Cost-Efficient Light-Weighting within the Aviation Sector

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Cost-efficient Light-Weighting within the Aviation Sector

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Abstract

Rising fuel prices and growing concerns over the impacts of aviation on the greenhouse effect have increased the pressure on the commercial aviation sector to develop measures that improve fuel efficiency. Since commercial aircraft normally remain in service for more than 20 years, it is of interest for aircraft operators to consider fuel efficiency improvements that can be made on existing aircraft. This study develops a method to measure cost efficiency of replacing components with light-weight versions of the same component type, in order to reduce aircraft empty weight. Fuel cost reductions arising from weight reductions are discounted and aggregated over the light-weight components lifetime to produce a net present value (NPV) of the intervention. In addition break-even values (NPV=0) of unit fuel costs, weight reductions, and net investment costs are also derived. Calculations for economy class passenger seats and catering service trolleys, along with a range of generic intervention scenarios, are conducted. Results show that replacing catering service trolleys is beneficial even at relatively low unit fuel costs -break-even occurs at unit fuel costs between 2 and 24 US$/barrel - while the break-even unit fuel costs for economy class passenger seats ranges from 38 to 359 US$/barrel, depending on the circumstances. Results from generic scenario calculations reveals that - at unit fuel costs of 100 US$/barrel and a component lifetime of 10 years - any intervention with a net investment cost below 1,094 US$ per kg of weight reduction will be profitable.

Executive Summary

Aviation fuel prices are currently at historically high levels, and fuel costs now constitute around 30% of airlines operating costs, up from 10% just a few years ago (ATA 2008b, c). In addition, there are growing concerns over the impacts of aviation on the greenhouse effect, and the commercial aviation sector will, most probably, be implemented in the European Union's emissions trading system by 2012 (Zalewski 2008). This dual stress increases the pressure on the sector to develop measures that improve fuel efficiency. Since commercial aircraft remain in service over relatively long periods of time, normally for 20 years or more (Rolls Royce 2006), it is of interest for aircraft operators to consider fuel efficiency improvements that can be made on existing aircraft.

The challenge lies in identifying interventions that improve fuel efficiency at the lowest cost possible. There are numerous interventions available, ranging from technological measures such as engine and aerodynamic efficiency improvements, to operative measures such as increased maintenance frequencies, fleet renewal programs, and capacity utilisation improvements. This thesis will, however, focus on interventions that reduce aircraft weight.

This study aims to explore the possibilities for cost-efficient fuel use – and CO_2 emissions - reductions from the aviation sector through light-weighting of existing aircraft. A linear conversion factor is attained, to link incremental reductions in aircraft weight with reductions in fuel use. A net present value (NPV) based method is developed to analyse light-weighting interventions in terms of profitability, and to identify break-even values for unit fuel cost (US$/barrel), net investment cost (US$/unit), and weight reduction (kg/unit). The NPV increases with rising unit fuel costs, weight reductions, and decreasing net investment costs

(Figure I). An actual unit fuel cost or weight reduction above the break-even values, or a net investment cost below the break-even net investment cost, yields a positive NPV.

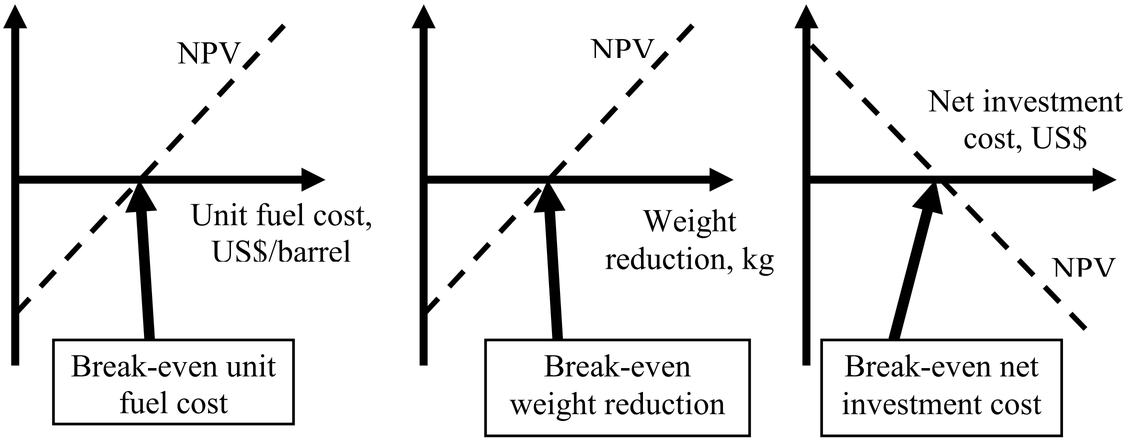

Figure I. Schematic net present value (NPV) curves and break-even points for unit fuel cost, weight reduction, and net investment cost. All other variables are held constant.

Two component types related to passenger services - catering service trolleys and economy class passenger seats - are analysed in a range of scenarios. The net present values of all the eight catering service trolley scenarios are positive, ranging from 2,492 to 5,868 US$/unit, while the break-even fuel cost ranges from 2 to 24 US$/barrel. The net present value of the eighteen economy class passenger seat scenarios vary from minus 1,118 to plus 1,304 US$/unit, and the break-even unit fuel cost ranges from 38 to 359 US$/barrel. The major driver causing the differing results between the two component types is the net investment cost per kg of weight reduction.

In addition to these two case studies, generic intervention scenarios are also analysed. In the reference scenario - where the fuel cost is 100 US$/barrel, the annual interest rate 5%, and the expected lifetime of the component is 10 years - the break-even net investment cost is 1,094 US$ per kg of weight reduction, indicating that all net investment costs lower than this yields a positive net present value for the reference scenario intervention. The net investment cost is always equal to the discounted lifetime revenue at break-even so every change – higher unit fuel cost, higher aircraft utilisation, lower annual interest rate or higher component lifetime expectancy - that increases the discounted lifetime revenue also increase the break-even net investment cost.

The break-even fuel cost is proportional to the net investment cost and inversely proportional to the weight reduction and to aircraft utilisation. In addition, it increases with rising interest rates and decreasing component lifetime expectancy.

List of abbreviations

ASK	Available seat kilometre
ATA	Air Transport Association of America
DLR	Discounted lifetime revenue
EU ETS	European Union’s emissions trading system
FTK	Freight tonne kilometre
GbD	Greener by Design
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
MLW	Maximum landing weight
MTOW	Maximum take-off weight
NPV	Net present value
OEW	Operating empty weight
RF	Radiative forcing
RFF	Radiative forcing factor
RPK	Revenue passenger kilometre

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1 Introduction

Aviation fuel prices are currently at historically high levels, and fuel costs now constitute around 30% of airlines operating costs, up from 10% just a few years ago (ATA 2008b, c). In addition, there are growing concerns over the impacts of aviation on the greenhouse effect, and the commercial aviation sector will, most probably, be implemented in the European Union's emissions trading system by 2012 (Zalewski 2008). This dual stress increases the pressure on the sector to develop measures that improve fuel efficiency. Since commercial aircraft remain in service over relatively long periods of time, normally for 20 years or more (Rolls Royce 2006), it is of interest for aircraft operators to consider fuel efficiency improvements that can be made on existing aircraft.

The challenge lies in identifying interventions that improve fuel efficiency at the lowest cost possible. There are numerous interventions available, ranging from technological measures such as engine and aerodynamic efficiency improvements, to operative measures such as increased maintenance frequencies, fleet renewal programs, and capacity utilisation improvements. This thesis will, however, focus on interventions that reduce aircraft weight. ***The aim of this study is to explore the possibilities for cost-efficient fuel use – and CO_2 emissions - reductions from the aviation sector through light-weighting of existing aircraft.***

The scope of this investigation is to explore possibilities for incremental weight reductions in existing aircraft, and to develop a method to assess the cost-efficiency of this type of interventions. The method should highlight important variables, and at what variable values different light-weighting interventions become beneficial.

The following method and study objectives are to be reached in order to successfully complete this study.

Study objectives

- Determine whether particular light-weighting interventions are profitable under various circumstances.
- Identify break-even values for unit fuel costs, net investment, and weight reductions for different types of interventions.
- Develop a tool that advices aircraft operators in light-weighting intervention decisions.

Research questions

- What are the characteristic features of beneficial aircraft light-weighting interventions?
- What are the significant break-even values for unit fuel costs (US$/barrel), net investment costs (US$), and weight reductions (kg), under various circumstances?
- How do different variables, such as net investment costs, unit fuel costs, weight reductions, interest rate, and lifetime expectancy, influence the profitability and the break-even values of a specific intervention?

Method objectives

- A literature review is conducted to build up the context of the study, and to review historical trends and projections of future fuel efficiency improvements.
- Historical aircraft weight trends are investigated, using fleet information data from Ascend Air (2008) and specific aircraft data from Jane's Information Group.

- A method to assess the cost-efficiency of incremental light-weighting interventions is developed
- Data on investment costs, weight savings and lifetime expectancies from replacing aircraft components with light-weight versions are collected from industry representatives.
- In addition generic intervention scenarios are investigated, to generate characteristic features for cost-efficient interventions under different circumstances.

Section 2 reviews relevant literature for the study. The relationship between aviation activities and climate change are discussed, followed by an overview of recent trends in fuel price and aviation activities. The emphasis in this section is, however, on trends in aviation fuel efficiency and on measures available to further improve this efficiency. Section 3 presents and analyses historical trends in weights of commercial aircraft. In Section 4 a method to investigate the cost-efficiency of incremental weight reductions in existing aircraft is developed and the results arising from two case studies and generic scenarios are analysed. Finally, the conclusions are summarised in Section 5.

2 Characteristics of the Aviation Sector

This section reviews relevant background literature for the study conducted in this thesis. In the first part of the section implications of aviation on the greenhouse effect will be investigated. The recent development of aviation fuel prices, and fuel cost implications of the probable inclusion of the aviation sector in the European Union's emissions trading system will then be discussed. Following that historical trends and future projections of passenger and cargo aviation volumes, along with trends in fuel efficiency, are presented to give a picture of the expected increase in CO_2 emissions from the sector. More detailed investigations of possible future technological and operational efficiency improvements are also conducted, to present a range of possible interventions to reduce fuel use and CO_2 emissions from the commercial aviation sector. Then the specific timescales and inherent inertia within the commercial aviation sector will be discussed briefly. Finally there will be a summary of the most important findings, as well as conclusions for the further development of this thesis.

2.1 Aviation and Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has produced a comprehensive review (Penner *et al* 1999) on the aviation sectors impacts on climate change. The principal emissions from aviation include carbon dioxide (CO_2), water vapour (H_2O), nitric oxide (NO) and nitrogen oxide (NO_2) (Figure 1). The two latter substances are commonly termed NO_X. All of these have implications for the greenhouse effect.

The amounts of CO_2, H_2O and NO_X emitted are relatively well known, but the climate impacts arising from these are more difficult to quantify. Penner *et al* (1999) uses radiative forcing (RF) - a measure of the change in average net radiation (in Wm^{-2}) at the top of the troposphere resulting due to a change in atmospheric greenhouse gases concentrations - to quantify the impacts on of different emissions. It should be noted that while RF gives reasonably good representation of global mean climate change, it does not cover regional impacts. Since aviation activity is not homogenously spread across the globe and since some of the emissions (e.g. NO_X and water vapour) have mainly regional impacts; the impact of aviation on regional climate could be important, even though it is not represented by the RF indicator.

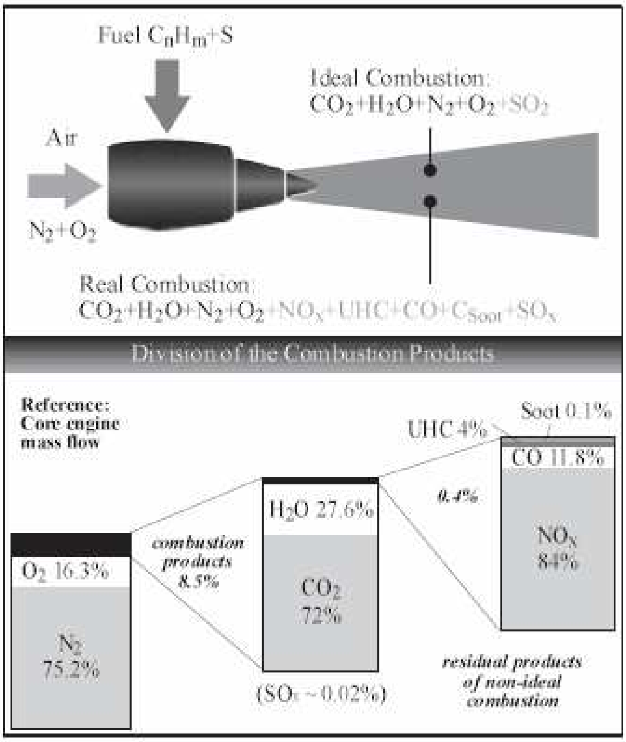


Figure 1. Schematic of ideal and non-ideal combustion products in a typical jet engine (Penner *et al* 1999)

The emissions of CO_2 are directly related to fuel burn, such that one kg of fuel burnt causes the emission of 3.15 kg of CO_2 (Eyers *et al* 2004). Since CO_2 has a long residence time (approximately 100 years) in the atmosphere and becomes homogenously mixed throughout the atmosphere, the emissions from aircraft have the same effect as emissions from any other source (Penner *et al* 1999).

NO_X affects the greenhouse effect in two opposing ways (Penner *et al* 1999). First, NO_X emitted from aircraft in subsonic flight in the upper troposphere and lower stratosphere (at altitudes of 9-13 km) takes part in ozone chemistry. Ozone is a greenhouse gas, and concentrations of ozone in the upper troposphere and lower stratosphere are expected to rise in response to increases in concentrations of NO_X. On the other hand, NO_X emissions also decrease the concentration of methane (CH_4), which is also a greenhouse gas, and thus have a cooling effect. On aggregate NO_X has a positive effect on radiative forcing.

Emissions of water vapour from aircraft gives rise to contrails, and may also affect the formation of cirrus clouds. In 1992, aircraft-induced contrails were estimated to cover about 0.1% of the Earth's surface on an annually averaged basis (Penner *et al* 1999). There are large regional differences, though, since they remain concentrated near flight routes. The radiative forcing properties of contrails depend on the particles emitted from the aircraft, and on the ambient atmospheric conditions. Cirrus clouds have been observed to develop after the formation of contrails. As with contrails, increasing coverage of cirrus clouds tends to warm the Earth. The mechanisms around cirrus cloud formations are, however, not well understood, and the impacts from aviation on cirrus cloud formation and climate change is thus highly uncertain.

Penner *et al* (1999) produced estimates of RF for each emission source, based on 1992 data. These calculations were updated with 2000 data, and more recent research, by the TRADEOFF project (Sausen *et al* 2005). The results of both these studies are shown in Figure 2. The blue bars indicate the best estimates of RF in Penner *et al* (1999), and the white extensions on these bars illustrate a scaling up from the 1992 emissions data to the emission levels in 2000. The line associated with each bar is a two-thirds uncertainty range. The red bars indicate the best estimates from the TRADEOFF project.

The major difference between the two studies is that the RF from contrails is approximately a factor three to four smaller in the more recent TRADEOFF study, than in Penner *et al* (1999). The impacts of NO_X are also smaller in the later study, but the aggregate effect of NO_X is similar between the two studies. The uncertainties surrounding cirrus clouds are still too large to allow any clear judgements on their RF impacts. Nevertheless, Sausen *et al* (2005) concludes that the RF impacts of cirrus clouds is somewhere between zero and an estimated upper bound.

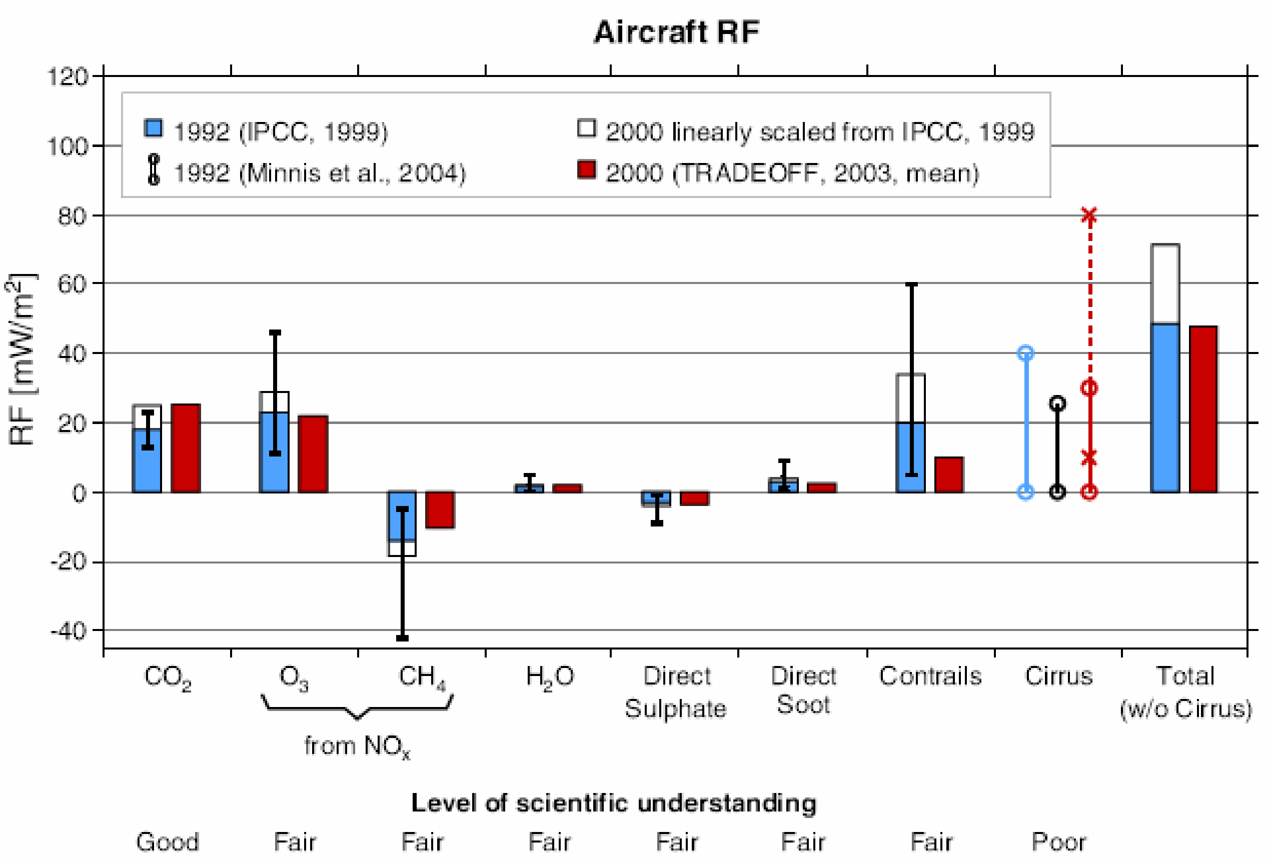


Figure 2. Estimates of the globally and annually averaged radiative forcing (RF) from subsonic aircraft emissions in 1992 and 2000. The evaluations below the graph ("good," "fair," "poor," "very poor") indicate the level of scientific understanding of each of the components. (Sausen *et al* 2005)

Worth noting from Figure 2 and Table 1 is that CO_2 accounts for a relatively small part of the total RF caused by aviation, unlike most other sectors where CO_2 is the major contributor to climate change. Penner *et al* (1999) estimated that radiative forcing impact caused by aviation was 2.7 times larger (mean value) than that caused by CO_2 emissions alone. This will in the following be referred to as the radiative forcing factor (RFF). This approximation was moderated by Sausen *et al* (2005) who estimates that the RFF is approximately 1.9.

Year	Study	Radiative Forcing (mW/m^2)		Radiative Forcing Factor (RFF)
		CO_2	Total (without Cirrus)	
1992	Penner *et al* (1999)	18.0	48.5	2.7
2000	Penner *et al* (1999) scaled to 2000	25.0	71.3	2.9
2000	TRADEOFF	25.3	47.8	1.9

Table 1. Estimated radiative forcing caused by aviation activities, from CO_2 and all other sources (except cirrus clouds), according to Penner *et al* (1999) and the TRADEOFF study. The radiative forcing factor (RFF) is the ratio of the total value over the CO2 value. Data extracted from Sausen *et al* (2005)

CO_2 emissions from civil and military aviation have exceeded half a billion tons annually (Table 2), and the aviation sector is now responsible for about 2% of the global CO_2 emissions (Eyers *et al* 2004). Military aviation is responsible for 11% of the total fuel used - and CO_2 emitted - by all aviation activities.

	Fuel Used (Tg)	CO_2 Emitted (Tg)
Civil Aviation	156	492
Military Aviation	20	61
Total	176	553

Table 2. Fuel used and CO2 emitted from civil and military aviation activities globally in 2002. Data extracted from Eyers *et al* (2004).

2.1.1 Aviation and EU ETS

While greenhouse gas emissions from other modes of transportation, and other sectors, have been exposed to taxation in most Western countries for several years by now, emissions from international aviation are still largely exempt from taxation or other economic policy instruments. Other types of environmental impacts from commercial aviation, such as noise and emissions affecting the local air quality, are regulated through conventions agreed upon within the International Civil Aviation Organization (ICAO), as well as by national governments through various levies and charges (Keen and Strand 2006). Taxation of fuel for international aviation is largely prohibited by ICAO conventions and by bilateral aviation agreements (ICAO 2004).

Nevertheless, the European Union (EU) is attempting to implement the aviation sector into its emissions trading system (EU ETS) (EC 2003). According to a recent agreement (Zalewski 2008) all flights starting from, or landing on, an airport within the EU will be included in the EU ETS by 2012. Consequently, aircraft operators will then be obligated to hold emissions permits equivalent to the amount of CO_2 emitted during its aviation activities. This will only cover CO_2 emissions, and not the other emissions from aviation affecting the greenhouse effect. Consequently no radiative forcing factor (RFF) will be used when deciding the amount of permits needed to cover for an aircraft operator's emissions.

2.2 Fuel prices and operation costs

Aviation jet fuel prices are closely related to the price of crude oil (ATA 2008c). Fuel prices have increased from around 30 US$/barrel at the turn of the century, to around 80 US$/barrel in 2005-2007, and have during 2008 been far above 100 US$/barrel (ATA 2008c). This has had significant effects on airline operating costs (Figure 3). In the early 2000's fuel was responsible for around 10% of the operating costs of US passenger airlines; following the increase in fuel prices, fuel costs represented nearly 30% of the operating costs in the first quarter of 2008 (ATA 2008b).

The inclusion of the aviation sector into the EU emission trading system (Section 2.1.1) will lead to additional fuel costs for all flights starting from, or landing on, an EU airport. Since the relationship between fuel use and CO_2 emissions is proportional, such that 1 kg of fuel emits 3.15 kg of CO_2 when burnt, the costs of emissions permits will have a proportional effect on the unit fuel cost (Appendix B).

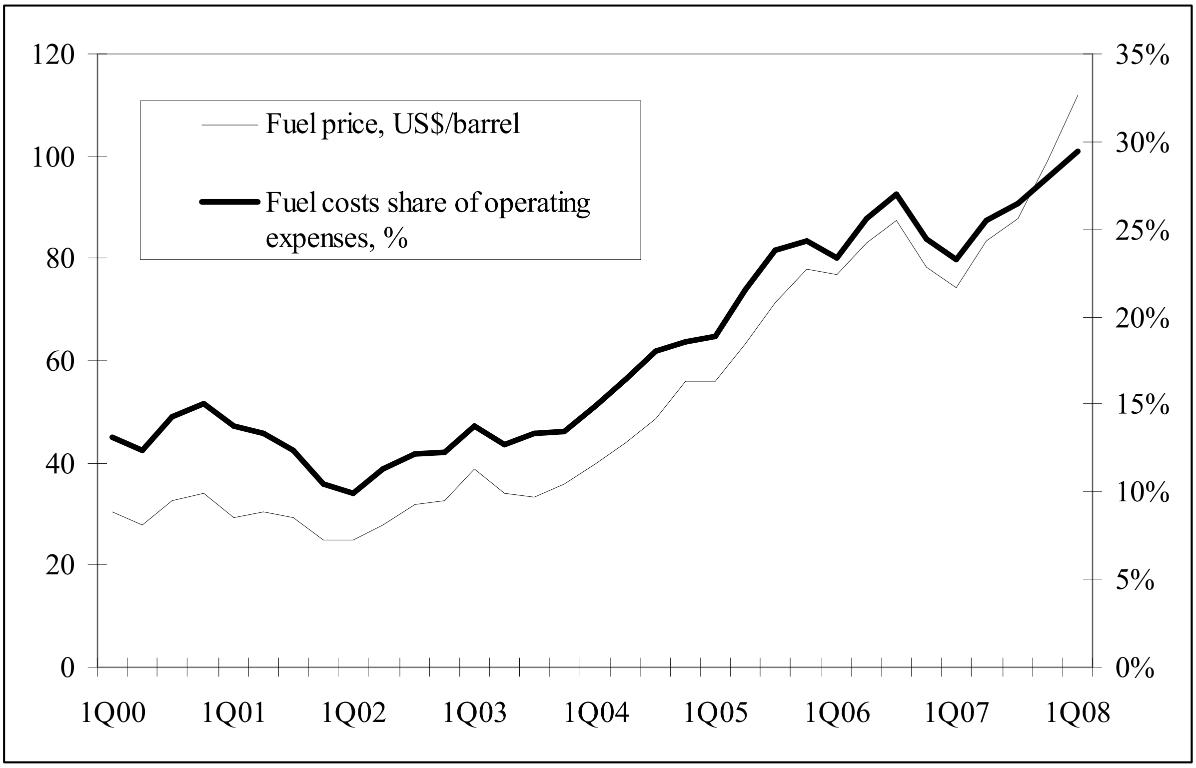
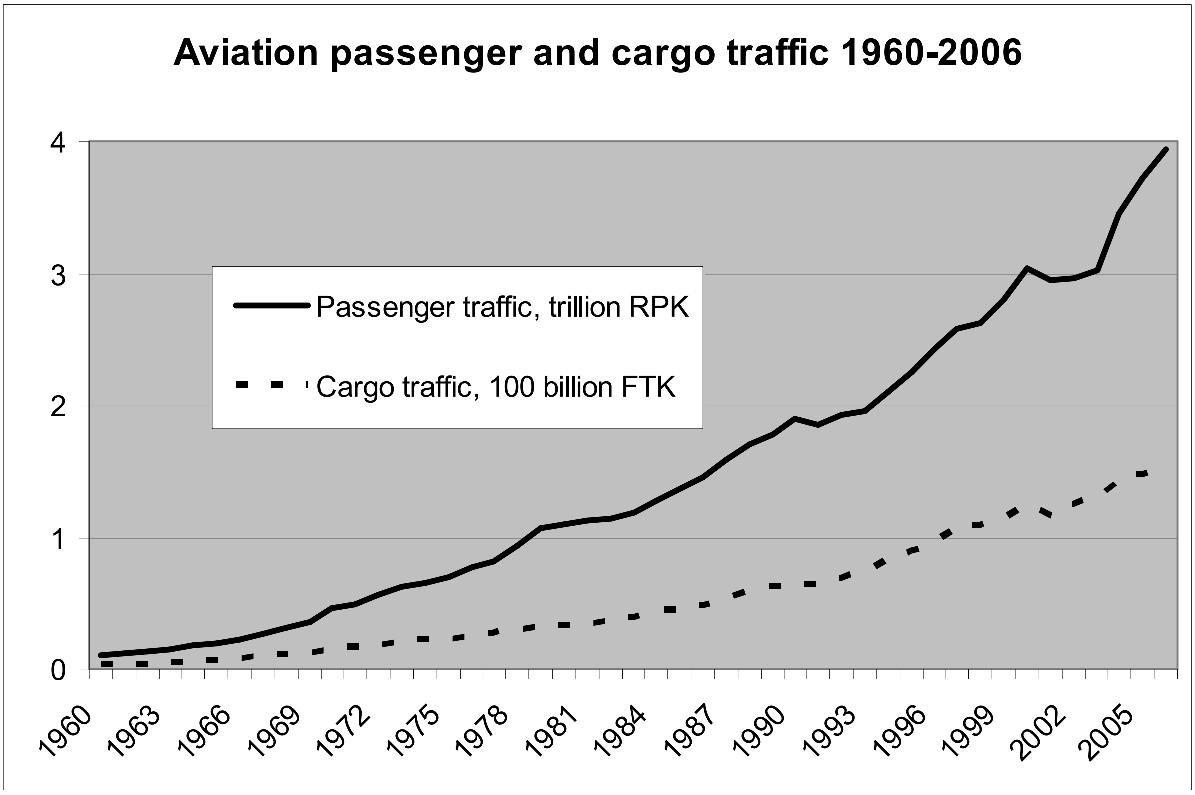


Figure 3. Aviation jet fuel price and fuel costs share of operation expenses in US passenger airlines. Data extracted from ATA (2008b).

2.3 Trends in commercial passenger and cargo aviation volumes

Commercial aviation has grown rapidly over the last decades. Figure 4 shows that scheduled passenger traffic has increased from just above 100 billion revenue passenger kilometres (RPK) in 1960 to nearly four trillions in 2006 (ATA 2008a). Cargo traffic has increased from 2.65 to more than 150 billion freight tonne kilometres (FTK) during the same period.

In the 1960s the annual growth rates were around 15% in passenger traffic and 20% in cargo traffic, and even if the growth rates have slowed down since - to around 5% annually – both global passenger and cargo air transportation still grow considerably faster than the world economy (ATA 2008a). Even though cargo traffic has grown at slightly higher rates, passenger traffic still accounts for a clear majority of the commercial aviation sector, and in addition, most of the freight is carried in the belly hold of passenger aircraft.



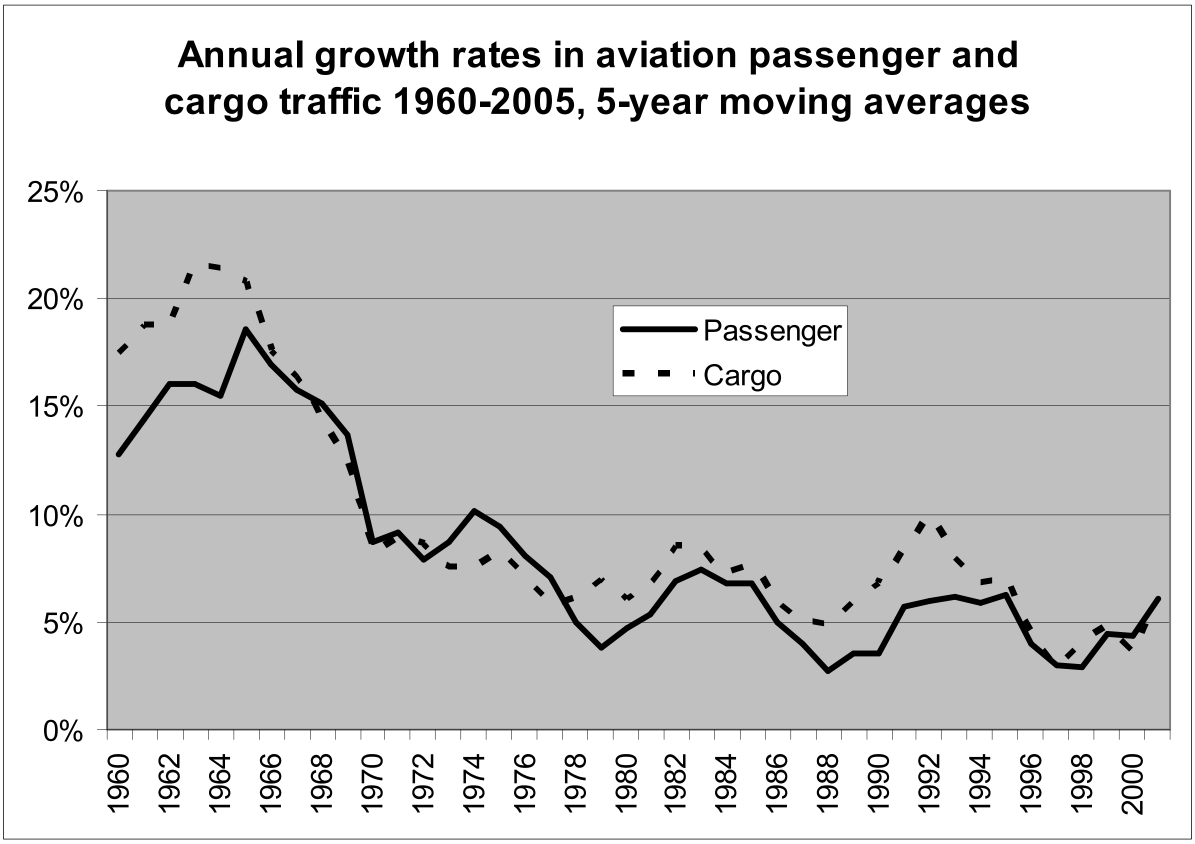


Figure 4. Aviation passenger and cargo traffic 1960-2006. Annual revenue passenger kilometres (RPK) and freight tonne kilometres (FTK) in scheduled activity of airlines operating worldwide, as recorded by ICAO, and annual RPK and FTK growth rates. Domestic operations within the former USSR are excluded from the data prior to 1970, hence causing the traffic volumes in the 1960s to be somewhat underestimated. Data extracted from ATA 2008a.

Commercial aviation is expected to continue to grow at annual rates similar to those of the last 30 years over the coming two decades as well. Major industry representatives project that passenger traffic is to grow at around 5% per year, and that cargo traffic is projected to grow even faster, at about 6% per year (Table 3) (Airbus 2007, Boeing 2007, Rolls Royce 2006, IATA 2007). This indicates that passenger traffic (RPK) will be more than 2.5 times (at 5% annual growth), and cargo traffic (FTK) more than 3 times (at 6% annual growth), bigger in 2026 than in 2006.

	Airbus 2007-2026	Boeing 2007-2026	Rolls Royce 2006-2025	IATA 2007-2011
Passenger traffic (RPK)	4.9	5.0	4.8	5.1
Freight traffic (FTK)	5.8	6.1	6.8	4.8

Table 3. Aviation industry projections of annual growth in passenger and freight volumes, %. Data extracted from Airbus (2007), Boeing (2007), Rolls Royce (2006) and IATA (2007)

However, these forecasts may be overstating the future growth of the sector as they were all made before the recent increase in fuel prices. Recent traffic data from IATA states that cargo volumes (FTK) have dropped 0.8% and that passenger traffic (RPK) grew at a modest rate of 3.8% between June 2007 and June 2008 (IATA 2008). In addition, the Official Airline Guide (2008) reports that the world’s airlines will have 7% lower seat capacity in the fourth quarter of 2008 than during the same period in 2007. It is still open to debate whether these statistics are merely a result of a temporary slump of the commercial aviation sector, or whether they indicate a more permanent trend of slower growth.

2.4 Measures to Reduce Commercial Aviation's Impact on the Greenhouse Effect

The measures available when attempting to reduce the impact on the greenhouse effect caused by commercial passenger aviation can be separated into three categories. First there are substitutive measures, aiming to reduce the demand for aviation altogether. Then there are measures to reduce the amount of fuel used per unit of transport revenue, e.g. gallons of fuel per revenue passenger kilometre. A third type of measures is to replace the fossil kerosene fuel currently used with another type of fuel, with less per unit impact on the greenhouse effect. This thesis will focus on the fuel efficiency measures. Substitutive measures will be discussed briefly, while alternative fuels are outside the scope of this investigation.

In the next section the historical development of fuel efficiency will be overviewed. This will be followed by investigations into the historical development, and future potential, of technological and operational efficiency improvements, and lastly, substitutive measures will be discussed briefly.

2.4.1 Trends in aviation fuel efficiency

Fuel efficiency - in terms of fuel intensity, i.e. units of fuel used per revenue passenger kilometre (RPK) or freight ton kilometre (FTK) - has improved continuously during the history of commercial aviation, but generally at rates lower than the growth in aviation activities, creating a net effect of increasing levels of aviation fuel use. Since almost all commercial aviation uses the same type of jet kerosene fuel, energy efficiency can be assumed to be equivalent to fuel efficiency.

All fuel efficiency improvements can generally be divided into two categories: technical and operational improvements. Technical improvements can in turn be divided into three types of efficiencies: engine efficiency, aerodynamic efficiency, and structural efficiency; while operational efficiency depends on a range of factors where fleet composition, capacity utilisation, and air traffic management are among the most important ones.

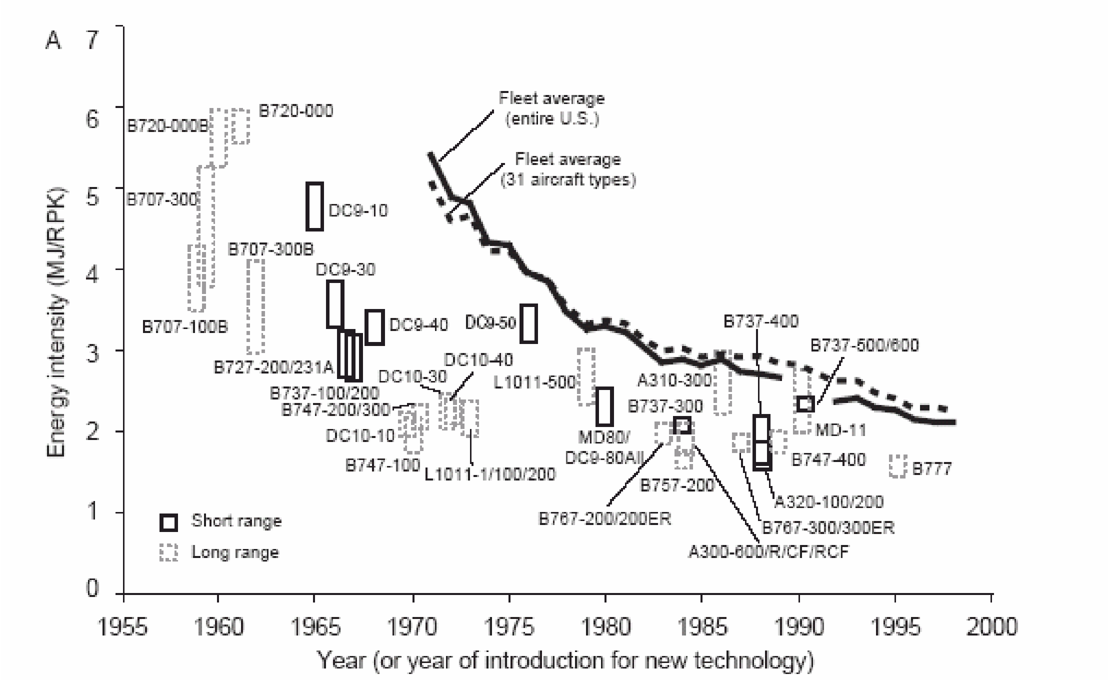


Figure 5. Energy intensity (MJ/RPK) of individual aircraft types introduced from 1960 and onwards, and US passenger fleet average from 1971 to 1998 (Lee *et al* 2001).

In the following three studies into the historical development of fuel efficiency will be presented. Lee *et al* (2001) investigated how fuel efficiency has evolved over time, by analysing performance data of 31 commercial passenger jet aircraft introduced between 1959 and 1995. These 31 aircraft cover 50%-85% of all domestic and international RPK operated by all US carriers since 1968, and can thus be assumed to give a fair representation of the entire commercial fleet over the studied time period. The study concludes that technological and operational improvements in combination has led to reductions in fuel intensity – fuel use per RPK – of the US fleet of more than 60% over the period 1971-1998 (Figure 5), with an average annual rate of 3.3%; of this 2.4% can be attributed to technological improvements in fuel use per seat kilometre, while the rest of the improvement comes from increased load factors. The efficiency improvement rate was faster in the first half of the period. Between 1971 and 1985 fuel intensity decreased by 4.6% per year, while the average annual reduction over the period 1985-1998 was only 2.2%.

Smith (1981) and Greene (1992) looked at the fuel efficiency improvements - divided into technical and operational components – in US commercial air travel, during the periods 1973-1980 and 1980-1989 respectively. From 1973 to 1980 revenue passenger miles per gallon increased by 52% - from 16.93 to 25.73 – and inversely fuel intensity decreased by 34%, with an average annual decrease of 6.0% (Smith 1981). This efficiency improvement could be subdivided into four components, where load factor (37% of the improvement) was the single most important factor, followed by seating capacity (22%), fleet mix changes (20%), and technical and operating efficiency (15%)[1]. The efficiency improvement 1973-1980 was considerably larger than during previous years (the fuel intensity reduction between 1967 and 1972 was merely 10%) and can, at least partly, be explained by the rising fuel prices during the period. From 1980 to 1984 fuel efficiency improved by 10.4%, and inversely fuel intensity decreased with 9.4%, at an annual average rate of -2.5% (Greene 1992). During this period increased seating capacity accounted for most of the improvement (5.5%), followed by continued aircraft improvements (3.0%) and the introduction of new aircraft types (1.8%), while load factor improvements made a marginal contribution (0.4%). Between 1984 and 1989 the fuel efficiency increased with 8.5%, and the fuel intensity dropped with 7.8%, at an average annual rate of -1.6%. The load factor was, unlike in the previous period, the component that contributed most (6.4%) to the efficiency improvement, followed by the introduction of new aircraft types (3.8%), while seating capacity (1.0%) and the

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[1] A residual of 6% was experienced, partly due to inconsistencies in the data sets.

discontinuation of obsolete aircraft (0.9%) made smaller contributions. On the other hand, the efficiency of continued aircraft decreased considerably (3.6%) during this period. One likely explanation presented by the author is that increased air traffic congestion caused by greater hubbing by airlines, resulted in longer delays and ground time, and thus hampered efficiency. The increased use of hubbing by airlines was in turn an effect of the airlines' ambition to increase load factors. This outcome thus illuminates the trade-off between load factors and in-flight efficiency caused by the use of hubbing.

	Lee (2001)		Smith (1981)	Greene (1992)	
	1971-1985	1985-1998	1973-1980	1980-1984	1984-1989
Total change in fuel intensity	-60%		-34%	-9.4%	-7.8%
AAGR in fuel intensity	-4.6%	-2.7%	-6.0%	-2.5%	-1.6%
AAGR in global RPK	7.3%	5.0%	8.1%	4.0%	6.6%

Table 4. Average annual growth (AAGR) in fuel intensity in US commercial passenger aviation and in global revenue passenger kilometres (RPK). Fuel intensity is defined as units of fuel used per RPK. Data on RPK are gathered from ATA (2008a), see previous section.

Table 4 summarises the results from the three studies on reductions in energy intensity in US passenger aviation, and compares them with the growth rates in passenger aviation globally. Assuming that the fuel intensity reductions in the US sector can be taken as a proxy for the development globally; at least two conclusions can be made from these results. First, the average annual reduction in fuel intensity from the 1970s and onwards has been considerably lower than the growth in passenger volume, leading to continuously increasing levels of aviation fuel use. Secondly, the rate of reductions in fuel intensity were considerably larger during the period 1973-1980, when fuel prices were relatively high, than in the following periods 1980-1989, as well as during the entire period 1971-1998.

Several projections of the future development of aviation fuel efficiency have been conducted (DfT 2007). Penner *et al* (1999) uses the data presented in Greene (1992) to extrapolate future efficiency improvements. The projections result in diminishing increases in available seat kilometres per fuel unit, from 1.3% annually 1990-2010, to 1.0% in 2011-2020, and 0.5% over the period 2021-2050. Lee *et al* (2001) predicts 1.2%-2.2% annual reduction in fuel intensity until 2025, of which 1.0%-2.0% occurs as reductions per passenger seat, and the remainder comes from increased load factors and improvements in air traffic management. Peeters *et al* (2005) reinterprets the data sets in Penner *et al* (1999) and Lee *et al* (2001), and fits them to power curves to make predictions of future efficiency improvements. This results in slightly lower fuel intensity reduction predictions than in the original studies. The Penner *et al* (1999) data now indicates an annual intensity reduction of 0.8%, while the data in Lee *et al* (2001) suggests a reduction rate of 0.6% per year; both on a per available seat kilometre basis over the period 2000-2040.

Study	**Time period**	**Projected annual efficiency improvement**	
Penner *et al* (1999)	1990-2010	1.3%	Available seat kilometres (ASK) per unit of fuel used
	2011-2020	1.0%	
	2021-2050	0.5%	
Lee *et al* (2001)	2000-2025	1.0%-2.0%	Fuel used per ASK
Peeters *et al* (2005)	2000-2040	0.8%	
	2000-2040	0.6%	
ACARE target	2000-2020	3.5%	

Table 5. Projections of future fuel efficiency improvements according to three studies, and the ACARE target for new aircraft.

In contrast, Arguelles *et al* (2001) has initiated a strategic research programme, named Advisory Council for Aeronautics Research in Europe (ACARE), where one of the ambitions is to reduce the fuel use per seat kilometre by 50% in aircraft introduced 2020 relative to new aircraft of 2000. This target, commonly referred to as the ACARE target, implies an average annual reduction rate of 3.5%. This will be addressed through airframe and engine research, as well as through improvements in air traffic management. In the light of the fuel efficiency projections made above, this target must be considered very ambitious.

2.4.2 Technological efficiency

Lee *et al* (2001) also investigates, in more detail, the improvements made in technological efficiency over the period 1959-1995. Engine efficiency - measured as specific fuel consumption in cruise – has improved by approximately 40% over the period, indicating an average annual improvement of 1.5%. However, most of this improvement was obtained with the introduction of high bypass engines before 1970. In addition, aerodynamic efficiency – improvements in the lift-to-drag ratio – has increased by about 15% in total, or by 0.4% annually on average. The structural efficiency of aircraft – the ratio of operating empty weight (OEW) over maximum take-off weight (MTOW) – shows no significant changes over time, even though more light-weight materials have been introduced. This absence of significant weight reductions can be partly explained by the introduction of the relatively heavy bypass engines. As much as half of the overall efficiency improvements from installing more efficient engines can be lost due to negative effects on weight and aerodynamics.

The technological efficiency improvements reported in Lee *et al* (2001) are largely consistent with those of Birch (2000). New aircraft are three times more fuel efficient than the early turbo-jet powered aircraft introduced around 1960. Around two thirds of this improvement is due to efforts made in reducing specific fuel consumption in the engine, and most of the improvements were made prior to 1970. The Greener by Design (GbD) reports (2001, 2002, and 2005) points out that as much as three quarters of the improvement came in the decade before 1970, and it took another 30 years to achieve the last quarter; which could suggest that the current standard aircraft configuration is approaching limits set by the laws of physics.

It is worth noting that the early turbo jet powered aircraft had energy intensities about two times higher than those of the last piston engine powered commercial aircraft introduced in the late 1950s (Peeters *et al* 2005). These aircraft actually had levels of energy used per seat kilometre similar to those of the most efficient jet aircraft of today. However, the levels of performance – in terms of speed and range - of the piston engine aircrafts were considerably lower than the jet aircraft, which made the jet aircraft more competitive at the time.

2.4.2.1 Engine efficiency

Reductions in engine specific fuel consumption is, at a given flight speed and fuel calorific content, proportional to increases in the thermal (η_{th}) and/or the propulsive (η_{prop}) efficiencies of the engine (Birch 2000). According to Birch, only modest gains in thermal and propulsive efficiency can be achieved until 2020, as most efficiency improvement possibilities have been realised. In addition, demand from aircraft operators are for high thrust engines that can achieve higher climb rates, in order to overcome congestion restrictions in the crowded air traffic control system, which can lead to engines that are not optimised for minimum fuel burn in cruise. Current rates of annual specific fuel consumption improvements of around 1% are therefore likely to decline to approximately 0.5% by 2020, which implies a total specific fuel consumption improvement of 10-15% by 2020, compared to the most efficient engines in 2000. This is also in line with projections made by Lee *et al* (2001).

2.4.2.2 Aerodynamic efficiency

Lee *et al* (2001) concludes that aerodynamic efficiency has improved with 15% over the period 1959-1995, at an average rate of 0.4% per year. According to Greener by Design (GbD 2001) is the potential for improving aerodynamic efficiency of aircraft with fully turbulent boundary layers constrained by physical limits, and can probably not be improved by more than a few percent relative to the best designs currently available. The application of laminar flow control technologies seems to offer more promising efficiency opportunities. Technology assessments indicate potential fuel savings of up to 25% through the use of full chord laminar flow control (Lee *et al* 2001).

2.4.2.3 Structural efficiency

Structural efficiency refers to the weight of an aircraft. One measure of structural efficiency is the ratio of operating empty weight (OEW) over maximum take-off weight (MTOW). As mentioned above, the OEW/MTOW-ratio of new aircraft shows no trend of improvement since the 1960s (Lee *et al* 2001). An alternative way of measuring structural efficiency is the OEW or the MTOW per seat, which will be investigated in Section 3. There is, however, a potential for increased structural efficiency, primarily through the application of light-weight composite materials to replace the metal materials that currently dominates aircraft structures. Composite materials, such as carbon-fibre reinforced plastics, are approximately 20% lighter than the aluminium alloys currently used as the main material in aircraft structures (GbD 2001, Peel 1996). In major aircraft types designed in the mid 1990s (A330, B777), composites made up around 15% of the aircraft empty weight. Assuming an increase to 65% composites, at the expense of aluminium alloys, a 10% reduction in empty weight can be achieved. Another possible weight reducing intervention is the implementation of the more electric aircraft, where additional generators are attached to the engines to generate enough power to reduce, or even eliminate, the need for pneumatic and hydraulic systems. Weight reduction is not the primary objective of this technology, as lower costs and higher reliability is expected, but it is nevertheless capable of reducing the aircraft empty weight by around ¼% (Birch 2000, GbD 2001). Further light-weighting in passenger services and electronic systems can also be expected, potentially reducing empty weight by ½%, but this may be offset by increasing requirements for flight control, and passenger demands.

Lower structural weight can be of significant importance when designing new aircraft types. The difference between MTOW and OEW is the disposable load of the aircraft, which is distributed between the carriage of fuel and payload. For a given design range and fixed levels of aerodynamic and engine efficiency, fuel takes up a given share of the take-off weight, and consequently, any reduction in the OEW potentially allows an equal increase in payload weight (GbD 2001). The resulting potential percentage increase in payload fuel efficiency is then greater than the percentage reduction in empty weight by a factor equal to the ratio of the OEW over the weight of the payload. This ratio is around 2.0 for aircraft designed for ranges around 5000 km, while it is closer to 3.0 for an aircraft with a design range of 15.000 km. However, achieving this potential efficiency gain requires that the additional payload weight can be accommodated in the aircraft.

Greene (1992) derives elasticities of the relationships between the weights and fuel used of 21 aircraft types. The conclusions are that a 1% reduction in operating weight (using maximum landing weight as a proxy for operating weight) reduces fuel use by 0.38-0.75%, while a 1% reduction in empty weight reduces fuel use by 0.23-0.52%. Henderson (2005) uses an estimate of 0.7% fuel use reduction for every 1% in reduced operating empty weight, which translates to 1.4% fuel use reduction for every 1% reduction in take-off weight, assuming an OEW/MTOW-ratio of 0.5. However, the method used to obtain this estimate is not presented.

2.4.3 Operational efficiency

This section covers those measures that improve fuel efficiency, and that are not primarily technological, but more apply to how the aircrafts are used and managed. These measures can be categorised into capacity utilisation, fleet management, and air traffic management. These categories will be investigated below, starting with capacity utilisation.

2.4.3.1 Capacity utilisation

Capacity utilisation refers to how well the aircrafts capacity to carry payload over a certain range is utilised. This includes load factors and seating density.

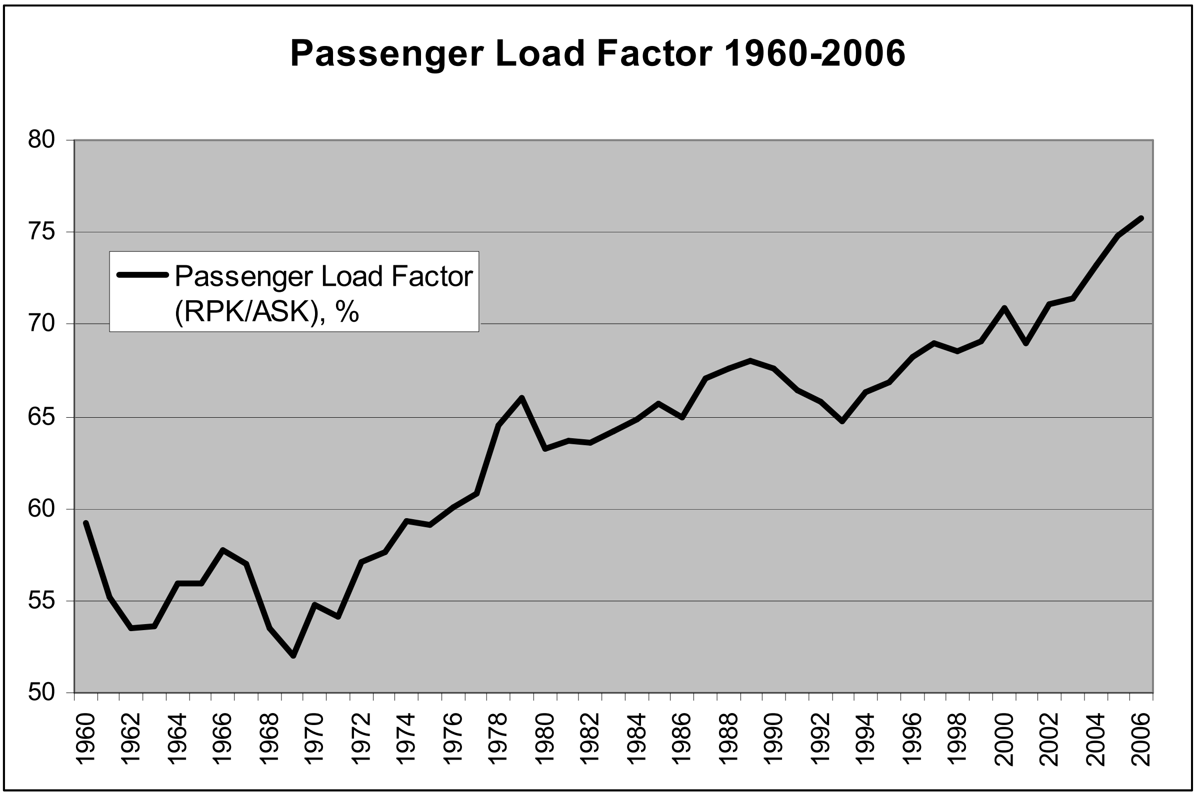


Figure 6. Passenger load factor 1960-2006 – expressed as the ratio of revenue passenger kilometres (RPK) over available seat kilometres (ASK) - in scheduled activity of airlines operating worldwide, as recorded by ICAO. Domestic operations within the former USSR are excluded from the data prior to 1970. Data extracted from ATA (2008a)

While most of the engine efficiency improvements were obtained prior to 1970, the increases in passenger load factor – the ratio of revenue passenger kilometres (RPK) over available seat kilometres (ASK) - have largely occurred after 1970 (Figure 6). Between 1970 and 2006 the load factor has risen by roughly 20 percentage points, from 55% to 75% (ATA 2008a). Since the addition of passengers to empty aircraft seats have very incremental effects on the overall fuel consumption of the aircraft, increases in passenger load factor is, more or less, proportional to fuel intensity. The average annual decrease in fuel intensity occurring from load factor improvements have been around 0.9% during the period 1970-2006. Obtaining the historical 0.9% annual decrease in fuel intensity from load factor improvements for another 20 years would imply load factors rising above 90%, which probably is unlikely to happen. Future projections of load factors in the literature do not show any major improvements relative to the current levels. Rolls Royce (2006) and Lee *et al* (2001) predicts load factors of 76.5% by 2026, and 77% by 2025, respectively. These projections are at level with the load factors currently experienced.

The number of passenger seats in an aircraft varies considerably between different modes of operation. First class and business class seats require more space (and generate more revenue per unit) than economy/tourist class seats. For example, the standard two class configuration of an Airbus 320 has 150 seats – 12 in business class and 138 in economy class – while the same aircraft type with a single class high density seat configuration would include 180 seats (Jane's Information Group). In this case, the amount of fuel used per passenger seat thus differs 20% depending on the seat configuration of the aircraft.

2.4.3.2 Fleet management

Fleet management refers to how an aircraft operator can influence fuel use by deciding which aircraft are being used on which routes, how these aircraft are maintained, and how they are operated. The efficiency measures investigated here are early retirement, maintenance intervals, and reduced fuel tankering.

As aircraft has become more efficient over time, and can be expected to become more efficient in the future (Section 2.4.1), replacing an old aircraft with a new one is thus a way of improving the fuel efficiency of the fleet. Passenger airplanes are generally in service for 20-30 years. The old aircraft can either be scrapped, or used in alternative operations. The fleet of planes dedicated to freight traffic is predominately made up of converted old passenger aircraft; typical freighters retire at 35-40 years (Rolls Royce 2006, Boeing 2007, Airbus 2007).

Typical time between major maintenance overhauls is 2.5 to 3 years for engines, and 6-8 years for airframes. As aircraft are used, their engine performance is reduced and their aerodynamic efficiency is deteriorated. According to a report on aviation emissions control by Henderson (2005), much of the original performance of an aircraft can be restored through maintenance. Potential fuel burn reductions from maintenance typically peak at 4-6%, with the engine and airframe responsible for equal shares. More frequent maintenance can thus reduce fuel burn, at the cost of increased maintenance costs and increased downtimes when the aircraft cannot be used.

Fuel tankering refers to the practice of carrying larger amounts of fuel than necessary to travel safely during a particular flight. The practice is driven by variations in fuel prices, fuel quality, facilities, and turn-around time, between different airports (Henderson 2005). Fuel tankering is mainly practiced on short-haul flights to shorten turn-around times. Fuel tankering results in unnecessary weight increases, resulting in higher rates of fuel use. Reduced fuel tankering would reduce fuel use; however, it would also increase the burden on airports to speed up refuelling processes (Morris *et al* 2008).

Another intervention to reduce fuel use is to divide long haul flights into two or more stages. Long-range aircraft, designed for ranges above 10,000 km, generally have poorer fuel efficiency than short and medium range aircraft (GbD 2001). The reason for this is that a substantial fraction of the fuel used over the first part of the journey is to carry the fuel for the remainder of the journey, and to carry the structure (wing, undercarriage etc) needed to carry the extra fuel. The current configuration of aircraft has the highest fuel-efficiency when designed for ranges around 4,000-6,000 km, and there is thus scope for improving fuel efficiency through dividing long distance flights into two or three stages. Greener by Design (GbD 2001) suggests that dividing a 15,000 km flight into three stages would reduce fuel consumption with approximately 40%. Fillipone (2008) makes a similar investigation and concludes that dividing a 12,000 km flight into two 6,000 km stages decreases the total fuel use by 16%, at a cost in excess flight time of approximately one hour, of which 12 minutes are in-flight and the remainder is for refuelling on the ground.

2.4.3.3 Air traffic management

Air traffic management measures to improve fuel efficiency are related to improvements in the air traffic control infrastructure. This category of measures includes direct routing and continual descent.

There are on-going projects in both North America (NextGen) and Europe (Sesar) to modernise and internationally integrate air traffic management (ATM) systems. This involves more direct routing, thus avoiding unnecessary aircraft miles. The potential reduction in fuel use for a specific flight from A to B is stated to be anything from a just a few percent up to 10-15% within the next 10-20 years (Penner *et al* 1999, Hughes 2007). There is also scope for reducing congestion by improving the ATMs. This would, to some extent, cause a rebound effect, in terms of allowing further increases in aircraft movements, thus decreasing the gains in reductions of fuel use and environmental impacts generated by the more efficient routing.

The current practice of aircraft descending from cruising altitude towards runway approach involves stepping down to lower altitudes with periods of maintaining a constant altitude. The continual descent approach (CDA) requires aircraft to descend along uninterrupted paths from their cruising altitude towards runway approach under minimum engine thrust conditions (Hughes 2007). Tests have shown that a fairly limited CDA reduces fuel use with 30-100 US gallons per flight, which could be doubled with the use of more advanced ATM systems.

2.4.4 Substitutive measures

One way of reducing the environmental impacts of aviation is to prohibit air transportations from taking place at all. This can be done in two different ways, either through making some transports unnecessary, or through substitution to other modes of transportation. For example can phone or video conferencing potentially reduce the need for business travel, while local tourism can reduce the demand for leisure travel. Another type of measure is to that substitute air travels with other modes of transportation. The AERO2k emissions inventory (Eyers *et al* 2004) provides a comprehensive data base of emissions from the aviation sector in 2002. Figure 7 shows the relative percentages of fuel used and NO_X emitted distributed by stage length. More than 20% of all fuel used in the aviation sector are used for flights shorter than 1,000 km, nearly half of the fuel used are for flights shorter than 2,500 km. Many of these flights could be substituted with other modes of transportation, particularly by rail. Improvements in rail infrastructure and other improvements in rail travel services can, thus, potentially be a substitute for many of the short haul flight services.

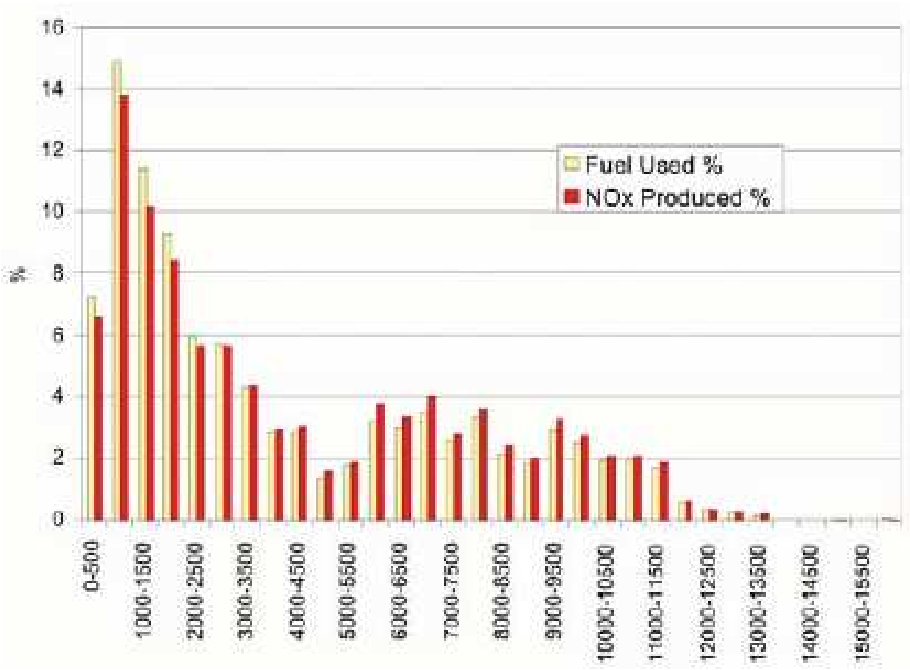


Figure 7. Shares of fuel use and NO_x emissions distributed by flight distance in 2002 (GbD 2005, extracted from AERO2k emissions inventory (Eyers *et al* 2004))

2.5 *Timescales*

Changes in the commercial aviation sector are relatively slow, due to the long timelines of aircraft design, development, and expected use. Lee *et al* (2001) states that it - as an effect of the inertia within the industry - has taken about 10-15 years for the US commercial passenger fleet to obtain the same average fuel efficiency as that of a newly introduced aircraft type. The development times for new aircraft types - from initial idea, through research labs and technical demonstration – is at least 5-10 years (Stinton 1998, GbD 2001, Lee *et al* 2001). In addition, manufacturers need long production lines to pay for the development costs spent during the initial stage, thus successful aircraft types can stay in production for more than 20 years, with incremental changes over time (GbD 2001). On top of that, commercial passenger aircraft generally stay in service for 20-30 years, and may also be used as freighter planes for another decade (Rolls Royce 2006). So if this trend continues, it is likely that the new aircraft types that are entering the market today will still be in service in 2050.

2.6 Summary and conclusions of literature review

Aviation has an impact on the greenhouse effect. The commercial aviation sector is responsible for about 2% of the global $C0_2$ emissions, and emissions of NO_x and water vapour has additional impacts, making the aggregate impact on the greenhouse effect approximately 1.9 times larger than that caused by CO_2 alone (Penner *et al* 1999, Eyers *et al* 2004, Sausen *et al* 2005).

Commercial passenger aviation – in RPK - is expected grow at average annual rates of around 5% over the next two decades (Airbus 2007, Boeing 2007, Rolls Royce 2006, IATA 2007). Cargo aviation – in FTK - is expected to grow even faster, at 6% annually, over the same period.

New aircraft are three times more fuel efficient than the early turbo-jet powered aircraft introduced around 1960. Around two thirds of this improvement is due to efforts made in reducing specific fuel consumption in the engine, and most of the improvements were made prior to 1970, with the introduction of high-bypass engines (Birch 2000, GbD 2001). Nevertheless, over the period 1971-1998 fuel use per RPK in US commercial aviation decreased by, on average, 3.3% annually (Lee *et al* 2001). This reduction in fuel intensity can largely be attributed to operational improvements, such as fleet composition and capacity utilisation. Projections of future fuel intensity reductions are, however, less optimistic and points towards improvements of about 1% annually (Penner *et al* 1999, Lee *et al* 2001, Peeters *et al* 2005), which is far below the expected growth in traffic volume. Combining the projections of growth in RPK and FTK, with the projected improvements in fuel efficiency, indicates that aviation fuel use – and CO_2 emissions – will increase by 4-5% annually over the coming 20 years, yielding CO_2 emissions 2-3 three times higher than current levels.

The costs of aviation fuel have risen dramatically over the last few years. Since the turn of the century the fuel prices have increased from around 30 US$/barrel to the current levels well above 100 US$/barrel. Fuel costs now account for nearly 30% of airline operating costs (ATA 2008b). Whether the fuel prices will continue to rise, or fall back, in the future is highly uncertain. What is more certain, though, is that the commercial aviation operators will have to pay for the CO_2 emitted during its activities (Zalewski 2008). The, most probable, inclusion of the aviation sector into the European Union's emissions trading system (EU ETS) will have direct effects on the fuel costs of all flights departing from, or arriving to, airports within the EU from 2012 and onwards.

In terms of implementation of new technology, there is great inertia arising from the relatively long timescales inherent in aircraft operations. Successful aircraft types can be expected to stay in production for as long as 20 years, and, on top of that, commercial passenger aircraft normally remain in service for 20-30 years (GbD 2001, Lee *et al* 2001, Rolls Royce 2006).

The stress on the commercial aviation sector caused by relatively high fuel prices and the inclusion of aviation activities into the EU ETS increases the pressure on the sector to develop measures that improve fuel efficiency. Since commercial aircraft remain in service over relatively long periods of time it is of interest for aircraft operators to consider fuel efficiency improvements that can be made on existing aircraft. This study will in the following explore possibilities for incremental weight reductions in existing aircraft, and to develop a method to assess the cost-efficiency of this type of interventions. But first will historical weight trends among commercial aircraft be investigated.

3 Historical Weight Trends

3.1 Methodology

The purpose of this section is to present the historical trends in weights of commercial passenger aircraft. Sixty-three aircraft types still in service are investigated (Appendix A). All have 90 seats or more, and together they make up more than 90% of the current commercial aircraft fleet.

Data on introduction year, seating capacity, design range, and all-up weights are gathered from Jane's Information Group, while data on numbers of aircrafts currently in service, and the age of these aircraft are extracted from Ascend Air (2008).

The aircraft types are categorised into single-aisle and twin-aisle aircrafts, in accordance with Boeing (2007). Data on maximum take-off weights (MTOW), operating empty weights (OEW), structural efficiency – the ratio of OEW over MTOW – and design range are plotted against year of introduction, in order to observe trends in these data over time.

3.2 Results and Analysis

Figure 8 displays the design range of 63 commercial aircraft types that were introduced between 1963 and 2007. Single aisle aircraft types have had design ranges around 2,000 nautical miles (nm) throughout the period. The larger twin aisle aircraft types have, on the other hand, experienced increasing ranges over time. The early twin aisle types, introduced around 1970, have design ranges between 2,000 nm and 6,000 nm, while those introduced after 2000 are designed for ranges up to between 6,000 nm and 9,000 nm. One conclusion from this trend is that while single aisle aircraft are still servicing the same short and medium haul sectors as they have done throughout the period, the larger twin aisle aircrafts are used for long haul intercontinental flights.

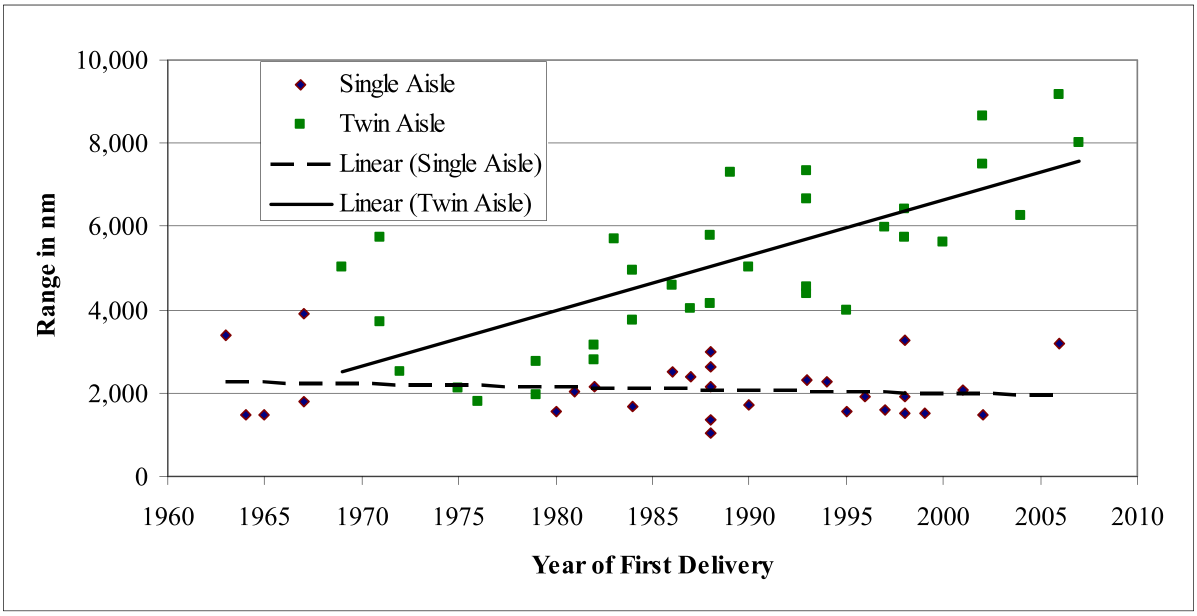


Figure 8. Design range – in nautical miles - of new single aisle and twin aisle aircraft 1963-2007

Below, two indicators of weight efficiency – all-up weight per seat, and the OEW/MTOW-ratio – are investigated. Figure 9 shows the all-up aircraft weights per passenger seat. Two interesting observations can be made from these plots. First, neither the operating empty weight (OEW) nor the maximum take-off weight (MTOW) per seat show any trend over time for twin aisle aircraft, although there is a slightly positive trend for MTOW per passenger seat. Weights per passenger in single aisle aircraft, on the other hand, clearly decreased from the 1960's to the 1980's, and have stayed fairly constant since then. These results indicate that while light-weighting technologies have decreased the weight per passenger seat in single aisle aircraft, this has not been the case in twin aisle aircrafts, which can - at least partly – be explained by the longer range of twin aisle aircraft. Longer flights require more fuel to be carried at take-off than shorter flights; in addition this extra fuel weight requires some of the structural components – e.g. wings, undercarriage – to be larger as well. Other possible explanations are the additional demands for passenger comfort and services (catering, entertainment systems, seat pitch and width) experienced on longer flights, and that twin aisle aircraft might carry more freight than single aisle aircraft.

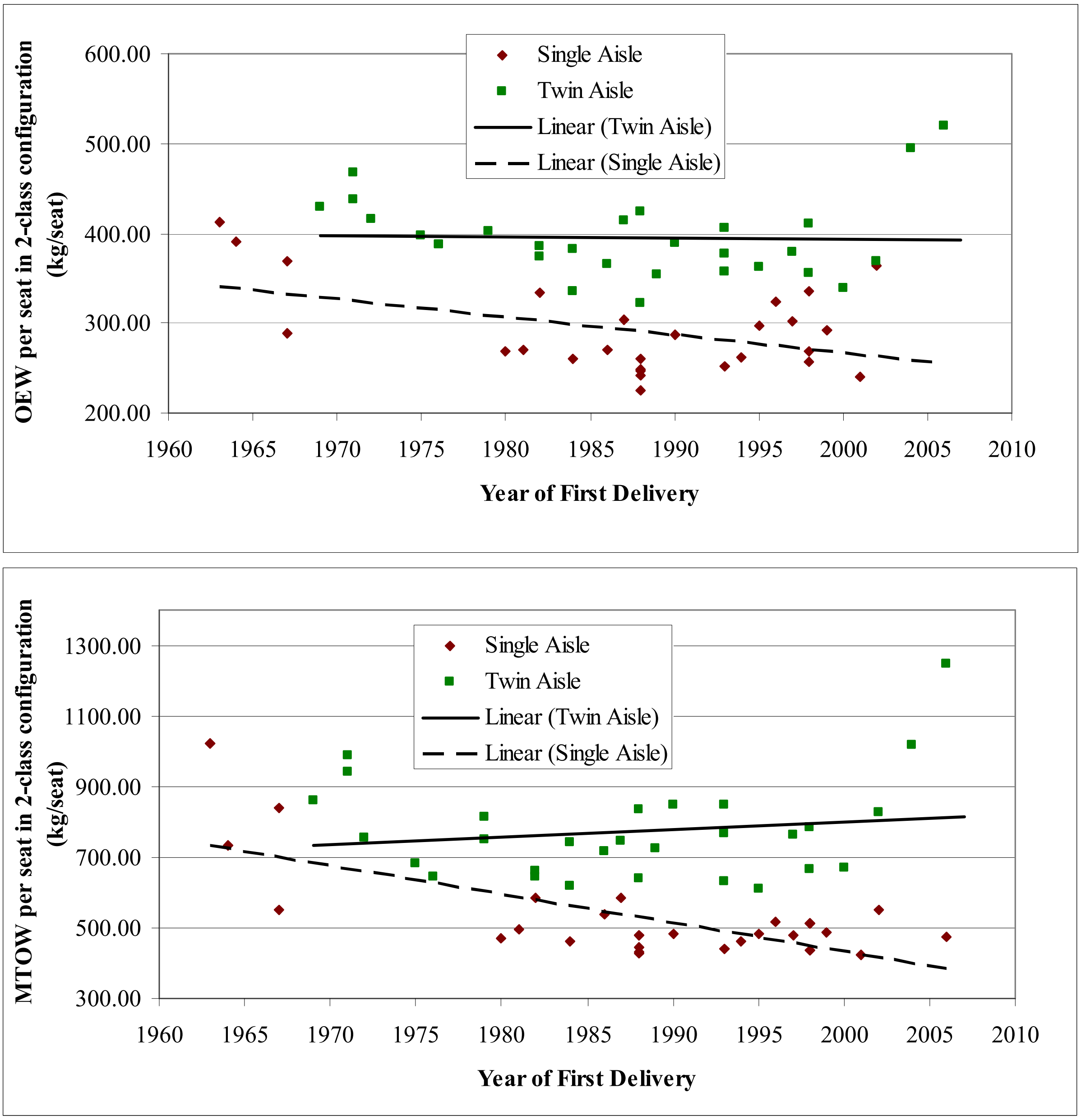


Figure 9. Operating empty weight (OEW) and maximum take-off weight (MTOW) per seat - in 2-class configuration – of new single aisle and twin aisle aircraft 1963-2006

The ratio of OEW over MTOW is a measure of structural efficiency. The ratio is inversely related to the disposable load, which is the difference between the MTOW and the OEW of an aircraft. A low OEW/MTOW-ratio value indicates high structural efficiency, since a relatively low share of the all-up weight is covered by the aircraft structure, fuel reserves, and furnishings and other payload fittings, and a relatively large share can be used for the payload and the fuel required for the flight. Figure 10 reveals ambiguous trends in this measure over time. The OEW/MTOW-ratio has a positive trend over time for single aisle aircraft, while there is a negative trend for twin aisle aircrafts. Worth noting is that more recently introduced twin aisle aircrafts generally are designed for longer ranges than older aircraft types, and that they are designed to carry large amounts of fuel, so the larger OEW/MTOW-ratio of these aircrafts is somewhat compromised by the fact that a relatively high share of the disposable load is covered by fuel rather than payload. The overall conclusion, that there is no clear positive or negative trend for the OEW/MTOW-ratio over time, is on par with that of Lee *et al* (2001).

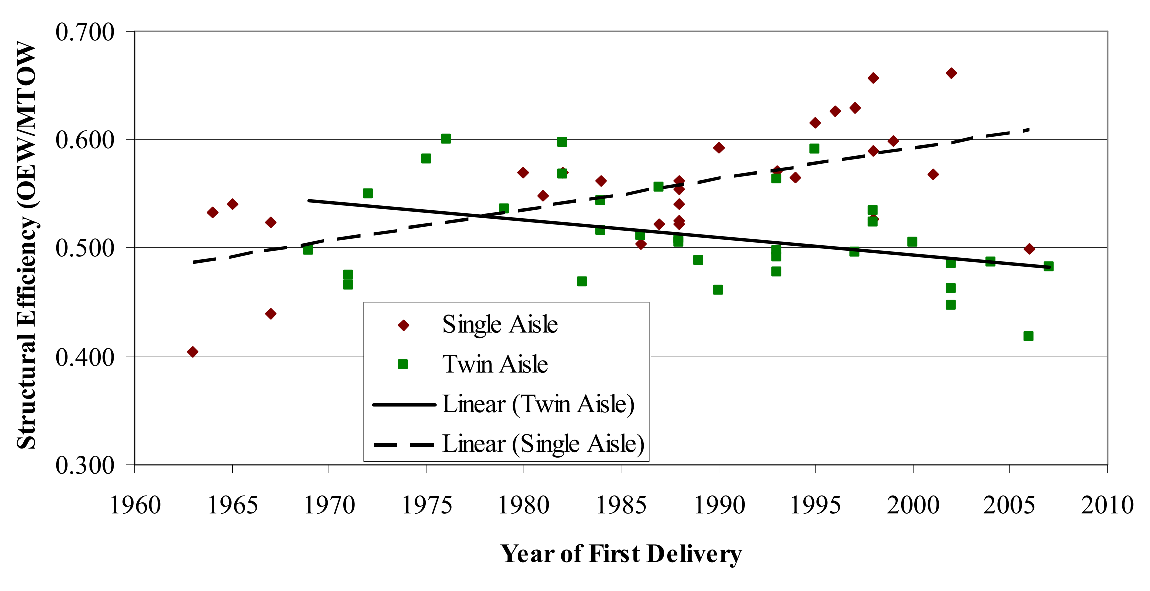


Figure 10. The OEW/MTOW-ratio of new single aisle and twin aisle aircraft 1963-2007

4 Light-weighting and cost-efficiency

Reduced weight of an aircraft component can be used to improve aircraft fuel efficiency in three alternative ways (Poll 2008). The first alternative is to maintain all other aircraft features constant, and to reduce airline costs through the reduction in fuel use associated with lower aircraft operating weight. Another alternative is to use the saved weight to increase the payload of the aircraft, either by increasing the freight carried or by increasing the number of seats. A third, more radical and long term, alternative is to redesign the aircraft based on the new component weights, which would yield the highest efficiency gains possible, but is not deemed as a viable option in this context. The second alternative could also offer considerable efficiency improvements (Section 2.4.2.3), but it also requires that there is space made available, through, for example, higher density seating configurations. To change seating configuration and interior design of an aircraft is a rather complicated process, with design and approval costs attached to it (Diment 2008). This study will therefore only consider the first alternative above, and investigate the fuel cost reductions arising from weight reducing interventions.

4.1 Methodology

The original ambition of this thesis is schematically described in Figure 11. It was based on the assumption that break-downs of one or two common aircraft types' all-up weights into component weights were accessible. This could then have been used to identify a range of weight-reducing interventions, and together with costs of these interventions, cost-efficiency could be derived.

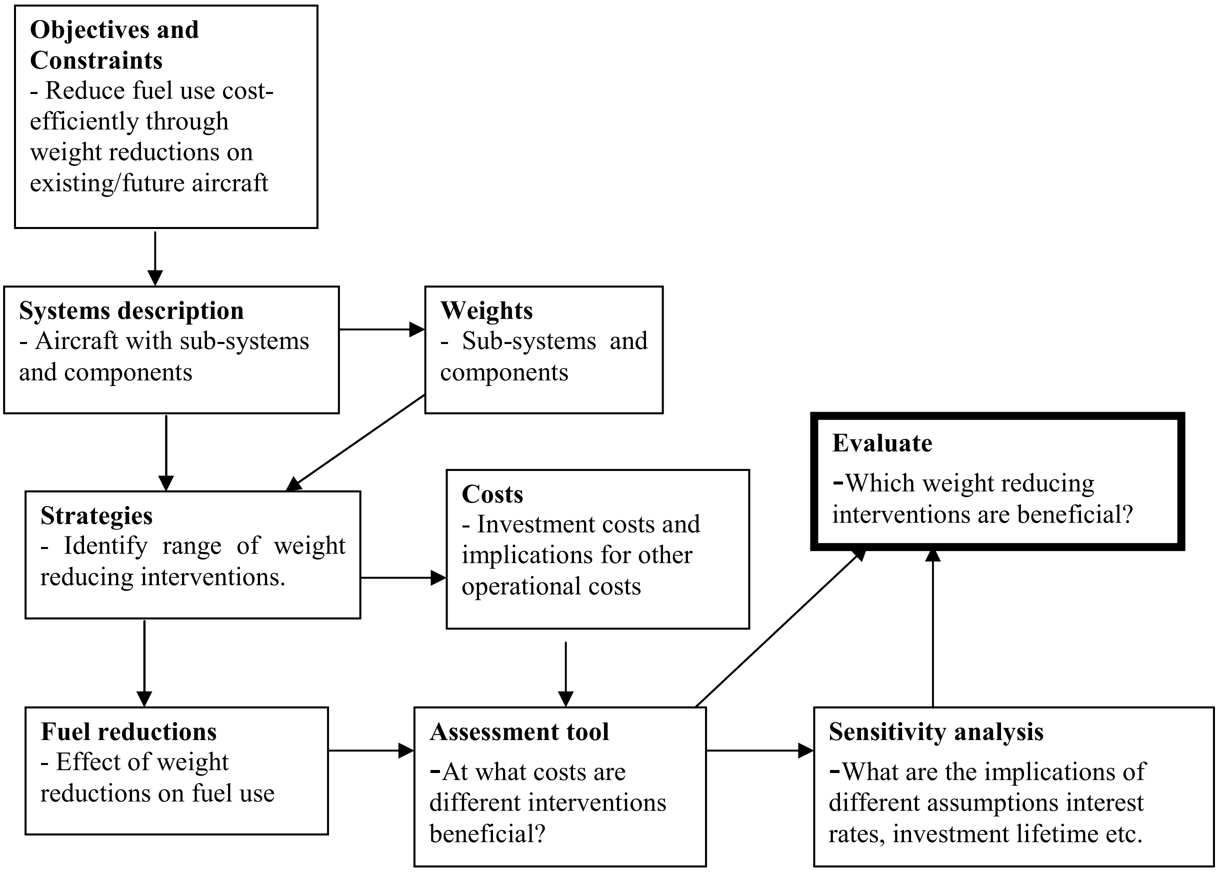
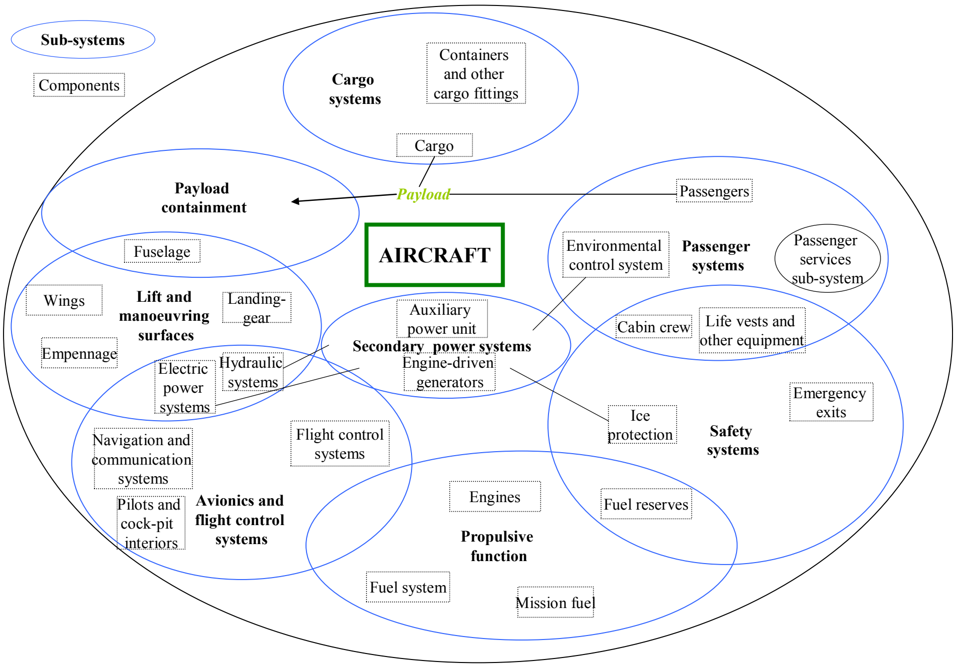


Figure 11. Schematic overview of 'optimal' research process

A systems map of a typical commercial passenger aircraft was produced, through consultations with aircraft design literature (Fielding 1999, Stinton 1998), to categorise aircraft components into various sub-systems (Figure 12 Top). In combination with component weights obtained from aircraft manufacturers, this system map could be used to derive weights for the different sub-systems. Major aircraft manufacturers were approached in order to obtain a break-down of aircraft all-up weight into component weights. These attempts, however, turned out to be unsuccessful, since they were unwilling to share that information. In response to this, a decision was made to instead focus on a few components in the passenger services sub-system, as identified in Figure 12 (Bottom), and to ask component manufacturers for data on costs, weights, and lifetime expectancy of their products.

Aircraft with Sub-systems and Components



Detailed Overview of the Passenger Services Sub-system

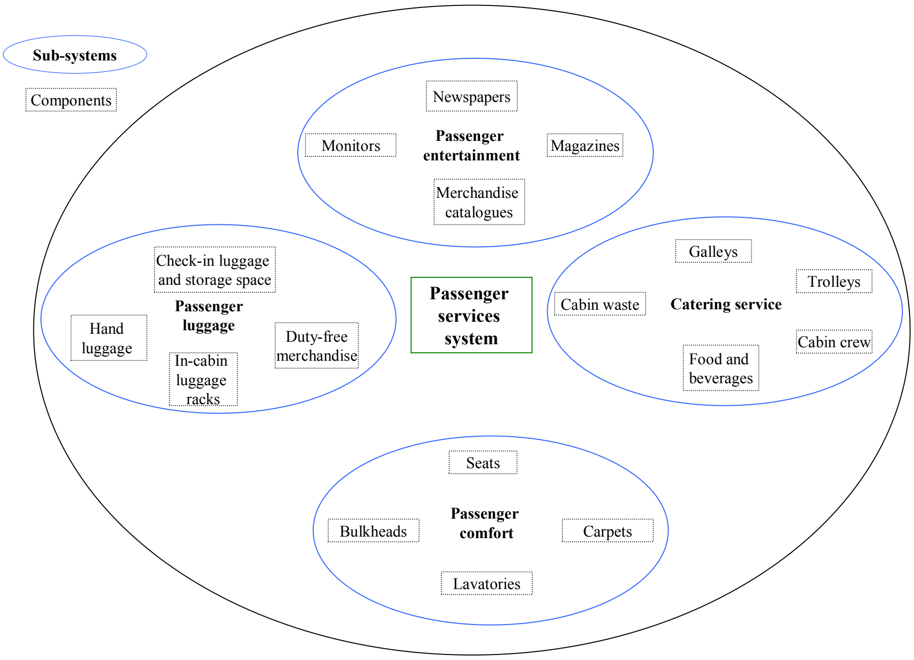


Figure 12. ***Top:*** Systems map of a typical commercial aircraft, where components have been assigned to various sub-systems. ***Bottom:*** Systems map of the passenger services sub-systems. Manufacturers of galleys, trolleys, economy class passenger seats, and carpets were approached, to deliver data for the study.

4.1.1 Model methodology

The scenario investigated is when a new lighter component replaces an older component, delivering the same kind of service. This component replacement is assumed to yield an incremental reduction in the aircraft operating weight. The method used to measure cost efficiency is based on a net present value (NPV) calculation, which consists of three parts:

NPV = - Investment Cost + Discounted Lifetime Revenues + Discounted End of Life Value

The investment cost (*I*) is the sum of the component purchasing cost and the costs of installation and eventual aircraft downtime, minus the net value of the replaced component. The net value is the second hand value minus the remaining debt of the replaced component.

The new component's value at end of life (*V*) is here defined as the initial value times a factor indicating the share of the initial value remaining at end of life. This value is then discounted to obtain the present value of this future revenue.

The middle part of the NPV equation is the revenue stream – in terms of reduced fuel costs – that the light-weight component generates over its time in service. This is made up of annual revenues that are discounted and aggregated to a component lifetime benefit. The annual revenue stream is defined as the annual fuel use reduction (*R*) times the unit cost of fuel (*C*). The annual fuel use reduction is calculated as the annual fuel use of an aircraft, times the relative weight reduction achieved, and times a conversion factor capturing the relative effect a 1% reduction in aircraft take-off weight has on the fuel used during a certain flight. The use of a conversion factor implies an assumption about linearity between reductions in aircraft weight and fuel use. This can be considered to be a justified simplification, since the weight reductions studied here are considered to be incremental to the total aircraft operating weight.

C refers to the aircraft operators' cost of using one unit of fuel, and consists of the fuel price and the costs of greenhouse gas emissions from one unit of fuel. The relationship is such that every US$/ton of CO_2 emitted affects the cost of fuel with 41 US cents per barrel (or just under 1 US cent per US gallon), when the radiative forcing factor (RFF) is not considered (Appendix B). Assuming a RFF of 1.9, as in Sausen *et al* (2005), every US$ per ton CO_2 equivalent then increases the fuel cost by 77 US cents per barrel (1.8 US cents per US gallon). The annual revenue stream from a weight reducing intervention is thus defined as

$R * C$ = Annual Fuel Use * (Weight Reduction / Aircraft Take-off Weight) * Conversion Factor * (Unit Fuel Price + Cost of Emissions from 1 Unit of Fuel)

Over the component's life, the present value of the aggregate benefit – or the discounted lifetime revenue (DLR) – is defined as a sum

$$DLR = \sum_{t=1}^{L} \left[\frac{(R*C)_t}{(1+i)^L} \right] = \frac{(R*C)_1}{(1+i)} + \frac{(R*C)_2}{(1+i)^2} + \ldots + \frac{(R*C)_L}{(1+i)^L}$$

Where *L* is the component's expected lifetime (in years), and *i* is the annual interest rate. Assuming that the annual revenue stream is constant over the component life

$$(R*C)_1 = (R*C)_2 = \ldots = (R*C)_L = (R*C).$$

This yields a shorter expression for the discounted lifetime revenue, namely

$$DLR = \frac{(R * C)}{i}\left(1 - \frac{1}{(1+i)^L}\right).$$

The net present value (NPV) of a weight reducing intervention can then be formally expressed as

$$NPV = \frac{(R * C)}{i}\left(1 - \frac{1}{(1+i)^L}\right) - I + \frac{V}{(1+i)^L}. \tag{1}$$

Setting NPV=0 allows us to calculate break-even values for a certain variable under different scenarios. Within this study break-even values of three different variables – unit fuel cost, net investment cost, and weight reduction - have been considered. The break-even unit fuel cost is defined as

$$C = \frac{i}{R}\left(I - \frac{V}{(1+i)^L}\right)\left(\frac{(1+i)^L}{(1+i)^L - 1}\right), \tag{2}$$

where

$$\left(\frac{(1+i)^L}{(1+i)^L - 1}\right) = \frac{1}{\left(1 - \frac{1}{(1+i)^L}\right)}.$$

The net investment cost is defined as the net value of the investment cost and the discounted remaining end of life value of the new component, and is equal to the discounted lifetime revenue

$$\left(I - \frac{V}{(1+i)^{L}} \right) = \frac{(R * C)}{i} \left(1 - \frac{1}{(1+i)^{L}} \right). \qquad (3)$$

The weight reduction is inherent in the annual fuel use reduction (*R*) component of the model. R is defined as:

$$R = AnnualFuelUse * \left(\frac{Weight\mathrm{Re}duction}{AircraftTakeoffWeight} \right) * ConversionFactor,$$

and the break-even weight reduction can then be expressed as

$$Weight\mathrm{Re}duction = \frac{i}{C} \left(I - \frac{V}{(1+i)^{L}} \right) \left(\frac{(1+i)^{L}}{(1+i)^{L} - 1} \right) \frac{AicraftTakeoffWeight}{AnnualFuelUse * Conv.Factor}. \qquad (4)$$

These break-even points are illustrated in Figure 13. Holding all other variables constant and just changing the cost of one unit of fuel yields an upward sloping net present value (NPV) curve – a weight reducing intervention generates more benefits, in terms of reduced fuel costs, the higher the cost of fuel - and the point of intersection with the x-axis gives the break-even unit fuel cost. Similarly, the NPV increases with the amount of weight reduced, while it decreases when the net investment cost increases. Consequently an actual unit fuel cost or weight reduction that is higher – or an actual net investment that is lower - than the break-even value indicates a positive net present value. The break-even expressions ((2), (3) and (4)), along with the net present value equation (1), will be used to generate results for light-weighting intervention scenarios in Section 4.2.

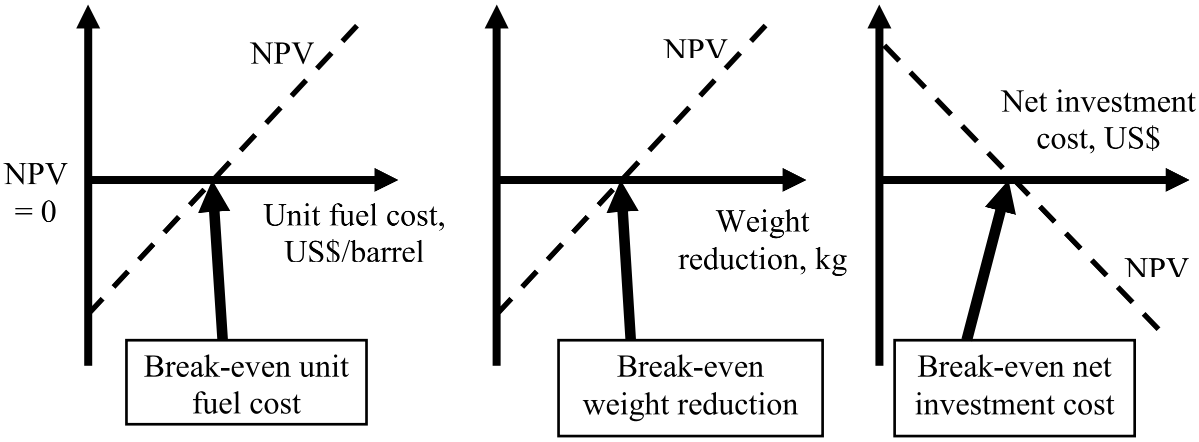


Figure 13. Schematic net present value (NPV) curves and break-even points for unit fuel cost, weight reduction, and net investment cost. All other variables are held constant.

4.1.2 Model inputs and assumptions

The Airbus 320 (A320) was used as an example aircraft in this study. The A320 is one of the most commonly used short and medium haul aircraft types in service. There are 1,871 A320s in commercial service (Ascend Air 2008), and thus it makes up more than a tenth of the global commercial passenger and cargo fleet (Boeing 2007).

The maximum take-off weight (MTOW) of an A320 is 73,500 kg, while the maximum landing weight (MLW) is 64,500 kg[2] (Jane's Information Group 2008). The MTOW is used here in the reference scenario calculations, but since aircrafts rarely operate fully loaded, the MTOW is probably an overestimate relative to the actual take-off weight. Greene (1992) uses

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[2] These weight data varies slightly between different configurations of the A320. Data for the basic configuration have been used here, other configurations weigh up to 77,000 kg (MTOW) and 66,000 kg (MLW) (Jane's Information Group 2008).

the MLW as a proxy for average in-flight operating weight. Therefore calculations with the MLW are also made in the sensitivity analysis.

Greenslet (2006) analyses operating costs of five US airlines A320s in service for the year 2005. Together these airlines operate more than a sixth of the global A320 fleet. The annual average fuel use of an A320 is, according to this analysis, 3,364,626 US gallons, or 80,110 barrels.

The factor converting a relative reduction in take-off weight of an aircraft to a reduction in fuel use for a specific flight is a vital part of the model. This is also a rather complex issue, which is not covered very thoroughly in the literature reviewed for this study. Greene (1992) derives weight-fuel use relationships between different aircraft types, rather than the effect of weight reductions for one aircraft, while Greener by Design (GbD 2001) estimates the relative fuel efficiency improvements of using the weight saved to carry more payload to be about two times the relative reduction in weight for short and medium haul aircraft, such as the A320 (Section 2.4.2.3). A more reliable estimate of a factor converting a relative reduction in take-off weight to a reduction in the fuel needed on a specific aircraft for a certain flight was obtained from Poll (2008), which concludes the conversion factor to be around 1.3 for medium haul flights with an A320-type aircraft, i.e. that a 1% reduction in take-off weight leads to a 1.3% reduction in fuel needed for a certain flight (Appendix C). This estimate primarily concerns incremental changes in aircraft operating weight. To cover for the relative uncertainty surrounding this issue, sensitivity analysis will be conducted, testing conversion factors ranging from 1.0 to 2.0, where 2.0 refers to the fuel efficiency gain experienced when the saved weight can be used to accommodate additional payload.

The unit fuel cost is in the reference scenario assumed to be 100 US$ per barrel, including both the fuel price and the costs of emissions. This is below the current fuel costs experienced in the sector, but well above the fuel costs experienced historically. CO_2 emissions costs have not been considered historically, but will probably have to be included when accounting for fuel use in the future. Emissions costs of 50 US$ per ton CO_2, translates into just above 20 US$ per barrel in extra fuel costs (Appendix B).

An annual interest rate of 5% is used in the reference scenario. In sensitivity analysis annual interest rates from 1% to 15% are considered.

	Reference Scenario	**Alternative Scenarios**
Annual aircraft fuel use (US gallons)	3,364,626	-
Aircraft take-off weight (kg)	73.500	68,500
Conversion factor	1.3	1.0; 1.5; 2.0
Fuel cost (US$/barrel)	100	50; 150; 200
Annual interest rate	5%	1%; 10%; 15%

Table 6. Model inputs and assumptions

The assumptions are summarised in Table 6. In the component cost-efficiency calculations (Section 4.2.1) only the reference scenario will be used, while the reference scenario will be complemented by the alternative scenarios when conducting the generic calculations in Section 4.2.2.

4.1.3 Collection of data

Data on component unit costs, installation costs, weights, and lifetime expectancy have been collected directly from manufacturers and airlines via personal communications. Above components in passenger service systems were highlighted as an interesting area of research. Manufacturers of economy class passenger seats, catering trolleys, galleys, carpets, and in-flight entertainment (IFE) systems were approached via e-mail and phone. Respondents were asked to provide data on weights, costs and expected lifetime of their products, for fitting in an A320 with a standard 150 seat two-class configuration (138 economy class seats and 12 business class seats). They were also asked for the weight difference between components currently in production, and those that are commonly used in aircraft today, i.e. former generation of components. Economy class seat manufacturers were for example asked to provide data on weights, costs, and lifetime of their current products suitable for use in an A320, as well as weight data on seats produced 5 and 10 years ago.

This approach could cause a significant risk for biased information, since the surveyed firms might wish to promote their product and make it look more favourable than it actually is. The collected data can, however, be viewed on as illustrative case studies.

Due to business confidentiality, difficulty to get in contact with relevant contacts, and in some cases, project specific costs and weights, this proved to be a rather complicated and time consuming approach. The study was therefore narrowed down to two sectors where data appeared to be most easily accessible, and was focused on economy class passenger seats and trolleys for catering services.

4.2 Results

4.2.1 Component calculations

The data collected through personal communications with component manufacturers and airlines can be found in Appendix D. This section will present results from calculations of net present value (NPV), break-even fuel costs, break-even net investment costs, and break-even weight reductions for replacing old version catering service trolleys and economy class passenger seats with new light-weight versions.

4.2.1.1 Catering service trolleys

According to Dop (2008) a ship set of catering service trolleys for an A320 normally consists of eight full size (FS) and four half size (HS) trolleys. The weights saved by using new versions of trolleys, relative to five year old versions is 5.5 kg per unit for FS trolleys and 4 kg/unit for HS trolleys. The total weight savings potential for a full ship set of trolleys for an A320 is thus 60 kg – 44 kg for FS trolleys and 16 kg for HS trolleys. The new versions cost 150 US$ more per unit than the five year old version, or 975 US$ for FS and 787.50 US$ for HS trolleys. The expected lifetimes of the new trolleys are 7 to 10 years.

Eight different scenarios - four for each trolley type -have been calculated. Two different estimates of lifetime expectancy – 7 and 10 years – and two net investment costs – ‘Full cost’ and ‘Excess cost’ – for each trolley type have been considered. The ‘Full cost’ scenarios represent replacing five year old trolleys with new versions, and assuming that the replaced trolleys have no net value. The ‘Excess cost’ scenarios represent cases where the decision is to invest in the new light-weight trolleys or in the five year old versions. The results from these scenario calculations can be seen in Table 7.

4.2.1.2 Economy class passenger seats

The weight saved by using new versions of economy class passenger seats varies with the age of the seats that are to be replaced. Estimates provided by Gaither (2008) suggest that five year old versions are 0.6 kg heavier per unit than the most recent economy class seats. Ten year old seats are 1.2 kg to 1.5 kg heavier than new versions. The total potential weight savings for an A320 with 138 economy class seats are 82.8 kg when replacing five year old seats; when replacing ten year old seats the potential is 165.6-207 kg. New economy class seats of the most basic type cost around 1,500 US$ per unit (Gaither 2008). The installation costs experienced when replacing economy class seats in a commercial aircraft is around 50 US$ per unit (Diment 2008). New seats can be expected to remain in service for 6-14 years, with 10 years as a reasonable approximate for the average lifetime (Bauer 2008).

Eighteen different scenarios are considered here, six for each of the three estimated weight reductions above. Three different lifetime expectancies – 6, 10, and 14 years – and two net investment costs – 1,550 US$/unit and 800 US$/unit – are considered. The 1,550 US$ net investment per unit consists of 1,500 US$ for the component and 50 US$ for the installation. The scenarios with 800 US$ net investment cost per unit represents the same as above, but with the addition of a second hand value for the replaced seat of 750 US$/unit, i.e. half the component cost of the new seat. The results from these scenario calculations are presented in Table 7.

Trolleys	*Net investment*	*Expected life*	**Net present value** (US$/unit)	**Break-even net investment** (US$/unit)	**Break-even weight reduction** (kg/unit)	**Break-even unit fuel cost** (US$/barrel)
Full size 5.5 kg weight reduction	Full cost 975 US$/unit	7 years	3,534.34	4,509.34	1.19	21.62
		10 years	5,042.57	6,017.57	0.89	16.20
	Excess cost 150 US$/unit	7 years	4,359.34	4,509.34	0.18	3.33
		10 years	5,867.57	6,017.57	0.14	2.49
Half size 4 kg weight reduction	Full cost 787.50 US$/unit	7 years	2,492.02	3,279.52	0.96	24.01
		10 years	3,583.92	4,376.41	0.72	17.99
	Excess cost 150 US$/unit	7 years	3,129.52	3,279.52	0.18	4.57
		10 years	4,226.42	4,376.41	0.14	3.43

Seats	*Net investment*	*Expected life*	**Net present value**	**Break-even net investment**	**Break-even weight reduction**	**Break-even unit fuel cost**
Versus 5-year old (0.6 kg)	1550 US$/unit	6 years	-1,118.49	431.51	2.16	359.20
		10 years	-893.54	656.46	1.42	236.11
		14 years	-708.47	841.53	1.11	184.19
	800 US$/unit	6 years	-368.49	431.51	1.11	185.40
		10 years	-143.54	656.46	0.73	121.87
		14 years	41.53	841.53	0.57	95.06
Versus 10-year old (1.2 kg)	1550 US$/unit	6 years	-686.98	863.02	2.16	179.60
		10 years	-237.08	1,312.92	1.42	118.06
		14 years	133.06	1,683.06	1.11	92.09
	800 US$/unit	6 years	63.02	863.02	1.11	92.70
		10 years	512.92	1,312.92	0.73	60.93
		14 years	883.06	1,683.06	0.57	47.53
Versus 10-year old (1.5 kg)	1550 US$/unit	6 years	-471.23	1,078.77	2.16	143.68
		10 years	91.16	1,641.16	1.42	94.45
		14 years	553.83	2,103.83	1.11	73.68
	800 US$/unit	6 years	280.73	1,078.77	1.11	74.16
		10 years	841.16	1,641.16	0.73	48.75
		14 years	1,303.83	2,103.83	0.57	38.03

Table 7. Net present values, and break-even values for catering service trolleys and economy class passenger seats scenarios

4.2.2 Generic scenarios

In addition to the component calculations with actual weights and costs data, above, calculations of generic scenarios are also conducted. These calculations are based on a reference scenario, with investment costs and lifetime expectancy assumptions based on the data applicable to changing economy class seats in an A320 (Table 8). This reference scenario is amended with alternative scenarios where various values for the different variables are changed one at a time. We can now use these scenarios to calculate break-even unit fuel costs, break-even net investment costs per kg of weight reduced, and break-even weight reductions, under different circumstances (Table 9).

	Reference Scenario	**Alternative Scenarios**
Annual aircraft fuel use (US gallons)	3,364,626	-
Aircraft take-off weight (kg)	73.500	68,500
Weight reduction (kg)	1.0	-
Conversion factor	1.3	1.0; 1.5; 2.0
Fuel cost (US$/barrel)	100	50; 150; 200
Annual interest rate	5%	1%; 10%; 15%
Expected lifetime (years)	10	1; 5; 20
Net investment costs (US$)	1,500	100; 500; 5,000

Table 8. Generic scenario assumptions

Scenario		**Break-even net investment** (per kg of weight reduced)	**Break-even weight reduction** (kg)	**Break-even unit fuel cost** (US$/barrel)
Reference scenario		1,094.10	1.37	137.10
Aircraft take-off weight	73,500	1,094.10	1.37	137.10
	64,500	1,246.77	1.20	120.31
Conversion factor	1.0	841.62	1.78	178.23
	1.3	1,094.10	1.37	137.10
	1.5	1,262.43	1.19	118.82
	2.0	1,683.24	0.89	89.11
Unit fuel cost	50	547.05	2.74	X
	100	1,094.10	1.37	X
	150	1,641.16	0.91	X
	200	2,188.21	0.69	X
Net investment costs	100	x	0.09	9.14
	500	x	0.46	45.70
	1500	x	1.37	137.10
	5000	x	4.57	457.00
Interest rate	1%	1,342.00	1.12	111.77
	5%	1,094.10	1.37	137.10
	10%	870.63	1.72	172.29
	15%	711.12	2.11	210.94
Expected lifetime	1	134.94	11.12	1,111.57
	5	613.45	2.45	244.52
	10	1,094.10	1.37	137.10
	20	1,765.79	0.85	84.95

Table 9. Break-even values for the generic reference scenario; and for scenarios where one variables at a time deviate from the reference scenario.

4.3 Analysis

4.3.1 Variable analysis

This section will analyse the impacts on the net present value equation (1) and the break-even values (NPV=0) equations: unit fuel cost (2), net investment cost (3), and weight reduction (4)[3]; from changes in the input variables.

$$NPV = \frac{(R*C)}{i}\left(1 - \frac{1}{(1+i)^L}\right) - I + \frac{V}{(1+i)^L} \tag{1}$$

$$C = \frac{i}{R}\left(I - \frac{V}{(1+i)^L}\right)\left(\frac{(1+i)^L}{(1+i)^L - 1}\right) \tag{2}$$

$$\left(I - \frac{V}{(1+i)^L}\right) = \frac{(R*C)}{i}\left(1 - \frac{1}{(1+i)^L}\right) \tag{3}$$

$$Weight\mathrm{Re}duction = \frac{i}{C}\left(I - \frac{V}{(1+i)^L}\right)\left(\frac{(1+i)^L}{(1+i)^L - 1}\right)\frac{AicraftTakeoffWeight}{AnnualFuelUse * Conv.Factor} \tag{4}$$

The variables analysed in the generic scenarios above (Table 8 and 9) can be categorised into three groups. First there are the variables that affect the annual revenue stream (the aircraft take-off weight, the conversion factor, and the unit fuel cost). Changes in annual fuel use are indirectly captured here, since they are equivalent to changes in the conversion factor, and both variables directly affects *R* proportionally. A second category of variables are the expected lifetime and the annual interest rate, which affect the translation of an annual revenue stream into discounted lifetime revenue (DLR). Lastly there is the net investment cost, which at all break-even situations is equal to the DLR.

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[3] For more detailed explanations of equations (1) - (4) see Section 4.1.1

Lower total weight makes a particular weight reduction relatively more important. A change in the take-off weight is inversely proportional to the change in relative weight reduction. The annual fuel use reduction (*R*) is proportional to the relative weight reduction, and changes in the break-even net investment cost are proportional changes in *R*. Therefore the break-even net investment cost (3) is inversely proportional to the reduction in aircraft take-off weight. The break-even unit fuel cost (2) is inversely proportional to *R*, and is consequently, proportional to changes in aircraft take-off weight. The break-even weight reduction (4) is also, obviously, proportional to changes in aircraft take-off weight. Consequently, a 12.2% decrease in take-off weight, from 73,500 kg to 64,500 kg, increases the break-even net investment costs with ((73500/64500)-1=) 14.0%, while it decreases the break-even unit fuel cost and the break-even weight reduction with 12.2%.

Changes in the conversion factor are proportional to changes in *R*, and thus also to changes in the annual revenue stream (*R*C*), which in turn are proportional to changes in the discounted lifetime revenues from a weight reducing intervention. The break-even investment cost is thus proportional to changes in the conversion factor. The break-even unit fuel cost (*C*) is inversely proportional to *R* and the conversion factor, since *R*C* remains constant only when a particular increase in *R* is accompanied by a proportional decrease in *C*. The break-even weight reduction is inversely proportional to changes in the conversion factor, since *R* remains constant only when a particular increase in the conversion factor is followed by a proportional decrease in the amount of weight taken away from the aircraft.

Changes in the unit fuel cost (*C*) obviously has proportional effects on the annual revenue stream (*R*C*), which in turn is proportional to the discounted lifetime revenues from a weight reducing intervention. The break-even investment cost is equal to the discounted lifetime revenues and is, thus, proportional to changes in the unit fuel cost. The break-even weight reduction, on the other hand, is inversely proportional to changes in the unit fuel cost, since the same annual revenue stream can be obtained at a proportionally smaller reduction in weight as the unit fuel cost increases.

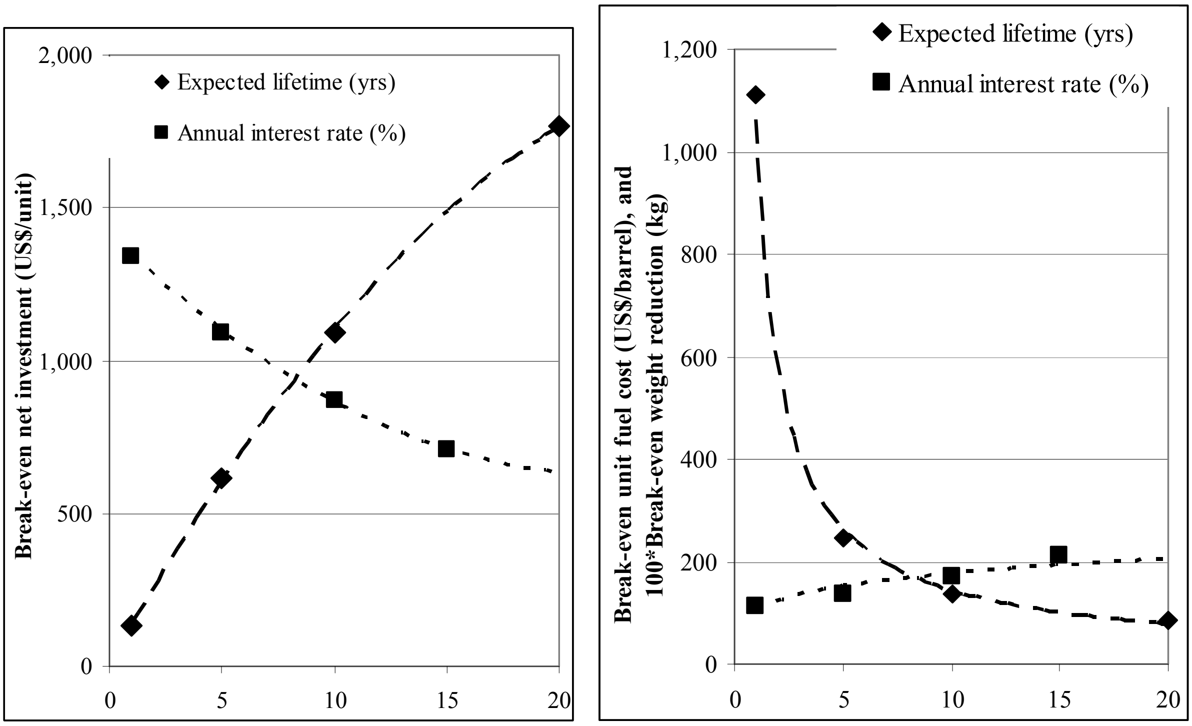

Figure 14. Impacts, of changes in annual interest rate and component lifetime expectancy, on the break-even values of net investment costs (left), unit fuel costs, and weight reduction (right), in the reference scenario (Table 8). The break-even values for weight reductions are (in the reference scenario) 100 times smaller than the break-even values for unit fuel costs.

The annual interest rate (*i*) and the lifetime expectancy (*L*) affects the discounted lifetime revenue arising from the new component, and, in the cases where there is a value for the component at end of life, it also affects the net investment costs. The net present value of a particular weight reducing intervention is improved by increased lifetime expectancy and by reduced interest rates, since a longer lifetime yields a longer revenue generating period and since a lower interest rate makes the present value of future revenue streams larger than at a higher interest rate. The break-even net investment cost is always equal to the discounted lifetime revenue stream, consequently it also grows with rising lifetime expectancy and decreasing interest rates. The reversed conditions hold for the break-even values of unit fuel costs and weight reduction, since they need to be larger to maintain constant discounted lifetime revenue when the interest rate increases or the expected lifetime decreases. The impacts of changes in annual interest rate and lifetime expectancy on the break-even values in the generic reference scenario are illustrated in Figure 14.

At break-even (NPV=0), the net investment cost is always equal to the discounted lifetime revenue of the investment (3). Changes in the net investment costs are proportional to changes in the annual revenue stream ($R*C$), and are therefore also proportional to changes in the break-even weight reductions, and the break-even unit fuel cost.

4.3.2 Results analysis

As mentioned above, the total weight savings potential for a full ship set of trolleys for an A320 is 60 kg – 44 kg for FS trolleys and 16 kg for HS trolleys. The weight savings for an A320 with 138 economy class seats are 82.8 kg when replacing five year old seats with new light-weight versions; when replacing ten year old seats the potential is 165.6-207 kg. The weight savings potential from the two interventions investigated here are thus 142.8-267 kg, or 0.19-0.36% of the MTOW of the aircraft. Employing the conversion factor of 1.3 yields a fuel savings potential of 0.25-0.47%, or approximately 202-378 barrels of fuel – at a value 20,200-37,800 US$ - per year for an A320, under the assumptions in the reference scenario (Table 6).

4.3.2.1 Catering service trolleys

The net present values of all the catering service trolley scenarios are positive, which is also reflected in that the break-even net investment costs are significantly higher than the actual net investment costs, and also in that the break-even weight reductions are lower than the actual weight reductions.

In the ‘Full cost’ scenarios the break-even weight reductions are 0.72-0.96 kg/unit for half size trolleys, and 0.89-1.19 kg/unit for the full size versions. In the ‘Excess cost’ scenarios the break-even values are, obviously, even lower and the required weight reduction is only 0.14-0.18 kg/unit. The lower values in the ranges are for scenarios where 7 years component life has been assumed, while a 10 years assumption yields the higher values.

The break-even net investment costs increase with longer lifetime expectancy and larger weight reductions. The scenario results range from 3,280 US$/unit for half size trolleys saving 4 kg per unit and assumed to remain in service for 7 years, to 6,018 US$ per unit for full size trolleys that are 5.5 kg/unit lighter than the consecutive version and with an expected lifetime of 10 years. All break-even net investment values are several times larger than the actual net investment costs of 150-975 US$/unit, and the net present values are consequently high.

The calculations also indicate that replacing old version trolleys with new ones becomes beneficial at fuel costs higher than 16-24 US$/barrel, while the break-even unit fuel cost in the ‘Excess cost’ scenarios is as low as 2-5 US$/barrel.

4.3.2.2 Economy class passenger seats

The net present value of replacing a five year old seat with the new 0.6 kg lighter version is negative in all scenarios, except in the most optimistic one where it is assumed that the replaced seat has a net value equivalent to half the cost of the new seat and where the new seat is expected to last for 14 years. Using the low estimate – 1.2 kg/unit – for weight saved when replacing a ten year old seat with a new one yields positive net present values for all scenarios where the replaced seat is assumed to have a second hand value. Assuming no second hand value for the replaced seat, the NPV is negative when the expected lifetime is 6 years or 10 years, while the NPV is positive when the new seat is expected to last for 14 years. Using the higher weight saving estimate – 1.5 kg/unit – the NPV is positive in all scenarios, except the one where there is no second hand value of the replaced seat and the expected lifetime is only 6 years.

The break-even weight reductions are 1,11-2,16 kg/seat when there is no second hand value for the replaced seat, and 0.57-1.11 kg/seat when there is a net value of 750 US$ per replaced seat. The ranges occur from varying lifetime expectancies in the different scenarios, where the lower values are for expected lifetimes of 14 years, while the higher values are for scenarios when the seat is assumed to last for only 6 years. Any weight reductions above these levels make the NPV positive.

The break-even net investment costs are 432-842 US$/seat when the weight reduction is 0.6 kg per seat. The lower value is for lifetime expectancies of 6 years, while the higher is for 14 years. Since the break-even net investment costs are proportional to the weight reduction, the values are twice as high when the weight reduction is 1.2 kg per seat, and 1,079-2,104 US$ per seat when the weight reduction is 1.5 kg.

Unlike the two break-even values above, the break-even unit fuel cost depends on both the weight reduction and the net investment cost assumptions. It is proportional to the net investment cost, and inversely proportional to the amount of weight reduced. In addition the break-even fuel cost decreases with rising lifetime expectancy. The resulting ranges in break-even unit fuel cost from different variable assumptions are presented in Table 10. The lowest value occurs when the net investment cost is 800 US$, the weight reduction is 1.5 kg, and the expected lifetime is 14 years.

		Ranges of break-even unit fuel cost (US$/barrel)
Net investment cost (US$)	800	38-185
	1,550	74-359
Expected lifetime (years)	6	74-359
	10	49-236
	14	38-184
Weight reduction (kg/seat)	0.6	95-359
	1.2	48-180
	1.5	38-144

Table 10. Ranges of break-even unit fuel costs for passenger seat replacements under varying assumptions about net investment costs, lifetime expectancies and weight reductions

The results for the two components studied above vary substantially. The net present values (NPV) in the trolley scenarios are all positive and ranges from 2,492 to 5,868 US$/unit, while the NPV in the passenger seat scenarios is negative in eight scenarios out of eighteen, ranging from minus 1,118 to plus 1,304 US$ per seat. The break-even unit fuel costs are 2-24 US$ per barrel in the trolley scenarios and 38-359 US$/barrel in the passenger seat scenarios. One conclusion from this analysis is that investments in light-weight trolleys are profitable at relatively low fuel prices, while passenger seat investments require higher fuel prices to be beneficial. However, it is important to note that the total potential weight savings and profits are higher for passenger seats since the number of units concerned is considerably larger.

Since the expected lifetime of the trolleys and the seats are fairly similar, and the other assumptions are the same for all scenarios, the factor that drives this difference in result between the two component types must be the net investment cost per kg or weight reduction, which is 27-197 US$/kg in the trolley scenarios and 533-2,583 US$/kg in the passenger seat scenarios.

4.3.2.3 Generic scenarios

The assumed weight reduction in the generic scenarios is 1.0 kg, implying that all values for the break-even net investment costs are per kg of aircraft take-off weight reduced. In the reference scenario the break-even net investment cost is 1,094 US$, indicating that all net investment costs lower than this yields a positive net present value for the reference scenario intervention. The break-even fuel cost in the reference scenario - when the net investment cost is 1,500 US$ - is 137 US$/barrel, while the break-even weight reduction is 1.37 kg. All unit fuel costs or weight reductions larger than these break-even values generate positive net present values for the reference scenario intervention.

The break-even net investment cost increases with the lifetime of the new component, since the additional investment can be recuperated over a longer time in service (Figure 15). Since the break-even net investment cost is equal to the discounted lifetime revenue of the intervention, these values also capture the opposite situation where excess weight is added to the aircraft. For example, using leather dress covers instead of fabric versions, adds approximately 1.4 kg per seat (Appendix D). This excess weight comes at a fuel cost penalty of (1.4*135 =) 189 US$ per seat and year, which is nearly as much as the excess investment cost of 250 US$/seat of leather relative to fabric dress covers.

There is a linear relationship between the break-even unit fuel cost and the net investment cost, and the slope can be expressed as:

$$x = \frac{i}{R}\left(\frac{(1+i)^L}{(1+i)^L - 1}\right).$$

Using the reference scenario assumptions yields a slope of 0.0914, implying that a 100 US$ rise in net investment cost per kg increases the break-even unit fuel cost with 9.14 US$/barrel (Figure 16).

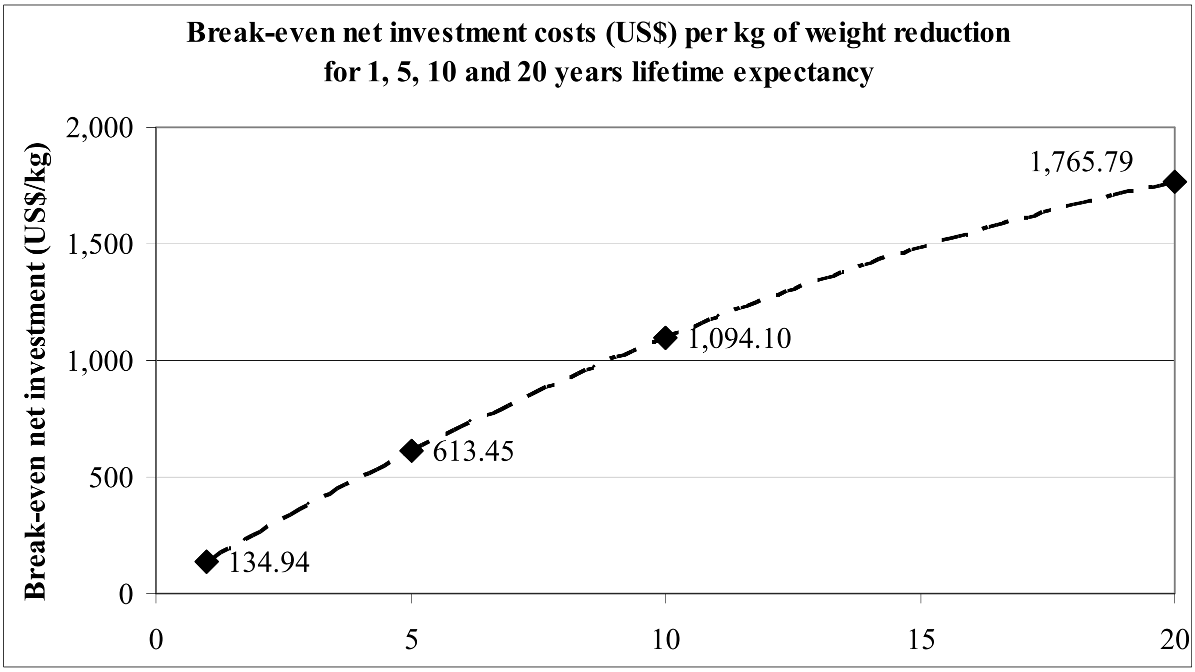

Figure 15. Break-even net investment costs – and excess weight cost - (US$) per kg of weight change for 1, 5, 10, and 20 years lifetime expectancy. Based on the reference scenario (Table 8).

The annual aircraft fuel use in the model is an average value; increasing the utilisation level above the average would yield additional revenue from a particular weight reduction. Increased utilisation is equivalent to using a higher conversion factor in the model. For example, an increase in the conversion factor from 1.3 to 1.5 is equivalent to a 15.4% increase in annual utilisation, which – in the reference scenario – would lead to a proportional increase in the break-even net investment cost to 1,262 US$/kg, and to a proportional decrease in the break-even unit fuel cost to 119 US$/barrel (Figure 17).

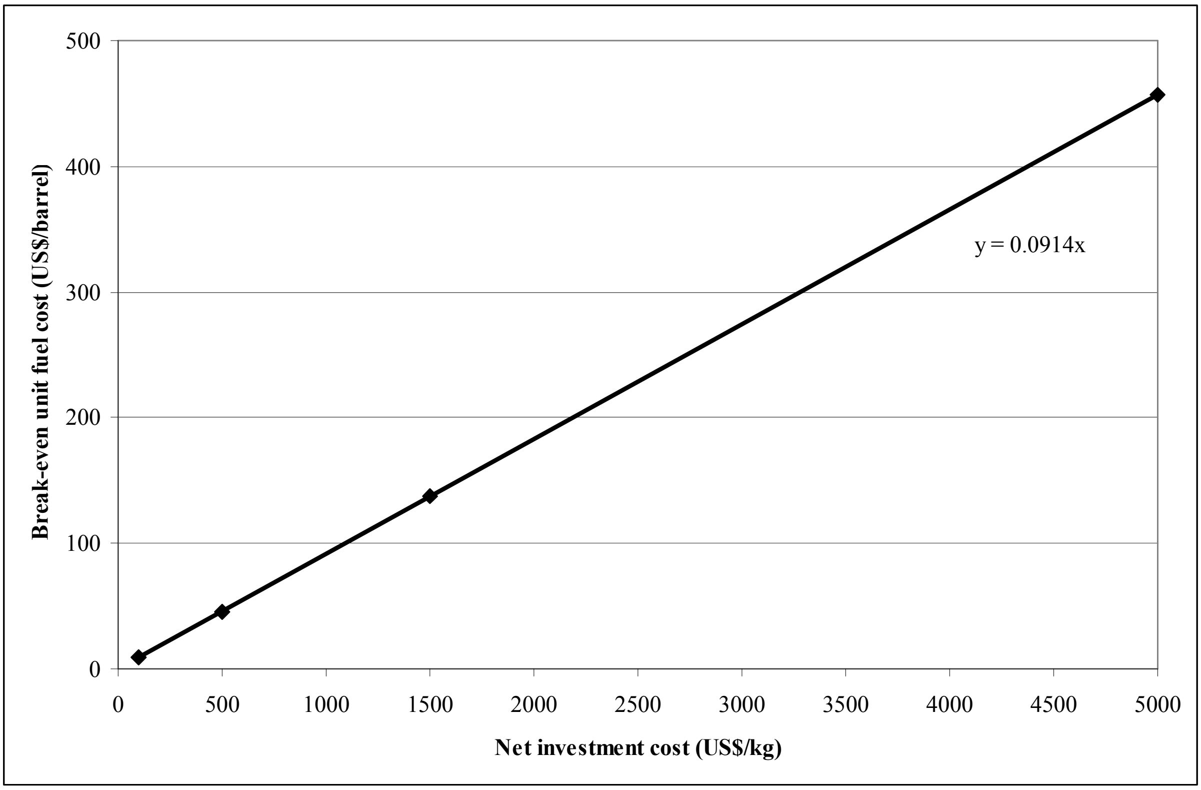

Figure 16. Relationship between the net investment cost and the break-even unit fuel cost in the reference scenario.

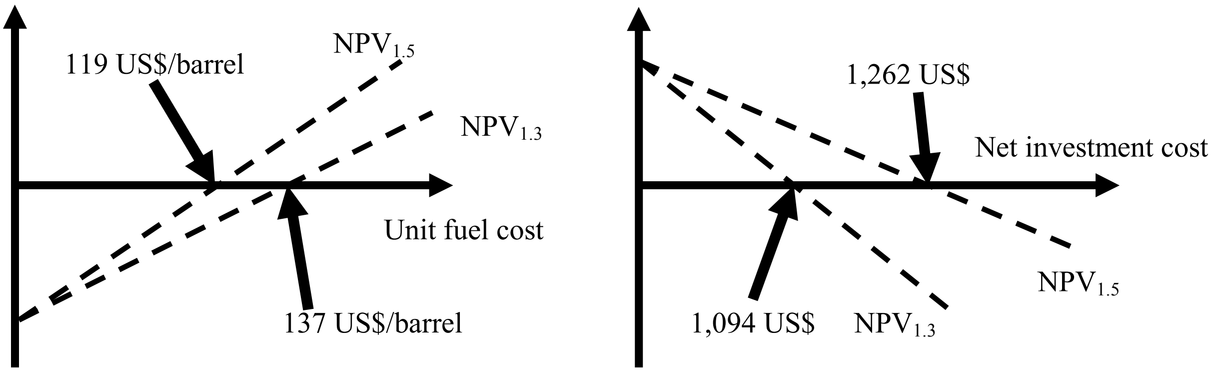

Figure 17. Impacts on the break-even unit fuel cost and the break-even net investment cost of increasing the conversion factor or the annual utilisation of an aircraft

5 Conclusions

The commercial aviation sector is responsible for about 2% of the global CO_2 emissions, and the emissions can be expected to increase even further as the growth in the sector is around 5% per year - in terms of revenue passenger kilometres (RPK) and freight tonne kilometres (FTK) - while the fuel efficiency - in terms of fuel used per RPK or FTK - is projected to improve by only 1% annually.

The costs of aviation fuel have risen dramatically over the last few years. Since the turn of the century the fuel prices have increased from around 30 US$/barrel to the current levels well above 100 US$/barrel. Fuel costs now account for nearly 30% of airline operating costs. In addition, the aircraft operators will in the future, most probably, have to pay for the CO_2 emitted during its activities.

The stress on the commercial aviation sector caused by relatively high fuel costs increases the pressure on the sector to develop measures that improve fuel efficiency. Since commercial aircraft remain in service over relatively long periods of time it is of interest for aircraft operators to consider fuel efficiency improvements that can be made on existing aircraft.

This study set out to explore the possibilities for cost-efficient fuel use and CO_2 emission reductions through incremental weight reductions in existing aircraft. A linear conversion factor is attained, to link incremental reductions in aircraft weight with reductions in fuel use. A net present value based method was developed to analyse light-weighting interventions in terms of profitability, and to identify break-even values for unit fuel cost (US$/barrel), net investment cost (US$/unit), and weight reduction (kg/unit).

Two component types related to passenger services - catering service trolleys and economy class passenger seats - were analysed in a range of scenarios. The weight savings potential from these two interventions were 142.8-267 kg, or 0.19-0.36% of the MTOW of the aircraft. Employing the conversion factor of 1.3 yields a fuel savings potential of 0.25-0.47%, or approximately 202-378 barrels of fuel – at a value 20,200-37,800 US$ - per year for an A320, under the assumptions in the reference scenario.

The net present values of all the eight catering service trolley scenarios were positive, ranging from 2,492 to 5,868 US$/unit, while the break-even fuel cost ranged from 2 to 24 US$/barrel. The net present value of the eighteen economy class passenger seat scenarios varied from minus 1,118 to plus 1,304 US$/unit, and the break-even unit fuel cost ranged from 38 to 359 US$/barrel. The major driver causing the differing results between the two component types was, of course, the net investment cost per kg of weight reduction. One conclusion from this analysis is that investments in light-weight trolleys are profitable at relatively low fuel prices, while passenger seat investments require higher fuel prices to be beneficial. However, it is important to note that the total potential weight savings and profits are higher for passenger seats since the number of units concerned is considerably larger.

In addition to these two case studies, generic intervention scenarios were analysed. In the reference scenario - where the fuel cost is 100 US$/barrel, the annual interest rate 5%, and the expected lifetime of the component is 10 years - the break-even net investment cost is 1,094 US$ per kg of weight reduction, indicating that all net investment costs lower than this yields a positive net present value for the reference scenario intervention. The net investment cost was always equal to the discounted lifetime revenue at break-even so every change – higher unit fuel cost, higher aircraft utilisation, lower annual interest rate or higher component lifetime expectancy - that increases the discounted lifetime revenue also increase the break-even net investment cost.

The break-even fuel cost is proportional to the net investment cost and inversely proportional to the weight reduction and to aircraft utilisation. In addition, it increases with rising interest rates and decreasing component lifetime expectancy.

6 References

Airbus. (2007). *Global market forecast 2007-2026*. Available at http://www.airbus.com/en/corporate/gmf/: Airbus S.A.S.

Arguelles, P., Bischoff, M., Busquin, P., Droste, B. A. C., Evans, R., Kroell, W., *et al*. (2001). *European aeronautics: A vision for 2020 meeting society's needs and winning global leadership*. Luxembourg: European Commission.

Ascend Worldwide Ltd. (2008). *Current fleet summary.* Retrieved June 22ndhttp://www.ascend-air.com/Air/LandingPage.aspx

ATA (Air Transport Association of America). (2008a). *Annual traffic and ops: World airlines.* Retrieved August 5th http://www.airlines.org/economics/traffic/World+Airline+Traffic.htm

ATA (Air Transport Association of America). (2008b). *Quarterly cost index: U.S. passenger airlines.* Retrieved August 13thhttp://www.airlines.org/economics/finance/Cost+Index.htm

ATA (Air Transport Association of America). (2008c). *Fuel cost and consumption report.* Retrieved August 19thhttp://www.airlines.org/economics/energy/MonthlyJetFuel.htm

Bauer, D. (2008). Personal Communication, Regional sales manager, Recaro Aircraft Seating, dietrich.bauer@recaro-as.com

Birch, N. T. (2000). 2020 vision: The prospects for large civil aircraft propulsion. *The Aeronautical Journal, 104*(1038), 347.

Boeing. (2007). *Current market outlook 2007 summary*. Available at http://www.boeing.com/commercial/cmo/index.html: Boeing Commercial Aircraft.

DfT (Department for Transport). (2007). *UK air passenger demand and CO2 forecasts*. Available at http://www.dft.gov.uk/pgr/aviation/environmentalissues/ukairdemandandco2forecasts/airpassdemandfullreport.pdf: Department for Transport.

Diment, G. (2008). Personal communication, Technical engineer, British Airways. graham.diment@ba.com:

Dop, L. (2008). Personal communication, Engineering manager, Driessen Aerospace Group, lex.dop@driessen.com

EC (Commission of the European Communities). (2003). *Directive of the european parliament and of the council amending directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the community* No. 2006/0304 (COD)). Brussels, Belgium: Commission of the European Communities.

Eyers, C. J., Norman, P., Middel, J., Plohr, M., Michot, S., Atkinson, K., *et al.* (2004). *AERO2k global aviation emissions inventories for 2002 and 2025* No. QINETIQ/04/01113). Available at http://www.cate.mmu.ac.uk/reports_AERO2k.asp: QinetiQ Ltd.

Fielding, J. P. (1999). *Introduction to aircraft design*. Cambridge, UK: Cambridge University Press.

Fillipone, A. (2008). Analysis of carbon-dioxide emissions from transport aircraft. *Journal of Aircraft, 45*(1), 185.

Gaither, L. (2008). Personal communication, Director sales and marketing, Weber Aircraft LP, larry.gaither@weber.zodiac.com

George, F. (2006). *Fuel system basics.* Retrieved September 2nd. http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=bca&id=news/fuel0606.xml

Greene, D. L. (1992). Energy-efficiency improvement potential of commercial aircraft. *Annual Review of Energy and the Environment, 17*, 537.

Greener by Design. (2001). *Air travel - greener by design the technology challenge*. Retrieved June 4th http://www.greenerbydesign.org.uk/resources/index.php: Royal Aeronautical Society.

Greener by Design. (2002). *Air travel - greener by design improving operations the technology challenge market-based options,* Retrieved June 4th http://www.greenerbydesign.org.uk/resources/index.php: Royal Aeronautical Society.

Greener by Design. (2005). *Air travel - greener by design mitigating the environmental impact of aviation: Opportunities and priorities,* Retrieved June 4th http://www.greenerbydesign.org.uk/resources/index.php: Royal Aeronautical Society.

Greenslet, E. S. (2006). Block hour operating cost by airplane type and airline. *The Airline Monitor, 19*(3), 9.

Henderson, J. (2005). *Controlling carbon dioxide emissions from the aviation sector* No. SC10752). Boulder, CO, USA: Stratus Consulting.

Hughes, D. (2007). ATM is no 'silver bullet'. *Aviation Week & Space Technology,* (August 20/27), 66.

IATA (International Air Transport Association). (2007). *IATA economic briefing october 2007 passenger and freight forecasts 2007 to 2011*. Available at http://www.iata.org/whatwedo/economics/issue_briefing_new.htm: The International Air Transport Association.

IATA (International Air Transport Association). (2008). *Freight volumes contract and passenger growth hits five-year low.* Retrieved 6/8/2008 http://www.iata.org/pressroom/pr/2008-08-04-01.htm

ICAO (International Civil Aviation Organization). (2004). *ICAO's policies on charges for airports and air navigation services* No. Doc 9082/7). Montreal, Canada: International Civil Aviation Organization.

Jane's Information Group. *Jane's all the world's aircraft*, Coulsdon, UK. Annual review of all aircraft currently available. Several hardcopy editions were used for this thesis, as well as the online database on http://www.janes.com

Keen, M., & Strand, J. (2006). *IMF working paper indirect taxes on international aviation* No. WP/06/124). Washington D.C., USA: International Monetary Fund.

Lee, J. J., Lukachko, S. P., Waitz, I. A., & Schafer, A. (2001). Historical and future trends in aircraft performance, cost, and emissions. *Annual Review of Energy and the Environment, 26*, 167-200.

Morris, J., Angus, A., Mann, M., & Poll, I. (2008). *OMEGA project (Ω1/014) A framework for estimating the marginal costs of environmental abatement for the aviation sector report of a workshop 6 th march, 2008.* Unpublished manuscript.

Official Airline Guide. (2008). *OAG reports a 7% drop in global airline capacity of 59.7million seats in 4th quarter.* Retrieved 6/8/2008http://www.oag.com/travel-news/oag-travel-news/oag-reports-a-7-drop-in-global-airline-capacity-of-597million-seats/

Peel, C. J. (1996). Advances in materials for aerospace. *The Aeronautical Journal, 100*(1000), 487.

Peeters, P. M., Middel, J., & Hoolhorst, A. (2005). *Fuel efficiency of commercial aircraft an overview of historical and future trends* Report No. NLR-CR-2005-669). Available at http://www.transportenvironment.org/Publications/prep_hand_out/lid:398: National Aerospace Laboratory NLR.

Penner, J. E., Lister, D. H., Griggs, D. J., Dokken, D. J., & McFarland, M. (1999). *Aviation and the global atmosphere, A special report of IPCC working groups I and II.* Cambridge, UK: Cambridge University Press.

Poll, I. (2008). Personal Communication. Professor of Aerospace Engineering, Cranfield University, i.poll@cranfield.ac.uk

Rolls Royce. (2006). *Market outlook 2006-2025*. Available at http://www.rolls-royce.com/civil_aerospace/overview/market/outlook/default.jsp: Rolls Royce Civil Aerospace.

Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D. S., Myhre, G., *et al.* (2005). Aviation radiative forcing in 2000: An update on IPCC (1999). *Meteorologische Zeitschrift, 14*(4), 555.

Smith, J. B. (1981). *Trends in energy use and fuel efficiency in the U.S. commercial airline industry* No. Transportation Research Record 870). Washington D.C., USA: US Department of Energy.

Stinton, D. (1998). *The anatomy of the airplane* (Second Edition ed.). Oxford, UK: Blackwell Science Ltd.

Zalewski, P. (2008). *MEPs and council presidency reach deal on airline emissions.* Retrieved August 19thhttp://www.europarl.europa.eu/news/expert/infopress_page/064-32956-175-06-26-911-20080627IPR32955-23-06-2008-2008-false/default_en.htm

7 Appendices

7.1 Appendix A - Historical Weight Trends Data

Single Aisle Aircraft	Year of Introduction	Numbers in Service	Average Age of Fleet (yrs)	Design Range (nautical mi)	Seating Capacity (2-class Conf)
A318	2002	56	2.75	1,455	107
A319	1996	1047	5.29	1,900	124
A320	1988	1871	7.95	3,000	150
B717-200	1999	154	6.40	1,510	106
B727	1964	461	31.57	1,470	94
B737-200	1967	531	27.67	1,799	88
B737-300	1984	1008	16.93	1,672	122
B737-400	1988	448	15.33	2,160	146
B737-500	1990	368	14.94	1,700	108
B737-600	1998	68	6.91	1,505	110
B737-700	1997	926	5.13	1,585	126
B737-800	1998	1399	4.84	1,925	162
DC-9	1965	329	36.06	1,484	
MD-81	1980	33	21.03	1,563	135
MD-82	1981	492	19.95	2,049	135
MD-83	1986	244	16.39	2,501	135
MD-87	1987	46	18.33	2,372	109
MD-88	1988	155	17.57	2,620	142
MD-90	1994	110	10.93	2,266	153
F100	1988	244	16.39	1,340	97
BAe146-300	1988	47	18.02	1,040	103
A321	1993	449	6.30	2,300	186
B707-320	1963	35	39.29	3,395	147
B737-900	2001	52	5.71	2,060	177
B737-900ER	2006	27	0.56	3,200	180
B757-200	1982	925	14.82	2,150	178
B757-300	1998	51	6.75	3,270	240
DC-8	1967	127	39.17	3,892	189
Tu204	1995	37	7.59	1,565	196

Single Aisle Aircraft	OEW (kg)	MTOW (kg)	OEW/MTOW	OEW per seat in 2-class conf	MTOW per seat in 2-class conf
A318	39,035	59,000	0.662	364.81	551.40
A319	40,125	64,000	0.627	323.59	516.13
A320	38,923	72,000	0.541	259.49	480.00
B717-200	30,970	51,710	0.599	292.17	487.83
B727	36,740	68,947	0.533	390.85	733.48
B737-200	25,432	48,535	0.524	289.00	551.53
B737-300	31,724	56,472	0.562	260.03	462.89
B737-400	32,976	62,822	0.525	225.86	430.29
B737-500	30,953	52,163	0.593	286.60	482.99
B737-600	36,954	56,245	0.657	335.95	511.32
B737-700	38,006	60,330	0.630	301.63	478.81
B737-800	41,554	70,535	0.589	256.51	435.40
DC-9	24,011	44,450	0.540		
MD-81	36,177	63,500	0.570	267.98	470.37
MD-82	36,534	66,680	0.548	270.62	493.93
MD-83	36,543	72,575	0.504	270.69	537.59
MD-87	33,183	63,503	0.523	304.43	582.60
MD-88	35,369	67,810	0.522	249.08	477.54
MD-90	40,007	70,760	0.565	261.48	462.48
F100	23,870	43,090	0.554	246.08	444.23
BAe146-300	24,878	44,225	0.563	241.53	429.37
A321	46,960	82,200	0.571	252.47	441.94
B707-320	60,725	150,138	0.404	413.10	1,021.35
B737-900	42,493	74,840	0.568	240.07	422.82
B737-900ER	42,493	85,138	0.499		472.99
B757-200	59,430	104,325	0.570	333.88	586.10
B757-300	64,590	122,470	0.527	269.13	510.29
DC-8	69,739	158,760	0.439	368.99	840.00
Tu204	58,300	94,600	0.616	297.45	482.65

Twin Aisle Aircraft	Year of Introduction	Numbers in Service	Average Age of Fleet (yrs)	Design Range (nautical mi)	Seating Capacity (2-class Conf)
A300-B2-200	1976	12	26.17	1,800	220
A300-B4-100	1975	10	28.40	2,098	220
A300-B4-200	1979	71	26.41	2,750	220
A310-200	1982	68	23.56	3,160	210
A310-300	1986	128	17.49	4,600	210
A330-200	1998	297	4.77	6,400	293
B767-200	1982	78	23.65	2,780	211
B767-200ER	1984	99	18.92	4,925	211
B767-300	1987	103	16.37	4,020	210
B767-300ER	1988	562	11.85	5,760	210
B767-400ER	2000	37	7.32	5,600	304
DC10	1971	157	30.19	3,710	255
L1011	1972	38	27.84	2,500	256
A300-600	1984	62	13.52	3,730	267
A300-600R	1988	229	12.52	4,155	267
A330-300	1993	239	6.56	4,550	335
A340-200	1993	18	14.17	7,350	303
A340-300	1993	212	9.84	6,650	335
A340-500	2002	25	3.84	8,650	
A340-600	2002	80	3.49	7,500	
B777-200	1995	85	10.64	3,970	375
B777-200ER	1997	402	7.23	5,960	375
B777-200LR	2006	19	0.95	9,150	279
B777-300	1998	60	7.63	5,720	451
B777-300ER	2004	148	1.66	6,240	339
MD11	1990	193	14.21	5,002	323
Ilyushin Il-86	1979	47	18.49	1,944	234
B747-100	1969	29	32.66	5,008	374
B747-200	1971	191	26.81	5,748	374
B747-300	1983	62	21.90	5,700	
B747-400	1989	481	13.51	7,300	500
B747-400ER	2002	39	3.08	7,500	500
B747-400F	1993	118	6.81	4,400	
A380	2007	4	1.75	8,000	

Twin Aisle Aircraft	OEW (kg)	MTOW (kg)	OEW/MTOW	OEW per seat in 2-class conf	MTOW per seat in 2-class conf
A300-B2-200	85,183	142,000	0.600	387.20	645.45
A300-B4-100	87,409	150,000	0.583	397.31	681.82
A300-B4-200	88,500	165,000	0.536	402.27	750.00
A310-200	78,650	138,600	0.567	374.52	660.00
A310-300	76,768	150,000	0.512	365.56	714.29
A330-200	120,563	230,000	0.524	411.48	784.98
B767-200	81,230	136,080	0.597	384.98	644.93
B767-200ER	80,825	156,490	0.516	383.06	741.66
B767-300	86,953	156,489	0.556	414.06	745.19
B767-300ER	89,131	175,540	0.508	424.43	835.90
B767-400ER	103,100	204,115	0.505	339.14	671.43
DC10	119,334	251,744	0.474	467.98	987.23
L1011	106,265	193,230	0.550	415.10	754.80
A300-600	89,715	165,000	0.544	336.01	617.98
A300-600R	86,172	170,500	0.505	322.74	638.58
A330-300	119,472	212,000	0.564	356.63	632.84
A340-200	122,769	257,000	0.478	405.18	848.18
A340-300	126,481	257,000	0.492	377.56	767.16
A340-500	170,300	368,000	0.463		
A340-600	177,100	365,000	0.485		
B777-200	135,580	229,520	0.591	361.55	612.05
B777-200ER	142,430	286,895	0.496	379.81	765.05
B777-200LR	145,150	347,815	0.417	520.25	1,246.65
B777-300	160,120	299,370	0.535	355.03	663.79
B777-300ER	167,830	345,050	0.486	495.07	1,017.85
MD11	125,874	273,289	0.461	389.70	846.10
Ilyushin Il-86		190,000			811.97
B747-100	160,301	322,050	0.498	428.61	861.10
B747-200	163,844	351,540	0.466	438.09	939.95
B747-300	176,900	377,840	0.468		
B747-400	177,218	362,875	0.488	354.44	725.75
B747-400ER	184,565	412,770	0.447	369.13	825.54
B747-400F	180,395	362,875	0.497		
A380	270,015	560,000	0.482		

7.2 Appendix B – Emissions Costs Impact on Fuel Costs

One US gallon of aviation jet fuel weighs 6.76 lbs (George 2006), or 3.07 kg. Every kg of jet fuel gives rise to 3.15 kg of CO_2 when burnt (Eyers *et al* 2004). Thus, every US gallon of fuel causes (3.07 * 3.15 =) 9.67 kg of CO_2 emissions. Every US$ per ton CO_2 in emissions cost then increases the cost of burning fuel by 0.97 US cents per US gallon. A barrel is equivalent to 42 US gallons, so every US$/ton CO2 translates to 41 US cents per barrel of fuel. An emissions permit price of 50 US$/ton CO_2 affects the costs of fuel with 20.30 US$/barrel.

The amount of CO_2 equivalents emitted can be estimated by the use of the radiative forcing factor (RFF) (Section 2.1). Sausen *et al* (2005) approximates that the RFF is about 1.9. Using this RFF indicates that every US gallon of fuel produces (9.67 * 1.9 =) 18.37 kg of CO_2 equivalents. Then every US$ per ton CO2 equivalent increases the cost of burning one US gallon of fuel by 1.84 US cents, or by 77 US cents per barrel.

7.3 *Appendix C – Converting Weight Reductions to Fuel Use Reductions*

This derivation is based on consultations with Poll (2008), and primarily concerns incremental changes in aircraft operating weight. The relationship between the mass of fuel needed for the flight (MF) and aircraft total mass (MTO) at take-off can be expressed as

$$\frac{MF}{MTO} = 1 - kEXP(-X) = \alpha\ ,$$

where k (=0.985) is a factor taking into account the fuel needed for the landing and take-off, and x is an aircraft performance factor depending on the propulsive and aerodynamic efficiencies (η*L/D), the energy density of the fuel (LCV) and the flight range (R, in nautical miles). For an A320, or similar type of aircraft

$$X = \frac{R * g}{LCV * (\eta L / D)} = \frac{R}{8600}\ ,$$

and for R=1,500 nm (which is the design range for an A320 at maximum payload).

$$\alpha = 1 - 0.985EXP\left(-\frac{1500}{8600}\right) = 0.189\ .$$

The take-off mass can be broken down to operating empty mass (MOE), mission fuel mass (MF), payload mass (MP), and the mass if fuel reserves (M_{fres})

$$MTO = MOE + MF + MP + M_{fres},$$

where the fuel reserves normally make up 4.5% of the total mass. Since

$$MF = \alpha * MTO$$

the weight break-down can be expressed as

$$MTO = MOE + \alpha * MTO + MP + 0.045 * MTO$$

$$MTO * (1 - \alpha - 0.045) = MOE + MP$$

and

$$MTO = \frac{MOE + MP}{(1 - \alpha - 0.045)},$$

and consequently

$$MF = \frac{\alpha}{(1 - \alpha - 0.045)} * \left(MOE + MP\right).$$

If we define the masses (MP and MOE) that can be reduced in order to save fuel as

$$M = MOE + MP$$

$$\frac{dMF}{dM} = \frac{\alpha}{1-\alpha-0.045}$$

$$dMF = \frac{\alpha}{1-\alpha-0.045} * dM$$

$$\frac{dMF}{MF} = \frac{\alpha}{1-\alpha-0.045} * \frac{dM}{MF}$$

$$\frac{dMF}{MF} = \frac{\alpha}{1-\alpha-0.045} * \frac{1}{\alpha} * \frac{dM}{MTO} = \frac{1}{1-0.189-0.045} * \frac{dM}{MTO}$$

$$\frac{dMF}{MF} = 1.306 * \frac{dM}{MTO}$$

Therefore any 1% reduction in aircraft take-off mass reduces fuel needed for a specific flight with approximately 1.3%.

7.4 Appendix D – Data Enquiries

Manufacturers of economy class passenger seats, galleys, catering service trolleys, and in-flight entertainment (IFE) systems were approached for data on their products. All respondents were asked to supply data for components installed in A320s, with 150 seat 2-class configuration (138+12), or similar aircraft types. The data asked for was weights, costs and expected lifetime of their current products. In addition they were asked about the weights of products currently in service, i.e. products sold one product-lifetime (5-10 years) ago. Sufficient data was only supplied by manufacturers of seats and trolleys. In addition, airlines were asked to supply data on the additional costs (installation costs) experienced when replacing economy class passenger seats.

Exchange rates of 1.5 US$ per €, and 2 US$ per £ have been used for these calculations.

7.4.1 Economy class passenger seats

Company:	Recaro Aircraft Seating
Contact:	Dietrich Bauer, Regional Sales Manager
Weight:	~40 kg/triple seat ➔ 13.3 kg/seat
Price:	1500-1700 € (2250-2550 US$) per seat
Expected life:	6-14 yrs, approximately 10 yrs on average

Company: Weber Aircraft LP

Contact: Larry Gaither, Director Sales and Marketing

Weight: 82 lbs (37.2 kg) per triple seat ➔ 12.4 kg/seat

Price: 1,400-1,600 US$/seat

Data are for low cost carrier type of seat, with fabric dress covers and no IFE. Leather dress covers will add around 3 pounds per seat, and at an extra cost of 250 US$/seat. IFE in its simplest form (audio only) will add around 8 to 10 pounds per triple. Video IFE generally used on long haul aircraft can add up to 20 pounds per triple.

Seat weights today are approximately 5% lighter than 5 years ago and 10%to 12% lighter than ten years ago. The weights of basic seats were then 13.0 kg/seat five years ago, and 13.6-13.9 kg/seat ten years ago.

Lifetime expectancy is very dependant on the maintenance and repair performed by the airline. Retrofit programs are more often than not brought on by new technology or the desire to incorporate new IFE systems.

Company: British Airways

Contact: Graham Diment, Technical Engineer

Removing and replacing seats,like for like, usually requires about one man hour a triple seat for installation and an approximate cost of £75 per man hour is used, indicating £25 (50 US$) per passenger seat.

7.4.2 Catering service trolleys

Company:	Driessen Aerospace Group
Contact:	Lex Dop, Engineering Manager

Typical shipset for an A320 consists of 8 full size (FS) and 4 half size (HS) trolleys.

Weights:	20 kg for FS
	12 kg for HS
	208 kg total shipset weight (8*20 + 4*12 = 208 kg)
Price:	650 € (975 US$) for FS
	525 € (787.50 US$) for HS
	7300 € total shipment cost (8*650 + 4*525 = 7300 €)
Expected lifetime:	7 top 10 years

Weight savings per unit relative to five year old versions:

Weight savings:	5.5 kg for FS
	4 kg for HS
	60 kg total shipset saving (8*5.5 + 4*4 = 60 kg)

The new versions cost about 100 € (150 US$) more per unit than the older versions.

Pris: 100:- (exkl moms)

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