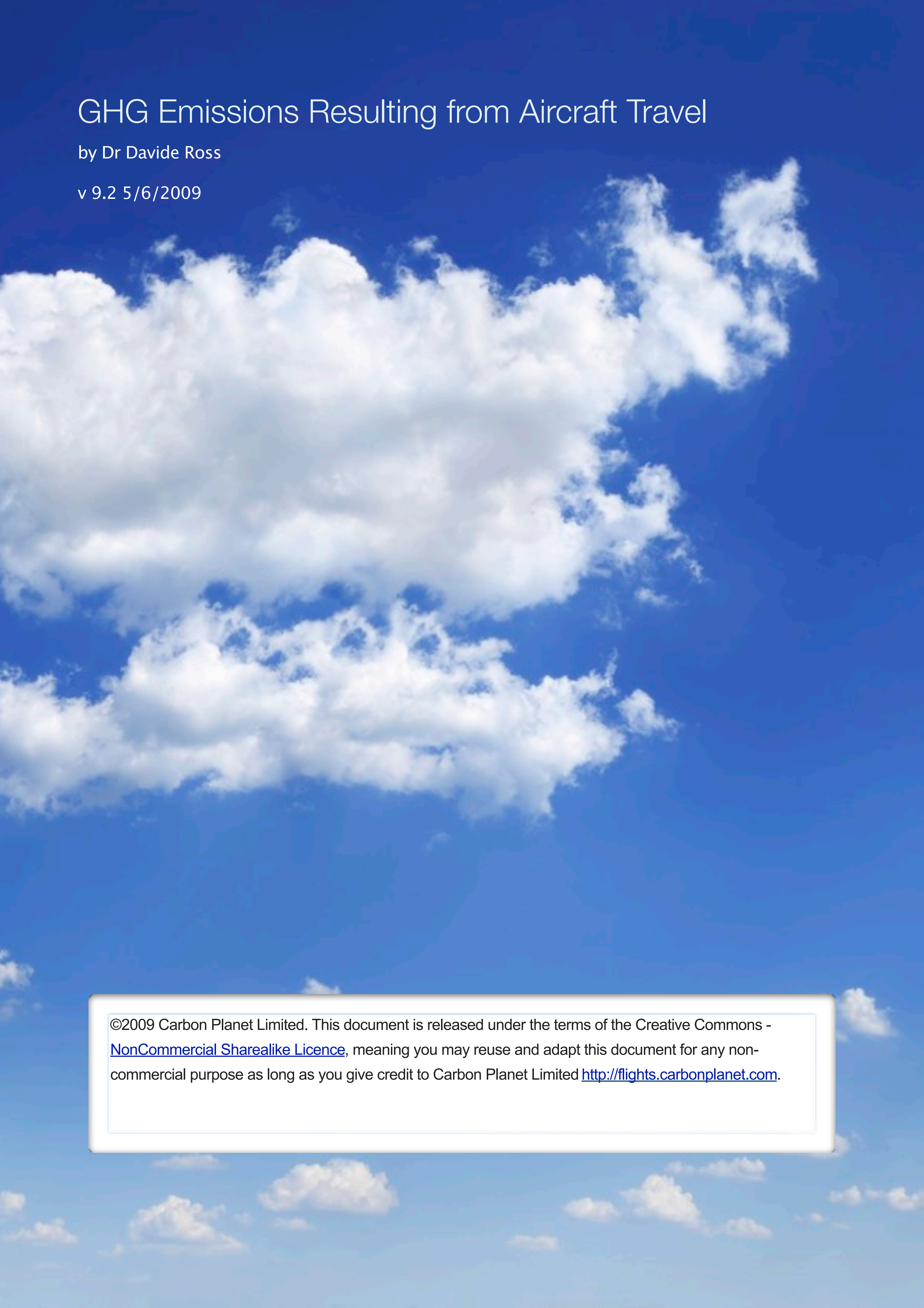
GHG Emissions Resulting from Aircraft Travel

Carbon Planet



GHG Emissions Resulting from Aircraft Travel

by Dr Davide Ross

v 9.2 5/6/2009

Introduction

Carbon Planet endeavours to provide our clients with concise, detailed and fully referenced background industry and scientific knowledge on the aviation industry and its impact on climate change. It is widely acknowledged that man–made emissions of greenhouse gases, predominately from the consumption of carbon based fossil fuels, are causing major changes to the planet's climate. Aviation emissions differ in that they have a greater climate impact than the same emissions made at ground level.

Emissions from aircraft flying at cruising altitudes (8 to 13 km) affect atmospheric composition in a height region where there might be significant climate impact through changes in the chemical and physical processes that have climate change consequences.

Future emissions from aircraft are expected to increase much more rapidly than emissions in general, with global aviation annual growth currently estimated between 4 to 5%. Therefore, not only will the overall impact of aircraft emissions increase, but also the importance relative to the total climate impact. In order for carbon credit offsetting to be credible, the calculation of greenhouse gas emissions resulting from flights requires a special approach, which is outlined in this report.

1. Aircraft Transportation

The rapid growth of worldwide air travel has prompted concern about the influence of aviation activities on the environment. Demand for air travel has grown at an average rate of 9.0% per year since 1960 and at approximately 4.5% per year over the last decade [1]. The estimated future worldwide growth will average 5% annually through at least 2015 [1].

Improvements in the energy efficiency of the aviation system have failed to keep pace with industry growth, resulting in a net increase in global emissions as shown in Figure 1 [2]. Flight emission factors were tabled in the book Aviation and the Global Atmosphere, Chapter 8: Air Transport Operations and Relation to Emissions, Section 8.3.2 Ambient Factors, which can be found on the United Nations Environment Program (UNEP) website [3,4].

The GHG intensity for various types of transport is re-presented in this report as Figure 2, and provides emission values in terms of grams of carbon per km each passenger travels. All business travel by air transport is categorised as Scope 3, indirect emissions.

The data for this diagram comes from an investigation conducted by the Centre for Energy Conservation and Environmental Technology (1997) on Energy and Emission Profiles of Aircraft and Other Modes of Passenger Transport over European Distances [3]. The range presented for C emissions for each passenger mode are due to differences in the values from each country and region under investigation, the types of fuel used to power the transport (e.g., non-fossil (renewable, nuclear) versus fossil), the infrastructure available, the efficiency of transport (i.e. grade of aircraft), and load of transport (i.e. passenger numbers).

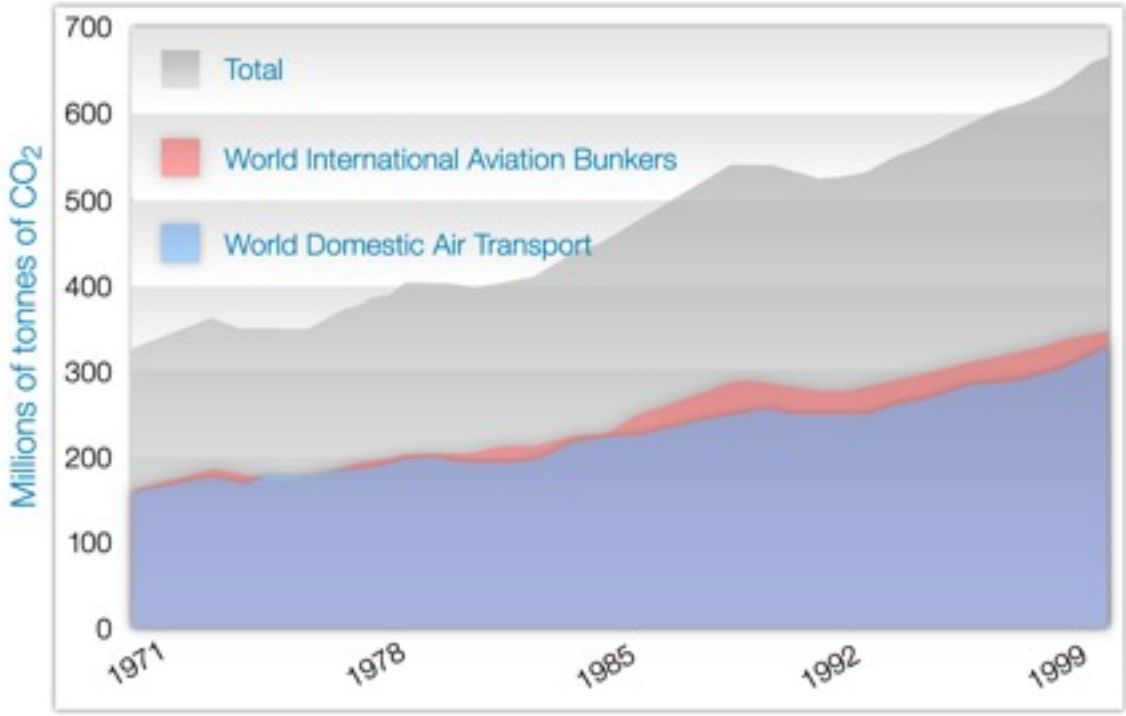


Figure 1: Global CO_2 emissions from domestic and international aviation 1971-1999. Source: IEA 2002 [2]

For aircraft transport in particular, GHG emissions vary according to the flight distance since the greater proportion of the emissions is at take-off which requires higher fuel consumption. Figure 3 is reproduced from a report on GHG emissions of the fuel intensity of passenger air travel [5].

The data was complied for specific fuel intensity of different types of aircraft, based on recent information from various European and Asian airlines' yearly environmental audits, some recent operating statistics for the American air carriers that are submitted to the US Department of Transport, and some information from a number of academic studies that analyse the fuel intensity of aircraft.

The use of more fuel-efficient aircraft engines and the introduction of larger aircraft accommodating more seats per aircraft in combination with an increase in the average stage distances, has reduced the fuel use per available seat kilometre (ASK). The improvement in the specific fuel consumption has furthermore reduced the necessary amount of fuel that has to be carried on flights of comparable distances leading to additional fuel savings. Furthermore, the operation at higher passenger load factors has contributed to reduce the fuel use per revenue passenger kilometre (RPK) [5].

A publication by Babikian et al. [6] focused on the impact of regional aircraft characteristics of turboprop and regional jet aircraft in the U.S. aviation system. In summary, regional aircraft are 40% to 60% less fuel efficient than their larger narrow- and wide-body counterparts, while regional jets are 10% to 60% less fuel efficient than turboprops.

Fuel efficiency differences can be explained largely by differences in aircraft operations, not technology. Direct operating costs per RPK are 2.5 to 6 times higher for regional aircraft because they operate at lower load factors and perform fewer miles over which to spread fixed costs [6].

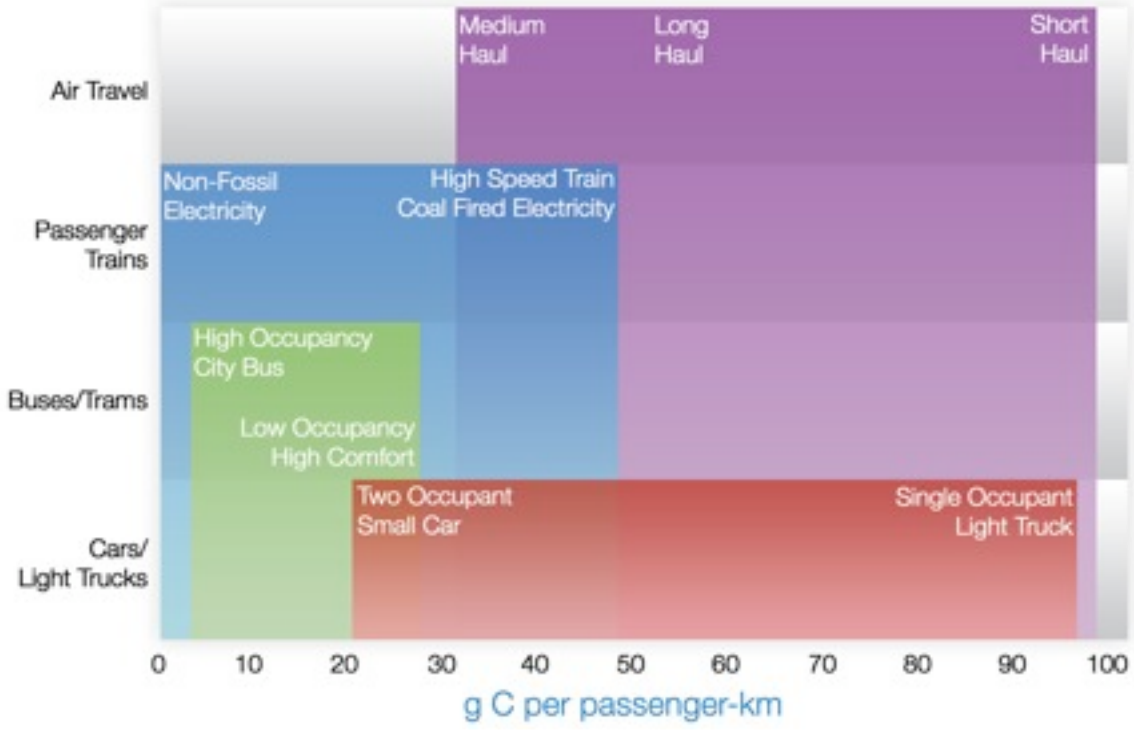


Figure 2: Carbon intensity of passenger transport (IPCC, 1999).

Aircraft operations—airports served, stage lengths flown, and flight altitudes—have a particularly significant impact on the emissions of regional aircraft. They fly shorter stage lengths than large aircraft, and as a result, spend more time at airports taxing, idling, and manoeuvring into gates, and in general spend a greater fraction of their block time in non-optimum, non-cruise stages of flight. The impact of operational differences, and especially distance flown, on emissions is evident in the reproduced Figure 4.

Aircraft flying stage lengths below 1000 km have energy use (EU) values between 1.5 to 3 times higher than aircraft flying stage lengths above 1000 km. Also, turboprops show a distinct pattern from that of jets, and are, on average, more efficient at similar stage lengths [6].

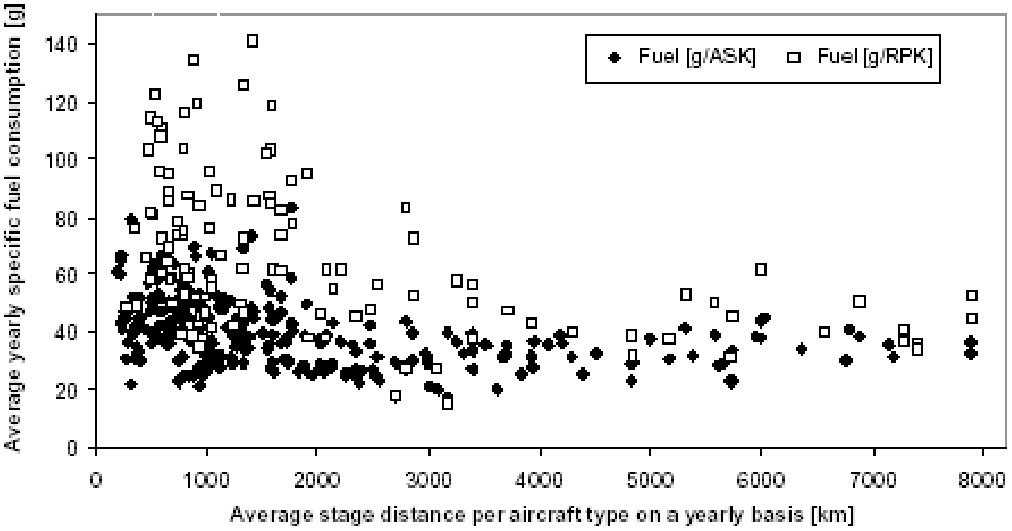


Figure 3: Specific fuel consumption versus stage distance for different types of aircraft [5].
Data sources: [Premiair 2001] [All Nippon Airways 1999, 2000a and 2000b] [Lufthansa 1999 and 2000] [Lufthansa City Line 1999] [Swissair 1999] [SAS 1999b and 2000] [Sarames 1984] [Air Baltic 2001] [DOT 2001] [Norwegian Air Shuttle 2001] [AEA 1999]

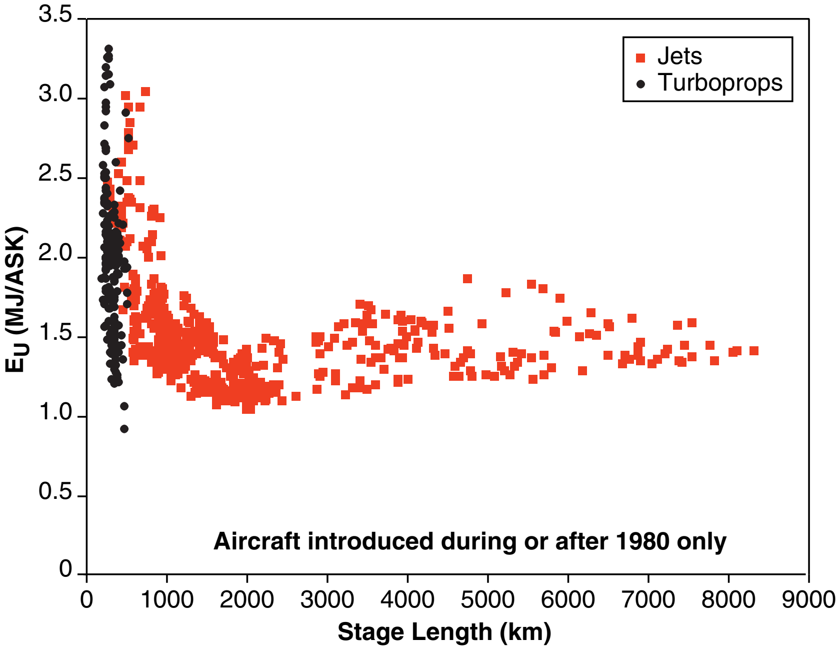


Figure 4: Variation of energy use (EU) with stage length for turboprop and jet-powered aircraft (both Regional jets and large jets) introduced during and after 1980 [6].

2. Radiative Forcing Index

However, an important consideration when dealing with aircraft emissions is that the effect of aviation is more than just that from CO_2 alone. The impact of aviation on the atmosphere needs to also include the effects of NOx compounds, ozone, methane, water, contrails and particles which are all emitted from aircraft exhausts at the same time as CO_2. As these compounds are released directly into the atmosphere, their potential to effect the anthropogenic radiative forcing that naturally takes place in this region, is much greater than that for fossil fuel production, due to the longer residence times required for the latter. This effect is taken into account by the development of the radiative forcing index (RFI) which compares the total radiative forcing effect caused by aviation to that caused by CO_2 alone [7]:

$$\mathrm{RFI} = \frac{\mathrm{RF}(\mathrm{CO_2}) + \mathrm{RF}(\mathrm{O_3}) + \mathrm{FR}(\mathrm{CH_4}) + \mathrm{RF}(\mathrm{H_2O}) + \mathrm{RF}(\mathrm{contrails}) + \mathrm{RF}(\mathrm{particles})}{\mathrm{RF}(\mathrm{CO_2})}$$

In 1992, the RFI for aircraft was estimated at approximately 2.7, with an uncertainty of at least ±1.5 [7]. 3-D inventories for present and projected future aviation operations have been produced with permission of NASA's Atmospheric Effects of Aviation Project (AEAP), the European Civil Aviation Conference's ANCAT and EC Emissions Inventory Database Group (EIDG), and DLR (German Aerospace Centre) and used to predict changes in RFI up to the year 2050.

RFI was deduced as 3.0 by 2015 but then drops to 2.6 for alternative technological scenarios by 2050 [7]. These studies revealed that the index can range from 2.2 to 3.4 within the year 2050 for the various subsonic aviation and technical options considered.

The UK Royal Commission of Environmental Pollution and the Commission of Integrated Transport [8] have both acknowledged that while there is continued debate and scientific review as to the exact value of the RFI, the present scientific evidence clearly indicates that RFI is an important factor towards the assessment of total GHG emissions from flying.

By definition, radiative forcing ranks the instantaneous effect of accumulated emissions up to a given point in time. Radiative forcing for aviation, represents the radiative forcing at a given time due to all prior and current aviation activity (accumulated CO_2 emissions, plus present day, short-lived impacts like contrails). Since different climate effects have different time scales, radiative forcing estimates can produce a misleading comparison of the relative contribution from short lived and long-lived effects.

A recent review by Forster et al. (2006) [11] suggested that the current RFI fails to account for resident time scales of emissions, and that this exaggerates the impact of non-CO_2 climate effects of aviation. Figure 5 displays predicted radiative forcing of CO_2 and non-CO_2 compounds from aircraft-induced emissions using a simplified carbon cycle model.

The scenario assumes constant current emissions as a basis (taking year 2000 as the reference point) and as a consequence, non-CO_2 RF's are set to be in equilibrium with their environment, i.e. they do not change (the constant line as shown in Figure 5). Non-CO_2 residence times in the atmosphere are much lower than CO_2. However, this is subject to high uncertainties and variances across individual components as shown in Figure 6 [12].

What results is a continual rise in CO_2 radiating forcing due to its long residence time, and hence a decrease in the radiative forcing index (RFI) over time.

The integrated RFI over a 100 year lifetime results in a value of ~1.8, a lower value than what is currently accepted by the IPCC. Unfortunately, the science behind non-CO_2 climate effects requires further assessment in order to accurately include them in the current RFI models.

Sausen et al. (2005) [12] provide estimates of the various contributions to the radiative forcing (RF) from aviation, presented mainly based on results from the TRADEOFF project [13], that updates those of the Intergovernmental Panel on Climate Change (IPCC, 1999) [17,14]. The new estimate of the total RF from aviation for 2000 is approximately the same as that of the IPCC's estimate for 1992. This is mainly a consequence of the strongly reduced RF from contrails, which compensates the increase due to increased traffic from 1992 to 2000.

The RF from other aviation-induced cirrus clouds might be as large as the present estimate of the total RF (without cirrus). However, the present day knowledge on aircraft-induced cirrus clouds is poorly understood to provide a reliable estimate of the associated RF.

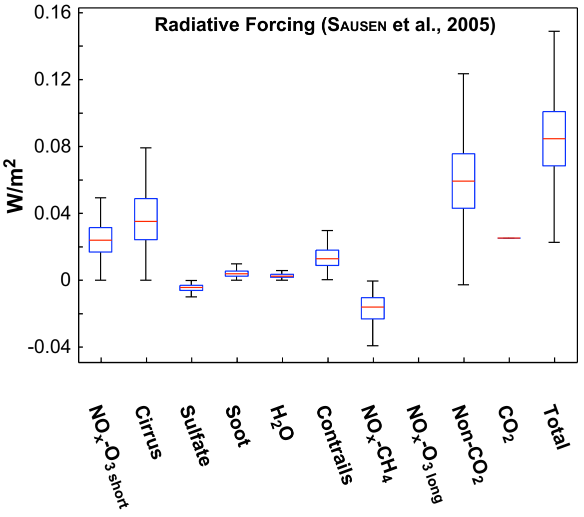


Figure 6 A comparison of CO_2 and non-CO_2 radiative forcing [12]

Apart from triggering linear contrails, aviation has the potential to change cirrus clouds in the following ways:

- Contrails do not always evaporate after short intervals (minutes). If the background atmosphere is sufficiently supersaturated with respect to the ice phase, they can grow to larger cirrus clouds, or contrail cirrus, which cannot be distinguished from natural cirrus clouds if their history is unknown. Mannstein and Schumann (2005) [15] estimated that the cover by contrail cirrus in central Europe is approximately 10 times larger than the cover by linear contrails.
- Aircraft directly emit particles (e.g., soot) and also precursors of volatile particles (e.g., sulphur oxides). These aerosols are eventually transformed into cloud condensation nuclei, which may trigger the formation of cirrus clouds much later than the original emission, if the background atmosphere has changed to a state allowing cloud formation (supersaturation). An observational proof of this effect is still lacking although theory allows this process.
- Aircraft-induced aerosols can additionally modify the micro-physical properties of cirrus clouds, change cloud particle sizes and forms, and the number of cloud particles. The result of such modification may include a change in the precipitation rate, in cloud lifetime and in cloud radiative properties. A quantification of this effect is still the subject of research.

Zerefos et al. (2003) [16], after removing the influences of natural phenomena found an increase in cirrus cover in high air traffic areas over Europe of +1.3% per decade, contrasting with a decrease of -0.2% per decade in adjacent low air traffic areas. Similar positive trends in cirrus cloudiness were found in other regions with high aircraft density.

Stordal et al. (2005) [17] extrapolated their result in time to cover a longer period of aircraft operations and on the global scale, assuming the radiative efficiency of cirrus to equal that of contrails. This yielded a "mean" RF of 30 mWm-2, associated with a large uncertainty range of 10 to 80 mWm-2.

Both the studies of Zerefos et al. (2003) and Stordal et al. (2005) are based primarily on correlation analyses. These studies can provide statistical evidence of an association between aviation and observed changes in cloudiness, but do not prove causality.

Coincidentally, the heaviest air traffic is found in regions where the subtropical and the subpolar jets are often found, i.e., the cloudiness in these regions is potentially sensitive to decadal natural climate variability and to anthropogenic climate change. Therefore, there are reservations in considering the RF above as a best estimate; and it is, rather, an order of magnitude estimate of the RF from aircraft-induced cirrus changes.

The assumption that the radiative efficiency of cirrus equals that of contrails is highly uncertain. Nevertheless, based on current knowledge the best estimate of aviation-induced cirrus RF is somewhere between zero and an estimated upper bound. Due to this lack of knowledge it is not yet possible to add the RF for aviation-induced cirrus changes to the total aviation RF. Evidently, if the actual value was close to the "mean" value of Stordal et al. (2005), the total RF would increase substantially, and consequently aviation's share to the total anthropogenic RF.

In summary, the recent TRADEOFF study has updated the RFI figure and a value of 1.9 is now the best-quantified estimate of radiative forcing index of aviation emissions excluding the probable but unproven effects of cirrus clouds [13].

Hence, aviation CO_2e emissions in this calculator use the current consensus estimate by DEFRA and TRADEOFF for the radiative forcing index of 1.9.

3. Emissions Factors

A final calculation of CO_2e emissions values from air transport including the enhanced radiative forcing index by aircraft of 1.9 was determined from a compilation of references [5,6,13,34,35].

Commercial flights have been classified into four groups, domestic, short, medium and long haul, based on the emissions profiles versus stage distance of the literature [5,6,]. This methodology has deviated slightly from DEFRA's application by segregating flights less than 1000 km into short haul and domestic haul flights (<400 km). This is summarised in Table 1.

Domestic flights exclude the contribution of RFI because of the limitation to the altitude attained in the CCD cycle for short distances as discussed in the following section. In addition, the majority of these short regional flights are taken by turboprop aircraft. Standard deviations were approximated from Qantas data [35]. All regional flights via turboprops and small jets were considered short/domestic haul not due to distance but due to efficiency of the flight [6]. As these average emissions factors are determined from industry data, they already incorporate passenger load factors.

In addition, if the specific sector distances flown are unknown, i.e. only the total passenger distance is available, then the Generic emissions factor should be used. This was determined from a summary of over 2200 flights across all four stage lengths [35].

The US Department of Transport, Research and Innovation Technology Administration (RITA) [18] publishes a monthly passenger revenue load factor. The most current data for August 2005 at 80.62 percent. This is reproduced in Figure 7 below. Load factor is the percentage of seating or freight which is utilised.

The data include both trans-border and foreign flights by large U.S. carriers, but do not include any flights by foreign carriers. In summary, short/domestic haul flights have higher emissions due to the strong influence of the Landing/Take Off cycle (LTO) on emissions, while longer haul flights have slightly higher emissions then medium haul flights due to the additional weight of fuel required for the longer journey.

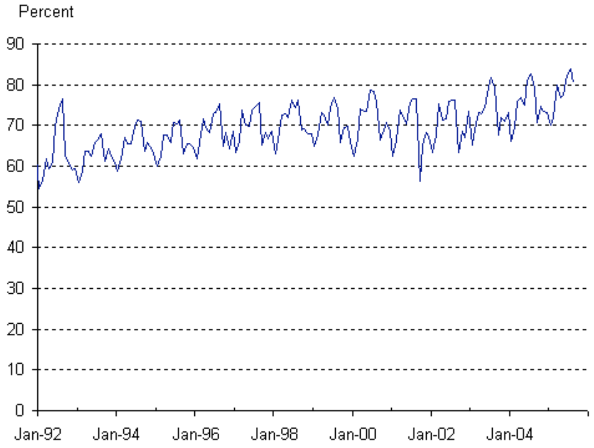


Figure 7 Passenger Revenue Load Factor (monthly) US carriers only [18]

TABLE 1: A summary of average aviation CO_2e emission factors versus stage length

Flight type	Stage Length (km)	Emissions ($kgCO_2e$/passenger.km)	Standard Deviation ($kgCO_2e$/passenger.km)
Domestic Haul [1]	0<DH<400	0.26	± 0.06
Short Haul	401<SH<1000	0.36	± 0.05
Medium Haul	1001<MH <3700	0.20	± 0.03
Long Haul	3700<LH<16000	0.23	± 0.04
Generic	0<Generic<16000	0.28	± 0.1

[1] Domestic flights (<400 km) are via either piston driven turboprop aircraft or jet aircraft which are limited to the altitude attained in the CCD flight cycle. Therefore no RFI was applied. All other flights use a RFI of 1.9. Standard deviations derived from Qantas data [35].

What about if my flight is only 50% full? Since the weight of a jet is determined to a large extent by the airframe and fuel carried, whether there are many or few passengers on board has minimal impact on total fuel consumption.

The increase in demand for air travel is an important factor in aircraft capacity utilisation. Airline economics dictate that costs, including fuel costs, be minimised, and therefore the load factor be optimised. A second important factor is the (further) development of the "hub and spoke" system in some parts of the world, such as the United States and Europe. Because transport efficiency is not always optimised by direct point-to-point travel, air travel has evolved from direct connections to a complex network that includes consolidation hubs.

Costs are minimised by maximal use of single-sector, out-and-back operations. By combining these sectors in a hub-and-spoke network, an efficient multiplication of potential point-to-point markets served can be achieved. Moreover, load factor and aircraft configuration are driven not only by the need for improved efficiency but also by market considerations[1].

A clearer understanding of the global fuel burn profile from aviation is seen in Figure 8 done using the processed data for the year 2000 [37].

The 4D gridded inventories are processed to aggregate fuel burn and emissions into 1° latitude by 1° longitude by 1 km world grids. The raw inventory contains the actual time a flight entered into each of these grids.

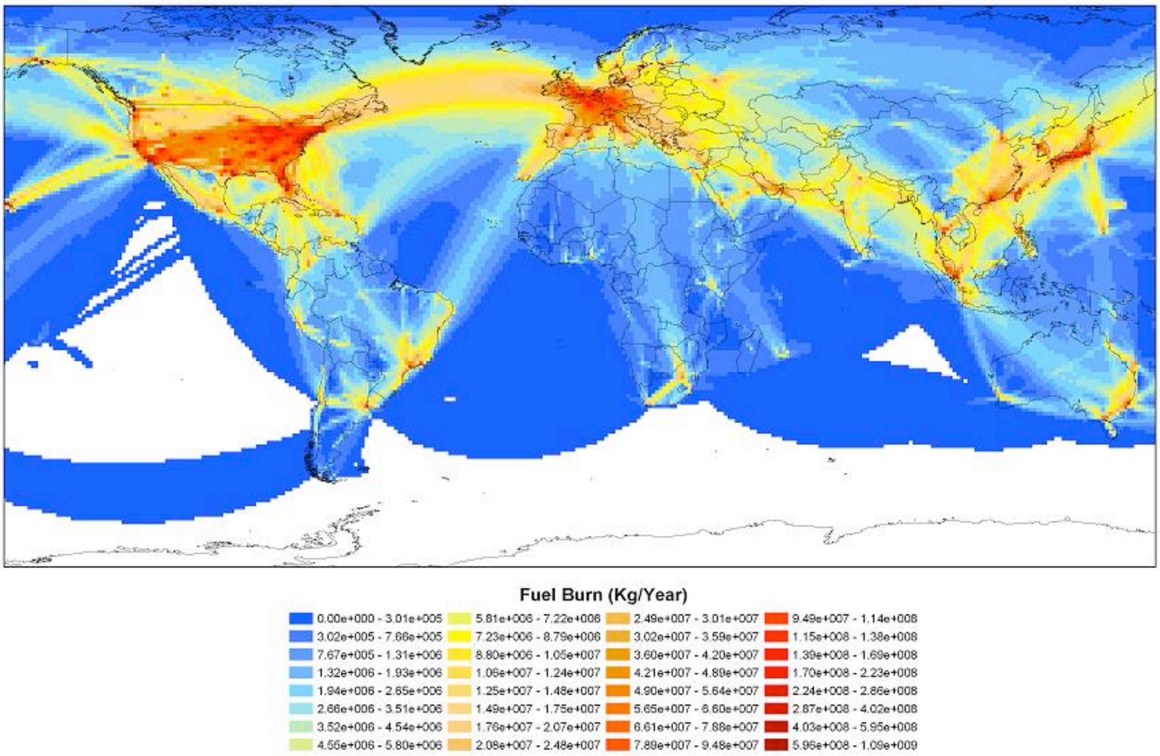


Figure 8 Gridded Plot of Global Fuel Burn for 2000 with all Altitudes Aggregated. (Reproduced [37])

4. Flight cycle

The operations of aircraft are usually divided into two main components (Figure 9) (EEA 2000 [19]):

- The Landing/Take-off (LTO) cycle which includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). This therefore includes taxi-in and out, take-off, climb-out, and approach-landing. The LTO is defined in ICAO (1993), and
- Climb, Cruise and Descent cycle (CCD) is defined as all activities that take place at altitudes above 3000 feet (1000 m). No upper limit of altitude is given. The fuel use accounts for the bulk of the flight distance, and varies with flight length.

The cruise phase, in which the aircraft covers a certain distance at a constant altitude can vary depending on the total stage length distance. The flight altitude of this phase varies typically on short-haul flights in the range from about 5 to 7 kilometres, and medium and long-haul flights vary between 10.5 to 13 kilometres.

Emissions and fuel used in the LTO phase are estimated from statistics on the number of LTOs (aggregate or per aircraft type) and default emission factors or fuel use factors per LTO (average or per aircraft type).

Some statistics count either a landing or a take-off as one operation. However it should be noted that both one landing and one take-off define a full LTO-cycle in this report.

Figure 9 Aviation flight cycle [19]

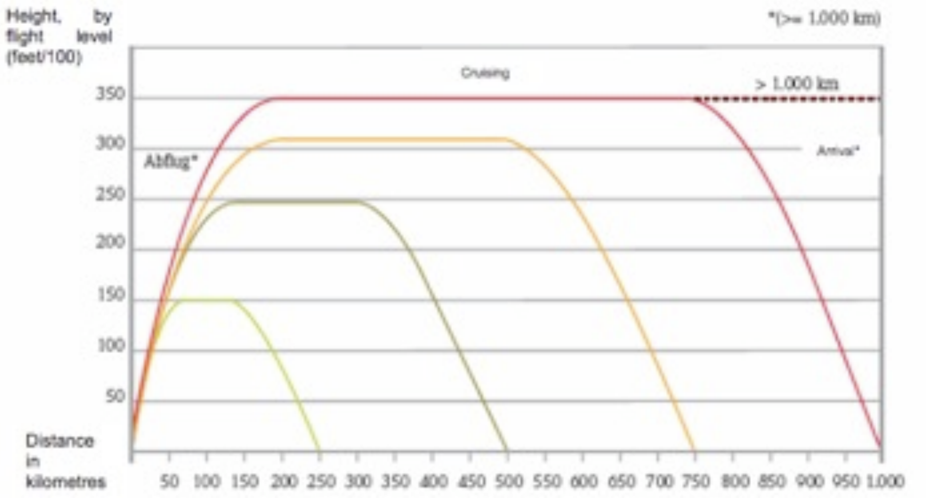


Figure 10 Simplified altitude profiles as a function of stage length. Reproduced from Atmosfair [24]

5. Seating Class

Apart from load factor, aircraft type, and level of technology of the plane, the configuration of an aircraft (number and class of seats, distribution between seating and cargo capacity) also has an important influence on fuel burned per passenger-km. The configuration is determined by the airline in consultation with the aircraft manufacturer and can be altered during the aircraft's lifetime. The configuration differs between airlines and is based on market considerations.

For passenger airlines, carrying passengers is the primary economic purpose of passenger aircraft, while freight is assumed to account for a small portion of fuel consumption. Taking a Qantas Boeing 747-400 with a maximum take off weight 396.8 tonnes, and a maximum indicated freight load capacity of 15.7 tonnes, freight would account for less than 4% of aircraft fuel consumption. The maximum total payload is 51.5 tonnes, which is small compared to maximum takeoff weight. This illustrates to a certain degree, that the space occupied by passengers and not the net weight contributed by each passenger is a determinant to the number of passengers an aircraft can carry, and therefore the energy intensity per passenger.

A good example to illustrate this fact is provided by the way Japan Airlines (JAL) configures its Boeing 747-400 aircraft [9]. The 747-400 in long-range full passenger configuration can have as little as 262 seats, whereas the 747-400D used in high-density local Asian service has 568 seats. Even when used for similar stage lengths, the energy intensity per seat-km is proportionally lower at 1.7 and 0.8 MJ per seat-km, respectively (4000 km stage flight). However, the total fuel consumption for the two aircraft configurations remains almost identical at, 52,710L (13.2 L/km) versus 53,775L (13.4 L/km), respectively. This clearly demonstrates that the different seating configurations occupied by each of the different classes; first, business, premium economy, and economy has an impact on net energy intensity per seat-km. It is interesting to note that the actual fuel consumption rate of the planes differ very little between the two scenarios. But this is easily understood in that the bulk of the mass moved between the two points lies in the aircraft body and the fuel carried.

Thus, to fly an equivalent number of passengers under these two scenarios, two standard flights in the long-haul configuration will be required for every single high-density flight. While this is an example of the upper limiting case of an all economy high density flight versus a mix of classes, it does illustrate that because of market considerations to accommodate passengers in business and first class who require larger seating space, the energy intensity per seat-km must increase.

The seating capacity varies between aircraft type, individual aircraft configurations and the airlines [9]. Reviewing market data complied by the SeatGuru web site [20], the typical seating requirements for the various classes are shown in Table 2 and discussed as follows.

Premium Economy, a separate class of seating and service, that differs from standard Economy. Premium Economy is found mostly on international flights and, compared to standard Economy, offers about 5-7 inches of extra legroom as well as additional amenities, which can include 1-2 extra inches of seat width and 2-3 extra inches of seat recline.

Business Class is found mostly on international routes and planes that are configured for long-haul travel. This class of service offers significantly more comfort and amenities than standard Economy and Premium Economy, which usually include double the seat pitch (legroom) compared to Economy and 2–3 extra inches of seat width compared to Economy.

First Class is only found on long–haul routes. This class of service offers more comfort and amenities than Business, which usually includes 10–30 extra inches of seat pitch (legroom) compared to Business and 1–2 extra inches of seat width compared to Business. In addition the type of seat offered can vary significantly. First Class and Business Class seats can be categorised by one of the following descriptions:

Recliner Seats: These seats do not offer the significant recline of the Lie–flat and Flat Bed Seats, but still offer excellent space and comfort.

Lie–Flat Seats: While airlines often market these seats as having 180 degrees of recline, in their fully reclined position they are slightly angled and do not lay completely horizontal. Passengers often find these seats to be extremely comfortable for relaxing and working, but not conducive to sleep when in the fully reclined position because of the awkward angle.

Flat Bed Seats: When fully reclined, these seats are completely horizontal, creating a bed that is fully flat. These seats always receive high accolades for being comfortable both as seats and beds.

Suite Seats: These seats offer the utmost in privacy and comfort. Each suite is essentially its own mini–cabin which includes a fully–flat bed, work station and television.

The sample size of the seating analysis was from a total of 758 airline observations, available on SeatGuru [20]. In summary, Table 2 shows that on average premium economy, business and first class seats occupy 1.3, 2.1 and 3.2 times the space of a single economy seat, respectively. Fuel consumption per seat is proportional to the space occupied.

Table 2 A summary of seat space across various classes

Flight Class	Seat Pitch (inches)	Seat Width (inches)	Comparison
Economy	32	17.5	1
Premium Economy	39	19.1	1.3
Business	57.3	20.9	2.1
Flat Bed	72.7	22.8	3
Lie–Flat	60.1	20.9	2.3
Recliner	48.3	20.1	1.7
First	77.6	23.1	3.2
Flat Bed	79	23.1	3.3
Lie–Flat	66.2	21.2	2.5
Recliner	61	20.9	2.3
Suite	82.1	24.6	3.6

Therefore, current market average data for the various stage length emission factors listed in Table 1, can be further apportioned to reflect the higher emissions attributed to flying different classes as shown in Table 3 and Table 4.

Table 3 summarises the following calculation methodology and Table 4 reflects 2008 DEFRA data [34].

The influence of seating type was based on a typical seating configuration for a Qantas Boeing 747–400 Longreach aircraft, with 14 first, 50 business and 315 economy seats, totalling 379 passengers [21].

Using the method of Rose (2006) [22], the following equation was used to determine the fuel accounted for by an all economy equivalent class seat (x, assuming average fuel consumption of 14.2 L/km):

$$3(14)x + 2(50)x + 315x = 14.2 \text{ L/km}$$

$$x = 0.031 \text{ L of jet fuel per km}$$

Multiplying by the Specific Energy content of aviation turbine, 36.8 MJ/L [23]

$$= 1.15 \text{ MJ/ economy seat km}$$

Assuming a 75% load factor:

$$= 1.54 \text{ MJ/ economy seat km}$$

Converting this to emissions, assuming EF of 0.0745 kg CO_2e/ MJ [23] and multiplying by 1.9 to take into account the effect of RFI, an emissions factor of 0.142 kg CO_2e per MJ, or

$$1.51 \times 0.142 = 0.22 \text{ kg } CO_2e \text{ per economy passenger km.}$$

For fuel consumption this means that Economy passengers consume 18% less than the average for all seats, while Business passengers consume 72% more, and first class passengers more then double the amount of the average seat.

This is in agreement with Atmosfair estimates, based on the seating configurations of the worlds 40 largest airlines [24]. An average configuration of 74 : 20 : 6 for economy : business : first class was derived for every 100 seats. By applying a seat space ratio of 1 : 1.9 : 2.6 for each class configuration, on average, CO_2 emission ratios are 0.8 : 1.5 : 2.0 for the three classes, respectively.

Table 3 Equivalent emissions factors for various seating classes for Qantas 747-400

No of seats	Emissions Factor	Net Emissions (kg CO_2e/km)	Comparison
Average 379 seats	0.22	83.4	–
Economy 315 seats	0.18	56.7	0.8
Business 50 seats	0.38	18.9	1.7
First 14 seats	0.56	7.8	3.1

Table 4 A summary of EF across various classes by DEFRA [34]

Stage length	Flight class	EF	Comparison
Medium	Average	0.20	1
	Economy	0.19	0.95
	Business	0.29	1.4
Long	Average	0.23	1
	Economy	0.17	0.7
	Premium	0.27	1.2
	Business	0.48	2.1
	First	0.67	2.9

The 2008 Guidelines to Defra's GHG Conversion factors also list air passenger emissions by passenger seating class [34]. These were developed on the basis of detailed analysis of the seating configurations of 24 aircraft model variants from 16 major airlines providing services within/to/from the UK. Indicative emission factors were calculated via the relative area on the aircraft occupied by different seating classes compared to an economy class equivalent per passenger.

All figures are only indicative averages and will vary considerably between different specific airline and aircraft configurations.

5 Freight Cargo

Airlines transport both passengers and freight cargo in passenger aircraft in order to make the most effective use of their aircraft. The additional cargo carried is generally handled flexibly, taking account of the seat occupancy rate by passengers for each flight.

An analysis for freight net contribution to commercial passenger flights has been calculated from information on the total cargo and passenger figures in Germany, taken from the Arbeitsgemeinschaft Deutscher Verkehrsflughäfen [ADV – German Airports Association] as reviewed by Atmosfair [24]. The ratio of cargo tonnes to passenger tonnes is around 16% in total (ADV), where a total weight of 100 kg per passenger including baggage was assumed [24]. By convention, 11.1 passenger tonne–km = 1 mass tonne–km for freight.

Australian data indicates that passengers account for over 90% of the mass carried by domestic aircraft [25]. In light of the weak correlation between payload and total fuel consumption, it is estimated that a proportion of almost 2% of the fuel consumption can be attributed to the additional freight cargo for any given flight [23], and this compares favourably to the previously stated maximum fuel consumption for freight carried on a passenger 747 flight of 4%.

6 Emissions Trading Scheme (ETS)

On the 16th of July 2008, the Australian Government's approach to the design of a national emissions trading scheme – Australia's Carbon Pollution Reduction Scheme (CPRS) Green Paper was released to the public for consultation. The CPRS will follow the so called "cap-and-trade" system, as is present in the EU. The Federal Government is currently awaiting the final completion of a comprehensive review by eminent economist, Professor Ross Garnaut.

An interim report by Prof Garnaut released on February 21st 2008, has indicated that the challenge of global warming is far worse than previously thought, requiring tougher cuts to GHG emissions than those already planned. It was indicated that the Federal Government should set a 2020 target this year and consider a deeper reduction target of beyond sixty per cent for 2050. This would necessitate radical cuts in emissions over the next 12 years.

While no price indicators have been released on the cost per tonne, a cost range somewhere between 10 and 30 dollars per tonne of CO_2e is likely.

In brief, the "cap-and-trade" system draws on the power of the marketplace to reduce emissions in a cost-effective and flexible manner. In practice, a cap-and-trade system creates a financial incentive for emission reductions by assigning a cost to polluting.

First, an environmental regulator establishes a "cap" that limits emissions from a designated group of polluters to a level lower than their current emissions. The emissions allowed under the new cap are then divided up into individual permits, usually equal to one tonne of CO_2e, that represent the right to emit that amount.

The essential difference between ETS and a carbon tax is that:

- with an ETS, the government sets the emission level to be achieved (less than business as usual) and the market determines the price of carbon
- with a carbon tax, the government sets the price of carbon and the tax produces the emission level.

The primary advantage an CPRS offers, over other approaches aimed at controlling emissions, is its environmental dependability (emissions are specifically limited).

Findings released by the Sustainable Tourism CRC, indicate that the impacts on international trip costs for two scenarios are highlighted in Table 5 [26].

Table 5 Expected total cost rise in airfares for a low and high carbon price and RFI factor [26]

Location	Carbon permit $20/tonne RFI =0	Carbon permit $50/tonne RFI = 2.5
New Zealand	2.4%	15.0%
Kong Kong	2.8%	17.4%
United Kingdom	3.4%	21.2%

In July of 2006, the European Parliament (EP) approved a resolution on reducing the climate change impact of aviation through the setting up of a separate – or closed – aviation-specific emissions trading system as a preliminary step prior to the possible inclusion of aviation in the EU's general ETS.

The scheme should initially cover all flights to and from any EU airport (if possible also intercontinental flights transiting through EU air space), irrespective of the country of origin of the airline concerned. The resolution is not legally binding, but it could influence legislation being prepared by the European Commission to include airlines in the EU's ETS.

Unlike domestic flights, carbon emissions from international flights are not included in targets established by the Kyoto Protocol to the United Nations Framework Convention on Climate Change, in part due to difficulties associated with target calculation, allocation and monitoring [27].

While financial cost is the main reason for the often glacial movements in environmental developments with respect to an ETS, for aviation there remains the much touted high uncertainties regarding "other" aviation effects (RFI).

In a recent study by Marais et al. [28], they explicitly capture some uncertainty for the science and economics by representing several model parameters as probabilistic distributions. The uncertainties are then propagated using Monte Carlo analysis to derive estimates for the impact of these uncertainties on the marginal future climate costs.

It was found that estimates of the change in global average surface temperature due to aviation are most sensitive to changes in climate sensitivity, the radiative forcing attributed to short-lived effects (in particular those related to contrails and aviation-induced cirrus), and the choice of emissions scenario.

Estimates of marginal future costs of aviation are most sensitive to assumptions regarding the discount rate, followed by assumptions regarding climate sensitivity, and the choice of emissions scenario. There are no surprises that the discount rate is top of the list regarding marginal costs for future cost modelling. The main criticism of the Stern Review (albeit mostly unwarranted) has focused on the claim that the discounting factor he used was extremely low, to yield implausible results [29].

7 Commercial Aircraft Specifications

The following tables lists some common seating configurations and specifications for commercial airline passenger jets in operation by Boeing and Airbus.

Statistics	Boeing 747-438ER	Boeing 747-438ER (Longreach)	Boeing 747-338	Boeing 737-400	Airbus 330-200	Airbus 330-300	Airbus 340-500
Seating configurations F: First B: Business E: Economy	14 F; 64 B; 265 E	14 F; 64 B; 265 E 14 F; 52 B; 315 E 56 B; 356 E	52 B; 398 E	8 B; 138 E	36 B; 199 E	30 B; 267 E	12F; 42 B; 259 E
Maximum Takeoff weight (kg)	412769	396894	377842	68040	233000	212000	372000
Average cruise speed (kph)	920	920	920	813	880	880	990
Maximum Fuel capacity (L)	227572	216507	204355	–	139100	97170	214440
Freight capacity (kg)	10976	15745	13140		13000	14500	
Volumetric payload (kg)	48208	51545	55340	23098	36000	47400	43300
Operating empty weight (kg)	238771	238771	238771	25671	118476	122200	170400

Carbon Planet makes no claim to the accuracy of the above figures. The data was complied from a variety of sources and due to variations across the aircraft models and individual airline configurations, the present information acts as a guide only to the particular aircraft specifications.

8 Aircraft Fuel Efficiency

The follow information has been sourced from the European Federation for Transport and Environment report–Clearing the Air–The Myth and Reality of Aviation and Climate Change, T&E 06/2 [30].

The gains in aviation fuel efficiency over the recent decades have been widely debated. A commonly cited figure of 70% gains between 1960 and 2000 is widely used as a reference for the industry's technological achievements.

The IPCC's Special Report on Aviation and the Global Atmosphere (1999) [14], included a graph showing trends in the fuel efficiency of new jet aircraft coming onto the market between 1960 and 2000. This graph – reproduced in Figure 11 below – shows a 70% overall fuel efficiency gain across this period (IPCC 1999; p. 298). Based on this figure, the IPCC has concluded that:

"The trend in fuel efficiency of jet aircraft over time has been one of almost continuous improvement; fuel burned per seat in today's aircraft is 70% less than that of early jets." (IPCC 1999)

Recent research undertaken on behalf of T&E by the Dutch Aerospace Laboratory (NLR 2005) shows that this figure of 70% improvement is only part of the picture at best and that over the last 50 years aircraft fuel efficiency has in fact hardly improved at all. Figure 12 shows the results of the analysis of this report.

The report states:

"If one takes new aircraft from the early sixties (i.e. the first jets) as the baseline (as presented in the IPCC report), an improvement of 55% is found rather than the 70% presented in the IPCC report."

The picture of aircraft fuel efficiency continuously improving is incomplete at best. Today's new aircraft are indeed much more fuel efficient than the earliest jets of the early 1960s, but these early jets burned two to three times more fuel than the aircraft they replaced, such as the Lockheed Constellation. The fuel consumption, per seat km, of aircraft sold in the 1950s is comparable to that of a typical new aircraft on sale today.

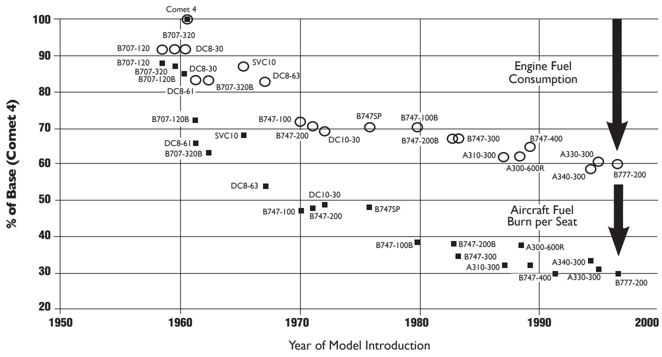


Figure 11 The IPCC's Figure 9–3, which forms the background of 70% fuel efficiency claims [14].

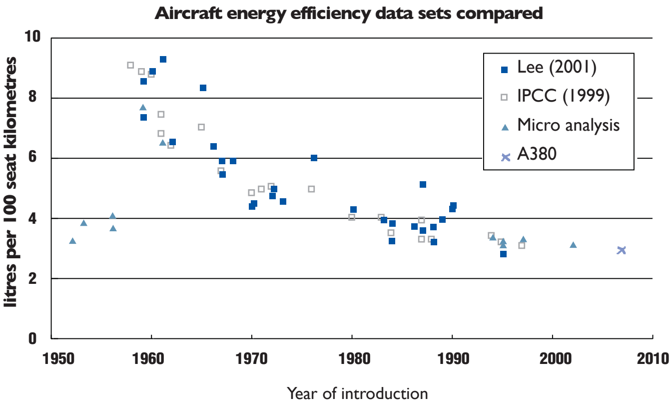


Figure 12 Development of fuel efficiency of new aircraft (in MJ per available seat kilometre) [30].

9 Market Outlook

The following short and longer term market outlook for aviation are sourced from ITAT [31] (2005–2009) and by Boeing [32] (2006–2026).

IATA forecasts for 2005–2009 project a 5.6% average annual growth rate (AAGR) for international passengers and 6.3% for international freight tonnage. The forecasts are based on the aggregate of airline expectations for major route areas. For the five-year forecast period, growth is expected to be strongest on routes connecting Asia and the Middle East, in line with strong regional economic growth and investment in capacity. International passenger growth will be lead by routes within Asia–Pacific which expect 6.8% AAGR, largely on the strength of Chinese and Indian economic expansion and liberalisation of markets.

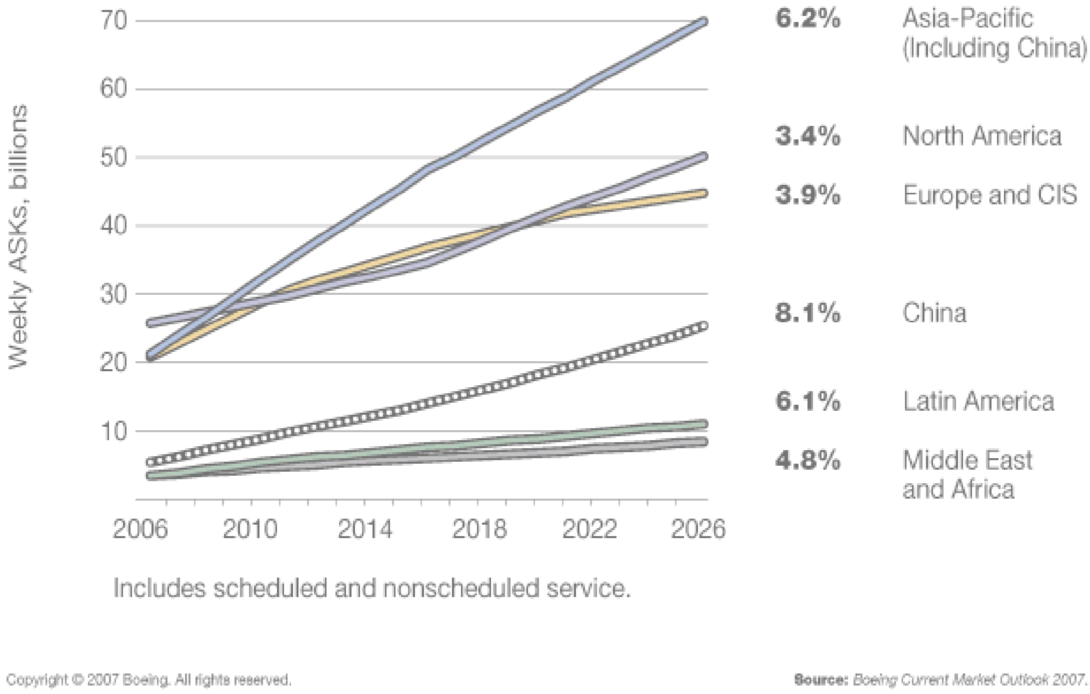
Intra-Europe traffic growth is forecast to be 5.1% AAGR, though routes in Central and Eastern Europe are expected to grow at a faster pace than in Western Europe. For individual countries, Poland's international traffic is expected to see the fastest rate of growth in passengers at 11.2%, followed closely by the China (9.6%) and the Czech Republic (9.5%).

Actual data in 2005 for the EU-25 member states saw air freight and mail grow by 3.5%, much less than air passenger traffic which grew by 8.5% in the same period. Air freight carried on domestic air services fell by more than 10%, most likely reflecting increased competition from road and rail. Intra-EU-25 freight transport accounted for 14% of all freight and mail transport by air in the EU-25. International extra-EU-25 freight transport was the largest segment of the market accounting for almost 80% of total EU-25 freight transport in 2005 [33].

Freight's projected 6.3% AAGR for international operations represents a return to trend growth rates from the weak growth seen so far in 2005. Freight flows within Asia–Pacific are expected to grow strongly with an AAGR of 8.5%, driven by the tremendous expansion in trade flows already in evidence in this region. Middle-Eastern airlines have been expanding the volume of freight they carry at double-digit growth rates, in line with their investment in expanded capacity.

Freight traffic on markets connected with the Middle East is expected to continue to expand rapidly, with an AAGR of 8.8% between the Middle East and Asia–Pacific. China is expected to see the fastest rate of growth with an AAGR of 14.4%. Overall, international air freight volumes are expected to grow from 25.2 million tonnes handled in 2004 to 34.2 million tonnes in 2009.

Projections by Boeing for the next 20 years clearly will see a substantial shift in the centre of gravity of the world airline fleet towards the Asia–Pacific region, inline with IATA projections. More than one third of the value of new airplanes delivered will be accounted for by Asia–Pacific, compared with about a quarter for North America and a quarter for Europe and the Commonwealth of Independent States (CIS).

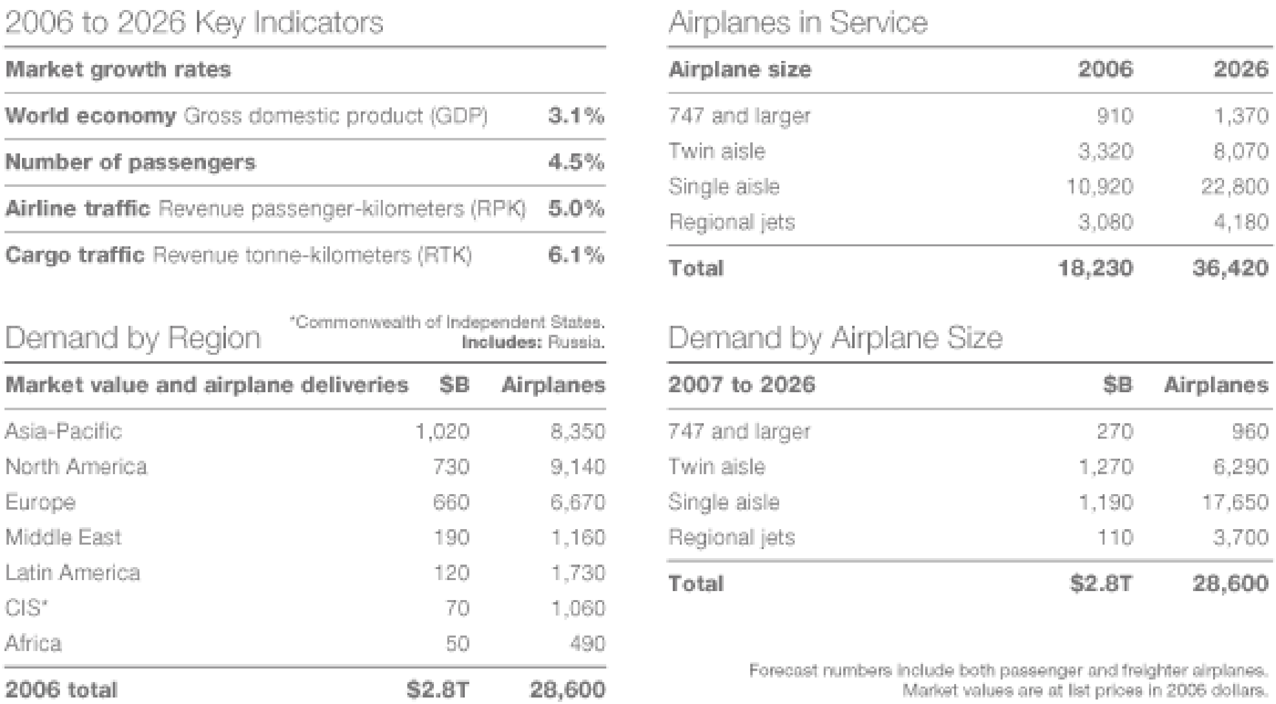


Includes scheduled and nonscheduled service.

Copyright © 2007 Boeing. All rights reserved.

Source: *Boeing Current Market Outlook 2007.*

Figure 13 Boeing current market outlook 2007 [32]



2006 to 2026 Key Indicators

Market growth rates	
World economy Gross domestic product (GDP)	**3.1%**
Number of passengers	**4.5%**
Airline traffic Revenue passenger-kilometers (RPK)	**5.0%**
Cargo traffic Revenue tonne-kilometers (RTK)	**6.1%**

Airplanes in Service

Airplane size	**2006**	**2026**
747 and larger	910	1,370
Twin aisle	3,320	8,070
Single aisle	10,920	22,800
Regional jets	3,080	4,180
Total	**18,230**	**36,420**

Demand by Region

*Commonwealth of Independent States. **Includes:** Russia.

Market value and airplane deliveries	**$B**	**Airplanes**
Asia-Pacific	1,020	8,350
North America	730	9,140
Europe	660	6,670
Middle East	190	1,160
Latin America	120	1,730
CIS*	70	1,060
Africa	50	490
2006 total	**$2.8T**	**28,600**

Demand by Airplane Size

2007 to 2026	**$B**	**Airplanes**
747 and larger	270	960
Twin aisle	1,270	6,290
Single aisle	1,190	17,650
Regional jets	110	3,700
Total	**$2.8T**	**28,600**

Forecast numbers include both passenger and freighter airplanes.
Market values are at list prices in 2006 dollars.

Figure 14 Forecast market values and key indicators 2006-2026 [32]

10 Terminology

Maximum Takeoff Weight of an aircraft is the maximum weight at which the pilot of an aircraft is allowed to attempt to take off. The Maximum Takeoff Weight is the heaviest weight at which the aircraft has been shown to meet all the airworthiness requirements applicable to it. The Maximum Takeoff Weight of an aircraft is fixed. It does not vary with altitude or air temperature or the length of the runway to be used for takeoff or landing.

Maximum Permissible Takeoff Weight, or the regulated takeoff weight, varies according to flap setting, altitude, air temperature, length of runway and other factors. It is different from one takeoff to the next, but can never be higher than the Maximum Takeoff Weight.

Zero Fuel Weight of an airplane is the total weight of the airplane and all its contents, minus the total weight of the fuel on board. Expressed more simply, any weight added to the airplane past the zero fuel weight must be in the form of fuel.

Maximum Zero Fuel Weight is the maximum weight of the airplane without usable fuel.

Maximum Taxi Weight is the certified maximum allowable weight of the airplane when it is on the ground. This limit is determined by the structural loading on the landing gear under a specified set of conditions and/or wing bending loads.

Maximum Landing Weight is the certified maximum weight of the airplane at touch-down. This limit is determined by the structural loads on the landing gear, but not under the same conditions that determine maximum taxi weight. Landing weight in operation, may also be limited to values less than Maximum Landing Weight by airplane performance and/or airfield characteristics.

Operational Empty Weight is the manufacturer's empty weight plus standard and operational items. Standard items include unusable fuel, engine oil, emergency equipment, toilet fluid and chemicals, galley, buffet and bar structure, etc. Operational items include crew and baggage, manuals and navigational equipment, removable service equipment for cabin, galley and bar, food and beverages, life vests, life rafts, etc.

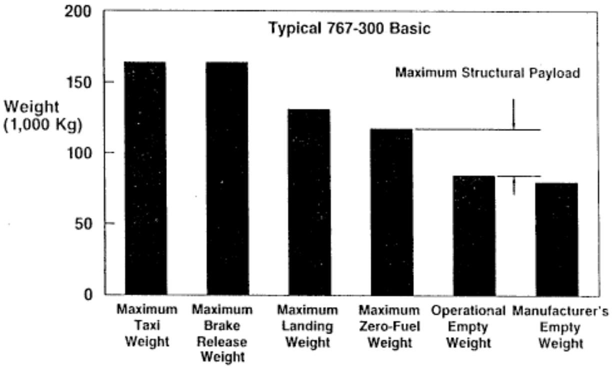


Figure 13 Aircraft component weights [33]

11 Nomenclature

Symbols	Description	Units
CO_2	Carbon Dioxide (CO_2)	tonnes (t)
CO_2e	Carbon Dioxide Equivalents	tonnes (t)
	Carbon Dioxide Emissions Factor	kg CO_2e/unit
RF	Radiative Forcing	–
RFI	Radiative Forcing Index	–
	Fuel Efficiency	–

12 References

1. ‘Aviation and the Global Atmosphere’, Chapter 8: Air Transport Operations and Relation to Emissions, Intergovernmental Panel on Climate Change (IPCC), 1999, http://www.grida.no/climate/ipcc/aviation/126.htm
2. Global CO_2 emissions from domestic and international aviation 1971-1999. (IEA) International Energy Agency, Paris, 2002.
3. Emission Factors for Aircraft Travel, Centre for Energy Conservation and Environmental Technology, 1997b: Energy and Emission Profiles of Aircraft and Other Modes of Passenger Transport over European Distances [Roos, J.H.J., A.N. Bleijenberg, and W.J. Dijkstra (eds.)]. Centre for Energy Conservation and Environmental Technology, Delft, The Netherlands, 106 pp. http://www.grida.no/climate/ipcc/aviation/125.htm
4. United Nations Environmental Program, UNEP/GRID-Adrenal, www.grida.no
5. Chapter 9 Airline reporting on fuel consumption, Miljøstyrelsen. http://www2.mst.dk/common/Udgivramme/Frame.asp?pg=http://www2.mst.dk/udgiv/Publications/2003/87-7972-489-2/html/kap09_eng.htm
6. Babikian R., Lukachko S., Waitz I., The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives. Journal of Air Transport Management, 2002, web.mit.edu/aeroastro/people/waitz/publications/Babikian.pdf
7. Radiative Forcing Index- Aviation and the Global Atmosphere http://www.grida.no/climate/ipcc/aviation/064.htm
8. Commission for Integrated Transport (CfIT), United Kingdom http://www.cfit.gov.uk/docs/2003/aec/aec/index.htm
9. http://en.wikipedia.org/wiki/Boeing_747-400
10. ‘Aviation and the Global Atmosphere’, Chapter 8.3: Other Operational Factors to Reduce Emissions, Intergovernmental Panel on Climate Change (IPCC), 1999, http://www.grida.no/climate/ipcc/aviation/124.htm
11. Forster P., Shine K., Stuber N., Atmospheric Environment, 40, 1117-11121, 2006
12. Sausen R., I. Isaksen, V. Grewe, D. Hauglustaine, D.S. Lee, G. Myhre, M.O. Kohler, G. Pitari, U. Schumann, F. Stordal, C. Zereros 2005: Aviation radiative forcing in 2000: An update on IPCC (1999). Meteorologische Zeitschrift 14(4), 555-561, DOI10.1127/0941-2948/0049.
13. TRAEOFF FP5 EU Project: Aircraft emissions: contribution of different climate components to changes in radiative forcing-tradeoff to reduce atmospheric impact. http://cordis.europa.eu/data/PROJ_FP5ACTIONeqDndSESSIONeq112362005919ndDOCeq116ndTBLeqEN_PROJ.htm
14. IPCC, 1999: Aviation and the global atmosphere - A special report of IPCC working groups I and III. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 365 pp.
15. Mannstein and Schumann (2005) Aircraft induced contrail cirrus over Europe. Meteorol. Z., in press.
16. Zerefos, C.S., K. Eleftheratos, D.S. Balis, P. Zanis, G. Tselioudis and C. Meleti, 2003: Evidence of impact of aviation on cirrus cloud formation. Atmos. Chem. Phys. 3, 1633-1644.
17. Stordal, F., G. Myhre, D.W. Arlander, T. Svendby, E.J.G. Stordal, W.B. Rossow, and D.S. Lee, 2005: Is there a trend in cirrus cloud cover due to aircraft traffic? Submitted to Atmos. Chem. Phys. See also Stordal et al., 2004: Atmos. Chem. Phys. Discuss. 4, 6473-6501
18. U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, October 2005. http://www.bts.gov/publications/white_house_economic_statistics_briefing_room/october_2005/html/air_passenger_revenue_load_factor.html
19. http://reports.eea.eu.int/EMEPCORINAIR3/en/B851vs2.4.pdf
20. www.seatguru.com

21. www.qantas.com
22. Ben Rose (2006), http://www.carbonneutral.com.au/usefulresources.htm, GHG-Energy Calc-Tool for self-audit of domestic Greenhouse Gas Emissions.
23. National Greenhouse Accounts (NGA) Factors, Department of Climate Change, Australian Government, Jan 2008.
24. ADV 2003: “ADV-Monatsstatistik” [ADV Monthly Statistics] for January to December 2003. Arbeitsgemeinschaft Deutscher Verkehrsflughäfen [Association of German Airports], Berlin/Stuttgart, http://www.adv.aero/eng/gfx/index.php. Reviewed as part of the Atmosfair emissions calculator background paper http://www.atmosfair.de/index.php?id=9&L=3
25. Australian National GHG Inventory, End use allocations 1990, 1995, 1999, pg 73.
26. Forsyth, P. (Sustainable Tourism CRC), Climate change challenges for aviation and tourism, ABARE Climate change workshop, Canberra February 5, 2008.
27. Hodgkinson D. and Coram A., Aviation, climate change and a proposal for an airline default passenger carbon offset scheme, The Hodgkinson Group, Aviation Advisors, 2006. www.hodgkinsongroup.com
28. Marais K., Lukachko S., Jun M., Mahashabde A., Waitz I., Assessing the impact of aviation on climate, Meteorol. Z.
29. Quiggin J., Stern and the critics on discounting, ARC Fellow, School of Economics and Political Science and International Studies, University of Queensland, Dec. 2006. johnquiggin.com/wp-content/uploads/2006/12/sternreviewed06121.pdf
30. European Federation for Transport and Environment report–Clearing the Air–The Myth and Reality of Aviation and Climate Change, T&E 06/2, 2006.
31. IATA http://www.iata.org/pressroom/pr/2005-10-31-01.htm
32. Current Market Outlook 2007 Boeing http://www.boeing.com/commercial/cmo/index.html
33. Luis de La Fuente Layos, Air transport in Europe in 2005, Publication date 8/2007. Available EUROSTAT http://ec.europa.eu/eurostat/
34. Total weights http://adg.stanford.edu/aa241/structures/totalweights.html
35. DEFRA 2008 Gluidlines to GHG Conversion Factors, Annexes updated April 2008, pg 11.
36. Qantas Airways. Estimated average emission factors under the Australian Greenhouse Office Greenhouse Friendly™ program.
37. System for assessing Aviation’s Global Emissions (SAGE), Version 1.5, Global Aviation Emissions Inventories for 2000 through 2004,September 2005 (Revised Jan-2006 & March-2008).
38. Reproduced from National Weather Service, Layers of the Atmosphere. http://www.srh.noaa.gov/jetstream//atmos/layers.htm

13 Useful reference links

1. Boeing 747-400 http://www.airliners.net/aircraft-data/stats.main?id=100
2. Airbus A340-500/600 http://www.airliners.net/aircraft-data/stats.main?id=28
3. Boeing 737-400 http://www.airliners.net/aircraft-data/stats.main?id=93
4. Airbus A340-200/300 http://www.airliners.net/aircraft-data/stats.main?id=27
5. Airbus http://www.airbus.com/en/
6. Boeing http://www.boeing.com/commercial/

Appendix: Levels of the atmosphere [38]

The envelope of gas surrounding the Earth changes from the ground up. Five distinct layers have been identified using thermal characteristics (temperature changes), chemical composition, movement, and density. Each of the layers are bounded by "pauses" where the maximum changes in thermal characteristics, chemical composition, movement, and density occur.

Troposphere begins at the Earth's surface and extends up to 4-12 miles (6-20 km) high. The gases in this layer decrease with height and so does the temperature in the troposphere. Almost all weather occurs in this region. The height of the troposphere varies from the equator to the poles. At the equator it is around 18-20 km high (11-12 miles), at 50°N and 50°S, (5½ miles) and at the poles just under (4 miles) high. The transition boundary between the troposphere and the layer above is called the tropopause. Both the tropopause and the troposphere are known as the lower atmosphere.

Stratosphere extends from the tropopause up to 31 miles above the Earth's surface. This layer holds 19 percent of the atmosphere's gases and but very little water vapor. Temperature increases with height as radiation is increasingly absorbed by oxygen molecules which leads to the formation of Ozone. The temperature rises from an average -76°F (-60°C) at tropopause to a maximum of about 5°F (-15°C) at the stratopause due to this absorption of ultraviolet radiation. The increasing temperature also makes it a calm layer with movements of the gases slow. The transition boundary which separates the stratosphere from the mesosphere is called the stratopause.

Mesosphere extends from the stratopause to about 53 miles (85 km) above the earth. The gases, including the oxygen molecules, continue to become thinner and thinner with height. As such, the effect of the warming by ultraviolet radiation also becomes less and less leading to a decrease in temperature with height. On average, temperature decreases from about 5°F (-15°C) to as low as -184°F (-120°C) at the mesopause. Average temperature profile for the lower layers of the atmosphere

Thermosphere extends from the mesopause to 430 miles (690 km) above the earth. This layer is known as the upper atmosphere. The gases of the thermosphere are increasingly thinner than in the mesosphere. As such, only the higher energy ultraviolet and x-ray radiation from the sun is absorbed. But because of this absorption, the temperature increases with height and can reach as high as 3,600°F (2,000°C) near the top of this layer.

Exosphere is the outermost layer of the atmosphere and extends from the thermopause to 6,200 miles (10,000 km) above the earth. In this layer, atoms and molecules escape into space and satellites orbit the earth. The transition boundary which separates the exosphere from the thermosphere below it is called the thermopause.