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Fuel efficiency of commercial aircraft
An overview of historical and future trends

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Summary

This report assesses how the fuel efficiency of commercial aircraft has developed since their introduction in the 1930s. Existing estimates, such as the oft-cited 70% improvement from the IPCC Special Report on Aviation and the Global Atmosphere, ignore the record of the pre-jet era. Based on bottom-up (micro) and top-down (macro) analyses of aircraft fuel efficiency, it can be concluded that the last piston-powered aircraft were as fuel-efficient as the current average jet. This result was obtained by comparing several large piston-engined aircraft with both old and new jet airliners and was confirmed by the macro analysis, which reveals a sharp increase in fuel consumption per seat-kilometre as piston-engined aircraft were replaced by jet-engined. The last piston-powered airliners were at least twice as fuel-efficient as the first jet-powered aircraft.

Aircraft fuel efficiency is just one of the design parameters of interest to aircraft designers and the market. The common practice of defining future cuts in energy consumption per seat-kilometre in terms of a constant annual percentage reduction is therefore not very accurate. It ignores the fact that current aircraft configurations can never achieve zero fuel consumption. Nor does it take into account that the annual reduction rate is not a constant, but is itself also falling, as clearly demonstrated by both macro and micro analysis. This means that many studies on predicted future efficiency gains are rather optimistic.

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Contents

(37 pages in total)

1 Introduction

In 1990 air transport contributed some 3.5% to global greenhouse gas emissions. Depending on future trends in aviation, technology and the emissions of other sectors, this share may grow to 15% or more (Penner et al. 1999). As improved energy efficiency will directly reduce the CO_2 emissions of today's kerosene-based aviation, it is important to know how aviation energy efficiency has developed historically and what might happen in the future.

Mitigation of climate change is a subject of wide and intense debate. Although international air transport has thus far been exempt from the Kyoto Treaty on reducing greenhouse gas emissions, it is becoming increasingly clear that this will not remain so in the future. Past and future gains in aviation fuel efficiency have consequently 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 (Gössling and Peeters 2005).

This figure was published in the IPCC's Special Report on Aviation and the Global Atmosphere, which included a graph showing trends in the fuel efficiency of new jet aircraft coming onto the market between 1960 and 2000 (Penner et al. 1999; p. 298). It is this graph – reproduced here in Figure 1 – that suggests the figure of 70% overall fuel efficiency gains between 1960 and 2000, and based on this figure the IPCC indeed concludes: "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".

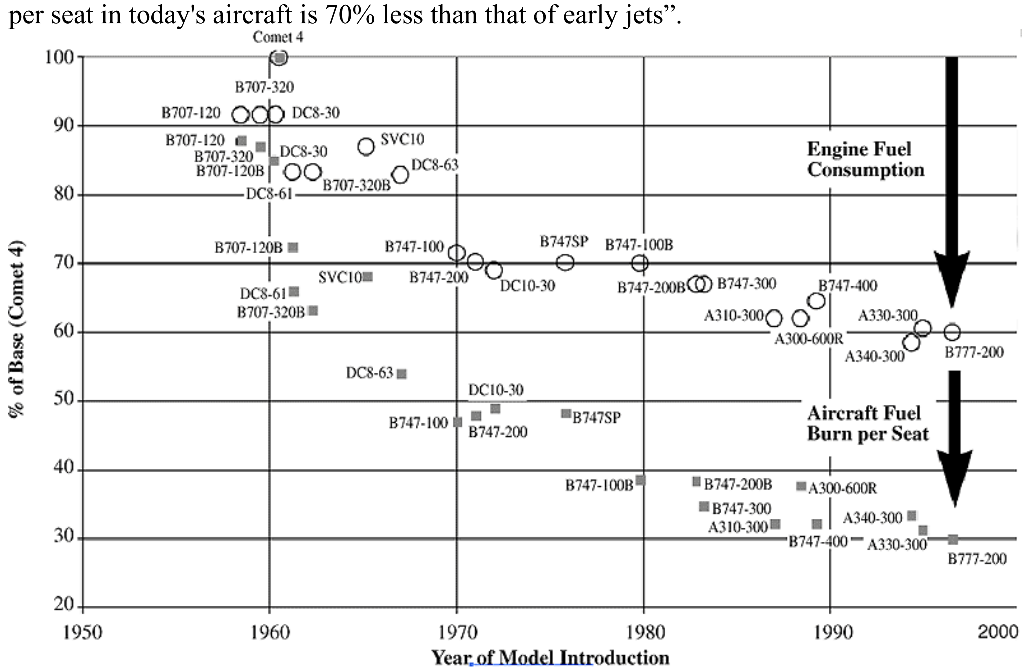


Figure 1: The IPCC's Figure 9-3, which forms the background of the present study (source: www.grida.no/climate/ipcc/aviation/avf9-3.htm).

However, this figure raises several questions: Is it representative of all individual jet aircraft? Is it also representative of the air transport fleet as a whole? Can it be used for future prognoses? And does it give (unbiased) information about technological achievements, or does it also include changes in operational performance? Does the aviation industry always use technology geared to maximum fuel efficiency (as mentioned by Bisignani 2005, for example)? This last question is important, as it appears from statements in several historical documents that early jet aircraft had substantially worse fuel efficiencies than the (final) piston-engined aircraft they replaced. ICAO, for example, encountered air traffic control problems because of "the high hourly fuel consumption of jet aircraft" (ICAO 1951, p. 5). A year later ICAO refers to "The introduction of jet-propelled aircraft, with their relatively high fuel consumption" (ICAO 1952, p. 17). In the 5th edition of his book on commercial aviation John Frederick notes that jets "consume more fuel in relation to loads carried and distances flown" as compared with both piston-powered and turboprop-powered aircraft (Frederick 1961; p. 18).

Against this background, the following research questions are addressed in this document:

1. What is the origin and validity of Figure 9-3 of the IPCC's Special Report on Aviation? What are the underlying data and assumptions of this figure?
2. Can this figure be extended with data from before the jet age (i.e. data for the last large piston-powered airliners) and can all data be based on the same set of assumptions in a single graph?
3. What is the fuel efficiency of air transport, as based on historical and current statistical data on total fuel consumption and total passenger- and freight-kilometres travelled?
4. What general conclusions can be drawn regarding long-term trends in worldwide aviation fuel efficiency since World War II?

These four questions were addressed in three project tasks. The first analyses the original IPCC graph (see §3). The second considers the fuel efficiency of several individual aircraft that have been in operation since 1945. The results of this micro analysis are presented in §4. However, the technological gains embodied in individual aircraft do not necessarily represent the overall technological gains of the fleet. In the third task, therefore, technological progress as such is analysed, based mainly on data for the United States (see macro analysis in §5). In §6 the results of these three phases are analysed and discussed, followed in §7 by some conclusions.

2 Energy consumption and air transport

2.1 Some theoretical considerations

Lee et al. 2001) introduced the term Energy Intensity (E_I) as a measure for the technological performance of individual aircraft or an aircraft fleet. E_I expresses the energy consumption per available seat-mile, and will be used in this report to compare aircraft models, as a measure of technological developments over time.
The energy intensity per available seat-mile depends on the following aircraft parameters:
- Aerodynamic efficiency, specifically the lift-to-drag ratio during cruise.
- Weight efficiency in terms of the share of payload in maximum take-off weight (MTOW) or the ratio between operating empty weight (OEW) and MTOW.
- For passenger aircraft: cabin layout and seating density (most aircraft are offered in both mixed-class layout and single-class high-density layout, with a difference of up to a factor two in the number of seats for approximately the same fuel burn per aircraft-kilometre).
- Engine efficiency in terms of specific fuel consumption (sfc).

In this study operational impacts – such as load factors, efficient routing, holding, weather impacts and delays – have not been explicitly included in the analysis. Load factors are irrelevant, because it is the energy per available seat-mile rather than passenger-kilometre that is being considered. In the aircraft performance (micro) analysis the other factors are excluded by assuming ideal zero wind conditions and a per-kilometre efficiency. In the macro analysis, however, these factors are implicitly included.
Many studies present technological trends in terms of a constant annual percentage efficiency gain. Lee et al. 2001, for instance, assert that this ratio will lie between 1.2% and 2.2% a year in the future, while Penner et al. 1999 use 1.4% for most future scenarios. In this report it will be argued that this practice is not entirely appropriate. Theoretically speaking, (today's conception of) the most efficient aircraft will never achieve near-zero fuel consumption. As long as there is aerodynamic drag, aircraft that are '100% fuel-efficient' will still burn considerable amounts of fuel. In the regression lines, therefore, at least some offset should be introduced. Another observation is that annual reductions are probably not constant. When a technology is born, there are vastly more opportunities for improvement than with a mature technology. A power-curve regression line will therefore fit the data better than one based on a fixed annual reduction.

2.2 Earlier historical research results

Lee et al. 2001) provide an extensive analysis of jet aircraft fuel consumption since 1960. They also make some predictions about future trends. Their main conclusions are as follows:

- Between 1960 and 2000 the main efficiency improvements in jet aircraft were achieved by improving engine fuel per unit thrust (69% of overall improvement).
- Aerodynamic improvements contributed 27%.
- The remaining 5% was due to other factors, such as the scale effects of larger aircraft.
- Structural efficiency improvements (weight reduction) made no contribution to improved energy efficiency.
- Between 1971 and 1998 the fleet-average annual improvement per available seat-kilometre was estimated at 2.4%.

Lee et al. also mention the reduction in the annual rate of efficiency improvement. When looking ahead to the future, however, they still assume a constant fall-off of annual energy consumption. This inevitably leads to too optimistic prognoses of fuel efficiency in the future. The declining annual improvement of fuel burn per seat-kilometre may be due to the growing difficulty, and thus cost, of developing ever more advanced technology for a given aircraft concept. The economic and strategic scope for introducing new technologies may therefore also play a part. Philips 1969), for example, describes a method for predicting the market for specific aircraft designs. His research, which is based on a mix of very different aircraft types, as his data cover the end of the piston-engined and start of the jet era, shows the following:

- Successful designs almost always have far lower operating costs (including depreciation) than the operating costs (excluding depreciation) of the aircraft then in use or unsuccessful aircraft under design.
- The most successful new aircraft designs add to this some ‘quantum leap’ in technology.
- Aircraft manufacturers adhering too long to their once-successful technology fail to retain their market shares.

This illustrates the strong case for operating cost in successful aircraft design. It means fuel efficiency is just one design parameter among others, the importance of which rises and falls with long-term fuel price projections. In §6.1 we show for one of the newest aircraft – the Airbus A380 – that non-technological and non-economic considerations also play a role in design decisions.

3 The IPCC figure: data and assumptions

The source of the IPCC figure reproduced in Figure 1 was a paper presented at a conference in April 1996 (Albritton et al. 1997; see Figure 2). The reference given in the conference proceedings was not very explicit - 'Rolls Royce plc' – and could not be tracked in time by the authors. The basis for comparison (flight distance, payload and flight path) is therefore unknown to the authors, as this figure has no specific reference. This in fact makes it difficult to assess the graph in any scientific way.

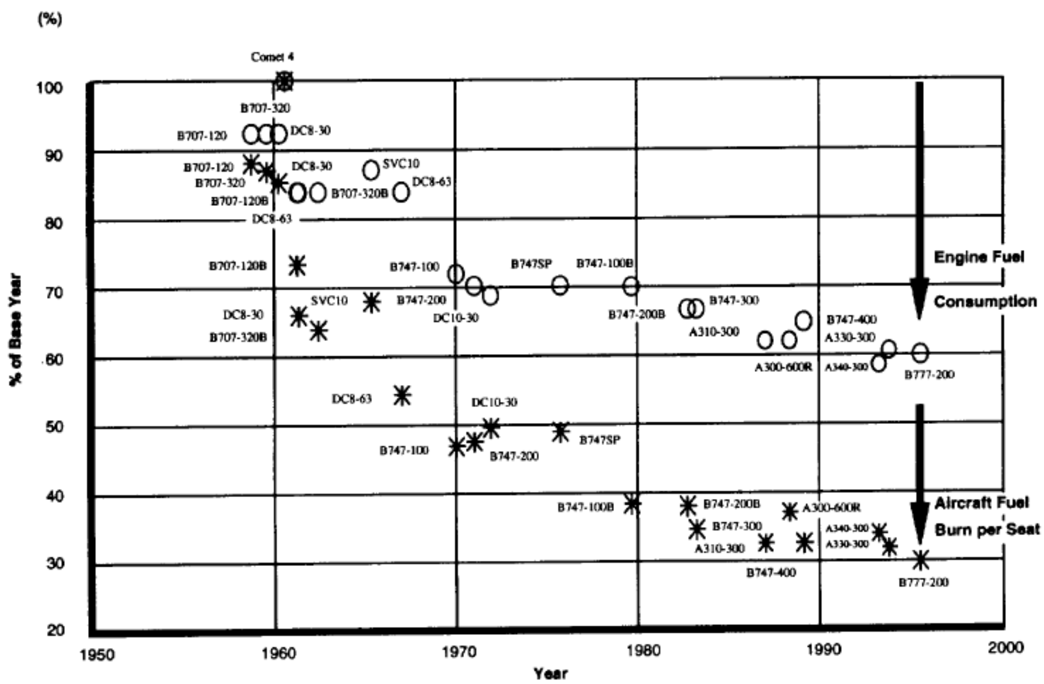


Figure 2: The original Rolls Royce figure presented in Albritton et al. 1997.

A closer look at the figure allows the following observations to be made:

- The figure represents mainly long-haul aircraft. As Lee et al. (2001; Figure 6) shows, fuel efficiency gains in this class of aircraft tend to be larger than for short-haul aircraft. The same phenomenon was found by CE (2000) in an aircraft design study. It is not surprising that long-haul aircraft are quicker to adopt fuel saving technologies, as the share of fuel in overall weight increases with (design) range.
- It should be noted, secondly, that the reduction in fuel consumption for the whole fleet is much less than the difference between the most fuel-efficient and least fuel-efficient aircraft operated at any one time, because the fleet is always represented by a mix of efficient and less efficient aircraft.

- The IPCC figure makes a distinction between gains from engine technology and gains from aircraft technology. Included in aircraft technology, however, are probably also assumptions on aircraft configuration, which have a major influence on seat number. The number of seats on a Boeing 777-200, for example, varies between 305 and 440, which is a range of 31% around the average. It is not known what aircraft configurations were used for the IPCC figure.

Lee et al. (2001) also provides a graph showing average energy consumption per available seat-kilometre, or ASK (see Figure 17 of the reference). Unfortunately, this graph does not show the names of the aircraft per data point. Using the B747-400 as an anchor-point, the data have been converted to absolute average energy consumption values (i.e. in MegaJoule per ASK). Figure 3 shows the IPCC data to be a little optimistic, probably owing to short-haul aircraft being ignored.

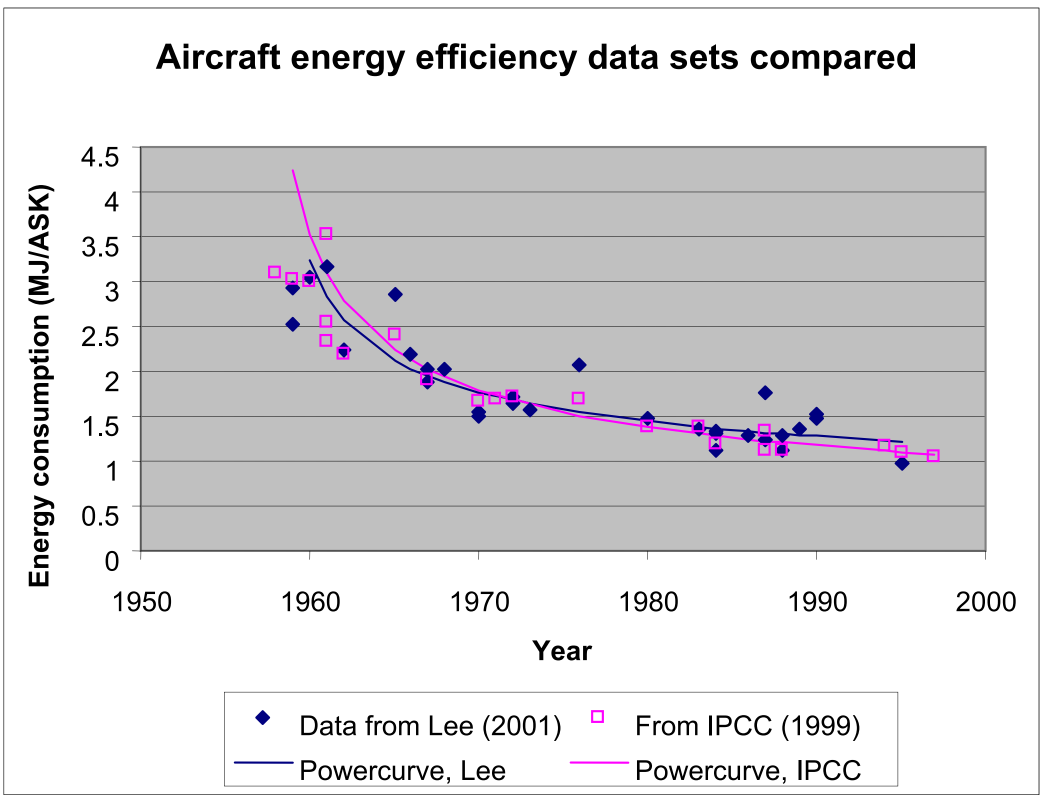


Figure 3: Data given by Penner et al. 1999 (IPCC) and Lee et al. 2001. The data from IPCC have been converted to MJ/ASK using the Boeing 747-400 as an anchor-point.

For both data-sets a power curve regression line has been estimated using FindGraph (software developed by Vasilyev 2002). The curve has the form:

$$E_i = e^{(a+b\cdot\ln(n))}$$

where E_i is the energy intensity (MJ/ASK) and n the number of years from the base year, while a and b are estimated constants. The two estimated curves show almost the same historical trend, though the IPCC curve is somewhat steeper than the curve from the data given by Lee. The IPCC fit is slightly more optimistic for energy consumption reduction. Based on the fitted curves, energy savings between 1960 and 2000 are as follows:

- IPCC: 75% reduction between 1960 and 2000.
- Lee: 64% reduction between 1960 and 2000.

However, the reduction depends very much on the time period chosen. For example, the twenty year reduction from 1960 to 1980 is as follows:

- IPCC: 67% reduction
- Lee: 55% reduction

while from 1980 to 2000 it is:

- IPCC: 26% reduction
- Lee: 20% reduction

Finally, the curves can be used to forecast potential gains between 2000 and 2040:

- IPCC regression line: 26% reduction
- Lee regression line: 20% reduction

IPCC assumes an annual reduction of 1.4% between 2000 and 2040 (Penner et al. 1999), giving an overall reduction of 43%. Lee takes an efficiency improvement of at least 1.2% a year, giving a 38% overall reduction. This again shows the difficulty of regressions based on constant annual improvements. The new A380 fits the curve estimated in this report rather precisely (see Figure 11).

4 Micro analysis

In the older literature there is some reference to the fact that in the transition from piston-powered to jet aircraft fuel efficiency was partly sacrificed in favour of speed and altitude (see, for example, Frederick 1961: 19). Because all the energy efficiency graphs in the recent literature ignore the period prior to the jet age, the micro analysis has been used to add a small number of data points, including the last, and hence most fuel efficient, piston-engined aircraft. Table 1 shows the four piston and seven jet aircraft chosen for the present analysis.

Aircraft model	Reference	Remarks
Lockheed Super Constellation L-1049	Jane's 1952-1953	Range assumed to be based on maximum payload.
Lockheed Super Constellation L-1049H	Swinhart 2001	Indicated 'Gross weight' assumed to be MZFW as it is almost equal to MZFW mentioned in NTSB 1974.
Douglas DC-7C	Jane's 1959-1960	MZFW estimated with Breguet formula using Jane's data; year of introduction is best estimate; 110 seats is from Boeing site.
Lockheed L-1649A	Prop-Liners of America Inc 2005 and Jane's 59-60	
Boeing B707-320 International	Boeing 2005	Max. payload at MTOW.
Boeing B707-120B Domestic	Boeing 2005	
Airbus A340-300	Airbus 2005b and Jane's electronic	Typical 295 passengers incl. 28 ton cargo.
Airbus A330-300	Airbus 2005a and Jane's electronic	Typical 295 passengers incl. 22 ton cargo.
Boeing B777-200 baseline	Boeing 2005	Standard day, zero wind, normal power extraction and air conditioning bleed, 0.84 Mach step cruise.
Boeing B777-200 high gross weight	Boeing 2005	Standard day, zero wind, normal power extraction and air conditioning bleed, 0.84 Mach step cruise.
Boeing B737-800 Winglet	Boeing 2005	Standard day, zero wind, 31-35-39000 ft step cruise, typical mission reserves, nominal performance, Mach = LRC

Table 1: Micro analysis of aircraft and data references (MZFW = maximum zero fuel weight; MTOW = maximum take-off weight).

The piston-powered aircraft chosen are the latest and most sophisticated airliners of their day. The two Boeing 707 variants represent the two most frequently used at the start of the jet era. The five other aircraft are representative of the current state-of-the-art aircraft for the short, medium and long haul.

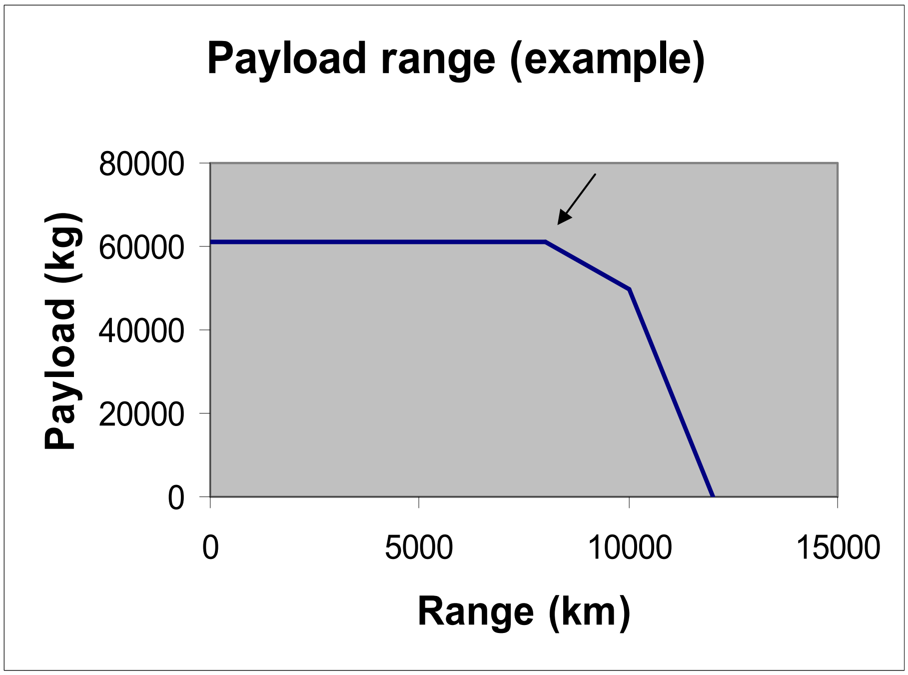


Figure 4: Example of payload-range diagram; the arrow marks maximum range at maximum payload.

The method used for this analysis is to find *comparative* fuel intensities both per available seat-kilometre and per available maximum payload ton-kilometre. Fuel consumption has been based on the maximum range with maximum payload, as derived from the payload-range performance diagram (see Figure 4). Now, to find the fuel consumption per unit payload-kilometre the following stepwise procedure was adopted (all data based on the references given in Table 1):

- Passenger capacity is defined based on the minimum and maximum seating configurations offered.
- The maximum payload in tonnes is taken as the difference between the standard passenger OEW and the MZFW.
- Total fuel consumption for the maximum range-maximum payload point is by definition the difference between MZFW and MTOW (i.e. reserves are ignored, which means actual fuel consumption is somewhat lower than found with this method).

Model	Year	OEW [kg]	MZFW [kg]	MTWO [kg]	Max. Range @ max payload [km]	Min. seats	Max. seats
L-1049	1952	31326	44719	54480	3943	92	106
L-1049H	1953	31789	49681	62368	4634	92	92
DC-7C	1956	35785	46030	64865	7458	62	110
L-1649A	1956	38675	52500	70700	8704	58	102
B707-320 International	1959	64600	83185	141500	6108	141	189
B707-120B Domestic	1961	57600	77200	117000	5152	137	174
A340-300	1994	129300	178000	275000	10458	295	440
A330-300	1995	122200	173000	230000	6610	295	440
B777-200	1995	133060	190500	242630	5684	305	440
B777-200-IGW	1997	135600	195000	286900	10001	305	440
B737-800 Winglet	2002	41413	62732	79016	3889	160	184

Table 2: Data used for calculating the energy intensity at maximum payload.

Two graphs have been drawn based on the data given in Table 2. Figure 5 shows E_I (energy intensity in energy consumption per ASK). From this figure it is clear the energy intensity of the last large piston airliners was only marginally higher than that of current jets, while the very first jet liners were significantly less fuel-efficient. As all current long-haul jets carry not only passengers (with luggage), but also a substantial freight load, a calculation based on available ton-kilometres has also been made: Figure 6 shows the result. Compared to Figure 5, the individual points shift slightly, but all three groups – piston-powered, early jets and modern jets – retain their relative position. The absolute energy intensities per ASK tend to be just slightly lower than given by Lee and the IPCC (Lee et al. 2001; Penner et al. 1999). As fuel consumption has not been corrected for fuel reserves, the actual still-air optimum fuel intensity must be some 5-15% lower. The impact will be larger for piston-engined aircraft, as these often reckoned with three hours of reserve fuel, while modern jets take on board reserves for a diversion of 200 nautical miles (NM), which is a smaller share of total fuel on a long-haul trip.

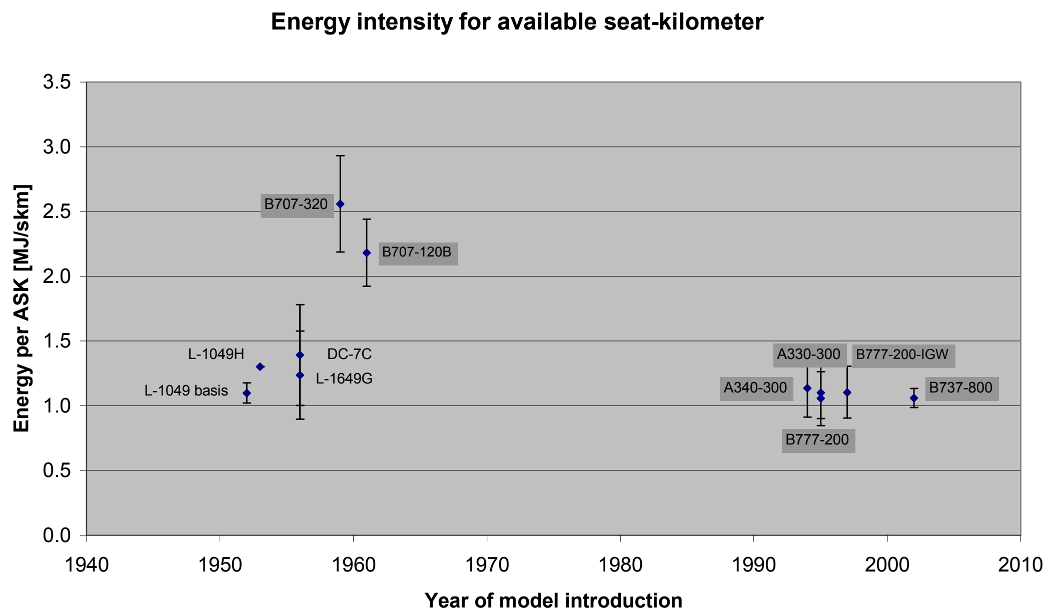


Figure 5: Energy intensity per available seat-kilometre. Ranges show the impact of different cabin configurations.

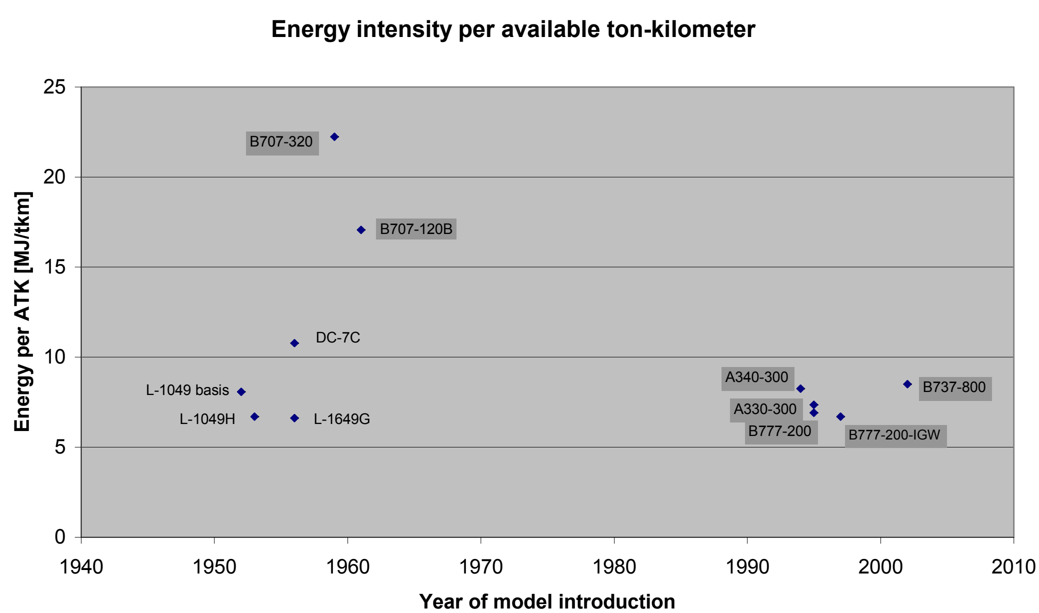


Figure 6: Energy intensity per available ton-kilometre.

It is interesting to see, now, how the new data from the micro-analysis fit into the original IPCC graph and the data given by Lee et al. 2001. For this purpose we have scaled the micro-analysis data to fit the Boeing 777. Figure 7 shows the result.

From this figure the following observations may be made:

- If one takes new aircraft from the early fifties (i.e. the last piston-engine aircraft) as the baseline, it shows that these last long-haul piston-powered airliners were as fuel-efficient as today's average turbojet aircraft.
- 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 main explanation for this difference is the different choice of baseline aircraft (B707 instead of DH Comet 4). The IPCC reference aircraft – the DH Comet 4 – has a rather atypical (i.e. very low) energy efficiency and only a very limited number were in operation. Further, the difference between the old and new aircraft chosen for the micro analysis is somewhat less than given by the IPCC. As we do not know the assumptions for the IPCC graph, it is not possible to provide an explanation for this difference.

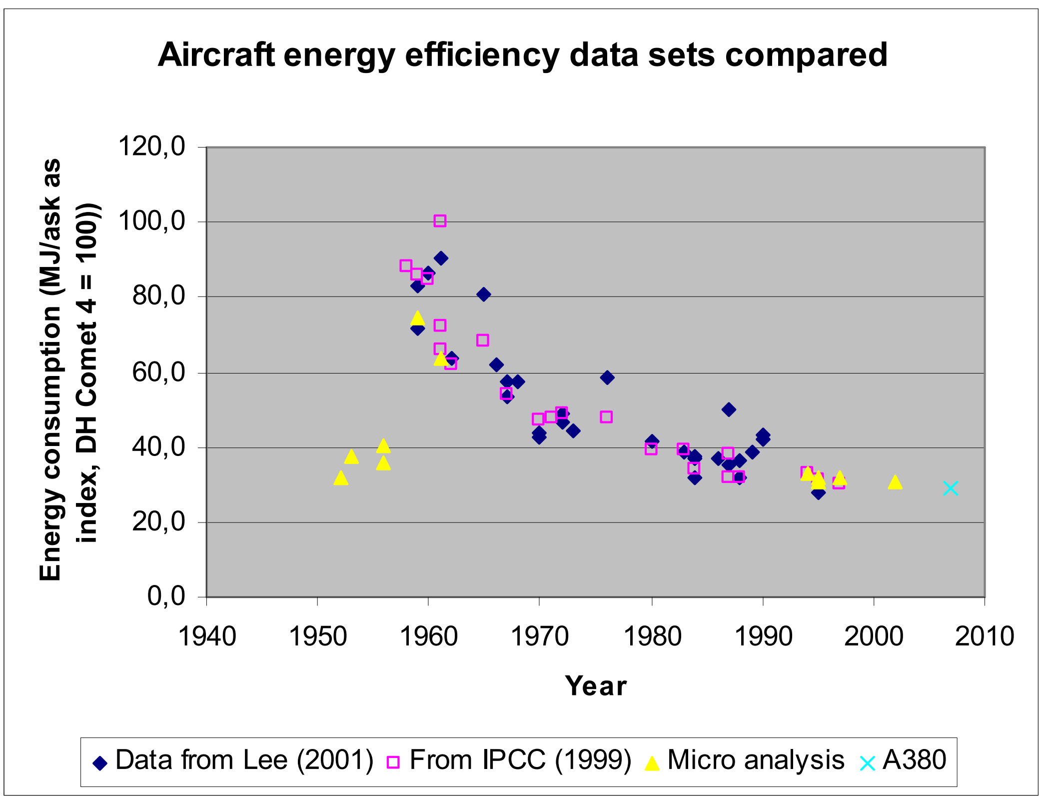


Figure 7: Micro data scaled to the IPCC graph as given in Penner et al. 1999 and the data by Lee et al. 2001. Piston-engined-aircraft shown as the four dots between 1952 and 1958.

5 Macro analysis

The aim of the macro analysis is to provide a time series for the overall average energy efficiency of a representative fleet of commercial aircraft, with energy efficiency defined as energy consumption per available seat-kilometre. The ambition of generating a time series for the world's commercial air transport fleet is frustrated by the absence of globally comparable transport volume and aviation energy use statistics. Although world aviation traffic statistics are available from several sources (e.g. IATA 1957-2004; Mitchell 1999), relevant fuel consumption data for commercial aviation are hardly available in appropriate format. The databases of IEA/OECD, for example, aggregate fuels across all aviation sectors (including the military, see e.g. OECD 2003).

At the regional level, though, there are reasonably well-documented and representative data available on commercial aviation from the United States. For this region the following data have therefore been used:

- Air Transport Association of America (ATA) annual reports.
- Bureau of Transport aviation fuel efficiency statistics.
- Historical statistics of the United States, colonial era through to 1970.

ATA has been recording transport data in its annual reports since 1927. The early reports (see ATA 1940; ATA 1950) contain such time series for the preceding ten-year period for both domestic and international passenger transport, for mail, express and freight, and for the total amount of aviation gasoline consumed, though prior to 1935 data on freight and express are lacking. After this period, fuel consumption data are no longer reported. The reports from the 1980s onwards, however, present average fuel efficiency in passenger-miles per gallon (see ATA 1980; ATA 2005). These data were recalculated to energy consumption per available seat-kilometre, using load factors from the Bureau of Transport historical data (Bureau of Transport Statistics 2005a; Bureau of Transport Statistics 2005b). As part of the payload consisted of mail, express and freight, ton-kilometres were converted to hypothetically available seat-kilometres using a figure of 160 kg per seat (see Annex III) and assuming the same load factor as given for passenger transport (no mail and freight load factors are available). The load factors for 1935-1939 were calculated from data on revenue miles, revenue passenger-miles and average available seats given by Lerner 1975. In this way a time series was created for the period 1935-1950 based on actual fleet fuel consumption data and for 1973, 1977-1979 and 2000-2004 using ATA generalised fuel consumption per passenger-kilometre data.

The BTS dataset contains complete energy intensity (energy/passenger-kilometre) and load factors for all the years between 1960 and 2004 (Bureau of Transport Statistics 2005a; Bureau of Transport Statistics 2005b). From these data the energy efficiency in MJ/seat-was derived and plotted. As no data on freight and mail are available in this dataset, these data have not been corrected for non-passenger payload. The period of main interest – the years between 1950 and 1970 – is not completely covered by these data.

Finally, data on both transport volume and fuel consumed in a time series from 1926 through 1970 was taken from Lerner 1975). From this series, data points were constructed for the years 1932, 1935, 1940, 1945, 1950, 1955, 1960, 1965 and 1970. The problem with these data is that the fuel data cover only aviation gasoline and not aviation kerosene. As a result, the registered amount of fuel (i.e. gasoline) starts to decrease from 1958 onwards, as jets start to replace piston-powered aircraft. This has been resolved by using the fuel consumption for 1960, 1965 and 1970 as given by the Bureau of Transport Statistics 2005b). This amount of fuel was assumed to give the total number of gallons, of which the amount given by Lerner 1975) is aviation gasoline and the remainder kerosene, which have different energy intensities (see Annex I).

Figure 8 gives an overview of the results for all three time series considered. The figure clearly shows two general trends of energy efficiency increase – i.e. steadily declining energy consumption per available seat-kilometre – one before 1955, the other after 1970. The discontinuity coincides neatly with the introduction of jet aircraft, as shown in Figure 9, showing changes in fleet composition. In terms of transport performance (available seat-kilometres) the shift must have taken place at a higher rate, as most new jet aircraft were larger than the average piston aircraft and cruise at higher speeds.

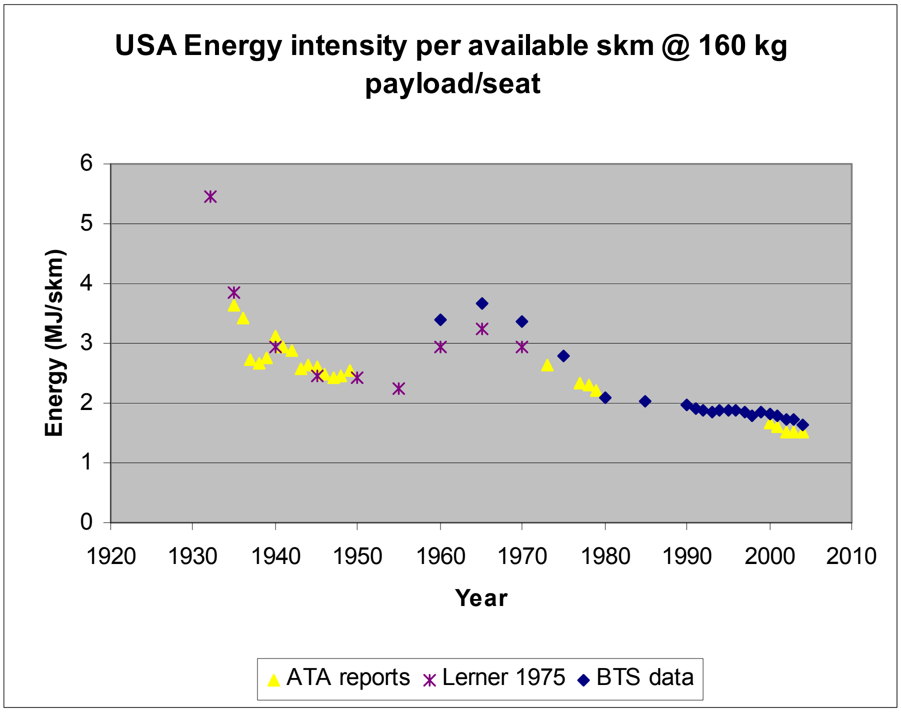


Figure 8: Overall results of the macro analysis. Data series based on ATA 1940; ATA 1950; ATA 1980; ATA 2005; Bureau of Transport Statistics 2005a; Bureau of Transport Statistics 2005b; Lerner 1975.

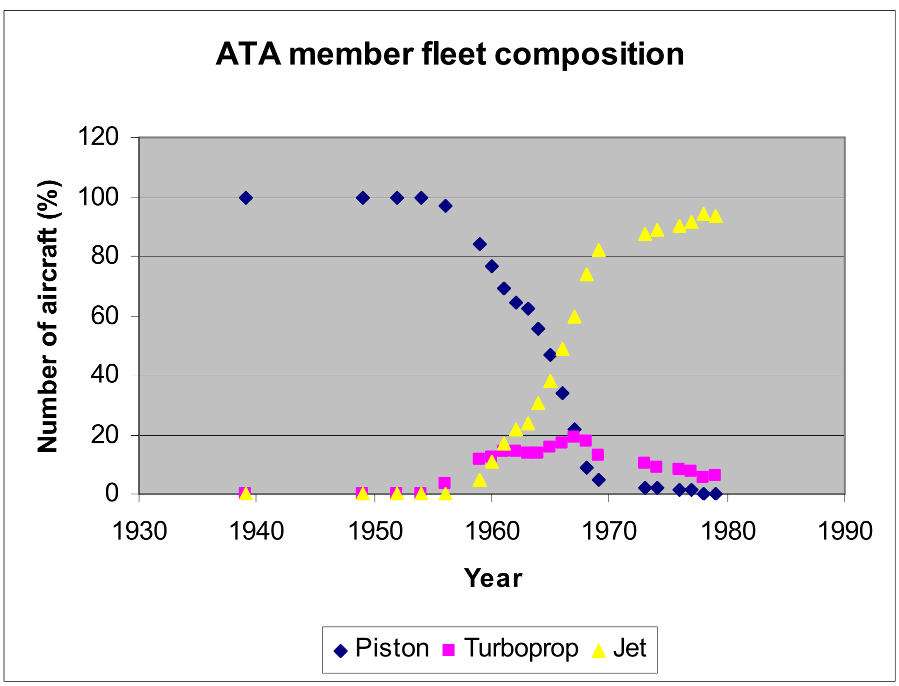


Figure 9: ATA fleet composition change between 1940 and 1980 (based on ATA annual reports).

The early turboprop aircraft had a fuel efficiency intermediate between piston and jet (Babikian et al. 2002; Frederick 1961). Consequently, the introduction of turboprops had a slight dampening impact on the upward trend of Figure 8.
To fit a curve for the macro trend we need to fit two regression lines: one for the piston era and one for the jet era. Figure 10 shows the result. As can be seen, the piston aircraft fleet reaches its ultimate fuel efficiency in 1960 at 2.1 MJ/ASK, while the jet aircraft fleet might reach technological maturity at 1.2 MJ/ASK somewhere in 2040.

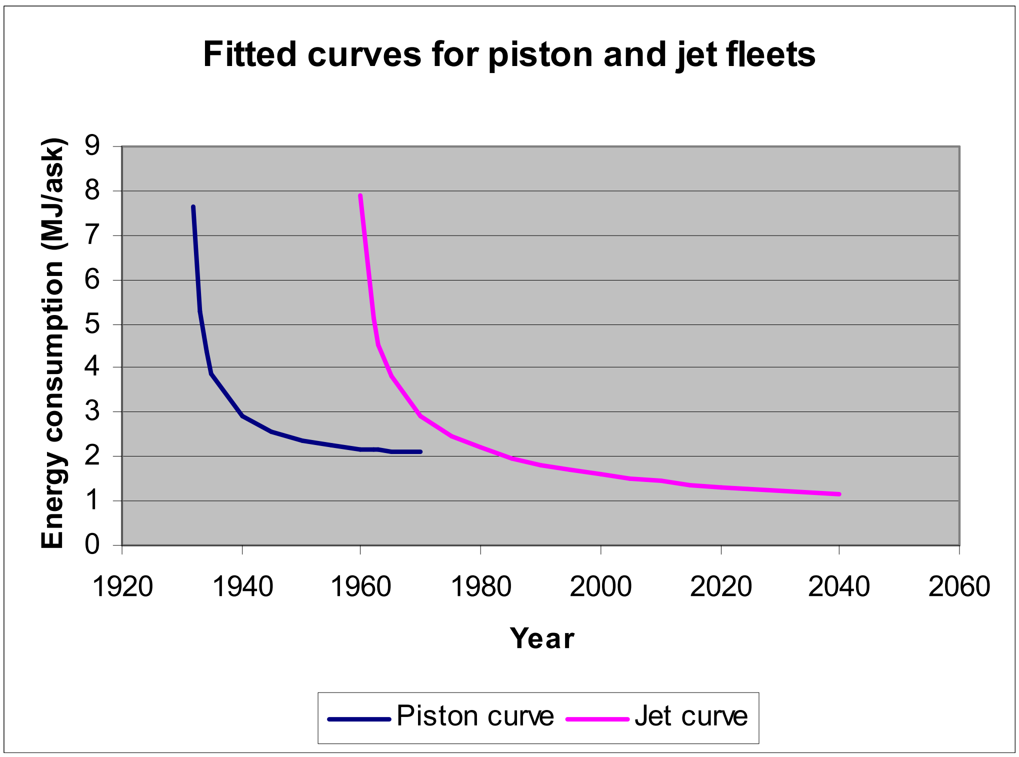


Figure 10: Development of energy consumption per ASK for the piston fleet and for the jet fleet (based on data from ATA 1980; ATA 2005; Bureau of Transport Statistics 2005b; Lerner 1975).

Finally, from the macro analysis it can be concluded that the overall fuel efficiency gain between 1960 and 2000 (including the impact of the remains of the last fleet of piston airliners) was 43%. However, between 1955 and 2000 (thus based on a fleet with only a small share of new jet aircraft in 1955) the fuel efficiency gain is only 23%.

6 Synthesis of results and discussion

6.1 Micro analysis

The micro analysis provides a few clues with respect to the IPCC graph. First, the IPCC graph seems to show a somewhat optimistic energy efficiency gain between 1960 and 2000. This is due mainly to the choice of the DH Comet 4 as the reference (first) jet aircraft. This was an atypical aircraft that did not capture much of the market and had a relatively high fuel consumption. If the first successful jets are taken as the reference – i.e. the Boeing 707 family – the decline in energy consumption per available seat-kilometre decreases from the 70% reported by IPCC to 55%.

A second important conclusion is that the last piston-engined long-haul aircraft were ** as fuel-efficient as the average current jet aircraft and thus twice as efficient as the first jets replacing them. The piston engines were a more or less mature technology and these aircraft had reached the end of their development cycle. The new jets were at the start of their cycle, of course, which will be one of the reasons for their far lower fuel efficiency.

A third observation from the micro data is that the first, fuel-inefficient jets appear to have been able to replace the more fuel-efficient piston airliners then in service. Fuel consumption is not quite the same as fuel cost; kerosene (powering jet aircraft) is much cheaper to produce than the aviation gasoline used by piston-engined aircraft. In addition, fuel consumption is only one of the criteria for airlines to purchase a specific aircraft model and thus only one of the design criteria for aircraft designers. If other characteristics like speed, comfort or range can be enhanced at lower cost, the designer and the aircraft market may opt for a less fuel-efficient design. This was indeed the case with the first jets that replaced the rather fuel-efficient pistons: the new aircraft had a 40-80% higher cruise speeds then their predecessors. According to Frederick 1961), the first jets were only marginally cheaper and had about the same maximum range capabilities.

The case of the new Airbus A380 also shows that technological advances may be greater when strategic considerations would have been ignored. The A380 is reported to be 12% more fuel-efficient per seat-kilometre than the much older Boeing 747-400 (Bickerstaff 2005). However, this very large aircraft could be up to 11% more fuel-efficient than currently planned if the wing aspect ratio had been designed for optimum fuel use (Dalhuijsen and Slingerland 2004). This optimum wing design would also lead to a 2.4% reduction in direct operating costs. Airport handling constraints result in a suboptimal wing design (energy-wise) limiting the wing span to 80 m. A solution with folding wingtips would keep the A380 within the 80 m limit and would still save 10.8% fuel and 2.1% DOC.

Figure 11 shows the original IPCC graph, augmented with the following information:

- The power curve regression defined in §4.
- A regression line showing the result for a constant 3% annual reduction of energy consumption per ASK, representing the 70% overall reduction between 1960 and 2000.
- The results of the micro analysis, distinguishing between 'piston airliners' and 'jets, micro analysis'.
- The Airbus A380 based on the 12% reduction with respect to the B747-400, cited by Bickerstaff 2005.
- The 'optimum wing' A380, as given by Dalhuijsen and Slingerland 2004.
- The 'typical research target' as used in several projects mentioned by ATAG 2005.

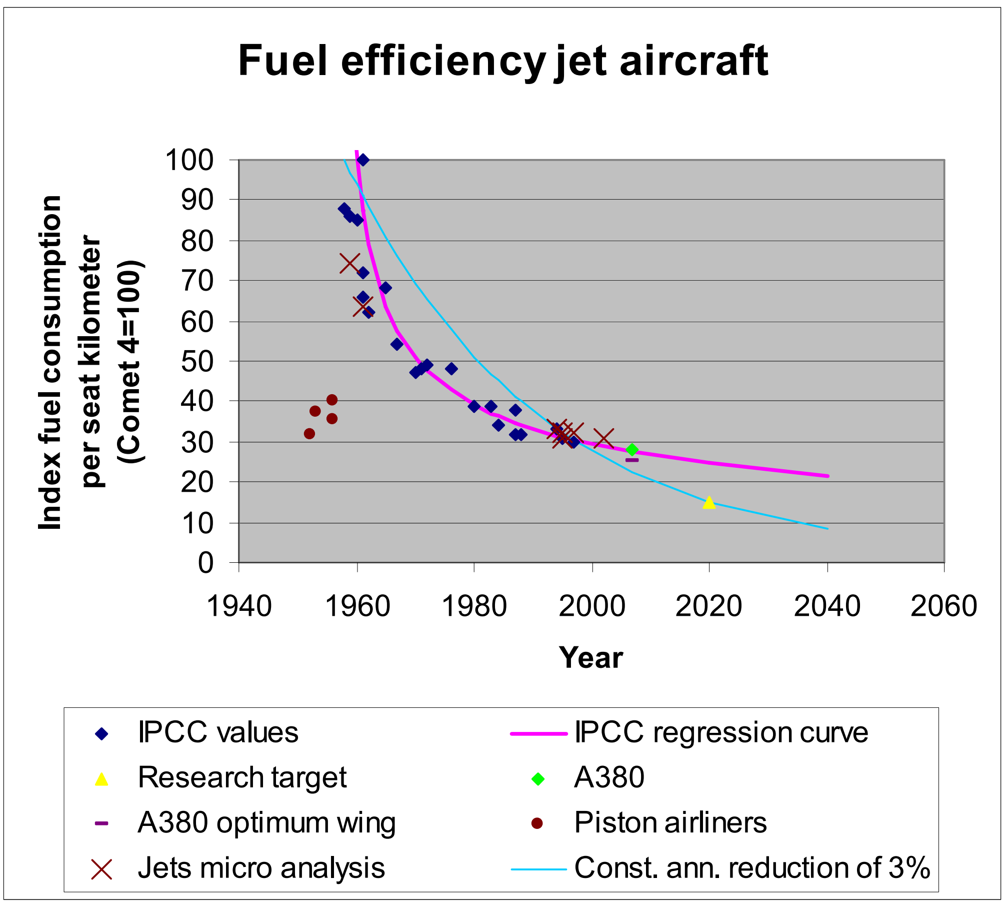


Figure 11: IPCC graph with additional data (see text for references).

Figure 11 the following conclusions can be drawn:

- The research targets for energy efficiency for the aircraft designs of 2020 are below the power curve trend of the jet age.
- The trend drawn from the IPCC graph shows far less technological progress than a curve based on a fixed annual reduction of 3%, representing the 70% reduction between 1960 and 2000.
- Energy efficiency is not the main objective of commercial aircraft designers, as shown both by the early jets replacing the last piston airliners and by the new Airbus A380.
- Between 1955 and 2000 overall aircraft design energy efficiency fell only marginally, owing mainly to the introduction of jet aircraft to increase cruise speeds, as required by the market.

The Airbus A350 and Boeing B787 were not considered in this study, as these aircraft are still in the development phase and reliable operational data are not yet available. The power curve regression still leaves some scope for development, though, and these new aircraft might to match it in the future.

6.2 Macro analysis

The macro analysis of aviation in the United States (domestic and international) clearly reveals the discontinuity in the development of fuel efficiency. While a general increase can be observed over the period from 1930 to 2000, introduction of the new jet aircraft at the end of the 1950s clearly halts the continuously declining trend in (piston) aircraft fuel consumption. Once the piston-powered fleet had been replaced by jets, however, a new trend of rising energy efficiency began that continues today. Both trends follow a power curve and therefore show a steady decline in annual efficiency gain, as already shown in the micro analysis in §6.1.

Between 1960 and 2000 overall energy consumption per ASK fell by 43%, which contrasts with the result shown in the IPCC graph. In even greater contrast is the fact that between 1955 and 2000 the reduction in fleet-wide energy consumption was only 23%. The main difference is due to the last fuel-efficient pistons flying in 1960. In 1965 the jet fleet outdid the piston fleet in terms of transport performance. Between 1965 and 2004 the efficiency gain is higher, at 53%, but still short of the 70% found in the IPCC graph.

Although the data used in this study were from three different datasets, the mutual fit is rather good, with differences readily explainable by whether or not a correction for freight was included.

Whether the US fleet results are representative of the world fleet cannot be tested, as comparable data on world aviation transport volumes and fuel consumption are not available. However, in terms of production volumes, most aircraft in the (world) fleet were built by US companies and, within the United States, successful aircraft designs from other countries have also been used. Finally, the micro data show there is no systematic difference in the performance of US and European aircraft. One possible observation is that growth of aviation occurred one or two decades earlier in the US than in the rest of the world. Therefore the average aircraft age in the US is currently lagging behind Europe and Asia.

6.3 Comparing micro and macro data

Cross-comparison of the micro and macro analysis is a difficult exercise, for many reasons. These stem from a variety of operational and economic factors affecting fuel consumption per available seat-kilometre. Thus, comparison of the energy efficiency of individual aircraft with fleet averaged values is complicated by the following issues:

- Fuel efficiency calculations for individual aircraft (micro analysis) are based on design conditions: the maximum range with full payload, where the aircraft is operated at optimal cruise conditions for the longest period of time. In everyday operations (macro analysis), aircraft rarely operate between airports at optimum range distance with lowest per-seat fuel consumption (see Figure 12). Hence, fuel efficiencies from the micro analysis probably overestimated compared to the macro analysis.

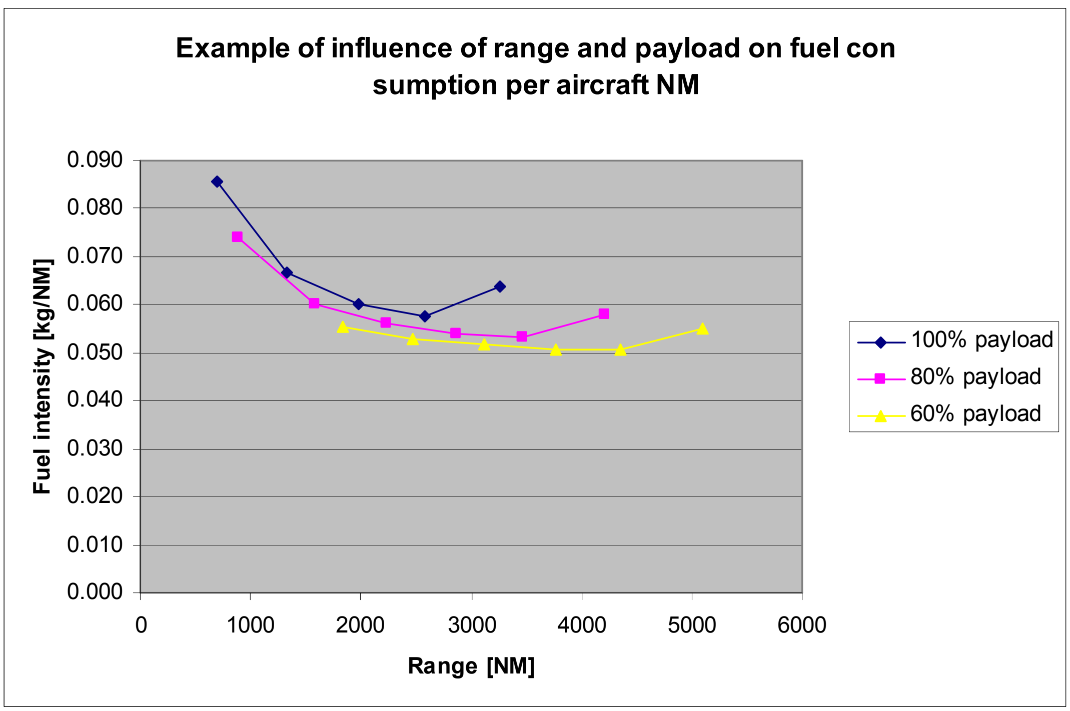


Figure 12: Influence of range and payload on aircraft fuel consumption per nautical mile.

- Micro analysis is concerned with specific aircraft, each with its own state-of-the-art technology embedded and quite often aimed at a specific market, while macro analysis is concerned with a fleet comprising aircraft from 0 to 35 years old and designed for different typical flight ranges and payloads. On average, it is estimated that fleet-average technology lags behind 'service-entry' technology by 5 to 15 years, varying by world region (see, for example, Lee et al. 2001). Micro analysis considers (mainly) long-haul aircraft that typically benefit more from fuel consumption-related technological improvements, whereas macro-analysis is based on a fleet mix of short-, medium- and long-haul aircraft. Again, the micro analysis fuel efficiencies are probably overestimates compared with the macro analysis numbers.

- Macro analysis fuel efficiencies are evaluated in terms of actual fuel consumption, whereas mileage is usually based on the great-circle distance between departure and destination airports. This implies that the effects of (ATM and airport) congestion, detouring (due to maximum allowable distance to alternative airports while crossing oceans, for example) and headwinds (having less impact with increased cruise speeds) all increase the effectively flown mileage and hence reduce the observed fleet fuel efficiencies. All these (operational) aspects have seen considerable changes over the last few decades, and hence clutter the observed numbers.
- The practice of tankering, whereby aircraft transport additional fuel for use on the next flight, increases fuel burn (due to increased weight). The increased operational and economic flexibility outweighs the increased fuel burn. Today's operations and technologies provide greater opportunities for tankering than in the past.
- The macro analysis is based mainly on US data. It is noted that in the last few decades the US fleet has become relatively aged.

6.4 Comparing pistons and jets

Most developments are driven by cost savings, revenue increases, safety improvements, increased range and take-off and landing performance. Fuel burn is only one of the cost components, albeit a major one. Some of the other aspects are elaborated on below, with the aim of putting the figures in some perspective:

- The transition from piston engines to gas turbines was made predominantly to increase aircraft speed and altitude (and to some extent range; see Figure 13). Fuel consumption was only an issue in terms of range, not cost. The overall effect at the outset of the transition was higher energy consumption.

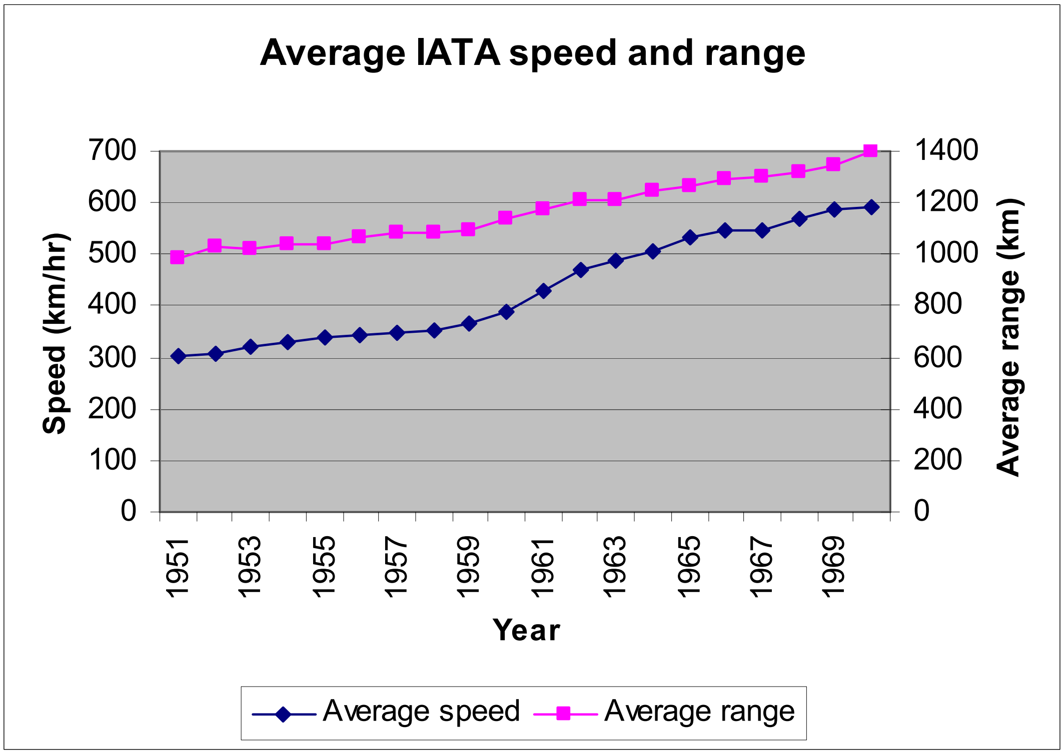


Figure 13: Changes in average speed and range for the whole IATA fleet (ref: IATA annual reports between 1960 and 1970).

- Fuel consumption reductions were not a major design driver until the 1980s. Even today, fuel consumption (or costs) is still only one of the many design drivers for aircraft and engine development.
- Kerosene is a ‘lower quality’ fuel than aviation gasoline, and the latter is consequently far more expensive. In comparing fuel efficiencies across jet and piston power, the costs and efficiencies of fuel production have not been considered.
- Comparing the performance of kerosene-fuelled and piston-powered aircraft in about the same year means comparing immature, early adoption of gas turbine technology with mature piston technology.
- In general, aircraft size, speed, range and (payload) weight all influence fuel consumption. Today’s aircraft differ significantly in these respects from aircraft in the past.
- Finally, load factors do have some influence on fuel consumption per seat-kilometre: extra payload costs extra fuel. As load factors increased between 1970 and 2000 (see Figure 14), this means that energy consumption per ASK has also been increasing, by several percent.

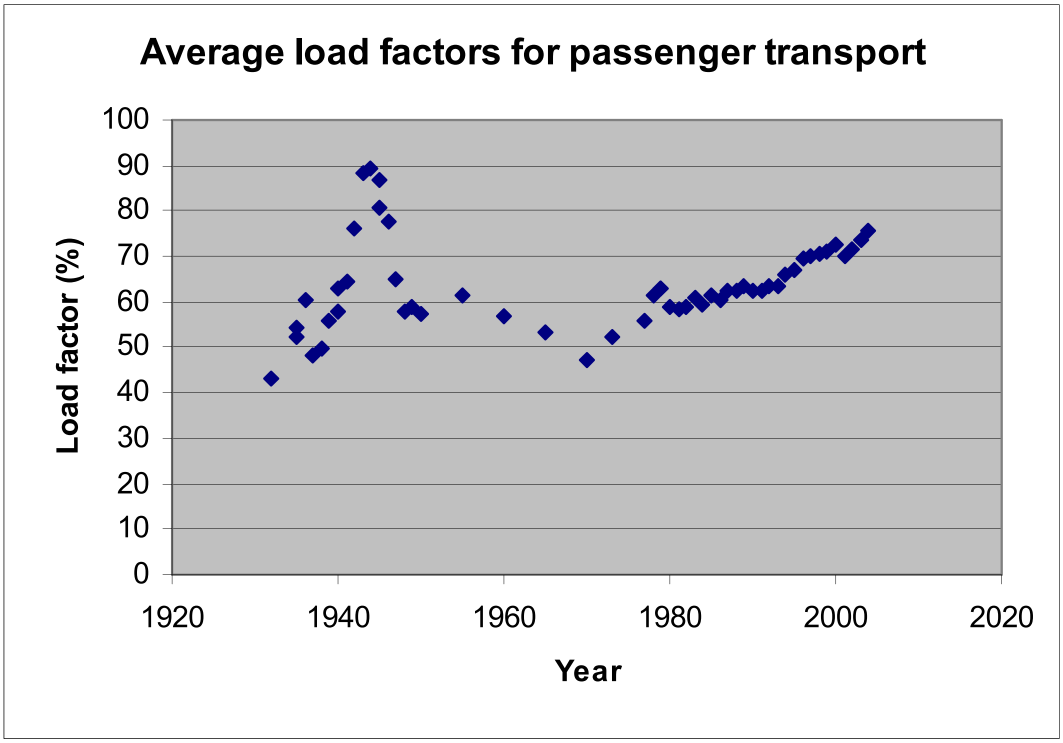


Figure 14: Load factors for the US fleet between 1930 and 2005 (source: ATA annual reports).

7 Conclusions

This study sought to address four research questions, which can now be answered concisely as follows.

1. *What is the origin and validity of Figure 9-3 of the IPCC's Special Report on Aviation? What are the underlying data and assumptions of this figure?*
   The graph is first referenced as Albritton et al. 1997 and was submitted by Rolls Royce plc.

2. *Can this figure be extended with data from before the jet age (i.e. data for the last large piston-powered airliners) and can all data be based on the same set of assumptions in a single graph?*
   A total of 11 new points have been calculated: four for piston-powered airliners, two for the first generation of jet-powered aircraft and five for modern jet-powered aircraft. By anchoring these data to the IPCC data, it was possible to extend the IPCC graph. The new Airbus A380 has also been added, using data from the scientific literature, as well as several regression lines.

3. *What is the fuel efficiency of air transport, as based on historical and current statistical data on total fuel consumption and total passenger- and freight-kilometres travelled?*
   The last piston-powered aircraft appear to have had the same energy efficiency per available seat-kilometre as average modern jet aircraft. The most modern jet aircraft (such as the B777-200 or B737-800) are slightly more efficient per avialable seat-kilometre. Per available ton-kilometre the difference is even less. In all cases the maximum range at maximum payload has been taken as the reference for calculating energy efficiency.

4. *What general conclusions can be drawn regarding long-term trends in worldwide aviation fuel efficiency since World War II?*
   - The overall gain in airliner fuel consumption depends significantly on the reference aircraft used.
   - The 70% improvement in efficiency, as reported in the IPCC Special Report on Aviation and the Global Atmosphere, is significantly higher than found in both the micro and macro analysis set out in this report; the DH Comet 4 is not considered a very suitable reference.
   - The last piston-powered airliners were at least twice as fuel-efficient as the first jet-powered airliners; if, for example, the last piston-engine aircraft of the mid-fifties are

compared with a typical turbojet aircraft of today, the conclusion is that fuel efficiency per available seat-kilometre has not improved.

- The fuel efficiency of aircraft is only one of several design features considered important by aircraft designers and the market.
- The common practice of defining future cuts in energy consumption in terms of a constant annual percentage reduction is not very true to reality: it ignores the fact that the asymptote of the regression line cannot be zero; nor does it take into account of the fact, shown clearly by the micro and macro data, that the annual reduction rate is not a constant, but is itself also falling. This means many studies on predicted future gains are rather optimistic.
- The results of the micro and macro analysis support all these conclusions.

Annexes

Annex I. Units

Quantity	Conversion factor	SI unit	Reference
1 BTU	0.001055	MJ	IEA 2004
1 ktoe	41870000	MJ	IEA 2004
1 mile	1.609	km	Kermode 1972
1 US ton	0.9072	metric ton	Fogt 2002
1 pound	0.4536	kg	Fogt 2002
1 gallon (US)	3.785	l	Fogt 2002
1 US gallon av. gasoline	131.8	MJ	Fogt 2002
1 US gallon kerosene	142.2	MJ	Fogt 2002
1 US ton	907.2	kg	Fogt 2002
1 litre aviation gasoline	34.81	MJ	calculated
1 litre jet fuel	37.57	MJ	calculated
1 kg kerosene	43.28	MJ	Chevron Products Company 2005
1 kg avgas	43.71	MJ	Chevron Products Company 2005
1 NM	1.852	km	Fogt 2002

Annex II. Abbreviations

ASK	Available seat-kilometre
ATK	Available ton-kilometre
E_i	Energy intensity in MJ/skm or MJ/tkm
MTOW	Maximum take-off weight
MZFW	Maximum zero-fuel weight
OEW	Operating empty weight
skm	Seat-kilometre
tkm	Ton-kilometre

Annex III. Converting number of seats to available revenue ton-kilometres

Energy efficiency is the amount of energy used to transport one unit of payload over a distance of one kilometre. However, the unit of payload is not as easy to define as it seems. Aircraft can be used for transporting passengers, freight/post/express or a mix of these. To calculate the pure technological energy efficiency of an aircraft we have used maximum payload capacity as the measure for payload; the load factor is not a technical property of the aircraft but a measure of the operational efficiency of the airline. The configuration of an aircraft also has a major influence on its payload capability. The operating empty weight of a full freighter is normally far less than that of a mixed-seating full passenger aircraft. It is therefore necessary to convert the number of available passenger-kilometres to available revenue ton-kilometres. This conversion generally assumes an average weight for passengers, including their luggage. However, extra weight should be added for the seats, catering, cabin staff and safety equipment. First we gathered information on the statistical average weight as used in several databases and studies (see Table 3).

Description	Period	Value/	Reference
Fixed average weight	2000	160 kg/pax	Wit et al. 2002, p. 30
Fleet average weight for available capacity	2005	98 kg/pax	Lufthansa 2005
BTS and US Bureau of the Census	1970	90 kg/pax	Bureau of Transport Statistics 2005b; Lerner 1975
BTS and US Bureau of the Census	1954	88 kg/pax	Bureau of Transport Statistics 2005b; Lerner 1975
IATA domestic average weight per pax	1999	89 kg/pax	IATA 2000
IATA international average weight per pax	1999	93 kg/pax	IATA 2000
IATA overall average weight per pax	1999	91 kg/pax	IATA 2000
IATA domestic average weight per pax	1960	86 kg/pax	IATA 1971
IATA international average weight per pax	1960	92 kg/pax	IATA 1971
IATA overall average weight per pax	1960	88 kg/pax	IATA 1971
AERO average weight per rev pax	1997	100 kg/pax	Pulles et al. 2002
USDOT Form 41 standard = 200 lbs	1998	90.7 kg/pax	Lee 1998, p. 65

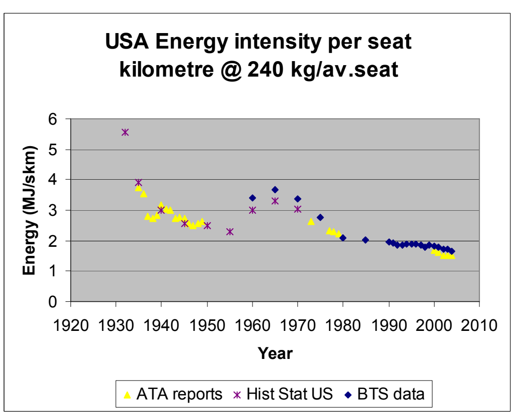
Table 3: Some macro-statistical average passenger weights.

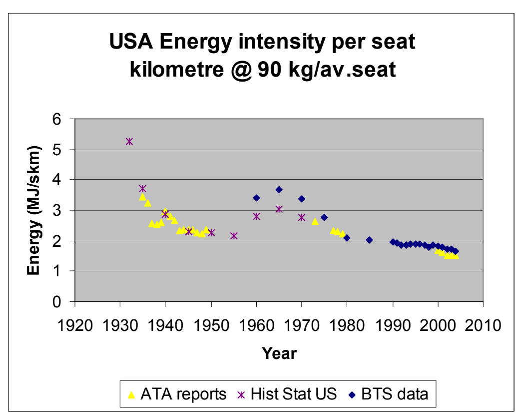
From an aircraft design perspective, it is important to look at the differences in aircraft OEW caused by different configurations. To find the OEW weight cost of passengers, several aircraft with a full passenger and a full freighter configuration were compared (see Table 4).

Aircraft type	OEW		MZFW		Payload		Seats	Pax weight	
	Pax kg	Freight kg	Pax kg	Freight kg	Pax kg	Freight Kg	Pax No.	Pax kg/ av. seat	Freight kg/ av. seat
B747-400	180755	129670	242670	242670	61915	113000	526	118	215
B757-200	57840	50475	84370	90720	26530	40245	239	111	168
MD-11	130165	113920	181435	204700	51270	90780	410	125	221
A300-600	90115	79050	130000	133800	39885	54750	376	106	146

Table 4: Some statistical average passenger weights (data from Jackson 1998).

This analysis shows that the statistical average weight of about 90 kg per passenger (including luggage) is small compared with the differences in weight-based payload capabilities of full passenger and full freighter aircraft configurations. The micro analysis reveals weights of up to 221 kg per available seat. Which value to take for further analysis depends on what we want to compensate for. If this is finding the number of seats that might have been carried if all freight capacity had been passenger capacity, then a high value is a reasonable choice, for example 160 kg/available seat. If a real payload based comparison is required, then an operational passenger weight is a more appropriate choice. For energy efficiency purposes, the high average passenger weight seems the best indicator. For this report we have used a figure of 160 kg, though below we show the impact on the results of taking 90 kg and 240 kg per average seat. The impact of two different seat weight assumptions is shown by following figures:





References

Airbus. (2005a). "Aircraft families / A330 / A340 family / A330-300 The wealth generator." Airbus S.A.S.

Airbus. (2005b). "Aircraft families / A330 / A340 family / A340-300 Pathfinder to profitability." Airbus S.A.S.

Albritton, D., Amanatidis, G., Angeletti, G., Crayston, J., Lister, D., McFarland, M., Miller, J., Ravishankara, A., Sabogal, N., Sundararaman, N., and Wesoky, H. (1997). "Global atmospheric effects of aviation. Report of the Proceedings of the symposium held on 15-19 Aprille 1996 in Virginia beach Virginia, USA." *NASA CP-3351*, NASA, Washington.

ATA. (1940). "Little known facts about the scheduled air transport industry." *Volume two*, Air Transport Association of America, Chicago.

ATA. (1950). "Air transport facts and figures." *11th edition*, Air Transport Association of America, Washington.

ATA. (1980). "Air transport 1980. The annual report of the U.S. scheduled airline industry." Air Transport Association of America, Washington.

ATA. (2005). "2005 Economic Report. New thinking for a new centry." Air Transport Association of America, Washington.

ATAG. (2005). "Aviation & environment summit discussion paper." Air Transport Action Group, Geneva.

Babikian, R., Lukachko, S. P., and Waitz, I. A. (2002). "The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives." *Journal of Air Transport Management*, 8(6), 389-400.

Bickerstaff, C. (2005). "Aircraft Technological Developments." AERONET III Workshop on Air Transportation Systems, Stockholm.

Bisignani, G. "Aviation and the environment." *First Aviation and the Environment Summit*, Geneva.

Boeing. (2005). "Airport Technology. Airplane Characteristics for Airport Planning." Boeing Commercial Airplanes.

Bureau of Transport Statistics. (2005a). "Annual 1981-2001."

Bureau of Transport Statistics. (2005b). "Historical Air Traffic statistics, annual 1954-1980."

CE. (2000). "ESCAPE: Economic screening of aircraft preventing emissions; main report." *Publ. code: 00.4404.16*, CE/Peeters Advies/ADSE, Delft.

Chevron Products Company. (2005). "Aviation Fuels Technical Review (FTR-3)." Chevron U.S.A. Inc., San Ramon, CA.

Dalhuijsen, J. L., and Slingerland, R. "Preliminary wing optimization for very large transport aircraft with wingspan constraints." *42nd AIAA Aerospace Sciences Meeting and Exhibit*, Reno.

Fogt, R. (2002). "Online conversion.com."

Frederick, J. H. (1961). *Commercial air transportation*, Richard D. Irwin, Inc, Homewood, Illinois.

Gössling, S., and Peeters, P. M. "“It does not harm the environment!” - An analysis of discourses on tourism, air travel and the environment." *4th International Symposium on Aspects of Tourism. The End of Tourism? Mobility and local-global connections*, Eastbourne.

IATA. (1957-2004). *World air transport statistics*, International Air transport Association, Montreal.
IATA. (1971). *World air transport statistics*, International Air transport Association, Montreal-Geneva-London.
IATA. (2000). *World air transport statistics*, International Air transport Association, Montreal-Geneva-London.
ICAO. (1951). "Report of the council to the assembly on the activities of the organization in 1950." *Doc 7148, A5-P/1*, International Civil Aviation Organisation, Montreal.
ICAO. (1952). "Report of the council to the assembly on the activities of the organization in 1951." *Doc 7270, A6-P/1*, International Civil Aviation Organisation, Montreal.
IEA. (2004). "2. Units and conversions." Energy balances of OECD countries, 2002-2003
International Energy Agency, Paris.
Jackson, P. (1998). "Jane's All the world's aircraft 1998-1999." DPA, London, 847.
Kermode, A. C. (1972). *Mechanics of flight*, Pitman Publishing Limited, London.
Lee, J. J. (1998). "Historical and future trends in aircraft performance, cost, and emissions," Massachusetts Institue of Technology, Cambridge.
Lee, J. J., Lukachko, S. P., Waitz, I. A., and Schafer, A. (2001). "Historical and future trends in aircraft performance, cost and emissions." *Annual Review Energy Environment*, 26, 167-200.
Lerner, W. (1975). "Air transportation (series Q 565-637)." Historical statistics of the United states. Colonial times to 1970, Bureau of the Sensus, 767-773.
Lufthansa. (2005). "Balance. Key data on environmental care and sustainability at Lufthansa. Reporting year 2004." Lufthansa, Cologne.
Mitchell, B. R. (1999). *International historical statistics. The Americas 1750-1993*.
NTSB. (1974). "Aircraft accident report aircraft Pool Leasing Corporation, Lockheed Super Constellation, L-1049H, N6917C, Mimami Florida, December 15, 1973." National Transportation Safety Board, Washington.
OECD. (2003). "Energy statistics odf OECD countries 2000-2001." Organisation for Economic Co-operation and Development, Paris.
Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., and McFarland, M. (1999). "Aviation and the global atmosphere; a special report of IPCC working groups I and III." Cambridge University Press, Cambridge.
Philips, A. (1969). "Operating cost, performace characteristics and the demand for aircraft by domestic trunk airlines: 1932-1965." AIAA 6th Annual Meeting and Technology Display, AIAA Paper No. 69-1059, Annaheim, CA.
Prop-Liners of America Inc. (2005). "Lockheed 1649A technical specifications." Prop-Liners of America, Inc, Hartford, CT.
Pulles, J. W., Baarse, G., Hancox, R., Middel, J., and van Velthoven, P. F. J. (2002). "AERO main report. Aviation emissions and evaluation of reduction options." Ministerie van V&W, Den Haag.
Swinhart, E. (2001). "The Lockheed Constellation." The Aviation History On-Line Museum.
Vasilyev, S. (2002). "FindGraph." Uniphiz Lab, Vancouver.
Wit, R. C. N., Dings, J., Mendes de Leon, P., Thwaites, L., Peeters, P. M., Greenwood, D., and Doganis, R. (2002). "Economic incentives to mitigate greenhouse gas emissions from air transport in Europe." *02.4733.10*, CE, Delft.