 20 : 6 (economy seats : business seats : first class seats) with a total of 100 seats available. The average space consumption of the different seats corresponds to the ratio of 1 : 1.9 : 2.6[5]. By combining the two ratios, this finally results in a ratio of 0.8 : 1.5 : 2.0 for fuel consumption. This means that, on a global average, a passenger in economy class consumes about 20% less fuel than the average of all seats. A passenger in business class, on the other hand, consumes 50% more fuel on a global average, and a passenger in first class twice as much.

For this reason, the atmosfair Emissions Calculator takes into account the flight classes on the respective routes. To this end, it uses detailed data for the respective distribution of seat classes for the different airlines, so that the exact factors can be applied for each individual flight.

3.2.10 Passenger load

The passenger occupancy rate achieved by airlines depends on various factors, including ticket prices, the type of flight and the flight region. The load factor multiplied by the passenger (seating) as well as cargo capacity results in the payload actually transported. The load factor is therefore a central factor for the fuel consumption (atmosfair, AAI 2013). The atmosfair Emissions Calculator therefore takes into account the "Passenger Load Factor" (PLF) of the individual airlines.

[5] www.flightguru.in

3.2.11 Cargo capacity

For each aircraft, regardless of the airline, there are specifications for maximum permissible weight with regard to take-off, landing, loading and refueling. The "Maximum Zero Fuel Weight" (MZFW) is the maximum permissible weight of an aircraft including load (passengers and cargo) and without fuel. Depending on the seating and passenger load factor, an upper limit is thus set for the payload of air freight. However, this limit is rarely reached for two reasons.

1. The volume of the cargo hold is limited. Before the maximum possible cargo mass is reached, the cargo space in the lower deck is often completely filled.
2. If kerosene is included, the "Maximum Takeoff Weight" (MTOW), the maximum permissible total weight at takeoff, must not be exceeded. Therefore, for longer flights and corresponding refueling, the available cargo capacity according to the MTOW cannot be utilized, as the total weight would exceed the MTOW.

The cargo capacity of a flight is thus not constant, but depends on other factors such as distance, seating and aircraft. These are directly controllable by the airline. It is also necessary to consider the actual payload as an influencing factor, as airlines differ significantly in their handling of freight capacity. The atmosfair Emissions Calculator therefore takes into account not only the "Passenger Load Factor" but also the "Cargo Load Factor" of the respective airline.

3.2.12 Cargo Load

The load factor achieved by the airlines for the cargo depends on various factors, such as the prices and capacities for cargo. The airlines have the option of increasing the amount of transported additional cargo when passenger numbers are lower.

The load factor is the most important factor in specific fuel consumption (atmosfair, AAI 2013). In addition, since the airlines fully control the load factor and differ in doing so, the load factor of the additional cargo is taken into account in the atmosfair Emissions Calculator.

3.2.13 Intermediate results on CO_2 emissions

The intermediate result of the above factors is the amount of CO_2 emissions per passenger on a given route, flown with a given aircraft of a given airline.

All detailed data is stored in the atmosfair database for all routes around the world and is updated annually. The atmosfair Emissions Calculator thus covers around 92% of global air traffic.

3.2.14 Displaying the results in the Emissions Calculator

- The user can individually select the aircraft type in the online calculator. The atmosfair Emissions Calculator then calculates the exact value of the CO_2 emissions based on the individual flight profile, the aircraft type and the other criteria mentioned above.

- If the user does not specify the type of aircraft, atmosfair calculates an average value for all aircraft of an airline flying on the entered route. The calculator then displays the values for the two best airlines on the searched route, as well as the value for an average airline (average value of all airlines flying on the searched route).

4 Climate impact of non-CO_2 emissions

Summary: Aircraft engines emit various pollutants that directly or indirectly warm the climate. Carbon dioxide (CO_2) is the easiest to describe in terms of its origin and effect. It is produced by the combustion of kerosene at the same rate as kerosene is consumed. CO_2 is used as the basis for calculating climate damage. The other pollutants and their effects can be combined using an internationally recognized calculation method to convert their warming effect into that of CO_2 The Emissions Calculator first calculates the fuel consumption per passenger and, based on this, determines the amount of CO_2 whose warming effect is comparable to that of all pollutants on the flight taken together (effective CO_2 emissions). This is the amount of CO_2 emitted by the calculator, which is then offset by atmosfair in climate protection projects.

The climate impact of the emissions and their effects depends on the altitude and the state of the atmosphere at the time the aircraft passes through it and emits the pollutants. Climate impact of non-CO_2 emissions are calculated only for those emissions emitted by an aircraft along the respective altitude profile at altitudes above 9000m. For a short-haul flight of 400 km, this fraction above 9000m is usually 0% (depending on the aircraft type) and then gradually increases to more than 90% (for distances of 10,000 km and more). To calculate the climate impact of non-CO_2 emissions above 9000 meters, the CO_2 emissions at this altitude are multiplied by a premium of 2 and then added to the pure CO_2 ("factor 3").

The climate impact of the various pollutants has been described in detail by the IPCC, the United Nations Intergovernmental Panel on Climate Change (IPCC 1999, 2013) and by subsequent studies directly based on the IPCC's findings (including Grassl, Brockhagen 2007, Dahlmann et al. 2019, Lee et al. 2020). This document will only address the major pollutants and their effects.

4.1 Nitrogen oxides and ozone

The formation of the greenhouse gas ozone from nitrogen oxides induced by the radiations of the sun is a process similar to the chemical smog reactions of nitrogen oxides coming from car exhausts in big cities in the summertime. However, the smog reaction takes place more effectively at high altitudes of about more than 9 kilometers than on the ground. The concentration of nitrogen oxides already present is decisive: if there are few nitrogen oxides, ozone is formed quickly, but if there are many, further nitrogen oxides can even lead to ozone being broken down again. Therefore, it plays an important role whether a flight is conducted on a route that is flown frequently or rarely and whether the aircraft climbs to the critical altitudes.

4.2 Particles and ice clouds

Long-lasting contrails and high hazy clouds of ice can only form if the air through which the aircraft is flying is humid and cold enough[6]. This is the case near the equator only at very high altitudes of about 12-16 kilometers above sea level. Since even modern civilian jets rarely fly that high, contrails and ice clouds are less likely to form here than in the temperate latitudes and polar regions of the world, where these clouds can form down to altitudes of about 5 kilometers. Humidity also generally depends on the time of year, so this also affects the likelihood of occurrence of aircraft-induced cloudiness.

[6] Oversaturation in terms of ice

4.3 Incorporating emissions in the Emissions Calculator

The Emissions Calculator cannot take these effects into account in detail, as this would require an enormous amount of data, which would not be in good proportion to the accuracy achieved. Furthermore, neither the passenger nor the airline can influence the current state of the atmosphere on the route and at the time of a flight. Therefore, it would not be justified that some passengers would have to pay a higher surcharge than others. Consequently, the Emissions Calculator only takes into account the most important systematic parameter, the flight altitude: emissions that occur during a flight at an altitude of more than 9 kilometers are added to the pure CO_2 by a factor of 2 (i.e. a total factor of 3). In this way, the effect of contrails, ice clouds and ozone from nitrogen oxides from air traffic is taken into account with average values. Since some flights do not even reach this altitude and a portion of the emissions from the remaining flights is always emitted below 9 kilometers (during takeoff and landing), the calculated average impact factor for all flights worldwide is approximately 2.7.

4.4 Metrics for measuring climate impact: RFI vs. GWP

The climate impact of non-CO_2 emissions at high levels can be converted to the climate impact of a given amount of CO_2 emissions using so-called metrics.

RFI

One metric, called the Radiative Forcing Index (RFI), is based on the radiative forcing of pollutants, which is the direct change in the energy balance of the atmosphere due to the introduced pollutant. The RFI expresses, for at a given point in time (i.e., 2015, for example), what the ratio is of these energy balance changes from the pollutants that are in the atmosphere at that time due to global aviation. The ratio is currently about 3 to 1 (a factor of 3). This means that the direct warming effect of all pollutants from aviation (non-CO_2 and CO_2) is three times greater than that of CO_2 alone (IPCC, 1999). Thus, by this metric, each flight would be three times more damaging to the climate than its CO_2 emissions alone. The disadvantage of the RFI as a metric for assessing non-CO_2 emissions is that it does not remain constant when air traffic is constant. In the case of a globally uniform fleet flying over many years, CO2 emissions would accumulate due to their long lifetime in the atmosphere and their share would grow steadily, while non-CO_2 emissions remain the same (always the same amount of ozone or cirrus clouds in the sky). The current value for the RFI is 3 (IPCC, 2013 for cirrus and contrails, Lee et al., 2020, for all other effects).

GWP

While the RFI was developed by the IPCC in 1999 to represent the climate impact of non-CO_2 emissions, other metrics are now (as of 2022) available for aviation. Chief among these is the Global Warming Potential (GWP), which has been used in other areas by the IPCC since 1990 to compare the climate effectiveness of long-lived greenhouse gases. The GWP integrates the instantaneous warming effect of a greenhouse gas over a time horizon to be defined (e.g., 100 years after emission), within which the concentration of the gas in the atmosphere decreases along its atmospheric lifetime, and compares this with the climate impact of an emitted ton of CO_2 using the same approach. However, the GWP was previously only applicable to long-lived greenhouse gases, whereas in aviation the emitted greenhouse gases are primarily short-lived. But research has derived a method that can also be used to derive a GWP for aviation (Lee et al. 2020). The following assumptions and literature are therefore the basis for the atmosfair Emissions Calculator:

- GWP time horizon (UNFCCC Convention): 100 years
- Discounting (Azar et al., 2012): 3%
- Accumulated RF aviation CO_2 in 2018 (Lee et al., 2020): 34 mW/m^2
- Pollutants and Effects (Lee et al., 2020 and IPCC, 2013): O_3 , methane, H_2O
  Sulfates, soot, cirrus clouds, and induced cirrus clouds, (effective Radiative Forcing, ERF, Lee et al., 2020): 66.6 mW / m2
- Level of Scientific Understanding (IPCC, 2013): At least low (very low excluded)

With these data, a GWP100 (Lee et al., 2020, Azar et al., 2012) results in a "GWP-based impact factor" of 3 according to David Lee's method. Thus, the two different metrics RFI and GWP are quantitatively in good agreement, although they qualitatively apply quite differently. The European Aviation Safety Agency (EASA) also uses the GWP* metric and talks about a triple climate impact as opposed to just CO_2 (EASA 2020).

The special role of the time horizon should be emphasized here: the shorter the time horizon, the greater the impact of short-lived gases and the higher the resulting impact factor for air traffic. For example, with a time horizon of 20 years, the impact factor can already be 4 (Lee et al., 2020). Thus, time plays a more prominent role in GWP compared to RFI. An extension of the GWP is the GWP*, which particularly considers the effect of short-lived gases with increasing air traffic (Lee et al., 2020) and which, like the GWP100 (see above), leads to a markup factor of 3 for air traffic.

ATR

Another metric, the ATR (Average Temperature Response) metric, can be selected for different time horizons, allowing short- and long-lived gases to be focused. The ATR metric is used in a study commissioned by the Federal Environment Agency. The impact of non-CO_2 emissions over a 100-year time horizon is reported to be three to five times (Dahlmann et al. 2019).

4.5 Deducing the climate impact of non-CO_2 Emissions:

Based on current research, a factor of 3 for non-CO_2 emissions on CO_2 emissions is used to account for non-CO_2.

This is a conservative, quantitative-qualitative average of two metrics (RFI and GWP) and their bandwidths. Both metrics agree with respect to their numerical value (3), with the higher-quality GWP even having the lower bandwidth.

This current value of 3 is right in the middle of the old IPCC range of RFI, which was given as 2-4 by the IPCC in 1999.

Inclusion in the atmosfair Emissions Calculator

Consequently, the atmosfair Emissions Calculator multiplies all CO_2 emissions that occur at altitudes above 9 kilometers by a factor of 3 to reflect the climate impact of the flight in CO_2. CO_2 emissions that are emitted at altitudes below 9 kilometers, on the other hand, do not receive such a markup factor, but are directly included in the climate impact of the flight.

5 Data sources

Summary: The Emissions Calculator uses only independent scientific data sources. Therefore, all main sources of the Emissions Calculator are results of independent scientific studies commissioned by UBA, the United Nations or the EU. Other data come from published literature or relevant compendia or specialized database services.

The CO_2 emissions of a flight are calculated in the atmosfair flight Emissions Calculator using the detailed method of the atmosfair Airline Index (AAI). The data sources belong to the heart of the AAI. The AAI places high demands on the quality, depth, timeliness and independence of the information. The AAI relies exclusively on high-ranking sources from international organizations or long-established, specialized service providers. In no case did the AAI use data published by the airlines via their websites, annual reports or own statistics, etc. To ensure the quality of the data, the AAI covers each influencing factor through at least two independent sources and subjects them to consistency checks. The AAI's key influencing factors are fed by the following data sources.

5.1 Piano-x

Lissys Ltd's "Piano-x" database and software is used for aircraft fuel and emissions calculations (PIANOX, 2008). Lissys Ltd is a company based in the United Kingdom. Aircraft manufacturers, as well as aviation authorities and universities and research institutes use Piano-x (see Appendix 2). ICAO also uses Piano-x for its Emissions Calculator. Piano-x from Lissys Ltd calculates the fuel consumption for all aircraft types depending on flight distance and payload carried. The program maps all specific design-related flight parameters[7]. The flight profile at a given flight distance is defined within the program. The fuel consumption and emission values on which the fuel calculation is based correspond to those of a standard engine typical for the aircraft in question. The quantity to be refueled is also calculated automatically by Piano-x, if not selected separately. For the reserve fuel, the program uses a standard calculation identical for all aircraft types.

5.2 ICAO

ICAO is the international civil aviation organization headquartered in Montreal. ICAO provides access to various operational and technical data on air traffic worldwide. These are collected as part of ICAO's "Statistics Program," which has been in existence since 1947. In this program, among other things, airline data is collected by ICAO contracting states, i.e., by their government agencies, and subsequently analyzed and processed.

ICAO TFS

The ICAO Traffic By Flight Stage Database (TFS) provides passenger and cargo capacity and load factors for international scheduled flights at the city pair / airline / aircraft type level. As this data source is not complete, the AAI additionally relies on other sources for capacity and load factor data[8].

ICAO Engine Emission Database

The ICAO Engine Emission Database contains (among other things) NO_x emission values of all common aircraft engines at four different standard thrust settings[9].

[7] e.g. drag and lift as a function of flap settings, thrust etc.
[8] see below, OAG, Airline Data, IATA WATS
[9] Cf. ICAO Engine Emission Database

5.3 ATI - Air Transport Intelligence

ATI is an online data service of the company FlighGlobal[10]. Among other things, it provides ICAO air traffic data in edited form. The AAI uses the following data from ATI (Airline Business Premium):

- Number of passengers of an airline
- Passenger load factors of an airline
- Passenger kilometers offered and demanded by an airline
- The 200 largest airlines in the world (each ranked by financial result or transport performance)
- Cataloging of the world's 25 largest low-cost airlines.

5.4 OAG - UBM

The Official Airline Guide (OAG) is a business arm of United Business Media Limited, a media company based in the UK. OAG has been offering the Official Aviation Guide since 1929 (at that time exclusively in the U.S. and with 35 airlines). OAG sits at an interface between airlines and airline ticket sales systems. OAG's database contains the flight schedules of all airlines that file their schedules with OAG. This flight database contains current and detailed information on completed and planned flights, particularly aircraft types and cargo or seat capacities (OAG, 2003).

The process for adding schedules to the database is as follows: Airlines send their schedules to OAG at intervals determined by them (daily, weekly or monthly, etc.). The data goes through a quality control process at OAG and is then standardized for inclusion in the database and distributed worldwide to travel agents' and airlines' computer reservation systems, online booking platforms, industry analysts, publishers, government agencies and airline industry service providers. The service is free to airlines. The incentive for airlines to submit their schedules comes from the associated marketing opportunity for their flight capacity.

OAG itself states on its website to be the most trusted source of flight schedules worldwide. Comparing the 2009 worldwide air passenger figures from OAG (2031 million passengers) with the IATA figures of 2228 million passengers 52, the coverage of total worldwide air traffic by OAG is just under 92%. The passengers missing here are most likely due to small regional airlines that do not want to participate in the ticket booking systems. In order to determine participation in the AAI, the AAI uses the passenger data of an airline from ATI independently of OAG These airlines report their flight schedules to OAG without exception, so that here the coverage relevant for the AAI is 100%.

5.5 Airline Data T100 International

Database Products Inc (Airline Data) is a company based in the USA. Airline Data offers flight data of the U.S. market, which the company obtains from the United States Department of Transportation (DOT) (DATA BASE PRODUCTS, 2011). The Airline Data T100I product contains detailed data for the U.S. market segment (flights within as well as to and from the U.S.), including passenger capacity and load factor as well as freight capacity and load factor.

[10] See FlightGlobal website: https://www.flightglobal.com/services/data-feeds/

5.6 JP Airline Fleets International

The JP Airline Fleets International (JP) catalog has been published by BUCHair (USA) Inc. for over 40 years[11]. The JP catalog contains detailed information on the fleets of the world's airlines, including exact aircraft type designations and their engines. Additional notes indicate the presence of winglets.

5.7 IATA WATS

The World Air Transport Statistics (WATS) catalog has been published by the International Air Transport Association (IATA) for over 50 years[12]. WATS catalogs the passenger and cargo load factors of the world's largest airlines, subdivided into domestic and international flights.

5.8 Aero Secure

AeroSecure is a commercial database service provider which, according to its own information, has databases on safety-related information of several hundred major airlines and offers these data to customers from the media and travel industry[13]. AeroSecure divides the airlines into different categories, some of which have been adopted in the AAI.

[11] See BUCHair website: www.buchair.com
[12] See IATA website: www.iata.org/publications/store/Pages/world-air-transport-statistics.aspx
[13] See aerosecure website: www.aerosecure.de/

6 Precision of methods and results

Summary: The Emissions Calculator is based on methods and data sources that allow a appropriately accurate calculation of the climate impact of a flight. Depending on the customer's input, the calculator operates at different levels of precision. The key factors for the climate impact of a flight are captured and mapped by the Emissions Calculator. Data sources and methods are of high quality and represent the current state of science.

6.1 Uncertainty factors

The AAI calculations for the airlines are subject to a mean overall error of ± 1.3 efficiency points at a confidence level of 95% (atmosfair, AAI 2013). In addition, there are the errors from the influencing factors that were not included in the AAI calculations because they do not cause a sufficiently large difference between the airlines (atmosfair, AAI 2013). This results in an overall error of the AAI ranking of ±1.5 efficiency points. Since a confidence level of 95% was used, the AAI can significantly differentiate between airlines whose efficiency scores differ by more than 1.5 efficiency points.

6.2 Data quality

The databases are part of the heart of the AAI. The AAI places high demands on them in terms of the quality, depth, timeliness, and independence of the information. The AAI only uses high-level sources from international organizations or long-established, specialized service providers. In no case did the AAI use data published by the airlines via their websites, annual reports or own statistics, etc. To ensure the quality of the data, the AAI covers each influencing factor through at least two independent sources and subjects them to consistency checks. The quality of these data is high. Among other things, they were the starting point for emission inventories in the IPCC report commissioned by the United Nations.

6.3 Quality of the methodology

The AAI methodology and the parameters used are sufficient to calculate the CO_2 emissions of different airlines on different routes to within 1.5 percentage points (atmosfair, AAI 2013)

6.4 Precision levels

The Emissions Calculator works on two different levels of precision.

1. If the customer knows the aircraft type and enters it via the input mask, the emissions calculation is performed directly via the aircraft type. The value determined by the atmosfair Emissions Calculator directly accesses all important parameters in detail. The atmosfair Emissions Calculator currently offers 74 aircraft types with their variants for selection.
2. If the user does not specify the type of aircraft, atmosfair calculates an average value for all aircraft of an airline flying on the entered route. The calculator then displays the values for the two best airlines on the searched route, as well as the value for an average airline[14].

[14] Average of all airlines flying on route

7 References

atmosfair, AAI 2011: atmosfair Airline Index – Dokumentation der Berechnungsmethode, Berlin 2011, abrufbar unter: https://www.atmosfair.de/de/atmosfair_airline_index

Azar et al., 2012: „Valuing the non-CO2 climate impacts of aviation“. Climatic Change Volume 111 (2012), 559 – 579

Brockhagen, Dietrich 1995: Der Flugverkehr der Stadt Köln und das Klimabündnis. Wuppertal Papers Nr. 43, Wuppertal: Wuppertal Institut für Klima, Umwelt, Energie.

Bucher, 2007: „JP Airline-Fleets International“. Zurich, Switzerland: Bucher & Co., jährliche Publikation.

Cao et al., o.J.: „JP Airline-Fleets International“. : A Preliminary Study on Operational Feasibility of Continuous Descent Approach. School of Aeronautics and Astronautics, Purdue University: http://web.ics.purdue.edu/~cao20/_private/report.pdf (01.03.11)

Dahlmann et al. 2019: “Integration of Non-CO2 Effects of Aviation in the EU ETS and under CORSIA”, Projektbericht Umweltbundesamt. 242

DATA BASE PRODUCTS (2011): Produktbeschreibung von der Data Base homepage, aufgerufen am 23.02.2011 (www.airlinedata.com/CurrentData.htm)

DLR 2000: Datenbanken mit Emissionsprofilen von zivilen Jets, erstellt vom Deutschen Zentrum für Luft- und Raumfahrt im Rahmen der Studie „Maßnahmen zur verursacherbezogenen Schadstoffreduzierung des zivilen Flugverkehrs“, F + E – Vorhaben 105 06 085 im Auftrag des Umweltbundesamtes, TÜV-Rheinland, DIW, Wuppertal Institut für Umwelt, Klima, Energie. Die Datenbanken liegen beim Umweltbundesamt.

EASA 2020: „Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)” (2020) 166
https://eur-lex.europa.eu/resource.html?uri=cellar:7bc666c9-2d9c-11eb-b27b-01aa75ed71a1.0001.02/DOC_3&format=PDF

ICAO 2010: „ICAO Carbon Emissions Calculator“. Version 3, Montreal 2010

IPCC 1999: „Aviation and the Global Atmosphere“. A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer. J.E.Penner, D.H.Lister, D.J.Griggs, D.J.Dokken, M.McFarland (Eds.), Cambridge University Press, UK.

IPCC 2013: „Changes in Atmospheric Constituents and in Radiative Forcing“. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Grassl, H und Brockhagen, D. 2007 Climate forcing of aviation emissions in high altitudes and comparison of metrics. An update according to the Fourth Assessment Report, IPCC 2007. MPI, Hamburg, 2007, accessible at: http://www.mpimet.mpg.de/wissenschaft/publikationen.html

Lee et al. 2010: „transport impacts on atmosphere and climate: aviation“, atmospheric environment 44 (2010), 4678 – 4734

Lee et al. **2020**: “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018”, Atmospheric Environment 244 (2020), 1117834

OAG (2003): About OAG data, website of OAG data (http://oagdata.com/aboutoagdata/overview.aspx)

PIANOX (2008): Aircraft Emissions Performance. User´s Guide, Piano-X © 2008 Lissys Ltd, London

UBA 2008: „Klimawirksamkeit des Flugverkehrs. Aktueller wissenschaftlicher Kenntnisstand über die Effekte des Flugverkehrs, Umweltbundesamt, Dessau, März 2008.