Aviation in a sustainable world

Fuel Efficiency Development and Prediction

Main Thematic Area: Climate Change

Bethan Owen

Manchester Metropolitan University

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Report prepared by	Bethan Owen
Reviewed / checked by	David Lee & Omega Office

Contents

1 INTRODUCTION

1.1 Study Aims and Objectives

The objectives of this study are: to explore the extent to which technology and operational factors have contributed to improvements in overall fuel efficiency; and to identify the drivers behind the historical trend. A more detailed understanding of past performance can help to guide future developments.
This study aims to explore the extent to which technology and operational factors have contributed to improvements in overall fuel efficiency. It unpacks past performance on fuel efficiency by looking at inventories and historical data to determine the trends for each element of cumulative efficiency improvement.

1.2 Fuel Efficiency Overview

Currently, there are no fuel efficiency standards adopted within the industry. Improving fuel efficiency of aircraft is however a major area of technological research and development, since together with environmental concerns, improving fuel efficiency directly improves airlines' direct operating costs. The main sources of fuel efficiency improvements are as follows:
Engine technology;
Airframe technology;
Aircraft size;
Load factor and
Operational improvements.

Improving engine fuel efficiency through design changes requires testing to ensure compliance with safety and reliability requirements. Moreover, noise and emissions (NO_x, HCs, CO soot) performance also needs to be considered. These engineering and environmental performance "tradeoffs" often impose constraints on the improvements being sought. Fuel efficiency can be improved through the use of higher pressure ratios in engines, although this development route can increase combustor temperatures and push material design limits beyond current capabilities and impact upon other emissions (principally NO_x), which imposes design and performance challenges.

Whilst fuel efficiency has been estimated to be improved by >60% over the past 40 years in terms of emissions of CO_2 per passenger km, i.e. since the introduction of the B707-120, many of these improvements have come from step changes in technology, e.g. turbojet to first generation turbofan engines and first to second-generation turbofans (B777-200). Some efficiency gains have also come about through improved airframe aerodynamics and material changes, reducing weights. In the near term, it is envisaged that most of the further improvements will be brought about through increased usage of lightweight materials. In the longer term, the IPCC Working Group Three (WGIII) considered that more radical designs such as blended wing body and unducted propfan-engined aircraft would be required to realise further step-change improvements (Kahn Ribeiro *et al*. 2007).

Biofuels may also offer some advantages, if they can be developed economically and in compliance with the exacting performance and safety standards that are required for civil aviation. However, there are fundamental questions of the economic and ecological viability of producing significant quantities of biofuels, which are likely to find more practical uptake and usage in other transport sectors.

Air traffic management and different operational practices hold some prospect for reductions in fuel usage or mitigation of environmental effects of aviation. The most obvious reductions in fuel usage might come about from an improved air traffic management system that would better optimize cruise altitudes through reduced vertical separation minimum (RVSM) and reduce delays and holding patterns on arrival. A EUROCONTROL study[1] showed that the introduction of RVSM over Europe has resulted in a reduction in fuel burn and CO_2 emissions of 1.6–2.3% yr^{-1} over the prior conditions. However, it should be stressed that this is a one-off saving and not a strategy that would offer further future savings. Non-CO_2 effects may also be reduced by changing cruise altitudes. Parametric modelling studies have shown that effects from contrails and O_3 can generally be reduced by lowering overall cruise altitudes. These studies did not propose implementing blanket reductions in cruise altitudes on a global basis but tested the hypothesis via a parametric study and it is clear that only minor tactical changes of altitude would be necessary on real flights to avoid ice-supersaturated regions, should suitable data become available on this parameter that would allow flight-by-flight prediction of contrail formation. However, there are tradeoffs that need to be considered in that reductions in cruise altitudes would incur a fuel burn penalty which is not straightforward to quantify, since the RF effects of CO_2 emitted on a particular flight are longer lasting than those of a contrail formed during the same flight.

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[1] http://www.eurocontrol.int/mil/public/standard_page/rvsm1.html accessed 23/04/09

Lowering flight speeds could also yield significant fuel savings but engines would require re-design to maximize the benefits. The technology for this already exists and unducted propfan engines could be developed that have been proven to be more fuel efficient. However, there are disadvantages in terms of increased noise and decreased passenger comfort as cruise altitudes would be reduced.

1.3 Fuel Efficiency Metrics

Fuel efficiency is sometimes expressed as the efficiency of a specific vehicle type against a set of standard criteria. For an aircraft this could be expressed as the Specific Fuel Consumption (SFC), essentially an engineering term that is used to describe the fuel efficiency of an engine design with respect to thrust output. SFC allows the efficiency of different sized engines to be directly compared and for thrust engines (e.g. turbojets, turbofans etc) the SFC is the mass of fuel needed to provide the specific net thrust for a given period e.g. g/(s·kN) in metric units - grams of fuel per second-kilonewton. Mass of fuel is used rather than volume (gallons or litres) for the fuel measure since it is independent of temperature.

In this study however, the actual efficiency of the collective fleet in airline service is being assessed on a global basis. Efficiency improvements considered in this study can be derived from aircraft engine specific fuel combustion (SFC) characteristic, airframe improvements and also from operational improvements and the most appropriate metric would be aircraft system fuel or traffic efficiency. Fuel efficiency is essentially the mass of fuel used in transporting a number or mass of passengers and freight. Traffic efficiency (i.e. ASK per mass of fuel used etc), is effectively the reciprocal of fuel efficiency. The traffic or fuel efficiency metrics used in this study incorporate the fleet usage and operational factors alongside actual aircraft performance capability.

Fuel efficiency is often expressed in terms of mass of fuel used per passenger kilometre, as either Available Seat Kilometres (ASK)/Seat Kilometres Offered (SKO) or Revenue Passenger Kilometres (RPK) per mass of fuel used. Fuel efficiency can also be expressed as mass of fuel used per payload (mass) multiplied by distance. Common descriptors include mass of fuel used per Available Tonne Kilometres (ATK) or Revenue Tonnes Kilometres (RTK). Payload (tonne) is a fleet total payload, defined as passenger and cargo carried. Payload is defined by mass and a typical passenger mass conversion factor of 91 kg/passenger (including baggage) can be used (this value is based on ICAO statistics for 2007[2]).

Efficiency expressed as mass of fuel per Revenue Passenger or Tonne Kilometre (RPK or RTK) includes the efficiencies derived from increased loading factors of aircraft a significant source of improvement over the recent years. Efficiency as mass of fuel per ASK or ATK, does not include the changes in loading.

Care should be taken when considering percentage changes in fuel or traffic efficiency over time - as a rate of change, it is not important to specify whether one is describing traffic or fuel efficiency, however if, for example a 20% improvement over ten years is cited then the nomenclature of traffic or fuel efficiency is important, as the traffic efficiency will increase with time and the fuel efficiency as the reciprocal will decline with time.

Other metrics include mass of fuel per kilometre travelled (fuel per AK or aircraft kilometre). This metric is less favourable as it takes no account of the aircraft size and number of passengers carried.

It is worth noting that, by using the metrics of fuel use per ASK or ATK or AK to investigate efficiencies no account is taken of changes in the circuitry of air traffic (circuitry may be defined as the actual distance travelled by the aircraft between origin and destination divided by the great circle distance, that is the minimum distance, between origin and destination). This is a potentially significant source of fuel use and some further discussion of this issue is made in Section 3.

As discussed, fuel is usually measured in terms of mass for aviation kerosene. It should be noted that a traffic efficiency metric should be expressed in terms of kerosene mass only. Kerosene (Jet A/A1) is used almost exclusively throughout the commercial aircraft fleet. Mass is the conventional output of airline fuel consumption data and also inventory modelling processes used in this study. If required, conversion to fuel energy can be carried out by using an appropriate kerosene energy density for the kerosene used by the fleet under

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[2] http://www.airlines.org/economics/traffic/ accessed 9/02/09

consideration. A similar approach could be taken should the metric need to be expressed in terms of fuel volume (e.g. litres). However, aircraft range/payload capabilities are sensitive to non-trivial changes to fuel density and energy content – for example if considering use of a non-kerosene fuel – and simplistic conversion of this system fuel efficiency metric for other applications beyond kerosene-type fuels would not be appropriate.

2 LITERATURE REVIEW

A review of fuel efficiency data in the scientific literature and from airline literature has been undertaken and the reviews are presented below.

2.1 Peer Reviewed Literature

A number of studies exist in the literature where past trends in fuel efficiency are extrapolated to predict future trends. The IPCC Special Report on Aviation and the Global Atmosphere (1999) draws on the research by Greene (1992) which looked at fuel efficiency (seat kilometres per kg of fuel) and is perhaps the most comprehensive study on the past and future predictions of aviation fuel efficiency. The values taken from Greene and published in the IPCC Report (1999) related to recent historical trends and future projections, an annual improvement rate in fuel efficiency of 1.3% per annum for the period 1990 to 2010 was concluded, falling to 1% per annum for 2011 to 2020 and to 0.5% thereafter to 2050. These figures have been widely used in subsequent work (e.g. DfT, 2007).

The Greene study used data on the US Commercial Aircraft Fleet from 1970 to 1989 identifying trends in fuel efficiency over this period and breaking down the changes into efficiency gains from load factor changes, changes in aircraft size and then changes in operational efficiency and efficiency due to fleet rollover changes and replacement of older less efficient aircraft with newer ones. Greene then described the major technological options under consideration by manufacturers and the National Aeronautics and Space Administrations (NASA) in the early 1990s and fed a range of technology options through a fleet rollover model with the FAA demand forecast to make fuel efficiency projections through to 2010. The baseline assumed that new aircraft entering the fleet would be newer more efficient but available types, the other scenarios assumed fairly ambitious technology changes for post-2000 aircraft including open-rotor or propfan engines. Greene estimated that post-2000 aircraft had a range of technologically achievable efficiencies of between 110 and 150 seat-miles per gallon (59 to 80 ASK per kg of fuel equivalent to 1.69 to 1.25 kg/100-ASK) which in 2009 is still some way off.

Lee *et al.* (2001) looked at fuel efficiency changes in the US only and suggests that energy efficiency improvements were relatively strong in the past but are set to slow to between 0.7 and 1.3 % per annum (as fuel per seat kilometre) from 2000 to 2025.

Peeters *et al*. (2005) took this work further to explore the impact of applying a fitted curve rather than a straight line to the IPCC data and to that of Lee (2001) with a resultant predicted fuel efficiency trend of 0.5% per annum improvement between 2000 and 2040.

2.2 Airline and Industry Literature

Airline and other industry literature appearing on the web also provides data on fuel efficiency and these data have been collated (although the information is expressed using a range of different metrics, requiring some conversion to allow inter-comparison). Data is presented from the International Air Transport Association (IATA), an international trade body, representing approximately 230 airlines comprising 93% of scheduled international air traffic. Other airline data reported below are those where fuel efficiencies are quantified in absolute terms rather than relative changes (for example, BA quotes a fuel efficiency improvement target on its website but does not quantify a current figure). This review is not exhaustive but Table 1 provides an illustration of the types of data currently reported by some of the larger airlines. The data in Table 1 uses a variety of different metrics and to allow some inter-comparison, conversion to fuel efficiency as kg/100-ASK, kg/100-RPK and litres/100-RPK has been made and presented in Table 2. Two major airlines (KLM/AIRFRANCE and Lufthansa) present fuel efficiency data for their fleet for 2007 between 3 and 3.4kg of fuel per 100-ASK respectively. These figures agree fairly closely with data derived from top-down global statistics presented in Section 3 of this report. The data presented by Airbus in Figure 1 also shows a fleet average fuel efficiency of about 4.75 l/100-RPK (approximately 3.0 kg/100SKO). Airbus presents a time series of calculated fuel efficiency trends from 1986 to the present day and then projects likely fuel efficiency trends forward to 2026 reproduced in Figure 1 below. The Airbus data shows the A380 aircraft which entered into service in 2002 with the nominal fuel consumption of 3 litres per 100 passenger kilometres assuming 100% load factor. However, the fleet average data shown by the blue dots on the same figure would be based on less than 100% capacity which may narrow the gap between the current fleet average shown in the Airbus figure and the A380 efficiency values.

Table 1. Collation of IATA and Airline Reported data on Fuel Efficiency

Source	Reference	Date Accessed	Information as provided
IATA Environmental Review, 2004 (most recent)	http://www.iata.org/ps/publications/9486.htm	24/02/09	1994 to 2003 : 51.3l/100RTK to 43.27l/100RTK (15.7% change) 32.35l/100ATK to 26.56l/100ATK (17.9% change)
IATA website Feb 2009	http://www.iata.org/whatwedo/environment/fuel_efficiency.htm	24/02/09	20% improvement over last 10 years and further 25% by 2020 5% improvements achieved in 2004/5 and 2005/6 new aircraft 3.5l per 100pkm A380 and B787 3l per 100pkm
BA website March 2009	http://www.britishairways.com/travel/csr-environment/public/en_gb	23/04/09	*Improve carbon efficiency by 25% by 2025 - reducing the grammes of carbon dioxide per passenger kilometre from 111 to 83 grammes 50% reduction in our net CO2 emissions by 2050*
KLM 2006/7	http://corporate.klm.com/en/topics/environment Sustainability Report 2006/2007" on the KLM website	24/02/09	206g/ATK 259g/RTK
KLM/AIR FRANCE	http://corporate.klm.com/assets/files/publications/AFKLM%20CSR-report-0708_ENG%20(2).pdf Corporate Social Responsibility Report, 2007-08	24/02/09	3.9L/PAX/100KM IN 2007 From 4.42 in 2000
Lufthansa	Annual Report, 2007		4.68l/100pkm in 2000 4.38l/100pkm in 2007
Cathay Pacific	CATHAY PACIFIC AIRWAYS LIMITED, Environmental Report, 2005 "a focused review"		280g/RTK and 40g/RPK in 2005 (estimated from graphs in report)

Table 2. Estimated fuel efficiencies from Table 1 based on consistent metric for comparison

Source	Information	kg/100-RPK*	l/100-RPK*	Comment
IATA Publication	51.3 l/100RTK	4.07	5.13	1994
	43.3 l/100RTK	3.44	4.33	2003
IATA website	3.5 l per 100pkm**	2.78	3.50	"for new aircraft"
	3.0 l per 100pkm**	2.38	3.00	"A380 and B787"
Lufthansa	4.38 l per 100pkm**	3.48	4.38	2007
	4.68 l per 100pkm**	3.72	4.69	2000
Cathay Pacific	40 g per RPK	4.00	5.04	2005
KLM 2005/6	259g per RTK	2.59	3.26	2005
KLM AIR FRANCE	3.9 l/PAX/100km**	3.51	4.42	2000
	4.42 l/PAX/100km**	3.10	3.90	2007

* Calculations based on 1 litre = 0.794 kg of kerosene and the approximation that 10 RPK = 1 RTK

** Not specified whether per seat kilometre or revenue passenger kilometre

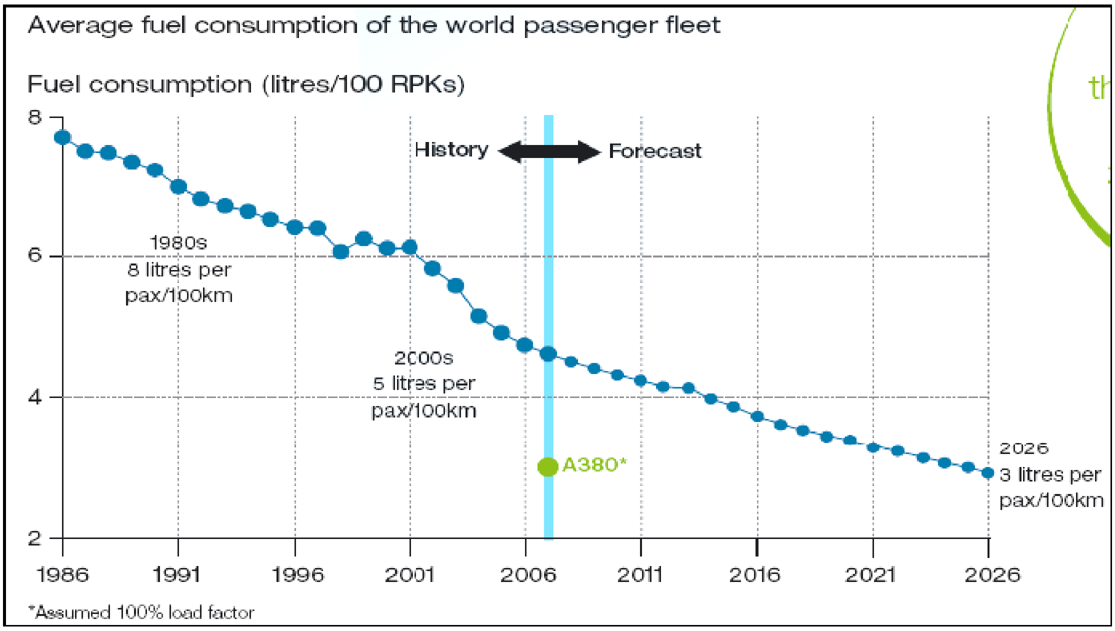

Figure 1. Airbus representation of fuel efficiency trends from 1986 and future projections (Airbus, 2007)

3 FUEL EFFICIENCY TRENDS AND CALCULATIONS

3.1 Calculation of Fleet-wide Fuel Efficiency Trends

There are a number of statistical data sources available that allow fleet-wide fuel efficiency trends to be estimated on a top-down basis. The International Civil Aviation Organisation (ICAO) collects and reports data on scheduled air traffic movements on an annual basis. The ICAO reports ASK (Available Seat Kilometres also known as SKO, seat kilometres offered) and RPK for scheduled passenger traffic and ATK and RTK (Available and Revenue Tonne Kilometre) for passenger and freight scheduled traffic.

The International Energy Agency (IEA) collect data on fuel supply and demand and provide a time series of kerosene and other aviation fuel demand on an annual basis. The kerosene demand time series does not distinguish between different types of aviation traffic and includes all aviation activities using this fuel including military operations.

The use of ICAO (2007) statistics on traffic data together with the IEA (2007) data on aviation fuel demand can theoretically provide a time series of actual fleet-wide fuel efficiency for the global air traffic fleet. However, the IEA data include all aviation kerosene usage including military operations whereas the ICAO statistics only include civil scheduled air traffic. The ICAO traffic relates only to civil scheduled traffic not including military or civil charter traffic; and the ICAO statistics are based on great circle distances between origin and destination rather than actual distances. Military emissions are estimated to make up approximately 11% of total aviation fuel usage (Eyers *et al.*, 2004) and the total fuel usage relating to civil aviation would consequently be lower than the IEA kerosene total. Furthermore, charter air traffic is estimated to amount to approximately 5% of total traffic (Sutkus *et al.*, 2003). The absolute value for the calculated traffic efficiency using the ICAO traffic statistics and the IEA fuel statistics would therefore be lower than the actual traffic efficiency (i.e. number of seat kilometres per mass of fuel used). The ICAO statistics are for civil aviation only and the distances flown are based on great circle distances between origin and destination rather than actual distances. Routing and ATM (air traffic management) inefficiencies generally mean that actual distances flown are approximately (on a global average basis) 10% than great circle distances (IPCC, 1999; Lee et al., 2005).

The IEA (IEA, 2007) and ICAO (ICAO, 2007) data are shown in Table 3. The time series from 1970 onwards is shown (ICAO data prior to 1970 excludes data from the former USSR). Approximate adjustments can be made according to the assumptions on military and charter traffic and distances flown as stated above and, using these assumptions an estimate of global aviation fuel efficiency and more importantly trends in fuel efficiency can be made. Trends in fuel efficiency from 1971 to 2006 are displayed in Figure 2 (the 1971 calculated fuel efficiency value is selected as the index = 100). Calculated global fleet fuel efficiency values are displayed in Figure 3 for the last twenty years (these calculations include assumptions on charter and military aircraft and routing as described in preceding section). A global fleet fuel efficiency of 3.35kg/100-ASK and 4.42kg/100-RPK is estimated for 2006 from these global statistics.

Trends in fuel efficiency (figure 2) confirm a 60% improvement in fuel efficiency as mass of fuel per ASK since the early seventies to today’s fleet (70% improvement is shown as mass of fuel per RPK). However a great part of this improvement was achieved during the 1970s (a 43% improvement is shown between 1971 and 1981). Further improvements over the last 25 years have been much more modest and fuel efficiency (as kg fuel per ASK) has fallen from 4.7 kg-fuel per ASK in 1981 to 3.3 kg-fuel per ASK in 2006 (approximately a 28% improvement).

Table 3. Time series of IEA global kerosene demand and ICAO scheduled traffic demand

Year	IEA Aviation fuel Tg	RPK (billions)	ASK (billions)	year	IEA Aviation fuel Tg	RPK (billions)	ASK (billions)
1971	102	460	840	1990	161	1,774	2,608
1972	108	494	914	1991	157	1,894	2,801
1973	111	560	981	1992	159	1,845	2,779
1974	108	618	1,073	1993	162	1,929	2,930
1975	109	656	1,108	1994	173	1,949	3,013
1976	109	697	1,179	1995	178	2,100	3,169
1977	116	764	1,270	1996	187	2,248	3,359
1978	110	818	1,346	1997	193	2,432	3,564
1979	112	936	1,451	1998	197	2,573	3,728
1980	114	1,060	1,607	1999	204	2,628	3,838
1981	111	1,089	1,724	2000	212	2,798	4,051
1982	113	1,119	1,757	2001	206	3,038	4,286
1983	115	1,142	1,795	2002	207	2,950	4,272
1984	124	1,190	1,852	2003	207	2,965	4,167
1985	128	1,278	1,972	2004	220	3,019	4,228
1986	137	1,367	2,081	2005	230	3,445	4,705
1987	145	1,452	2,235	2006	236	3,720	4,973
1988	153	1,589	2,368				
1989	160	1,705	2,524				

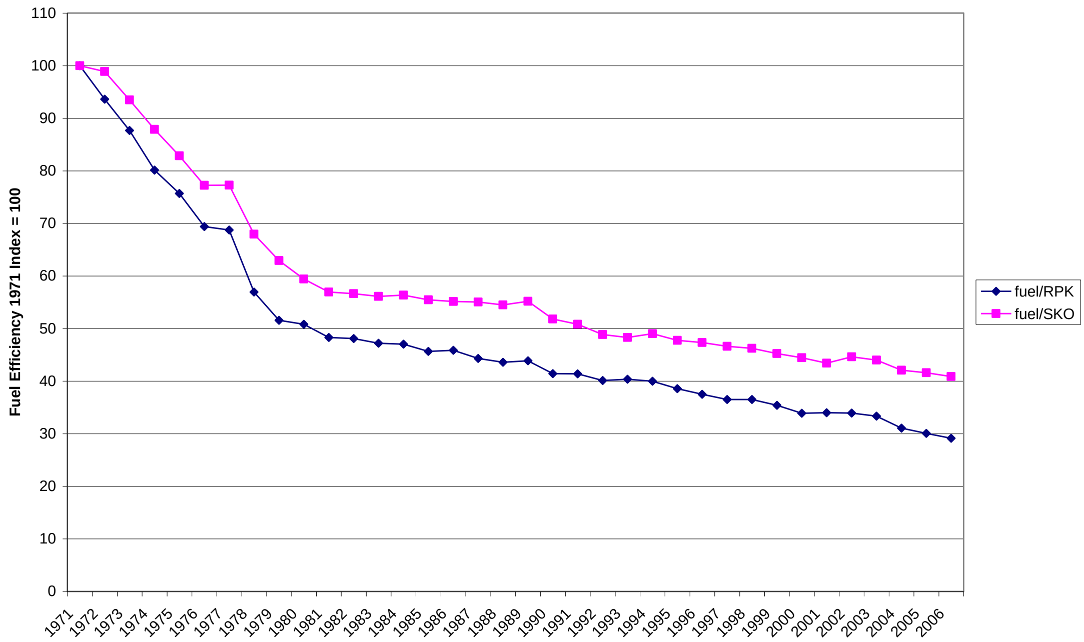

Figure 2. Trends in Global Aviation Fleet Fuel Efficiency (mass of fuel per ASK or SKO and RPK) from 1971 to 2006

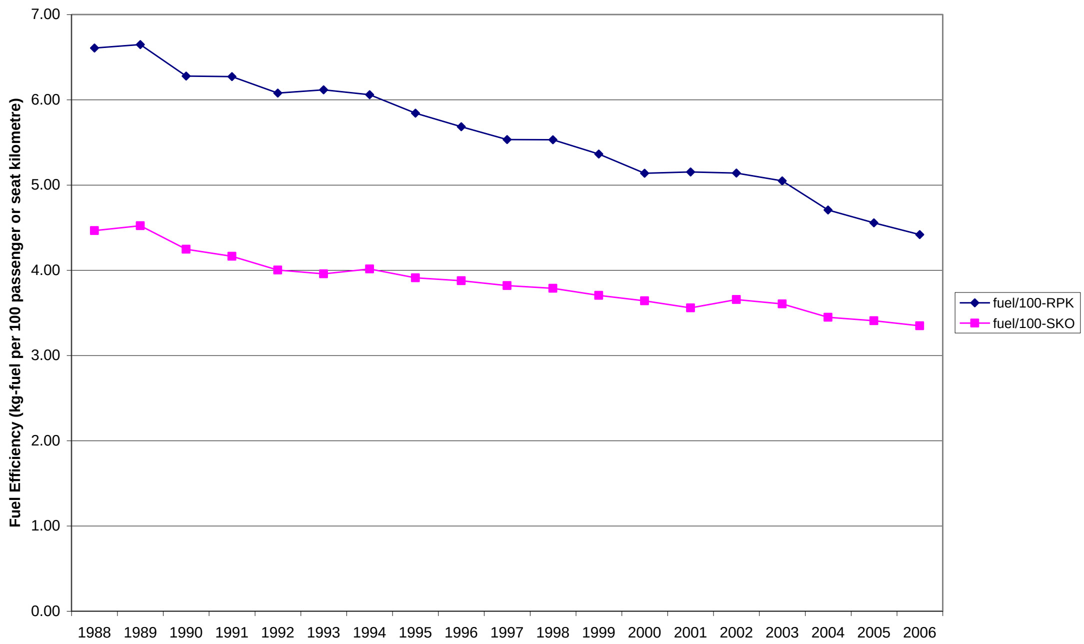

Figure 3. Calculated Global Fleet Fuel Efficiency Values from Global Fuel and Air Traffic Statistics (1986- 2006).

3.2 Estimation of source of fuel efficiency improvements

The changes in fuel use of the global aviation fleet air traffic, presented in the previous section, represent total changes in fuel use and efficiency and are the results of changes from four basic sources:

load factor, defined as RPK per ASK;

seating capacity[3];

mix changes, including the introduction of new aircraft and changes in the frequency of use of existing ones; and

technical and operating efficiency, a residual estimated by assuming that kg of fuel per AK would otherwise be constant over time for a given aircraft type.

Thus d) includes a range of operational factors such as, for example improved ATM, and possibly some retro-fitting technical actions such as fitting wing-lets.

Using air traffic operating statistics like those presented in the previous section, the following methodology, previously applied by Greene (1992), can be applied to provide an analysis to break down the overall changes in fuel use into the basic components of a), b) and c) plus d) combined. The methodology is based on relating the fuel use and RPK, load factor, seating capacity and fuel use per aircraft-kilometre (AK) as follows:

$$\text{Fuel Use} = \text{RPK} * (\text{RPK/ASK})^{-1} * (\text{Seat Capacity})^{-1} * (\text{Fuel/AK})$$

If we hold efficiency (all right hand terms except RPK) constant at a base-year level but increase RPK, we obtain a constant efficiency projection of future year fuel use. If we then allow load factor to vary, but hold all other factors (except RPK) constant at the base year levels, we obtain a projection of fuel use, which we can subtract from the constant efficiency projection to estimate the fuel savings due to improved load factor, "a" above. An estimate of the impact of aircraft size (ASK/AK) "b" is obtained in the same way. Changes in fuel use per aircraft kilometre include both "c" and "d" i.e. fleet-rollover to newer more efficiency aircraft

[3] Time series of Average Seats per Departure from Airbus (2007)

and operational improvements. The results of the analysis for the period 1970 to 2006 are shown in Table 4.

The time series for the three individual terms over time are shown in Figure 4 and the trends (index of 1970 =1) are shown in Figure 5. The load factor component has shown a pretty consistent upward trend since 1970 contributing to overall fuel efficiency savings.

Figure 4 shows that the average aircraft size increased between 1970 and 1990, contributing to fuel efficiency savings, at the same time the fuel used per aircraft kilometre also decreased, which provides strong evidence of improvements in aircraft engine/airframe technology and/or operational improvements. Since the early 1990s the size of aircraft has not increased dramatically. The average load factor has continued to increase leading to savings of fuel per RPK and the fuel use per aircraft kilometre has declined.

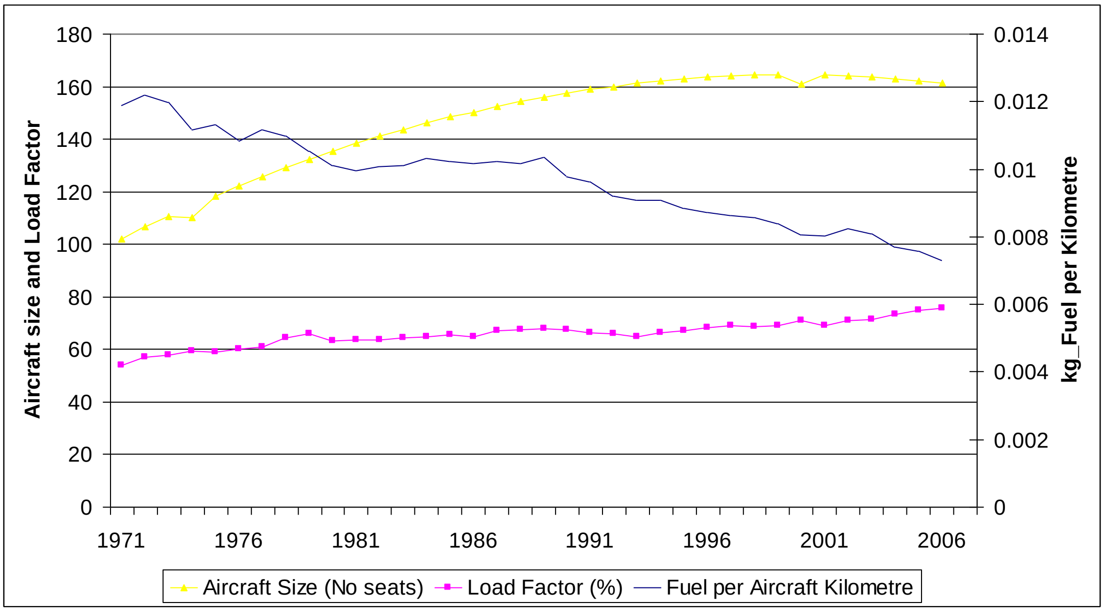

Figure 4. Estimation of Aircraft Size (number of seats), Load Factor (%) and Mass of Fuel (kg per aircraft kilometre) from Air Traffic Statistics

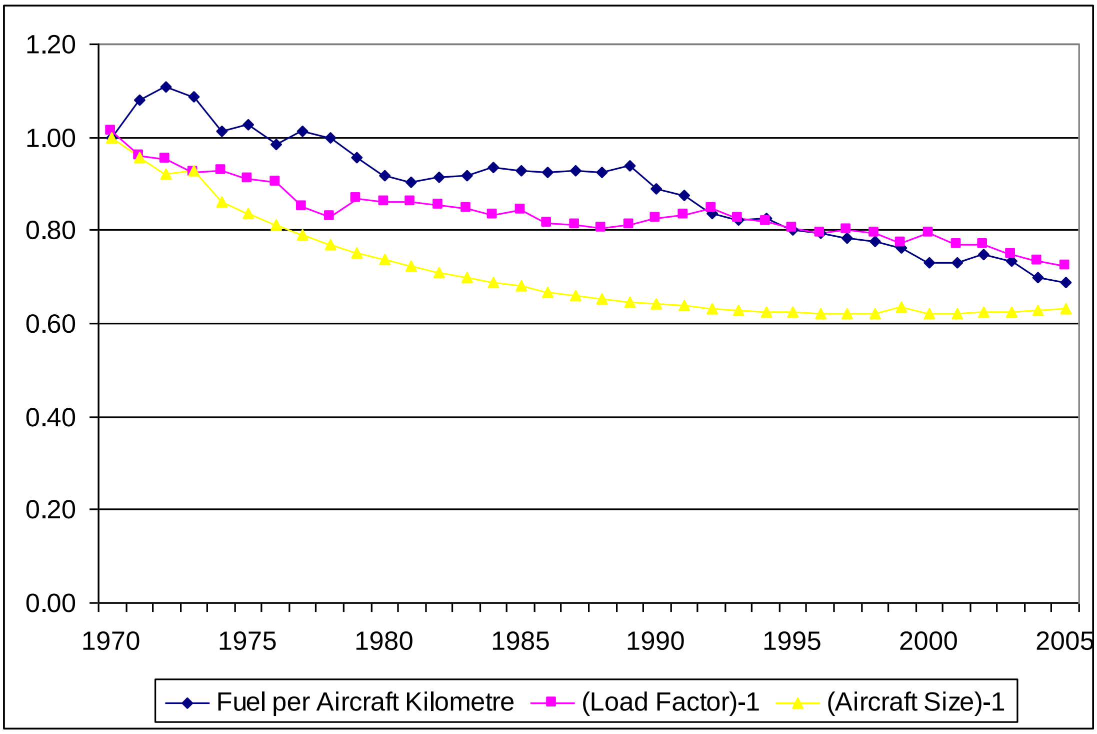

Figure 5. Trends in load factor, aircraft size, and fuel use per distance from 1970 to 2006 (1970 values = 1)

Table 4. Analysis of the changes in aviation jet fuel use, 1970-2006

Period	Source of improvement in Fuel Efficiency as Fuel per RPK			
	(a) Load Factor	(b) Aircraft Size	(c) and (d) Fuel per Aircraft-Kilometre	Overall
1970-2006	20%	26%	24%	70%
1970-80	11%	22%	7%	40%
1980-90	6%	12%	3%	22%
1990-2000	4%	2%	17%	23%
2000-2006	6%	0%	9%	15%

Estimation of the source of fuel efficiency improvements (Table 4) shows a 70% improvement in fuel efficiency as fuel per RPK between 1970 and 2006. These improvements can be broken down into improvements due to load factor (20%), aircraft size (26%) and finally technical and operational improvements to the fleet (24%).

Looking at the most recent 6-year period analysed in Table 4, the improvements in fuel-economy since 2000, mean that 15% less aviation fuel was used (and therefore emissions of CO_2) than would have been used without changes in efficiency. Over this 6-year period increases in load factor mean that a saving of 6% was made (1.1% per annum); there was no significant difference in average aircraft size; and a 9% saving was therefore made by changes in fuel burnt per aircraft kilometre i.e. fuel per ASK (1.4% per annum). Overall a 15% reduction (2.4% per annum) in fuel use per passenger kilometre (RPK) was seen over the 6-year period.

3.3 Calculation of Individual Aircraft Fuel Efficiency Trends

There are a relatively small number of commercial aircraft types, but a large variety of missions[4]. The fuel efficiency of an aircraft type is sensitive to the mission flown and there is not a single optimum mission. Different fuel efficiency values will be produced depending on the mission flown. Moreover, comparing the efficiency of one aircraft type against another on a single mission will not indicate that the comparison holds for the various missions which could be flown by those aircraft types. It is for these reasons that the applicability of this metric is explicitly restricted to fleet application only. For this application, a “fleet” is represented by a global set of flights for one year (i.e. 2000).

In this study, fuel efficiency values for each in-service aircraft weighted for the distribution of appropriate mission distances are determined from the FAST baseline 2000 inventory using the PIANO model and real flight data. The data are derived from the FAST fuel and emissions model and the fuel efficiency metric kilograms of fuel per available seat kilometre offered (kg/ask) by aircraft type is calculated. The FAST model uses a global movements dataset and therefore represents a typical range of flight distances undertaken by the shown aircraft types. This metric allows a historic trend to be established based on the aircraft types and their actual usage in the 2000 fleet. Aircraft currently in-service but not appearing in the 2000 global fleet such as the A380 and B787 are shown in Figures 6 and 7 and are estimated to have 20% better fuel efficiency than their current equivalents (based on manufacturers’ data).

[4] A mission is used here in the sense of a route of a certain distance with a certain seat/cargo demand, runway length, airport altitude, noise restriction etc

The metric shows the changes in fuel efficiency of replacement aircraft. This leads, through fleet rollover, to improvement of the fleet. It does not include any improvements from changes in load factor or in operational changes such as ATM improvements.

Many of the early improvements in the 1960s and 1970s have come from step changes in technology, e.g. turbojet to first generation turbofan engines and first to second-generation turbofans. This trend is illustrated by Figures 6 and 7 which show the fuel consumption per passenger seat kilometre (from FAST) for a range of aircraft types against their date of entry into service. These figures also clearly show that the trend for improvements in fuel efficiency tends to diminish with time.

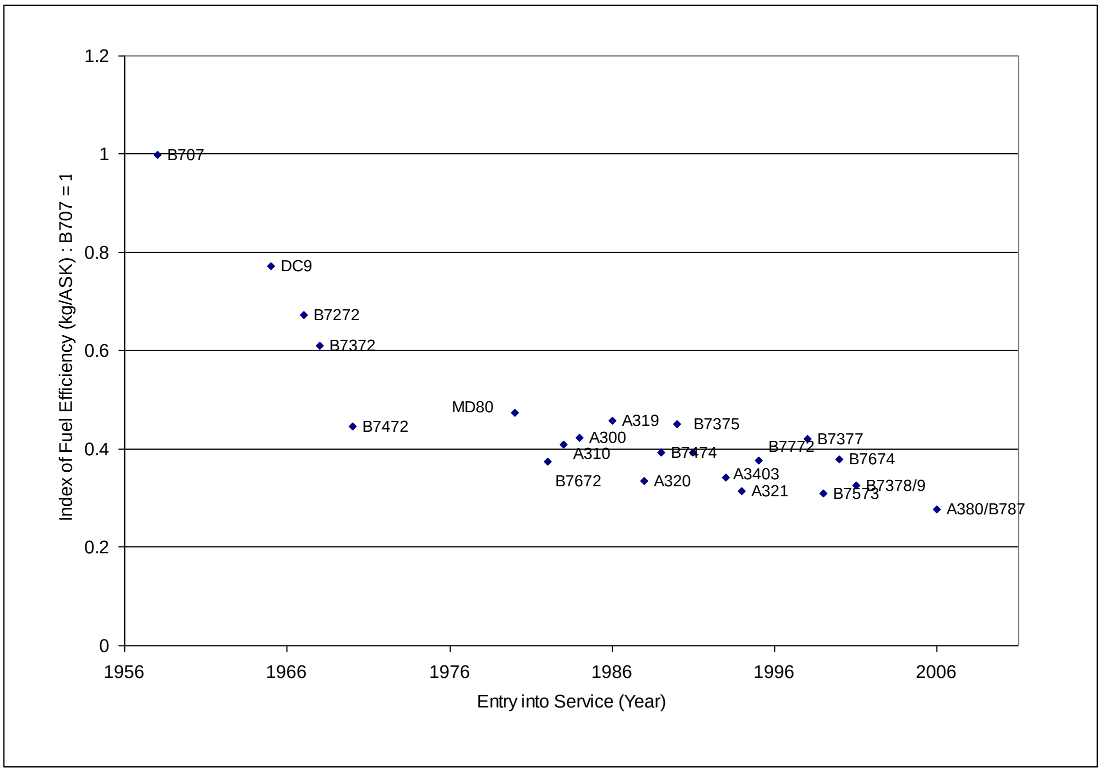

Figure 6. Fuel efficiency trend by aircraft Entry into Service date (from 1959) weighted for actual distance travelled (from FAST 2000 data)

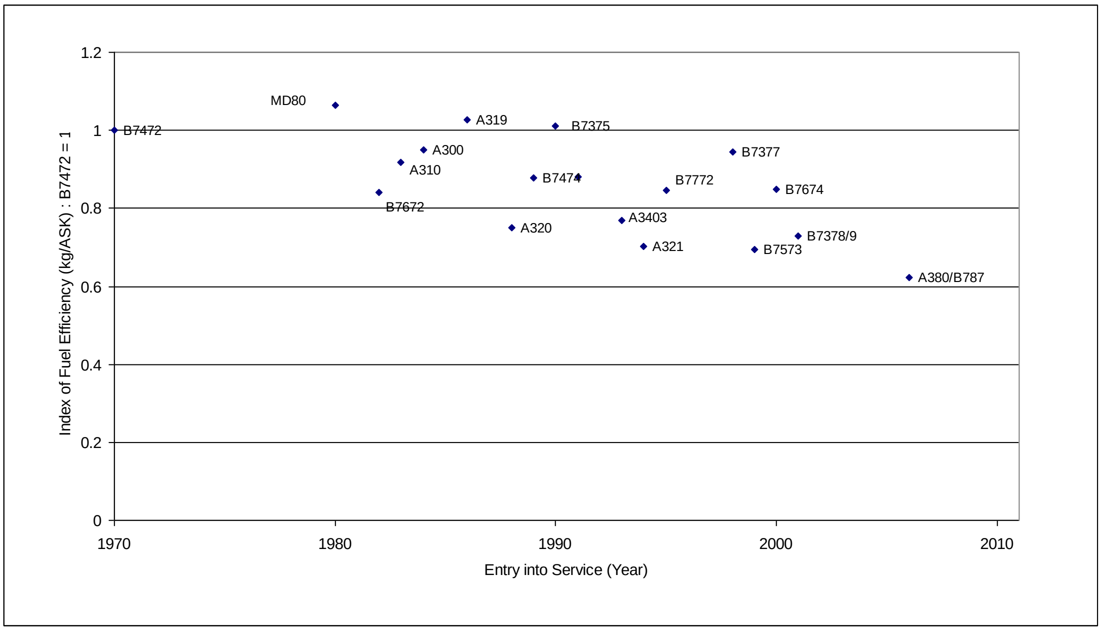

Figure 7. Fuel efficiency trend by aircraft Entry into Service date (from 1970) weighted for actual distance travelled (from FAST 2000 data)

Linear trends lines fitted to the data shown in Figure 6 and 7, provide the following linear relationships between time and fuel efficiency rates:

Figure 6 (data from 1959): fuel efficiency index, $y = -0.0003t + 0.032$

Figure 7 (data from 1970): $y = -0.0008t + 0.0534$

For the period 1959 to 2006, an *average* fuel efficiency improvement per annum of 3.45% is calculated for the data although it is clear from the chart that the most significant reduction occur during the first decade due to the introduction of the turbojet and first generation turbofan as also illustrated in figure 8 (from Martens, 1997). Taking the trend from 1970 to 2006 (figure 7) a more modest annual improvement rate in aircraft fuel efficiency of 1.12% per annum is calculated, noting again that this is an improvement rate based only on aircraft technology not including operational or loading improvements.

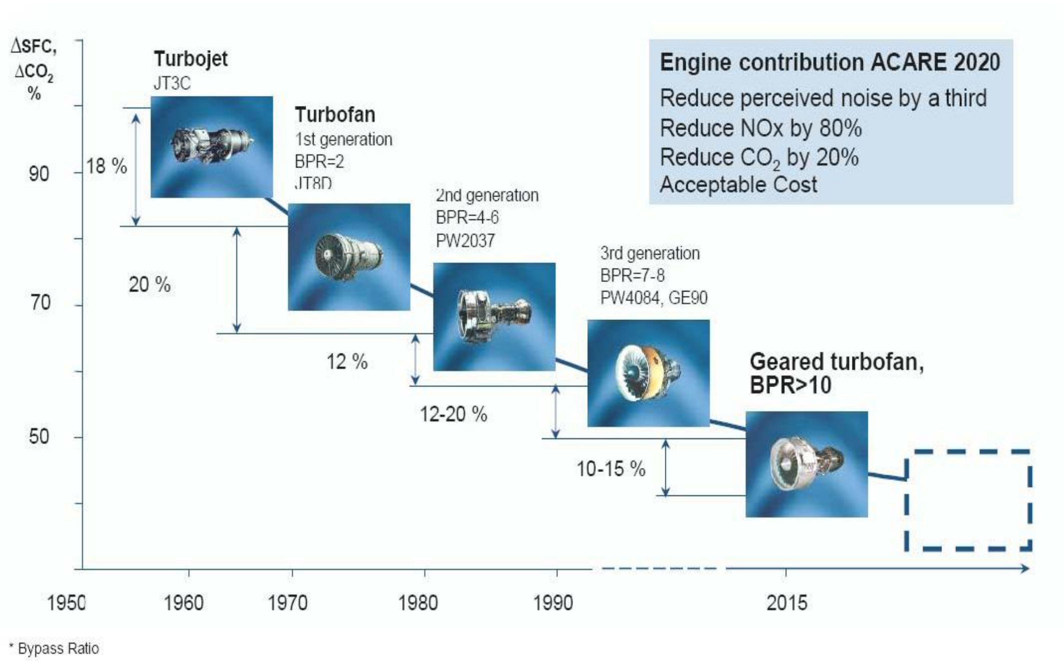

Figure 8 Development of BPR und SFC (Martens 2007)

These calculated annual improvement trends do not relate exactly to the fuel efficiency improvement of the entire global fleet as there is dependence on the mix of aircraft and their respective and changing proportional contribution to fuel usage. Fleet rollover dictates how quickly certain aircraft will be replaced and the level of demand will in turn dictate the rollover rate and how many new aircraft are required and over what distance ranges they fly.

Global flight data (OAG) was purchased for the years from 2000 to 2005, in order to calculate the fleet fuel efficiency changes over this period taking into account how the relative proportions of aircraft types may evolve. However, in processing the OAG data there were some major concerns that the trend in total movements and distance flown was not corroborated by either ICAO statistics on flight data or by other independent data sources (such as the US Federal Aviation Administration). A description of the OAG data and comparison with other data sources is provided in Annex 1.

The calculated annual fuel efficiency improvement trends (fuel per ASK) in new aircraft (1.12% per annum since 1970) includes the potential significant efficiencies gained by using larger aircraft but does not include any improvements from operational changes such as improvements in ATM.

3.4 Inventory Data

There are a number of detailed emission inventories reported in the literature which are generally calculated using detailed fleet and movements data together with fuel usage data on an aircraft type basis. The inventories are thus developed using bottom-up methods. However, in this study we can use the top-level outputs of the inventories to gather further information on fuel efficiency on a top-down basis. The US SAGE model provides results for 2000 to 2005 and allows a trend in fuel efficiency to be developed from internally consistent inventory results and using real flight data rather than future projected data.

Table 4. SAGE Inventory data

Year	Fuel Burn (kg)	kgFuel/flight	Kg/100-ASK
2000	1.81E+11	6,105	3.09
2001	1.7E+11	6,134	
2002	1.71E+11	5,999	3.00
2003	1.76E+11	6,130	
2004	1.88E+11	6,202	2.95

Other inventory data tend to report one base year and other future projections e.g. AERO2K (Eyers et al., 2004). The future projections are generally made by implementing assumptions on future fuel efficiency and are therefore not suitable for this type of analysis.

4 SUMMARY AND CONCLUSIONS

In this study the efficiency of the collective fleet in airline service is assessed on a global basis. Efficiency improvements considered in this study can be derived from aircraft engine specific fuel combustion (SFC) characteristic, airframe improvements and also from operational improvements and the most appropriate metric is the aircraft system fuel or traffic efficiency i.e. fuel used per available seat or revenue passenger kilometre.
Analysis of global fuel and aviation statistics has provided trends in overall aircraft system fuel efficiency from 1970 to 2006.

These trends in fuel efficiency calculated in this study confirm a 60% improvement in fuel efficiency since the early seventies to today's fleet as mass of fuel per ASK. However a great part of this improvement was achieved during the 1970s (a 43% improvement is shown between 1971 and 1981). Further improvements over the last 25 years have been much more modest and fuel efficiency (as kg fuel per ASK) has fallen from 4.7 kg-fuel per ASK in 1981 to 3.3 kg-fuel per ASK in 2006 (approximately a 28% improvement).
Estimation of the source of fuel efficiency improvements has shown a 70% improvement in fuel efficiency as fuel per RPK between 1970 and 2006 can be broken down into improvements due to load factor (20%), aircraft size (26%) and finally technical and operational improvements to the fleet (24%).

Looking at the most recent 6-year period analysed (2000 to 2006), the improvements in fuel-economy mean that 15% less aviation fuel was used (and therefore emissions of CO2) than would have been used without changes in efficiency. Over this 6-year period increases in load factor mean that a saving of 6% was made (1.1% per annum); there was no significant difference in average aircraft size; and a 9% saving was made by changes in fuel burnt per aircraft kilometre i.e. fuel per ASK (1.4% per annum).

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ANNEX 1 – OAG DATA

Official Airline Guide movements data was obtained for the years 2000, 2002 and 2005.

The OAG is compiled by the United Business Media company[5]. The OAG database provides information on worldwide scheduled commercial and cargo flights.
The OAG database covers scheduled movements only, thus, charter and freighter traffic (non-scheduled), for example, are not included. Twelve individual months of data from OAG were obtained each for 2000, 2002 and 2005.

The data included airport country, latitude and longitude; routes as identified by the airport of departure and final destination together with any intermediate stops; aircraft type; flight duration; aircraft carrier or carriers and the countries in which they are domiciled; and the number of flights per month, over the twelve months of the year. A suite of software routines to filter and pool the OAG data was developed and implemented in a Microsoft Access environment.

Simple trends in terms of total SKO and distance travelled were derived from the data and the expected increase in demand was not shown in the data, the OAG data were then compared with other independent data sources and the data showed a lack of correlation with either ICAO statistics on scheduled flights or the movements data from the FAA derived from the SAGE emissions inventory model, which includes scheduled and non-scheduled movements data (Kim *et al.*, 2006). Both the ICAO and SAGE data show an increase in aviation activity/demand between 2000 and 2005 (between 12 and 16%) wheras the OAG data shows an decline of just over 1% between 2000 and 2005. Two months (January and July) of 2005 movements data for Europe were also obtained from Eurocontrol for comparison. These data include scheduled and non-scheduled movements and it would be expected that the Eurocontrol data would thus be consistently larger than the schedule-only OAG data. However, the total kilometres travelled in 2005 between EU countries was 23% lower in the OAG in January and 45% lower in the OAG for July. Although the proportion of charter traffic for within and between EU nations is significantly higher than the global

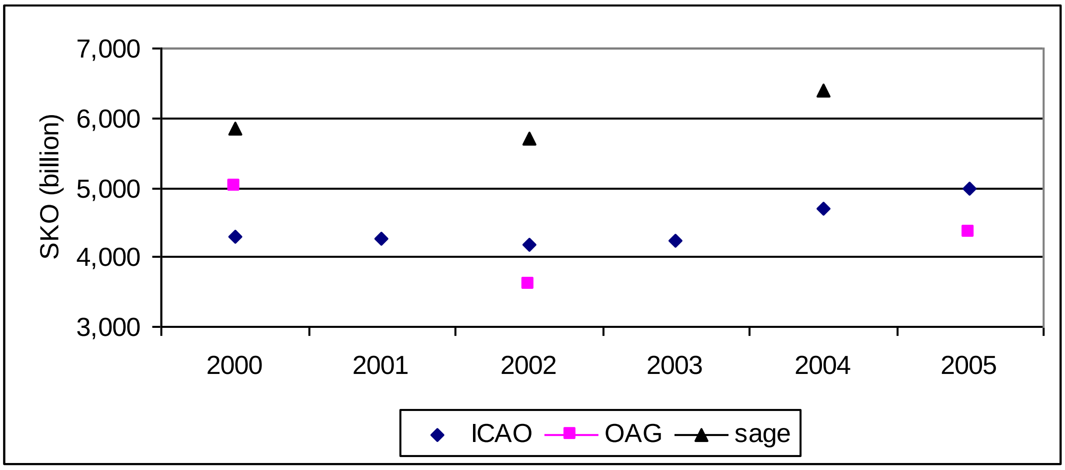
[5] http://www.oag.com

average (around 5%) these percentage differences are much larger than would be expected than just for non-scheduled movements data.

One problem with the OAG data is that they represent a timetable of future flights not a retrospective record of actual flights that have take place and therefore if the demand exceeds the predicted number of planned scheduled flights airlines will operate more than are shown by OAG. A discussion between OAG and MMU was undertaken and agreement was reached between OAG and our processing of the raw data to ensure that our processing tools were producing valid outputs. However, no resolution of the difference between OAG and other trends could be reached.

As this study aim is to assess trends it was considered that the OAG data for 2005 might not, in this case, produce valuable results.

Figure A1. Comparison of SKO between OAG and other data



SAGE data from Kim *et al*, 2006

ICAO data from:

http://www.airlines.org/economics/traffic/World+Airline+Traffic.htm (accessed 19-08-2008)