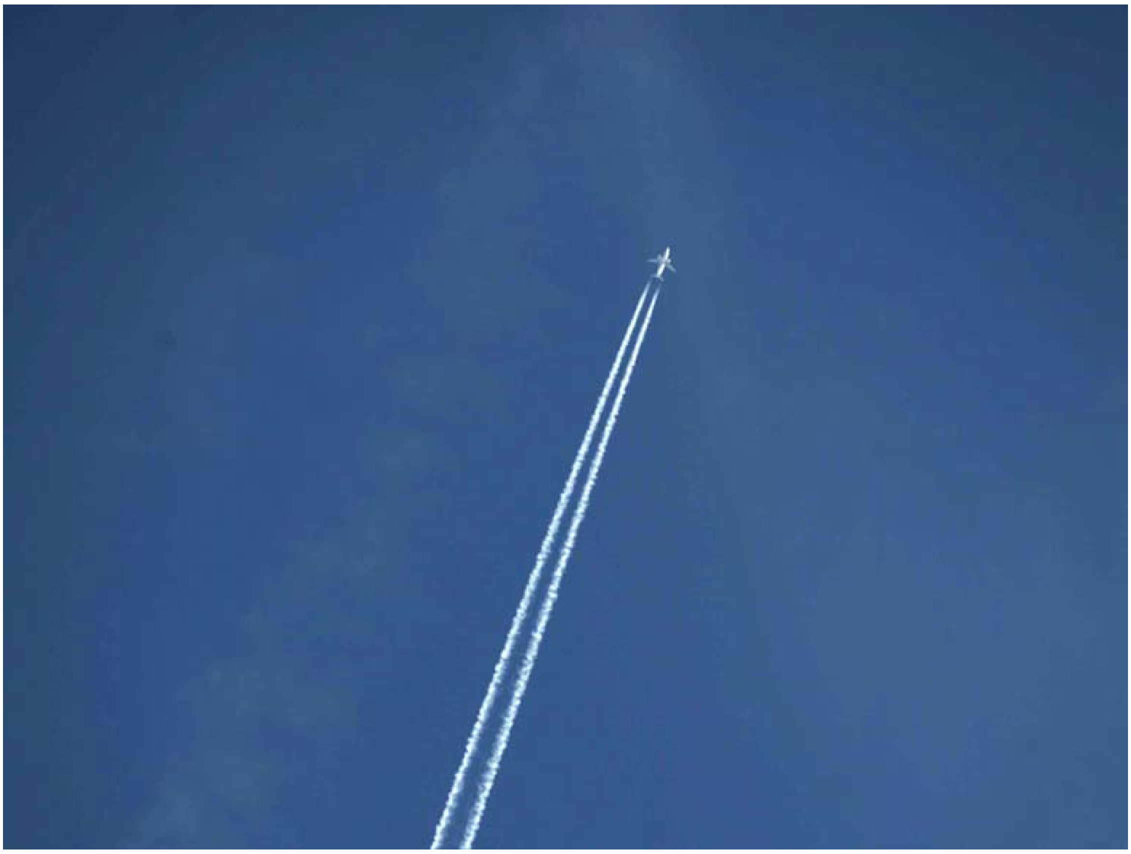
UK Aviation: Carbon Reduction Futures

Final Report to the Department for Transport



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This document was prepared by The Centre for Air Transport and the Environment at Manchester Metropolitan University and Cranfield University for the Department for Transport in 2008. The views expressed in the report are those of its authors and not necessarily those of the Department for Transport. The report is not intended to be relied upon by any third parties and is not intended to be regarded as a substitute for independent advice or research.

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Glossary

Acronyms

ACARE – Advisory Council for Aeronautical Research in Europe

ATC – air traffic control

ATM – air traffic management

APD –Air Passenger Duty

APU –auxiliary power unit

BAU –business as usual

CDA – continual descent approach

CORINAIR - the emission inventory guidebook prepared by the UNECE (United Nations Economic Commission for Europe) Task Force on Emissions Inventories and Projections provides a comprehensive guide to state-of-the-art atmospheric emissions inventory methodology.

EU ETS – EU emissions trading scheme

FAST – Future Aviation Scenario Tool, model for GHG emission calculation

GHG – greenhouse gases

ICAO – International Civil Aviation Organisation

IPCC – Intergovernmental Panel on Climate Change

LTO –landing and takeoff cycle

MAC- marginal abatement cost (curve)

OMEGA – a partnership to meet the environmental challenges of aviation growth

PIANO – Aircraft engine performance and design model (http://www.lissys.demon.co.uk/).

SES – Single European Sky

SKO – Seat Kilometre Offered

Terms

Blended Wing Body (BWB) – delta shaped flying wing with passengers seated in the main wing body

Composite Floor Beams – use of lighter materials to reduce airframe component weight

Conformal Antennae – panels shaped to fit the normal contours of the aircraft's skin

Geared Turbofans – a conventional turbofan engine with a reduction gear added between the front fan and the turbine driving the fan

Natural Laminar Flow – smooth non-turbulent flow to achieve lower drag

Open Rotor Engines – engine with no nacelle around the fan and the fan replaced with 2 contra-rotating swept propellers or rotors

Riblets – small grooves or raised lines on the airswept surface skin of the aircraft to reduce turbulence and friction drag

Tail Cone Changes – reshaping the aft-most part of the fuselage to reduce drag

Winglets – wingtip extensions designed to reduce cruise drag

Executive Summary

Objectives and scope of the project

The objective of this study, commissioned by the Department for Transport, is to determine the scope for, and cost of actions that can be taken by, the UK domestic aviation sector to reduce its emissions of CO_2. This involves estimating the cost of achieving CO_2 abatement to help ensure that the most cost effective measures can be identified. For the purposes of this project UK domestic aviation refers to internal passenger flights within the UK only. The timeframe considered is the period 2007 to 2050.

Given the timeframes involved and the evidence available, the costs and benefits of abatement options in this report are to be considered illustrative and represent broad orders of magnitude only. They are nonetheless indicative of the potential for abatement and relative costs.

Approach taken

The approach adopted involves the following steps:

- Define baseline emissions for UK domestic flights out to 2050
- Identify and consider a range of abatement options
- Estimate the potential impact on fleet emissions of each of these abatement options
- Set these against the estimated indicative costs of implementation to produce a marginal abatement cost (MAC) curve

While the project focuses on potential interventions available to the UK domestic aviation sector to reduce CO_2 emissions, the analysis is informed by measures at the European and global scale, since many options are generic and not specific to UK domestic aviation. The study does not consider fiscal instruments, measures requiring changes to other transport modes or demand changes arising from changing perceptions towards aviation.

The study focuses on the technical feasibility of abatement options for the UK aviation sector, allowing for current operational practices and business models. Actual uptake will depend on a wide range of factors, not least of which are the perceived commercial advantage of abatements, compatibility with existing or new business models, and the degree of uncertainty associated with new practices and technology.

The work draws on information from a range of sources including academic literature, manufacturers' reports and websites, and the findings of a broader parallel study funded by Omega, "A framework for estimating the marginal costs of environmental abatement for aviation." The Omega project sought the views and inputs from a wide range of industry stakeholders through a series of workshops and consultations. Hence this report also benefits from such valuable input.

Development of baseline carbon dioxide emissions to 2050

Forward projections of baseline emissions were made for UK domestic flights by first building up an understanding of UK aviation activity, scheduled flights and distances, fleet composition and fuel use. The engine design model, PIANO, and the 3D inventory model, FAST, were used to calculate baseline emissions for 2007 by aircraft type and distance. These baseline emissions reflect underlying trends in fuel efficiency and take account of abatement measures that are current policy or those that will be introduced shortly.

Future emissions are based on demand forecasts made by DfT and other research so the underlying assumptions are consistent with DfTs (as published in November 2007) including GDP, oil prices and the rate of take-up of ACARE targets. These imply fuel efficiency improvements of 1.3% per annum up to 2030, and 0.8% per annum from 2030 to 2050. While the projections include the progressive adoption of ACARE targets and the full implementation of Single European Sky by 2020, they do not assume any radical technological breakthroughs. The future level of fuel prices is a key driver of underlying trends in fuel efficiency.

Abatement options considered

A range of abatement measures capable of tackling CO_2 emissions from domestic flights are identified. These are split into three categories: engine and airframe technology, operational improvements and fleet management. The feasibility of these abatement measures is assessed, including their potential fuel savings, broad magnitude of costs, key drivers, take-up and timescale of introduction and interdependencies with other categories of emissions. In the absence of firm evidence, this assessment was essentially based on consultation with key stakeholders, using their expert judgement and that of the study team.

Estimating the costs of abatement options

There is generally little robust information available on the costs of the options considered given uncertainties over their stage of development; timing of their introduction; applicability to the wider fleet; level of investment in R&D etc. The costs presented are therefore necessarily illustrative and intended to indicate broad orders of magnitude only. They are nevertheless a useful guide to their relative significance.

Estimating marginal abatement cost curves

Given the significant uncertainties involved in estimating both the benefits of different options in terms of their impacts on emissions, and their costs in terms of their development and investment costs, it is not possible to generate robust abatement cost curves. However, for the purposes of illustration, curves have been presented based on the limited information available. They should be considered indicative only and are intended to reflect the broad orders of magnitude of relative effects.

Information on the characteristics of aircraft types operated, including their estimated fuel use and CO_2 emissions, is combined with information regarding estimated applicability and indicative costs to derive illustrative estimates of marginal abatement costs (MAC). MAC estimates can be used to rank and compare the cost effectiveness of different abatement measures. However, it should be noted that the abatement measures are considered independently of one another. Carbon dioxide savings from these abatement measures should not be treated as cumulative.

Findings of the illustrative MAC analysis

A range of interventions could, when considered individually, enable the UK aviation sector to abate up to 14% of its CO_2 emissions at negative or zero cost by 2012, up to 17% if fuel prices rise to ‘very high’ levels. After this point, MAC appear to rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/ t $CO_{2,}$ the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon).

By 2020, assuming no major technological breakthrough in airframe or engine performance, the potential for abatement at or below zero cost, with intervention abatement calculated individually, appears to be about 24% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits. This is not to say, however, that all these savings are possible in practice. There are significant limitations on the extent to which different technologies and interventions can be taken up. Furthermore, these estimates of reductions in emissions consider each intervention individually. Emissions savings will necessarily be lower once additivity and overlapping effects between abatement options are taken into account .

The most cost effective intervention measures in the short to medium term appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short hauls of the UK sector (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies, and, by 2020, introducing wide-scale ATM improvements that reduce travel distance. The implementation of these is therefore subject to the ability and willingness of airlines to make such changes to their operations.

New technology options are therefore not likely to be able to make a significant contribution to abatement in the period to 2020.

High fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency. It is difficult to predict the efficacy of intervention measures beyond 2020 that are associated with ACARE compliant standards.

The estimates of MAC for CO_2 for UK domestic aviation are based on a number of critical assumptions, some of which are purely illustrative, reflecting the lack of robust information on abatement technologies and their costs. Further stakeholder feedback and refinement of methods and data would of course add value to the approach used.

1 Introduction

A strategy paper published by the Department for Transport (DfT) in October 2007, “Towards a Sustainable Transport System”, committed the Department to consider the full range of options for putting transport on a less carbon intensive path and to examine potential effective emissions reduction options for different types of journey and transport. As part of this the DfT intends to draw up a paper setting out the agreed long-term challenges and goals for transport including for CO2 reduction and setting out the process within which options will be generated. This work will help input into that process. For the purposes of this report domestic aviation is defined as internal flights within the UK of passenger aircraft only.

The project detailed in this report focuses on potential interventions available to the UK domestic aviation to reduce CO_2 emissions. Although the work detailed here does not cover international aviation, the analysis is informed by measures available at the European and global scale since many options will be generic and not be specific to UK domestic aviation. However, the potential and cost effectiveness of some options may be different for the UK domestic aviation sector than for the industry as a whole.

The work which underpins this report has identified a number of technological, operational and fleet management options for achieving CO_2 reductions within domestic aviation. In the medium term, and in particular the longer term, achievement of significant reductions in emissions, such as the 50% reduction in CO_2 emissions to 2020 in the ACARE targets, will require technological breakthroughs over and above evolutionary improvements in airframe, engine technology and ATM systems. The advantages and disadvantages of each of these options have been assessed, together with possible synergies and trade-offs, taking into account the views of key stakeholders. While the focus has been on CO_2 emissions savings, interdependencies with other emissions have briefly been considered and their implications for the cost effectiveness of different interventions assessed. In the same vein, it was necessary to understand what barriers exist that may frustrate implementation of optimal solutions. Projections were made of baseline emissions, reflecting underlying trends in fuel efficiency, based on abatement measures and policies expected to be introduced in the future. The reductions in emissions and associated costs of additional abatement measures were compared against this business as usual scenario.

There are a number of potential abatement options and measures that are out of the scope of the study. For example, the work did not consider fiscal instruments (such as taxes and charges), measures requiring changes to other transport modes (such as surface transport to airports and inter-modal switching), demand changes arising from changing perceptions towards aviation and technological developments that are not expected to have an impact on CO_2 from UK domestic aviation. However, in dealing with interdependencies and barriers, it was necessary to consider the effects of current or potential market-based measures.

In addition the project team were able to draw upon the findings of a parallel study funded by Omega (www.omega.mmu.ac.uk) The Omega project, "A framework for estimating the marginal costs of environmental abatement for aviation" has assessed the cost effectiveness of abatement measures that can help aviation meet its medium and longer term goals. A workshop with key stakeholders in the aviation industry, held at Cranfield University in March 2008, considered the applicability, feasibility and effectiveness of a range of abatement measures identified in the literature.

However there are some important differences between the Omega study and the project funded by the DfT, which is narrower in scope in that it is limited to UK domestic flights and carbon dioxide emissions. While this study focuses on UK domestic aviation, identifying measures with potential application to this sector, it needs to be recognised that many of the options available will be generic in nature, with wider application to similar aircraft operating elsewhere, notably short-haul services.

The review of the literature undertaken for the Omega study, which has been updated for the purposes of this study, shows that much of the analysis of impacts of aviation emissions and measures to address them has taken place in the context of emissions trading. The inclusion of aviation in carbon trading schemes such as the EU Emissions Trading Scheme (ETS) has prompted interest in abatement potential, with the costs of abatement compared with the purchase of emissions permits. The consensus is that aviation is a relatively high abatement cost sector, resulting in it being a net purchaser of permits at current levels of carbon prices. However, it is recognised that the cost effectiveness of abatement measures is highly sensitive to fuel prices. Measures to reduce environmental emissions have been identified and these are drawn on below. Although the literature points to the importance of estimating marginal abatement costs, few studies have sought to tackle this with evidence of the scale of costs from abatement action by the aviation industry, with most applying assumptions on the level of abatement costs in their analysis of the impacts of emission trading on the aviation. The major points emerging from the literature are addressed more fully in Appendix 1.

The report is structured as follows: Section 2 provides a detailed classification of domestic aviation activity and provides a breakdown of the types of aircraft flown, average sector lengths and total seat km flown; Section 3 develops a baseline CO_2 emissions inventory for 2007 using CAA flight route and frequency data and provides a calculation of future CO_2 emissions up to 2050; Section 4 provides an analysis of the abatement options available to the aviation industry and offers a series of stakeholder comments; and Section 5 provides estimates of the cost effectiveness of different abatement measures.

2 Classification of Aviation Activity

Details of aircraft and airlines operating on UK domestic flights are shown in Tables 2.1 and 2.2 and discussed in more detail in Appendix 2. The source of data for the following observations is the Official Airline Guide (OAG) for May 2008. On the busy domestic trunk routes from London to major regional cities the aircraft types operated are similar to those used on a range of short-haul services within Europe eg B737-300,500,700, 800s and A319, A320 and A321s. On the thinner, mostly non-London based routes regional jets and turbo-props are operated, with the most common aircraft the Dash 8, Embraer 145 and 195. Turbo-props achieve much better fuel efficiency than regional jets, with the larger Dash 8 with 78 seats more efficient than the smaller turbo-props. Amongst jet aircraft, the larger B737-800 is more efficient in terms of seat kilometres per kg of fuel (SKO/kg) than smaller versions such as the B737-500.

Table 2.1: Top 10 aircraft by seat-kms offered, May 2008

Equipment	(Millions) Seats-kms	Average sector length (kms)
A319	403	470
Dash 8-400	179	355
B737-800	122	441
B737-700	96	421
B737-300	85,	387
A320	94	460
A321	74	442
Embraer 195	69	486
Embraer 145	58	407
B737-500	46	379

The top six airlines account for 91% of domestic seat-kms, with the top three, easyJet, BA and flybe accounting for almost two thirds.

Table 2.2: Top 10 airlines by seat-kms offered, May 2008

Airline	(millions) Seat-kms	Average sector length (kms)	% seat-kms
easyJet	316	457	22.6
British Airways	300	440	21.4
flybe	285	377	20.3
bmi British Midland	159	427	11.3
Ryanair	122	441	8.7
bmibaby	90	395	6.4

Summary:

- Aircraft used on UK domestic flights comprise those aircraft typically used on short-haul European routes for busy domestic trunk services and a mixture of regional jets and turboprops on many of the thinner routes.

- The top 6 airlines account for over 90% of domestic seat kilometres with 3 (easyJet, BA and flyBe) accounting for almost two thirds.

- The fuel efficiency of turboprops is much better than regional jets and B737-800s are more fuel efficient than earlier smaller versions of the B737.

3 Calculation of Projected Baseline Emissions

This section provides forward projections of baseline CO_2 emissions from UK domestic flights, reflecting underlying trends in fuel efficiency and taking into account abatement measures, including policies, expected to be introduced in the future: a so-called Business as Usual (BAU) projection.

A baseline needs to be defined to identify the projected level of emissions in the BAU scenario. This needs to reflect underlying trends in fuel efficiency based on abatement measures and policies expected to be introduced in the future. The reductions in emissions together with the associated costs of additional abatement measures are then compared against this baseline scenario.

Methodology and Key Assumptions

There is a range of methodologies by which aviation emissions of CO_2 may be calculated. The most detailed method is a so-called 'Tier 3B' method which entails flight route/frequency data and calculation of fuel burned and emissions throughout the full trajectory of each flight segment using aircraft and engine-specific aerodynamic performance information.

This study has used the engine design model, 'PIANO' to determine fuel flow during all flight phases[1]. PIANO is widely used across the industry and is one of the few tools recognized as an adequate and accurate aircraft performance tool.

Flight route and frequency data have been provided by the UK CAA and a baseline year of 2007 has been selected as a recent full year of data with other independent data available for comparison. The emissions performance data from PIANO and routes data have been compiled via an internationally recognized 3D inventory model 'FAST' used in both the atmospheric research arena (Lee et al., 2005[2]; Gauss et al. 2006[3]; Fichter et al., 2005[4]) and the CAEP arena. The general methodology is illustrated using a flow chart in Figure 3.1.

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[1] Simos, D., 1993: PIANO Version 2.5, a desktop option. World Aerospace Technology, 64-65; and Simos, D., 2004: PIANO: PIANO User's Guide Version 4.0, Lissys Limited, UK (http://www.lissys.demon.co.uk/).

[2] Lee D. S. , Owen B., Graham A., Fichter C., Lim L. L. and Dimitriu D. 2005: Allocation of International aviation emissions from scheduled air traffic * present day and historical (Report 2 of 3). Manchester Metropolitan University, Centre for Air Transport and the Environment, CATE-2005-3(C)-2, Manchester, UK

[3] Gauss M., Isaksen I. S. A., Lee D. S. and Søvde O. A. 2006: Impact of aircraft NO_x emissions on the atmosphere, tradeoffs to reduce the impact – a 3D CTM study. *Atmospheric Chemistry and Physics* 6, 1529–1548

[4] Fichter, C., S. Marquart, R. Sausen and D.S. Lee, 2005: The impact of cruise altitude on contrails and related radiative forcing. *Meteorologische Zeitschrift* 14, 563-572

Specific output from aircraft types within the PIANO database have been calculated both as fuel and emissions. This builds the most accurate possible estimation of domestic UK emissions with the highest-grade internationally (IPCC) recognized methodology. This level of detail is essential in the context of quantifying relatively small emission changes from some potential abatement proposals.

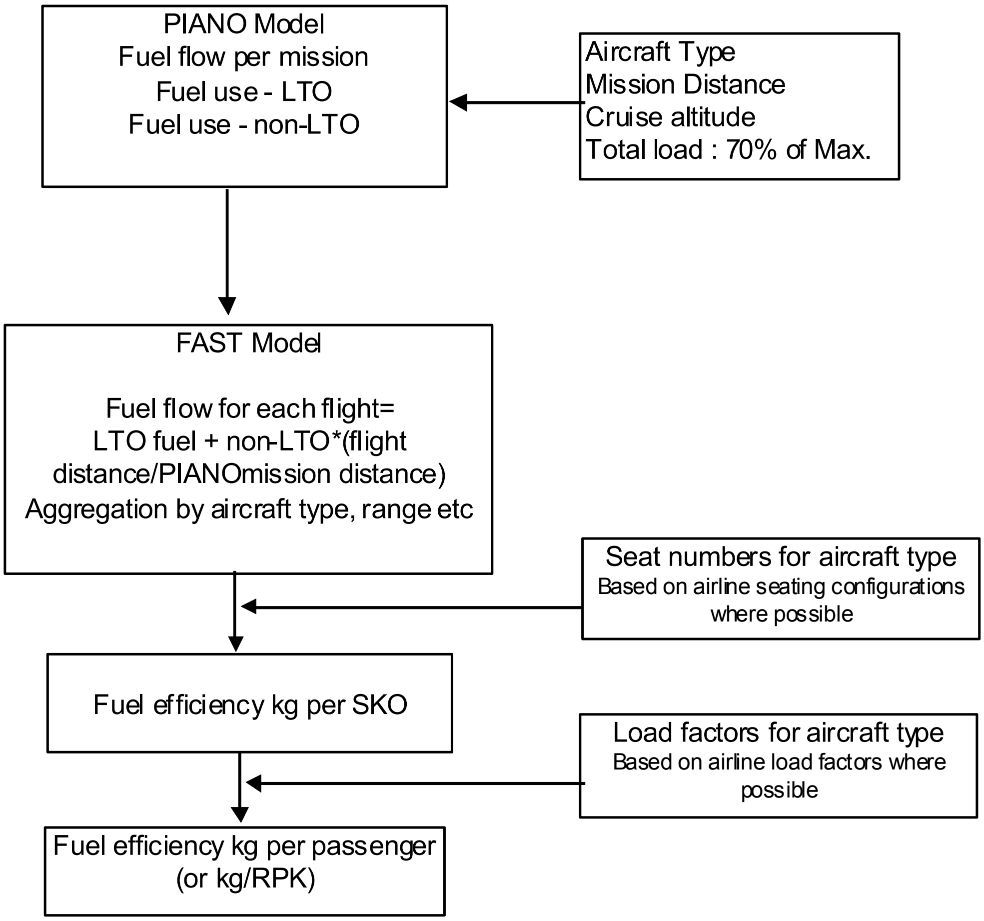

Figure 3.1 Inventory calculation methodology flow chart

In common with the methods used for the UK Green House Gas (GHG) inventory calculations, the calculation method outlined above uses the great circle distance between the departure and arrival airport. In reality, the route taken may not be the most direct, particularly for short-haul flights due to air traffic management and other reasons and 9% is added to account for this. The 9% uplift factor comes from the IPCC Aviation and the Global Atmosphere Report (IPCC, 1999), which states that 9-10% should be added to take into account non-direct routes (i.e. not along the straight-line great circle distances between destinations) and delays/circling. The 9%

uplift factor is also applied to the UK GHG inventory calculations and the UK DfT CO_2 forecast data[5].

In order to ensure consistency with estimated UK aviation emissions derived from fuel sales statistics, a further uplift factor of 10% is also added to UK non-LTO emission estimates derived from the bottom-up CORINAIR approach (used in the DfT study and DEFRA work), (DEFRA, 2008)[6]. In order to ensure consistency with the UK DfT and DEFRA approaches, this 10% factor has also been applied in this work.

Estimation of baseline/reference emissions for 2007

The calculation of reference fuel use data for the 2007 baseline year, using the method described above, are shown in Tables 3.1 to 3.3. Results are disaggregated by aircraft type and route distance in Table 3.1. Distance, fuel and SKO (Seat Kilometres Offered) data for the main aircraft types are shown in Table 3.2. The main contributing aircraft types are shown in Table 3.3, with their percentage contribution to the total calculated fuel usage.

Table 3.1 Estimated total fuel usage (thousand tonnes or Gg) by distance and by aircraft type for the UK domestic aviation sector[7]

Aircraft Type	<250km	250-500km	500-1000km	all distances
A300	0.2	5.6	0.0	5.8
A310	0.1	0.0	0.0	0.2
A319	16.5	23.9	123.7	164.1
A320	6.1	7.6	49.2	62.8
A321	0.5	0.3	3.1	3.9
A3302	0.2	0.8	0.1	1.1
B7372	0.2	0.1	0.1	0.4
B7373	3.3	45.9	33.5	82.7

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[5] DfT UK Air Passenger Demand and CO2 Forecasts, UK DfT, November 2007

[6] UK DEFRA (2008) Guidelines to Defra's GHG Conversion Factors

[7] For consistency with DfT and DEFRA estimates, an addition of 9% is applied to fuel use to account for use of Great Circle Distance and a further uplift of 10% is added (as in the national GHG inventory) for consistency with fuel use statistics

B7375	0.0	26.9	14.4	41.3
B7376	0.1	0.0	0.1	0.2
B7377	1.8	37.1	19.2	58.0
B7378	2.4	11.2	22.9	36.5
B7472	0.0	0.0	0.0	0.1
B7474	0.1	0.0	0.0	0.1
B7572	7.0	5.2	21.4	33.6
B7573	0.0	0.0	0.0	<0.1
B7672	0.0	4.5	0.0	4.5
B7673	1.1	3.0	0.7	4.8
B7772	0.0	0.0	0.0	<0.1
BAC111	0.0	0.0	0.0	<0.1
FA20	0.0	0.0	0.0	<0.1
CRJ100	0.0	0.0	0.0	<0.1
E145	1.8	17.9	8.3	28.0
F100	0.2	0.4	1.8	2.4
E190	0.0	2.2	1.1	3.3
MD80	0.0	0.0	0.0	0.1
MD90	0.1	0.0	0.0	0.1
Bae146/RJ85	0.5	16.8	29.6	46.8
Small turboprops	1.7	0.0	0.0	1.7
Medium Turboprops	6.7	17.7	2.5	26.9
Large Turboprops	5.0	33.1	26.6	64.7
Total	**55.3**	260.2	358.5	674.0

Table 3.2 Results in terms of total fuel usage, distance, SKO and fuel efficiency by aircraft type

Aircraft	Fuel (thousand tonnes)	Distance (thousand km)	SKO [1](millions)	fuel (kg/km)	fuel (kg/SKO)
A300	6	478	129	12	0.045
A310	<1	12	3	13	0.061
A319	164	33,762	5,031	5	0.033
A320	63	13,096	1,938	5	0.032
A321	4	716	143	5	0.027
A3302	1	73	21	15	0.051
B7372	<1	58	6	7	0.062
B7373	83	15,293	1,958	5	0.042
B7375	41	7,615	822	5	0.05
B7376	<1	41	5	6	0.046
B7377	58	10,943	1,652	5	0.035
B7378	37	6,133	1,159	6	0.031
B7472	<1	3	1	22	0.052
B7474	<1	3	1	28	0.066
B7572	34	4,073	725	8	0.046
B7573	<1	1	<1	13	0.056
B7672	5	431	93	10	0.049
B7673	5	454	95	11	0.05
B7772	<1	<1	<1	28	0.092
BAC111	<1	<1	<1	8	0.077
FA20	<1	21	<1	1	0.148
CRJ100	0	15	1	3	0.058
E145	28	15,929	796	2	0.035
F100	2	505	54	5	0.044

E190	3	1,720	134	2	0.025
MD80	<1	9	1	6	0.046
MD90	<1	7	1	11	0.073
Bae146/RJ85	47	14,026	1,192	3	0.039
Small turboprops	2	3,357	20	1	0.083
Medium Turboprops	27	26,893	995	1	0.027
Large Turboprops	65	32,354	2,265	2	0.029
TOTAL	674	188,021	**19,244**	**3.58**	**0.035**

Table 3.3 Percentage contribution by aircraft type to total fuel usage, distance and SKO (most significant, >1%, contributors only)

Aircraft	**%fuel**	**%distance**	**%SKO**
A319	24%	18%	26%
A320	9%	7%	10%
B7373	12%	8%	10%
B7375	6%	4%	4%
B7377	9%	6%	9%
B7378	5%	3%	6%
B7572	5%	2%	4%
E145	4%	8%	4%
Bae146/RJ85	7%	7%	6%
Medium turboprops	4%	14%	5%
Large turboprops	10%	17%	12%
	96%	**96%**	**96%**

Comparison with UK DfT and DEFRA estimates

The base year (2007) emissions estimate has been cross-referenced against other UK calculations, shown in Table 3.4 (e.g. The Department's own assessments and AEAT/NETCEN's estimates for the UK GHG inventory submission to the UNFCCC).

The data calculated for this study show good agreement with the UK DfT[8] and DEFRA[9] total estimates for domestic aviation in 2007.

Table 3.4 Comparison with UK government estimates of CO_2 for 2007

Flight distance	**<250km**	**250-500km**	**500-1000km**	**all distances**
This study Total Fuel (million tonnes)	0.055	0.260	0.359	0.674
This study Total CO_2 (million tonnes)	0.17	0.82	1.13	2.13
This study Total CO_2 (million tonnes) including APU[10]				2.4
Other estimates of CO_2 (million tonnes)				
UK GHG Estimate for 2006[11]				2.3
UK DfT Estimate for 2007[12]				2.4

Calculation of baseline/reference future emissions to 2050

A range of passenger demand scenarios exist to 2050 for the UK, from the Department's own research and international research (e.g. IPCC, 1999[13]; Owen and Lee, 2006[14]). The DfT domestic forecasts have been used as the basis for the baseline reference scenario. The forecast data for domestic traffic have been supplied[15] by aircraft type for the DfT Central Case to 2030 (data supplied for years 2007, 2010, 2020 and 2030). Between 2030 and 2050, the data are supplied as total air traffic movements only, without a corresponding fleet breakdown. The DfT demand forecasts have been applied to our 2007 baseline data as closely as

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8 DfT UK Air Passenger Demand and CO2 forecasts – domestic data provided by the Department (internal analysis)

9 Choudrie SL, Jackson J, Watterson JD, Murrells T, Passant N, Thomson A, Cardenas L, Leech A, Mobbs DC, Thistlethwaite G (2008) UK GHG Inventory Annual Report for Submission under the UNFCCC AEAT/ENV/R/2582 15/04/2008

10 APU and freight estimate added to domestic passenger aviation figures, internal analysis, Scott Wilson, July2008

11 Choudrie SL, Jackson J, Watterson JD, Murrells T, Passant N, Thomson A, Cardenas L, Leech A, Mobbs DC, Thistlethwaite G (2008) UK GHG Inventory Annual Report for Submission under the UNFCCC AEAT/ENV/R/2582 15/04/2008

12 DfT UK Air Passenger Demand and CO2 forecasts – domestic data provided by the Department (internal analysis)

[13] IPCC 1999: *Aviation and the Global Atmosphere*, J.E. Penner, D.H. Lister, D.J. Griggs, D.J. Dokken, M. McFarland (Eds), Cambridge University Press, Cambridge, UK.

[14] Owen B. and Lee D. S. 2006: *International Aviation Emissions Allocations – Future Cases, 2005 to 2050* Manchester Metropolitan University, Centre for Air Transport and the Environment, Report CATE-2005-3(C)-1, Manchester, UK

[15] Data supplied by the DfT consultants Scott Wilson.

possible. This detail of forecast means that retirement and replacement of certain aircraft types by fleet rollover is undertaken in a manner that is consistent with the DfT's own forecasts.

The DfT "Central" case assumes that ACARE compliant aircraft enter the fleet post-2020 at a moderate rate of 5% of new aircraft "entering service". For this central case by 2030, 25% of all new aircraft entering service are assumed to be ACARE compliant aircraft. The DfT also considered a 'Low' and 'High' case rate of ACARE adoption. This study uses the central case for ACARE adoption.

Forecasts of future fuel usage to 2030, and thereby CO_2 emissions, are made by combining the DfT's passenger demand forecasts[16] with the FAST-calculated aircraft type fuel efficiency values for existing aircraft and new ACARE aircraft. In addition, a fleet wide 9% improvement in fuel efficiency is applied due to ATM and operational improvements. This improvement is assumed to occur before 2020 and is consistent with the DfT forecast assumption. It is important to note that such an improvement is a one-off improvement and would not contribute to an ongoing rate of fuel efficiency improvement post-2020 in this study. The change or rollover in the aircraft fleet to newer more efficient known aircraft types up to 2020 together with the operational fleet efficiency improvement provides an annual fuel efficiency improvement of 1.3% per annum. This rate of increase is consistent with the fuel efficiency improvements used in the work in the IPCC Special Report on Aviation (1999). Between 2020 and 2030, the introduction of ACARE aircraft to the fleet leads to further fuel efficiency improvements, but without the more dramatic improvement brought about by operational and ATM advances shown in the previous decade, the overall rate of fuel efficiency improvement is assumed to be about 0.5% per annum. The overall rate of fuel efficiency improvement is again consistent with the DfT forecasts and the IPCC work. The calculated fuel use data for the BAU scenario up to 2030 are shown in Table 3.5. The data are presented by aircraft type.

After 2030, the demand forecasts are not disaggregated by aircraft type requiring fleet-wide generic fuel efficiency improvements to be applied. In this study the DfT assumptions on fuel efficiency improvements of 0.8% per annum are applied for the period between 2030 and 2050. In view of the large uncertainties attached to the

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[16] DfT's Air Passenger Demand and CO2 forecasting document
http://www.dft.gov.uk/pgr/aviation/environmentalissues/ukairdemandandco2forecasts/airpassdemandfullreport.pdf

forecasts in the longer-term, the more generic top-down approach to fuel efficiency is appropriate.

Table 3.5 Baseline Scenario to 2030 Fuel Use in thousand tonnes (or Gg): broken down by aircraft type

Aircraft	2007	2010	2020	2030
A300	5.78	2.59	0.00	0.00
A310	0.16	0.00	0.00	0.00
A319	164.05	208.63	235.32	257.03
A320	62.84	77.00	75.13	84.04
A321	3.87	4.06	4.47	5.53
A3302	1.09	0.00	0.00	0.00
B7372	0.39	0.00	0.00	0.00
B7373	82.68	76.25	27.32	0.36
B7375	41.31	16.29	0.00	0.00
B7376	0.25	0.27	0.22	0.00
B7377	58.01	71.60	125.25	169.41
B7378	36.50	41.42	55.18	63.06
B7472	0.06	0.00	0.00	0.00
B7474	0.09	0.00	0.00	0.00
B7572	33.57	28.30	3.07	0.00
B7573	0.01	0.01	0.01	0.00
B7672	4.51	2.04	1.43	0.00
B7673	4.77	3.89	0.57	0.00
B787 replacing the B767	0.00	0.00	10.43	27.19
B7772	0.01	0.00	0.00	0.00
FA20	0.02	0.00	0.00	0.00
CRJ100	0.04	0.00	0.00	0.00
E145	27.96	29.95	7.28	0.00

F100	2.38	2.13	0.00	0.00
E190	3.34	0.00	0.00	0.00
MD80	0.06	0.02	0.00	0.00
MD90	0.08	0.00	0.00	0.00
Medium Turboprops (eg SF34)	26.89	29.75	40.67	41.32
Large Turboprops (e.g. DH8D)	64.71	72.68	102.16	107.48
Bae146/RJ85	46.85	52.62	73.96	77.81
Small turboprops	1.68	1.68	1.53	1.53
ACARE1	0.00	0.00	0.27	7.55
ACARE2	0.00	0.00	1.23	55.56
ACARE3	0.00	0.00	0.50	28.66
TOTAL	**673.98**	**721.17**	**765.99**	**926.513**

ACARE 1,2,3 refers to the size of ACARE compliant aircraft. Specifically ACARE1 refers to seat banding 10-70; ACARE2 to seat banding 71-150 seats; and ACARE3 to >150 seats.

The total fuel use data and resultant carbon dioxide emissions for the BAU scenario calculated in this study are shown to 2050 in Table 3.6. The total emissions with the addition of emissions from APU and freight are also shown. Here the emissions data for APU and freight are taken directly from DfT estimates[17] and added to our independently calculated estimates for domestic aviation.

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[17] DfT UK Air Passenger Demand and CO2 forecasts – domestic data on APU and freight by the Department Consultants, Scott Wilson (internal analysis)

Table 3.6 Time Series of Business as Usual (BAU) Fuel Use and Carbon Dioxide Emissions to 2050

Year	**2007**	**2010**	**2020**	**2030**	***2040***	***2050***
Total fuel use (thousand tonnes or Gg)	673.98	721.17	765.99	926.51	*1035.58*	*1104.47*
CO_2 (million tonnes or Tg)	2.13	2.28	2.42	2.92	*3.27*	*3.49*
CO_2 (million tonnes or Tg) with APU and freight	2.38	2.56	2.76	3.32	3.68	3.89

The data in Table 3.7 show how the BAU scenario emissions calculated in this study compare with the DfT's own estimates for domestic aviation[18].

Table 3.7 Time Series of Business as Usual (BAU) Carbon Dioxide Emissions to 2050 showing comparison with DfT Domestic Carbon Dioxide Emissions (Central Case)

CO_2 (million tonnes or Tg)	**Source**	**2007**	**2010**	**2020**	**2030**	**2040**	**2050**
BAU	This study	2.1	2.3	2.4	2.9	3.3	3.5
BAU with APU and freight	This study	2.4	2. 6	2.8	3.3	3.7	3.9
DfT with APU and freight	DfT, 2008[19]	2.4	2.6	2.9	3.3	3.7	3.9

Identification of options and opportunities for emissions reductions under the BAU scenario

The main drivers of measures to reduce carbon dioxide emissions from domestic aviation need to be considered. The strongest commercial driver is the role of fuel prices in stimulating improved fuel efficiency. Recent increases in fuel prices have changed the cost effectiveness of some abatement measures and the view taken on future trends in fuel prices will be relevant in determining baseline emissions. Other

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[18] DfT UK Air Passenger Demand and CO2 forecasts – domestic data provided by the Department Consultants, Scott Wilson (internal analysis)

[19] As 18 above.

drivers include environmental policies and regulations arising from existing and possible future measures. These include bringing aviation into the EU ETS, the impact of changes to be made to the structure of APD, the impact of voluntary measures such as the ACARE targets and interdependencies arising from measures to tackle non-CO_2 emissions (eg fuel penalties arising from ICAO NOx standards, NOx charges or local noise restrictions). For example permit prices in the ETS will be influenced by both market factors and any future changes to the scheme (e.g. tighter allowances), and these will be relevant in determining the cost effectiveness of abatement measures.

In determining the level of baseline emissions, an underlying trend in fuel efficiency will need to be determined. The ACARE document published in 2002 identified voluntary environmental goals to be achieved by 2020, and work has started to identify longer term targets. For CO_2 these included a 50% improvement in fuel efficiency (CO_2 per seat km), with contributions of 20-25% from airframes, 15-20% from engines and 5-10% from optimising ATM. Evolutionary developments were seen by ACARE as capable of achieving less than half the improvements required to meet these ambitious targets, with technological breakthroughs, likely to have high costs and risks attached to them necessary to achieve the step change improvements necessary to meet the targets in full.

The CO_2 forecasts shown here as the BAU or reference scenario draw on many of the assumptions made in the DfT forecasts published in November 2007. These are based on future trends in fuel efficiency and the resulting forecasts can be interpreted as underlying or baseline trends. Historically improvements in fuel efficiency have averaged 1-2%pa. In making forward projections the ACARE 50% fuel efficiency improvement target has been taken as a starting point. With almost 10% of fuel efficiency improvements expected to arise from operational improvements, new aircraft entering service will have to be 40% more fuel efficient than their current equivalents to meet this target (current new state of the art aircraft such as the A350 and B787 are estimated to have 20% better fuel efficiency than their current equivalents). The DfT Central Case assumption has been adopted in the BAU case presented in this study i.e. that the share of new aircraft entering service that are ACARE consistent rises from 5% in 2020 to 25% in 2030. This results in a fleet fuel-efficiency improvement of approximately 25 % between 2007 and 2030.

Over the longer term from 2030 to 2050 continued propagation of ACARE consistent aircraft into the fleet is assumed, resulting in a slightly lower trend improvement of 0.8% over this period.

Forecasts of CO_2 emissions are made by combining DfT's passenger demand forecasts with these fuel efficiency trends. BAU CO_2 domestic emissions are projected to increase by 37% from 2.13 Mt CO_2 in 2007 to 2.92 Mt CO_2 in 2030. After 2030 further growth is slower as airport capacity constraints bite and passenger growth slow with market maturity.

The BAU view of projected baseline emissions is essentially based on a top-down analysis, but the following assumptions on future abatement measures taken by the aviation industry have been incorporated.

- No radical technological change before 2030
- ATM improvements of around 9% up to 2020
- Limited gains from retrofitting existing aircraft as these are viewed as small
- Some fuel efficiency gains provided by fleet rollover to existing more fuel efficient aircraft types
- Improvements of up to 20% included in new aircraft types such as the A350 and B787 are embodied but it is recognised that no current aircraft types could meet the required 40% fuel efficiency improvement
- The post 2030 trend is based on continued propagation of ACARE consistent aircraft into the fleet
- No step change technological developments are assumed post - 2030, but the projected trends implicitly reflect factors including alternative fuels and technologies, though these are not captured in the modelling.

The interpretation of this is that projected baseline emissions up to 2020 (and 2030) include ATM improvements from the full implementation of Single European Sky and improvements in technology and materials arising from the introduction of new aircraft types. However no radical technological improvements are included, with very few aircraft in the fleet capable of meeting the ACARE fuel efficiency target by 2020. In the longer term these assumptions could be interpreted as including technological developments such as blended wings and propfans, already under consideration, but no radical step change technological improvements resulting in any acceleration of underlying trends in fuel efficiency.

Assumptions are included in the forecasts on the future level of fuel prices as these are one of the drivers of the demand forecasts. Based on the BERR predictions of May 2008 (see Table 5.7), for the period to 2030 there is a central forecast of $65-75 (£36-41 at $1.83/£ exchange rate) per barrel, with lower and upper ranges of $45 (£25) and $150 (£82) respectively. The future level of fuel prices, will act as a supply side factor in influencing the cost effectiveness of abatement measures to improve fuel efficiency, with implications for their introduction and speed of take-up. This is not explicitly considered in the BAU or DfT forecasts, but it is reasonable to work on the basis that the underlying baseline trends are broadly consistent with the central fuel price assumption of $70 (£36) per barrel. As fuel prices rise, some interventions will become cost effective in their own right with negative marginal abatement costs, and higher permit prices will provide an additional spur. Where additional abatement measures are incentivised by higher fuel prices, these should be regarded as additional to the baseline. The DfT forecasts do not make specific mention of policy and regulatory measures as additional drivers of fuel efficiency trends. However, it is reasonable to assume that these reflect current policies and expected changes, but that they are neutral as regards possible future policy changes at the global, regional and UK levels and that these are not included in the baseline forecasts.

Summary

- The engine design model, PIANO and the 3D inventory model, FAST, were used to calculate baseline CO2 emissions for 2007 by aircraft type and distance.
- Future emissions projections to 2050 were based on forecasts made by DfT for the domestic sector and other research. The assumptions were based on those used in the DfT forecasts used to derive the take-up of the ACARE fuel efficiency targets over time. These imply fuel efficiency improvements of 1.3% pa up to 2030 and 0.8% pa from 2030 to 2050.

- While the projections of baseline emissions include the progressive adoption of ACARE targets and the full implementation of SES, they do not assume any radical technological breakthroughs

- Trends in fuel prices are dependent on future fuel prices. The DfT future passenger demand study of 2007 used BERR May 2007 future oil price estimates, with a central estimate of $50-55 per barrel (2004 prices). The BERR forecasts were subsequently updated in May 2008, and it is these later estimates that have been used within this study.

4 Identification of Abatement Options and Stakeholder Views

This section identifies and categorizes the abatement measures capable of tackling carbon dioxide emissions from domestic flights. The feasibility of these options is explored, including their likely take-up, barriers to implementation, timeframe and interdependencies with other emissions. This assessment is based on both knowledge gained from existing academic and industry published research, and the expert judgement of key aviation stakeholders garnered through a consultation process. The scope for interventions covered will involve changes in technology, operations and fleet management.

At the Omega workshop in March, the following criteria were identified in judging the effectiveness of techniques to reduce environmental emissions from aircraft:

- Impact in reducing emissions
- Capital and operating cost of abatement measure
- Impact on safety and aircraft reliability
- Impact on airworthiness certification
- Operational practicability
- Industry familiarity with the measures
- Customer acceptance

The application of these criteria to the various intervention options provided at the Omega workshop is being drawn on, but both these and a wider selection of stakeholders are being consulted, given the different objectives of this study with its focus on CO2 emissions from domestic flights.

Categories of intervention options

Carbon dioxide emissions abatement interventions fell into the following broad categories:

- Technology based
- Operational improvements
- Fleet management

Table 4.1 Summary of abatement intervention characteristics and effects

abatement interventions				timescales			change drivers			areas of effect					linkages	
group	sub-set	intervention		now	pre 2020	post 2020	weight	drag	lift	fuel use	capital costs	maintenance costs	crew costs	journey time	interventions	emissions
technologies	airframe	winglets	T1	√	√		+	-	0	-2.00%	+	+	0	0	F1	- NOx
		riblets	T2		√		+	-8.00%	0	-	+	++	0	0	T6	- NOx
		tailcone replacement	T3	X			-	-	0	-0.50%	+	0	0	0		- NOx
		lightweighting - new aircraft materials	T4		√		-15%	0	0	-	+++	?	0	0	F1	- NOx
		lightweighting - existing aircraft systems	T5	√			-0.50%	0	0	-	+	0	0	0		- NOx
		blended wing	T6			X	-14%	+	+	-30%	+++	+	+	0	T4, F1	- Noise, - NOx
		aircraft surface polish	T7	√			-0.15%	0	0	-0.1 to 0.75%	0	+	0	0	F3	- NOx
	engine	engine replacement	T8	√			0	0	0	-0.5% / year of engine	++	-	0	0	T10	?
		engine upgrades	T9	√			0	0	0	ave 1%	++	-	0	0		+ NOx
		open rotors	T10		√		+			-30%	++	+	0	+	F1	+ Noise - NOx
		APU removal operation / design	T11		√	√	-	0	0	-110 kg / hr APU use	0 / ++	0	0	0	F1	- NOx
	fuels	biofuels	T12		√		0?	0	0	~	+++	+	0	0		- NOx
		alternative fuels	T13			√	+?	0	0	~	++++	+	0	0?	T12, T8	?
	general	optmised aircraft design	T14		√		-	0	0	-30%	++	-	0	0/+?	F1, F6, F9	+ Noise - NOx
operational improvements		ATM improvements	O1		🟦		0	0	0	-10.5%	++++	+	0	-	O2, O3	- Noise, - NOx
		continous decent approach	O2	√	√		0	0	0	-	++	0	0	0	O1	- Noise, - NOx
		optimise flight - speed & altitude	O3		√		0	0	0	-0.2%	0	0	0	+	O1	+ NOx
		optimise flight - LTO practice	O4	√			0	0	0	-	0	-	+	0		- NOx
		reduced fuel tankering	O5	√			-	0	0	-0.4%	0/+	0	0	0		- NOx
fleet management		retirement of aircraft	F1	🟥	🟥	🟥	0?	0?	0?	-1% / year of aircraft	++	0?	0	0	T1,4,6,10, 11,12,13,F6	- Noise, - NOx
		maintenance - engine intervals	F2	√			0	0	0	-1.2%	0	+++	0	0	F4	- NOx
		maintenance - aerodynamics	F3	√			0	-	0	-0.46%	0	+	0	0	Meng	- NOx
		maintenance - engine wash	F4	√			0	0	0	- 0.5 to - 1.2%	0	++	0	0		- NOx
		fuel reserves	F5	?			-	0	0	-	0	0	0	0	O1	- NOx
		increase turboprop use	F6		√		-	0?	0?	-	-	+	-	+	F1	+ Noise - NOx
		better use of capacity	F7	√			-/+	0	0	-	+	- / 0	0	0	LW	?

The individual interventions are summarised in Table 4.1, covering timescale of implementation, changes to fuel saving drivers and details of effects upon aircraft performance and costs. The linkages column identifies which interventions may be linked, using interventions ID code, and what effect that intervention may have on other environmental emissions. Detailed information defining the interventions and their broader aspects is provided in Appendix 6, where technical information from academic and industry published research is collated and referenced.

Stakeholder consultation

The attached consultation document (Appendix 3) sent to stakeholders contains an outline of the project objectives, summary descriptions of the abatement options initially identified as applicable, together with a list of relevant questions and a table for a formalised response format.

Responses to the stakeholder consultation document received to date are set out in the paragraphs below, and included within Table 4.1 where possible. The responses broadly confirm the views expressed at the Omega workshop in March, and have also provided useful additional information and insights. Responses were evaluated for the possible strategic nature of opinions, based on a stakeholders industry position, and interpreted accordingly.

Airframe and engine technology

Improvements to existing airframes. These interventions include the fitting of winglets (wingtip extensions designed to reduce cruise drag with the key trade-off being whether drag reductions are outweighed by increased weight) and riblets (small grooves or raised lines on the airswept surface skin of an aircraft aligned with the direction of airflow to reduce turbulence and friction drag) to existing aircraft, as well as other design modifications, short term options possibly capable of offering operating costs savings from reduced fuel burn. High fuel prices are expected to make these abatement measures more cost effective.

Differing views were expressed on the feasibility of winglets on short flights operated by domestic services. While some responses indicated fuel savings of up to 4% on short haul European operations, with around 1.5% to 2% possible on domestic services, others were more doubtful whether these aerodynamic improvements would produce any net fuel saving benefits, because the additional fuel during the LTO cycle resulting from weight penalties could not easily be recovered through savings at cruise on short routes.

Riblets were expected to provide fuel efficiency gains around the 1-2% level, but may be offset by increased maintenance and recertification costs when provided using an adhesive film, as trials showed a short service life of only 2-3 years. Furthermore winglets, riblets and tail cone changes (the aft-most part of the fuselage where reshaped sections offer the possibility of small reductions in drag) were not seen as applicable to turboprop aircraft operating thin domestic services.

Small gains were seen by one respondent as possible from new technologies such as; conformal antennas (where antennae are built into panels shaped to fit the normal contours of the aircraft's skin, reducing weight and aerodynamic penalties), improving manufacturing process technology to provide smoother surfaces and from reductions in airframe component weights though the use of composite floor beams.

Responses also suggested additional barriers, such as capital costs, downtime for aircraft modifications requiring major overhaul, technical readiness (especially in the case of riblets) and limited technical opportunity (e.g. winglets having a limited range of applicable aircraft). A further barrier, which applies to a number of short-term options involving retrofitting of existing aircraft, is that many aircraft are leased, (up to a third of the UK domestic fleet) giving rise to difficulties in agreeing terms that would be financially attractive to both parties, when aircraft are already under an agreed contract.

Engine replacement. The scepticism with the business case of this option, expressed at the Omega workshop, was largely endorsed by industry stakeholders. This is a short-term option currently available to airlines, but responses confirmed that the high non-recurring costs associated with it, coupled with the need to recertify new improved aircraft/engine combinations, meant that it was not viewed as a viable option by many airlines. Operators needed to compare any increase in aircraft residual value with the up-front capital costs of engine replacement, and this has rarely been cost effective in the past due to large capital costs.

Additional comments were that most engine manufacturers were focussing on improving engine technology, both in the short term and for new generation engines, and that worthwhile improvements required aircraft with airframe and engine designed together. In the short term, more fuel efficient conventional power plants can be retrofitted (if economically viable) but the longer term more radical alternatives (with larger potential gains) will require the airframe and engine to be coupled at the design stage.

Engine upgrades. Views on this option were somewhat mixed, but many reiterated the scepticism expressed at the Omega workshop. While the concept was viewed as sensible, with the potential for operating cost savings from reduced fuel burn and reduced maintenance, the technical opportunities were seen as rather limited as suitable improvements were only available for older engine types. Requiring any upgrade to fit within the same airframe space envelope limited technical scope and could be cost effective only if component changes were worked into normal engine downtime.

Retrofitting of individual components to improve fuel burn might be feasible, but more radical changes were more problematic. Even small component changes would require design, development and overhaul effort, with a substantial benefit needed for upgrades to be cost effective. An example of an engine upgrade was BA’s replacement of RB-211-524GH to improve fuel efficiency and range, but this was not applicable to short haul operations. Increasing fuel prices were recognised as making such upgrades more viable.

One view was that natural laminar flow engine nacelle technology (non-turbulent, low drag flow achieved through smooth, well formed exterior forms) could provide up to a 1.5% reduction in total aircraft drag, although the example cited was the B787 where the bypass ratio and hence the nacelle diameter are large. However in principle this technology could be applied to any turbofan engine, particularly those with higher bypass ratios (bigger fans), but this means that the gains on aircraft typically deployed on domestic routes would be limited.

New airframe technology. This was viewed as providing potentially large reductions in fuel burn over the medium to longer term (post 2020). Commercial drivers were identified as fuel prices, the reduction of other operating costs and the potential for emissions reductions. However configurations such as the blended wing body (a delta shaped flying wing with no discernable separate fuselage, with passengers seated within the main wing body) were best suited for large aircraft and long range travel, therefore being less applicable for aircraft on UK domestic operations.

Promising concepts with potential application to the domestic sector included advanced materials, changes in airframe configuration to accommodate open rotor engines (engines with no nacelle around the fan and the fan replaced in most configurations with two contra-rotating swept propellers or rotors), advanced flow techniques and increased use of electrical systems. Incremental improvements such as these were seen as delivering useful reductions in fuel burn, though requiring a jump to next generation aircraft design. Breakthrough technologies were not identified, though they might be a long-term option.

Although not strictly a new technology, the use of small turboprops in place of small jets was seen as an effective option for reducing fuel burn on short flights. Most aircraft operated on short-haul sectors, such as UK domestic operations, have considerable additional range capability. Recent peaks in fuel prices have increased the demand by airlines for aircraft that are better suited to short journeys (e.g. reduced size fuel tanks and wing areas). Several respondents identified wing design as important, with a smaller wing area and lower thrust engines offering improved fuel efficiency.

Stakeholders identified barriers to all these new airframe technology options, including long design lead times, high development costs, manufacturing costs (e.g. costs of composites are higher than their metallic equivalents), new skills required and technology readiness. From the operator perspective, airlines needed to obtain sufficient benefit from their existing fleet before scrapping it or selling it on.

New engine technologies. This was viewed as being closely linked to airframe development, offering the potential for large fuel burn reductions compared to current turbofan engines. For example, the development of the geared turbofan, a conventional turbofan engine with a reduction gear between the front fan and the turbine driving the fan, has increased fuel economy by 10-15%. The reduction gear used increases the propulsive efficiency by slowing the rotational speed of the fan, allowing larger fans to be used for the same tip speed and permitting the turbine driving the fan to rotate at more efficient higher speeds. The development of open rotors with new concept core designs were expected to provide fuel burn savings of up to 25-30% in the longer term, but are likely to provide 10-15% in the medium term as they are developed around existing turbofan engine architecture.

Both these developments were viewed as potentially suitable for domestic operations, with any flight time penalties from open rotors being acceptably small on short-haul flights. It was noted that turboprop powered regional aircraft had much better fuel efficiency than regional jets, and that there is the potential to commercialise larger turboprop engines to achieve the same benefit in single aisle 150 seat aircraft. Barriers identified are similar to those associated with new airframe technologies, including long design lead times and high development costs. Impacts on aircraft noise from open rotor technology were highlighted as an issue which would need to be carefully managed for the technology to remain viable.

Biofuels. Biofuels were regarded as unlikely to displace a significant quantity of kerosene used for aviation in the near future. Current bio-fuels have been found unsuitable for aviation and any significant breakthrough into aviation will depend harnessing second or later generation, more sustainable bio fuels. The scope for using bio-fuels on domestic flights might be somewhat greater than average as the risk of fuel freezing on short hops with limited time spent at cruise altitudes was low. Barriers included technology readiness, the need to meet technical specifications for aviation kerosene, sustainability concerns with feedstock and investment costs of additional fuel distribution systems. If a sustainable low CO_2 feedstock could be found, this could be a way forward for aviation, including domestic services, but was generally felt unlikely to see widespread use before 2020.

Other alternative fuels. Synthetic fuels made from gas and coal, while feasible and applicable for security of supply reasons, result in increased life cycle carbon emissions. Hydrogen is a long term alternative to kerosene but faces major challenges, with barriers including sustainable hydrogen production technology, the need for worldwide implementation, significant investment in fuel system infrastructure and airframe/engine redesign. Other barriers to hydrogen include the much larger tanking requirements, certification of a non-kerosene based fuel and uncertainty over the overall impact on fuel efficiency. If bio-fuels do not work and environmental pressures mount, this might be a way forward, but implementation before 2040 was viewed as unlikely.

Operational improvements

ATM improvements. This was seen as a short-term win-win option capable of delivering one-off fuel burn improvements of between 6-12% over the next 10 years. This was felt particularly significant for aircraft flying through the most congested airspace including Southeast England, but less relevant for thin services using low usage airfields. There a number of institutional, technological, political and financial barriers to measures such as Single European Skies, primarily the significant investment costs required by service providers and the need for co-operation in Europe.

Reduced fuel tankering. The practice of fuel tankering was seen as being driven by the need for rapid turn round times on domestic operations, fuel availability at some airports and fuel price differentials (regarded as resulting from poor airport supply infrastructure and monopolies). However some airlines have found ways of refuelling during quick turn rounds. The high cost of fuel provides an incentive to limit the use of tankering.

Continuous descent approach. It was noted that this was already practised by airlines, where possible, from 6000ft, and was suggested that additional benefits of up to 2% reduced fuel burn could be gained through avoidance of stepped approach and/or being put on hold. This is closely related to ATM measures aimed at reducing delays and is a win-win option for NOx emissions and noise, as well as carbon dioxide. One barrier is that small airfields may not be able to provide sufficient help to enable pilots to fly CDA reliably. At the congested London Airports capacity constraints presented a problem and it might only be possible to introduce CDA by limiting throughput, which would have large opportunity costs, but greater potential exists at regional airports.

Changes to flight speed and altitude. In principle, flying slower and higher was viewed as the best way of minimising fuel burn, but several respondents viewed this as only a viable option at the margins for current aircraft operating domestic flights. Technical experts confirmed that current aircraft are most efficient flying at the speed and altitude for which they were designed. One response was that it was more important to minimise flight paths, optimise flight profiles and avoid holding. In the medium to longer term, designing aircraft for reduced cruise altitude and speed could enable wing area to be reduced with resulting weight reduction and fuel burn benefits. This was seen as closely linked to ATM improvements, with the implementation of Single European Skies allowing operators to fly their preferred trajectories. At present ATC represented a significant barrier, with the risk of losing a landing window, for example if a flight departing late did not make up sufficient time.

Fleet Management

Early replacement of aircraft. It was observed that airlines with strong balance sheets were best able to sell aircraft on the second hand market relatively early and operate young fleets incorporating best environmental performance. The financial viability of this option to airlines depends on the relative capital and operating costs of new and second-hand aircraft, and it was recognised that the pace of technological change and higher fuel prices could tip the balance in favour of early retirement. One suggestion was for fiscal mechanisms to encourage early retirement. It was noted that compulsory early retirement measures, such as phase-outs (applied in the past to noise) had potentially high costs, particularly when they resulted in the early retirement of aircraft with significant remaining service lives. Early retirement was viewed as less relevant to those domestic routes operated by small aircraft, as these tended to have low utilisation and later average uptake of improvements.

Reduced maintenance intervals. It was noted that the engine wash concept, which is currently being trialled in the UK, should reduce engine fuel consumption and could be widely employed if there was sufficient airline take-up. Engine washing might be expected to be more relevant to UK domestic services which spend more time in the more polluted lower atmosphere. Maintenance might be less of an issue for domestic operations as they have a higher cycle related maintenance burden but a lower hours related burden. It was noted that newer designs of aircraft were intended to reduce maintenance by increasing intervals between scheduled overhauls.

Reducing required fuel reserves. The calculation of reserve fuel based on diversion plus additional hold time is unlikely to be amended to reduce emissions. Therefore any change that involved reducing safety reserves would require a significant risk assessment by ICAO. However, while the need for a safety margin was recognised, improved fleet planning could result in fuel burn reductions up to 0.5% with little or no upfront costs.

Use of turboprops. This was noted as being the same question covered under airframe/engine design technology. Turboprop aircraft were viewed as becoming increasingly attractive for short-haul operations including domestic services with higher fuel prices. For example, it was suggested a 70-seat turboprop could burn 35% less block fuel on a 500nm sector than a similar sized turbofan powered regional jet. A key barrier was felt to be the perception by some passengers, that turboprops represented old technology and offered reduced cabin comfort.

Better use of capacity. Higher seat densities and load factors achieved by no-frills airlines, coupled with reducing weight carried (eg interior furnishings, duty-free trolleys, etc.) and incentives on passengers to carry less luggage, had the effect of reducing emissions per passenger. The option of consolidating flights from competing airlines to improve load factors was widely disliked and felt likely to be regarded as anti-competitive by the competition authorities. It was also noted that there will be a long-term requirement for smaller aircraft to access smaller airports and airfields on thin domestic routes e.g. to the Scottish islands.

Interdependencies

Abatement measures to reduce CO_2 may result in trade-offs or interdependencies with other emissions or noise. In most cases abatement measures designed to reduce fuel burn and CO_2 emissions will result in corresponding reductions in NOx emissions at both ground level and cruise altitude, with little or no impact on noise, but there are a few potential exceptions.

One area where interdependencies may exist is with major changes to engine technology designed to improve fuel efficiency. There is some evidence of a CO_2: NOx trade-off in engine design, though its size is unclear and could be quite small. The issue becomes more complex at the level of the whole aircraft as both aerodynamic and structural efficiencies come into play. Modern engines have higher overall pressure ratios (OPRs) than the older ones they are replacing, resulting in lower fuel consumption. At the same time they have higher NOx emissions per amount of thrust. The lower specific fuel consumption of the engine coupled with structural and aerodynamic improvements embodied in newer airframe designs have tended to offset these higher NOx emissions, resulting in the trend in NOx emissions per seat km remaining broadly constant over time. However, over the next 10 years, if the CAEP mid-term NOx goal is met, the reduced LTO NOx emissions should more than match the OPR effect, resulting in a reduction of NOx per seat km compared with first generation turbo-fan engines.

There is some evidence of CO_2: noise trade-offs in engine or airframe design, particularly where an increase in drag and weight arises from measures to tackle noise. This has arisen with the design of the A380 where such measures to reduce noise have resulted in higher fuel burn, due to drag increasing as a result of greater nacelle surface area and some weight gain.

CO_2: NOx trade-offs are likely to be of limited relevance for the engine technology abatement options identified in this study. They do not arise with engine retrofits or upgrades and have not been identified with major changes in aircraft technology such as geared turbofans or blended wing bodies. However there is evidence that open rotors may have lower LTO NOx, but higher NOx and noise at cruise. Most of the operational and fleet management measures will result in corresponding reductions in NOx. For major engine architecture changes LTO NOx should be reduced, but cruise NOx could be somewhat worse than current types. One abatement measure that may result in a CO_2: NOx trade-off is flying at higher altitudes where any CO_2 reductions will be offset by higher NOx emissions at cruise, with the net climate change impact subject to scientific uncertainty.

Summary

- This section draws on the OMEGA study developing a framework for estimating the marginal abatement costs of environmental abatement in the aviation sector.
- Three categories of abatement measures are identified: airframe and engine technology, operational improvements and fleet management
- Responses from stakeholders on a range of abatement measures under each of these broad headings are summarised and reviewed. These cover potential fuel savings, broad magnitude of costs, key commercial drivers and barriers, timescale of introduction and interdependencies between different environmental impacts. It should be noted that the carbon dioxide savings from these abatement measures should not be treated as cumulative.

5 Calculation of CO_2 Marginal Abatement Costs

This section estimates the costs of interventions to achieve reductions in carbon emissions from the UK domestic aviation fleet over the period 2007 through to 2050. It draws on the preceding information derived from multiple sources to derive estimates of the marginal (extra) costs of reducing successive units of $CO_{2.}$ These so-called marginal abatement costs (MAC) can inform the scope and priorities for the adoption of cost effective interventions by the aviation sector as it seeks to reduce its CO_2 emissions. Given the limited data available, the analysis necessarily contains many assumptions such that results require very cautious interpretation. Details of the major assumptions relating to abatement interventions are provided in Appendix 6.

There is generally little robust information available on the costs of the options considered given uncertainties regarding their stage of development, likely timing of introduction, applicability to the wider fleet and amount of investment in Research & Development in new technology. The costs presented are therefore necessarily illustrative and intended to indicate broad orders of magnitude only. They are nevertheless a useful guide to their likely relative significance.

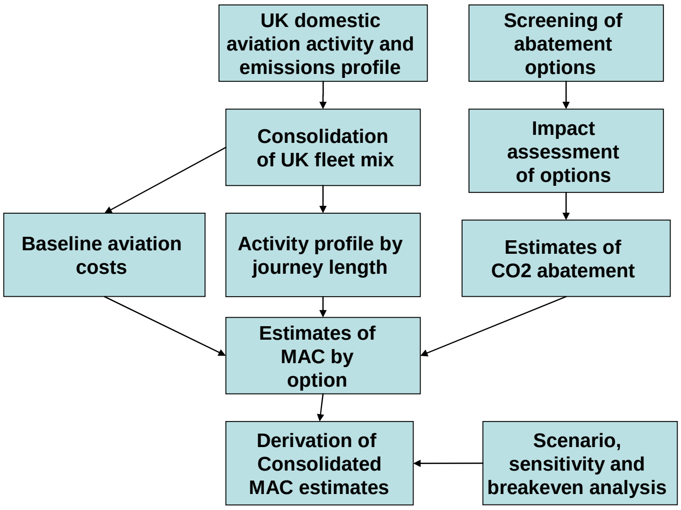
Given the significant uncertainties involved in estimating both the benefits of different options in terms of their impacts on emissions and their costs in terms of their development and implementation, it is not possible to generate robust abatement cost curves. However, for the purposes of illustration, the curves presented here based on the limited information available, reflecting broad orders of magnitude of relative effects.

It is noted that, in the analysis presented here, carbon dioxide savings from abatement measures should be considered independently and not be treated as cumulative. In reality, the incremental effect of any one intervention will depend on the type and extent of any preceding interventions.

Methods

Figure 5.1 describes the main steps in the methods used to derive estimates of the marginal cost of interventions to reduce CO_2 from the UK domestic aviation sector. These steps were contained within an Excel-based, multiple spreadsheet framework, to facilitate calculation. The following paragraphs provide detailed descriptions of each step in turn.

Figure 5.1: Method for Estimating MAC for UK Domestic Aviation Sector



Activity and emissions profile - estimates of total distance travelled in the UK domestic sector, SKO and fuel use, classified by journey length and airplane type, were compiled using the data and methods referred to in Section 3 and Tables 3.1.and 3.2 above. These drew on actual traffic data for 2007, and projections for future years based on DfT forecasts allowing for specified growth factors and changes in fleet composition. For the purpose of analysis, and to avoid double counting, the baseline future predictions were modified to exclude assumed take-up of ATM and technology options, which are the subject of interventions examined here. Interventions in successive years (2012, 2020, 2030) are considered independently and compared with the prediction of the baseline estimate for that year, allowing for traffic growth only. This point is explained further below.

Consolidation of fleet – the above activity data was sorted to identify 11 aircraft types which currently account for over 95% of distance travelled, fuel consumed and CO_2 emitted (Table 3.3 above). Subsequent analysis focussed on this sub-set, as well as their ACARE compliant substitutes.

Activity profile by journey length – The UK domestic sector is characterised by relatively short haulage distances, with implications for fuel use per SKO. Estimates of fuel use and SKO's were assembled for each type of airplane (95% of traffic) for three journey lengths, <205 km, 250-500km, and >500km, (drawing on Table 3.1 above).

Table 5.1 Estimated Block Hour Costs and Performance Indicators for UK Domestic Sector Aircraft.

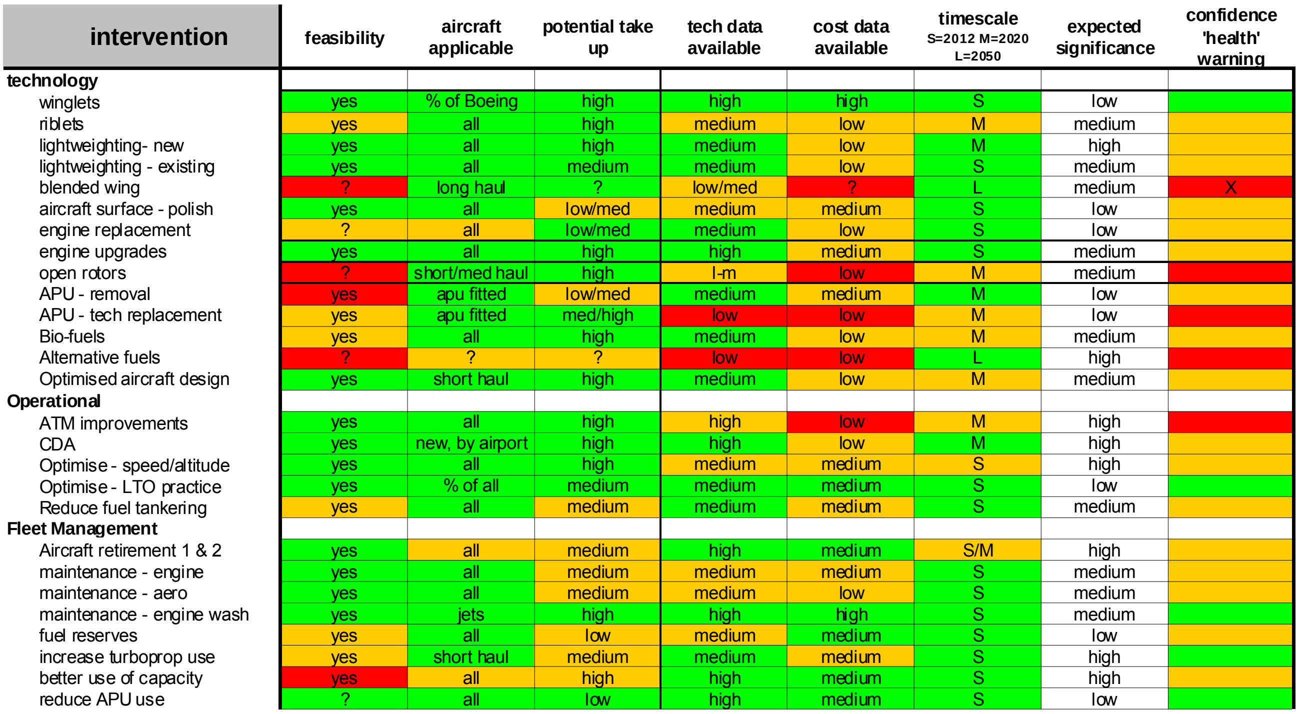
Average Block Hour Cost by Aircraft : UK Domestic 2008 (Fuel price US$107/brl , £0.48/l)

		A319	**A320**	**B737-300**	**B737-500**	**B 737-700**	**B 737-800**	**B 757-200**	**ERJ145**	**PROP6 (Saab 340)**	**PROP7 (Dash 8 400)**	**RJ85 (Bae 146-300)**	**ACARE 1**	**ACARE 2**	**ACARE 3**
Costs	**Units**														
total block hour cost	£/hour	2805	2787	2854	2764	2661	3200	4434	1245	709	1239	2198	1872	2719	4582
depreciaiton/rent	£/hour	350	270	251	270	188	330	624	198	83	138	297	198	270	624
fuel	£/hour	1085	1072	1208	1210	1184	1329	1854	393	177	385	746	393	1210	1854
crew	£/hour	411	432	421	417	456	529	722	229	208	310	358	229	417	722
maintenance	£/hour	260	295	353	321	143	228	356	153	78	125	336	153	321	356
sub total	£/hour	1757	1800	1983	1948	1782	2086	2931	774	463	820	1440	774	1948	2931
ATC fees	£/hour	214	222	200	187	209	212	259	116	74	118	172	288	205	293
landing fees	£/hour	153	165	135	118	146	151	224	45	24	56	100	278	141	288
airport passenger fees	£/hour	332	330	285	241	336	421	397	111	64	107	189	334	156	446
sub total	£/hour	699	717	620	546	691	784	880	272	162	281	461	900	501	1027
Performance															
block hours	hours/yr	3212	3212	3212	2628	3358	3066	3212	2774	2628	2628	2628	2774	2628	3212
total cost	000's £/yr	9011	8951	9168	7264	8936	9810	14243	3453	1862	3255	5776	5194	7147	14716
distance	000's km/yr	1445	1445	1445	1183	1511	1380	1445	1248	920	999	1183	1248	1183	1445
SKO	million SKO/yr	215.4	213.9	185.0	127.7	228.2	260.8	257.3	62.4	34.0	69.9	100.5	187.2	82.8	289.1
fuel	000's kg/yr	7025	6938	7820	6410	8009	8209	11997	2197	938	2037	3950	2197	6410	11997
fuel /SKO	kg/SKO	0.033	0.032	0.042	0.050	0.035	0.031	0.047	0.035	0.028	0.029	0.039	0.012	0.077	0.042
CO2	000's kg/yr	22198	21924	24710	20255	25308	25941	37910	6943	2965	6438	12482	6943	20255	37910
CO2/SKO	kg/SKO	0.103	0.102	0.134	0.159	0.111	0.099	0.147	0.111	0.087	0.092	0.124	0.037	0.245	0.131
£/SKO	£/SKO	0.042	0.042	0.050	0.057	0.039	0.038	0.055	0.055	0.055	0.047	0.057	0.028	0.086	0.051
Aircraft required to supply annual SKO	No. of	23.4	9.1	10.6	6.4	7.2	4.4	4.3	12.8	29.2	32.4	11.9	N/A	N/A	N/A

Baseline aviation costs – estimates of average block hour capital and operating costs for the selected airplanes were derived drawing from four main data sources, namely: Form 41 USA data reporting costs by aircraft types, UK CAA data reporting costs by aviation operator (some of which operate virtually single aircraft type fleets), published financial results of operators, and data from manufacturers' websites. Obtaining estimates of aviation operating costs was challenging. Table 5.1 contains estimates of costs and performance indicators for the aircraft used here for analysis. Direct flying costs include depreciation/rental charges, fuel, maintenance and aircrew. Other costs include navigation and airport charges, and aircrew training costs. These costs were used to inform selected aspects of the MAC, such as changes in maintenance costs or travel time, or changes in the mix of airplanes. The number and type of aircraft that would be required to work full time to provide the UK sector's total annual SKO is also shown in Table 5.1. For example, 23.4 full time equivalent A319 airplanes are required to carry out the work undertaken by A319s in 2007.

Screening of abatement options – ‘candidate’ abatement interventions, identified in Section 4 and Table 4.1 above, were carried forward for further analysis. These were screened against a number of criteria, as shown in Table 5.2. These options are perceived to offer potential benefit, although they vary in applicability, potential acceptance amongst stakeholders, availability of data to support analysis, and timescale of adoption. They include technological, operational and fleet management options. Attention is drawn to the limited data availability on the costs of implementation, and hence the considerable uncertainty in the derivation of abatement costs.

Table 5.2 Screening of UK Domestic Aviation Sector Abatement Options for estimation of MAC



intervention	feasibility	aircraft applicable	potential take up	tech data available	cost data available	timescale S=2012 M=2020 L=2050	expected significance	confidence 'health' warning
technology								
winglets	yes	% of Boeing	high	high	high	S	low	🟩
riblets	yes	all	high	medium	low	M	medium	🟧
lightweighting- new	yes	all	high	medium	low	M	high	🟧
lightweighting - existing	yes	all	medium	medium	low	S	medium	🟧
blended wing	?	long haul	?	low/med	?	L	medium	🟥 X
aircraft surface - polish	yes	all	low/med	medium	medium	S	low	🟧
engine replacement	?	all	low/med	medium	low	S	low	🟧
engine upgrades	yes	all	high	high	medium	S	medium	🟧
open rotors	?	short/med haul	high	l-m	low	M	medium	🟥
APU - removal	yes	apu fitted	low/med	medium	medium	M	low	🟧
APU - tech replacement	yes	apu fitted	med/high	low	low	M	low	🟥
Bio-fuels	yes	all	high	medium	low	M	medium	🟧
Alternative fuels	?	?	?	low	low	L	high	🟥
Optimised aircraft design	yes	short haul	high	medium	low	M	medium	🟧
Operational								
ATM improvements	yes	all	high	high	low	M	high	🟥
CDA	yes	new, by airport	high	high	low	M	high	🟧
Optimise - speed/altitude	yes	all	high	medium	medium	S	high	🟧
Optimise - LTO practice	yes	% of all	medium	medium	medium	S	low	🟩
Reduce fuel tankering	yes	all	medium	medium	medium	S	medium	🟧
Fleet Management								
Aircraft retirement 1 & 2	yes	all	medium	high	medium	S/M	high	🟧
maintenance - engine	yes	all	medium	medium	medium	S	medium	🟧
maintenance - aero	yes	all	medium	medium	low	S	medium	🟧
maintenance - engine wash	yes	jets	high	high	high	S	medium	🟩
fuel reserves	yes	all	low	medium	medium	S	low	🟧
increase turboprop use	yes	short haul	medium	medium	medium	S	high	🟩
better use of capacity	yes	all	high	high	medium	S	high	🟧
reduce APU use	?	all	low	high	medium	S	low	🟩

Degree of estimation uncertainty: Green: low Amber: moderate Red : high

Impact assessment of options – the impact of abatement options on fuel use, expressed as a % saving, and hence on CO_2 emissions, was estimated for each flight stage, namely taxiing, take-off, climb out, cruise, descent and landing for each aircraft type. This drew on modelled data using PIANO and FAST programme outputs, as well as data from ICAO test sources. This approach recognises that different abatement measures, such as continuous descent, affect different stages of the LTO cycle in different ways. Table 5.3 shows the study estimates of the potential savings in fuel burn, and thus CO_2 emissions, associated with individual interventions and by flight phases. These basic estimates of fuel savings for interventions were, for the most part, kept constant throughout the future time periods, interacting with assumptions on aircraft type and adoption of interventions in different time periods, as appropriate.

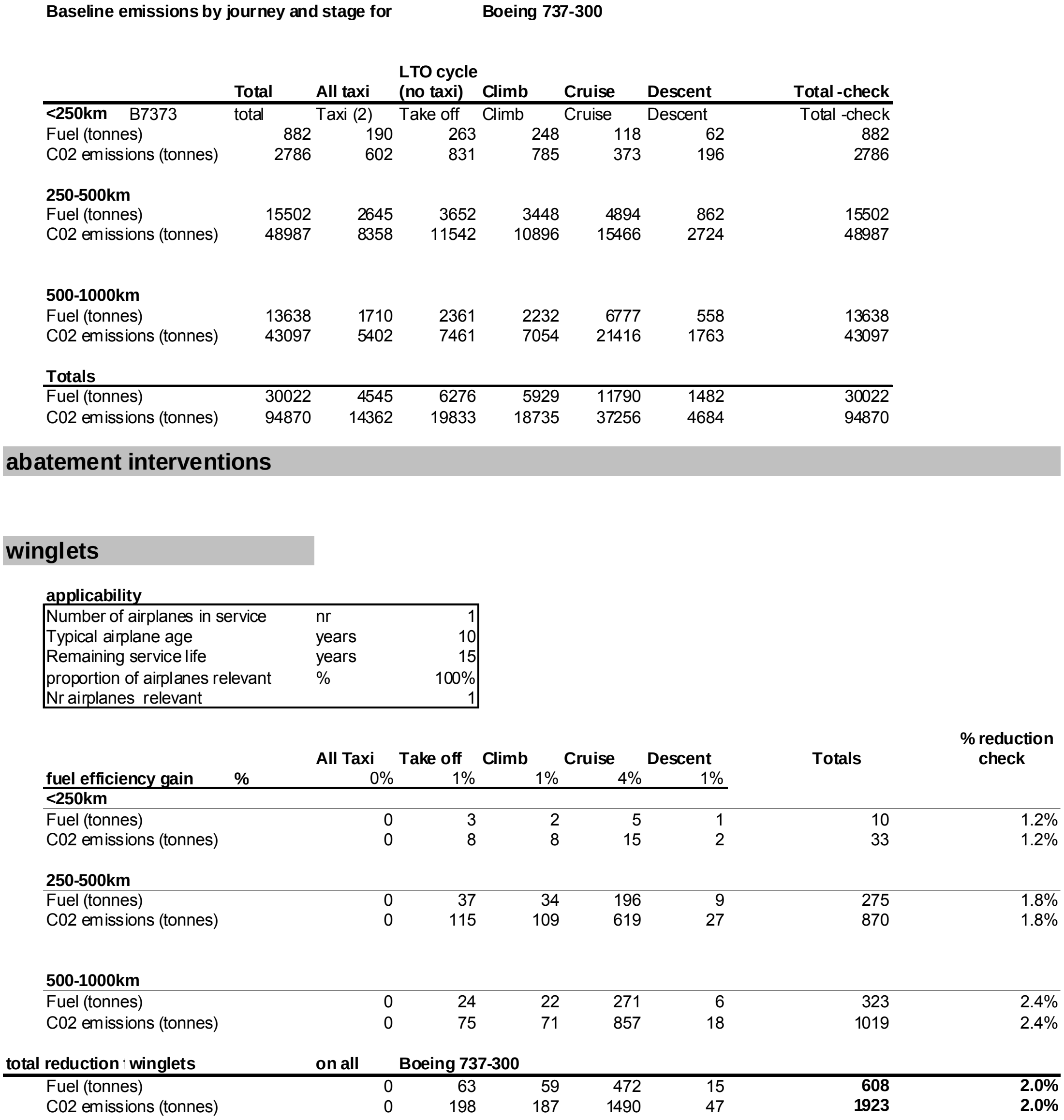
Table 5.3 Estimated % Fuel Burn Reduction, by Intervention and Flight Phase.

abatement	taxi	take off	climb	cruise	descent
Technology					
winglets	0%	1%	1%	4%	1%
riblets	0%	0%	0.5%	2.0%	0.5%
lightweighting- new	4.5%	7.5%	7.5%	7.5%	7.5%
lightweighting - existing	0.9%	1.7%	1.7%	1.7%	1.7%
blended wing	0%	0%	0%	0%	0%
aircraft surface - polish	0.36%	0.36%	0.36%	0.36%	0.36%
engine replacement	5%	5%	5%	5%	5%
engine upgrades	1%	1%	1%	1%	1%
open rotors	30%	30%	30%	30%	30%
APU - removal	0.3%	0.6%	0.6%	0.6%	0.6%
APU - tech replacement	0.0%	0.0%	0.0%	0.0%	0.0%
Bio-fuels (20% blend)	12.3%	12.3%	12.3%	12.3%	12.3%
Alternative fuels	100%	100%	100%	100%	100%
Optimised aircraft design	30%	30%	30%	30%	30%
Operational					
ATM improvements	10.5%	10.5%	10.5%	10.5%	10.5%
CDA	0%	0%	0%	0%	38%
Optimise - speed/altitude	0%	0%	0.2%	0.2%	0.2%
Optimise - LTO practice	41.7%	3.1%	0%	0%	0%
Reduce fuel tankering	0.4%	0.4%	0.4%	0.4%	0.4%
Fleet Management					
Aircraft retirement 1 & 2	25%	25%	25%	25%	25%
maintenance - engine	1.2%	1.2%	1.2%	1.2%	1.2%
maintenance - aero	0.46%	0.46%	0.46%	0.46%	0.46%
maintenance - engine wash	0.75%	0.75%	0.75%	0.75%	0.75%
fuel reserves	0.38%	0.38%	0.38%	0.38%	0.38%
increase turboprop use	30%	30%	30%	30%	30%
better use of capacity	3.7%	3.7%	3.7%	3.7%	3.7%
reduce APU use	1.47%	1.47%	1.47%	1.47%	1.47%
Acare	25%	25%	25%	25%	25%

Note to table : eg aircraft fitted 'with' winglets achieve 1% saving in fuel burn during climb out and 4% saving in cruise phases, compared to the same type of aircraft 'without' winglets

Estimates of CO_2 abatement– the potential reductions in fuel use and CO_2 emissions attributable to each abatement option were estimated for each aircraft, allowing for the particular activity profile, ie distance travelled by airplanes on different journey length. Thus, for example as shown in Table 5.4 , installation of winglets on a B7373 can deliver an overall 2% saving in fuel and reduction in CO_2 emissions allowing for the mix of journey lengths operated by a B7373 on the UK domestic sector during a year. This annual CO_2 saving is the abatement attributable to that intervention.

Table 5.4 Example of Abatement Option: Fuel and CO_2 Reductions associated with Installation of Winglets on A737-300 Airplanes used in the UK Domestic Sector



Baseline emissions by journey and stage for **Boeing 737-300**

	Total	**All taxi**	**LTO cycle (no taxi)**	**Climb**	**Cruise**	**Descent**	**Total -check**
<250km B7373	total	Taxi (2)	Take off	Climb	Cruise	Descent	Total -check
Fuel (tonnes)	882	190	263	248	118	62	882
C02 emissions (tonnes)	2786	602	831	785	373	196	2786
250-500km							
Fuel (tonnes)	15502	2645	3652	3448	4894	862	15502
C02 emissions (tonnes)	48987	8358	11542	10896	15466	2724	48987
500-1000km							
Fuel (tonnes)	13638	1710	2361	2232	6777	558	13638
C02 emissions (tonnes)	43097	5402	7461	7054	21416	1763	43097
Totals							
Fuel (tonnes)	30022	4545	6276	5929	11790	1482	30022
C02 emissions (tonnes)	94870	14362	19833	18735	37256	4684	94870

abatement interventions

winglets

applicability

Number of airplanes in service	nr	1
Typical airplane age	years	10
Remaining service life	years	15
proportion of airplanes relevant	%	100%
Nr airplanes relevant		1

		All Taxi	**Take off**	**Climb**	**Cruise**	**Descent**	**Totals**	**% reduction check**
fuel efficiency gain	**%**	0%	1%	1%	4%	1%		
<250km								
Fuel (tonnes)		0	3	2	5	1	10	1.2%
C02 emissions (tonnes)		0	8	8	15	2	33	1.2%
250-500km								
Fuel (tonnes)		0	37	34	196	9	275	1.8%
C02 emissions (tonnes)		0	115	109	619	27	870	1.8%
500-1000km								
Fuel (tonnes)		0	24	22	271	6	323	2.4%
C02 emissions (tonnes)		0	75	71	857	18	1019	2.4%
total reduction winglets		**on all**	**Boeing 737-300**					
Fuel (tonnes)		0	63	59	472	15	**608**	**2.0%**
C02 emissions (tonnes)		0	198	187	1490	47	**1923**	**2.0%**

Estimates of Marginal Abatement Costs (MAC) for individual interventions – the extra annual costs of achieving the aforementioned abatements were estimated by aircraft type. Costs include additional investment costs, spread over the relevant investment life to give an annual equivalent cost, plus changes in annual operating costs such as fuel, maintenance, crew time, and other costs such as training where relevant. Additional investments in items such as air traffic management and research and development for new engine/airframe technology are charged as extra investment costs per plane, where these can be estimated and attributed. An estimate of £/tCO_2 abated within a given year was derived for a specified intervention for a specific plane employed on specified mix of journeys. 2008 constant prices are used throughout, although allowance is made for changes in relative fuel prices.

Table 5.5 continues the example for winglets retro-fitted to A737-300 planes. An extra capital cost of £400k gives an annual equivalent cost of £65k, assuming a 10 year investment life and a 10% discount rate (used here throughout). There is some small addition to annual operation and maintenance cost (£8k). Fuel savings of 2% of the estimated total annual fuel consumption for a plane of this type are obtained (from Table 5.4 above), based on estimated typical block hours per year per plane (based on industry data) , km distance per plane (from OAG/CAA) and average fuel consumption per km (modelled estimates). It is assumed that the plane is entirely engaged on UK operations (which of course it is often not).

Fuel savings are valued at the BERR 2007 central value of $73/brl (translating to £0.33/l for aviation fuel, equivalent to £0.41/kg at 0.8075kg/l for aviation fuel) to give an annual saving of £65k, and a net saving in annual costs of £57k. Overall, there is an additional equivalent annual cost of £8k (£65k minus £57k). The annual CO_2 abatement, assuming a ratio of 1:3.16 for fuel kg/CO_2 kg, for one A737-300 plane fully engaged on the UK sector is 501 tCO_2. This gives a marginal abatement cost (MAC) of £17/tCO_2 for this intervention. The total annual abatement cost for this intervention on the A7373-300 working in the UK sector is £32k (1923 tCO_2 abated (from table 5.4) multiplied by £17/ t CO_2 abated). Based on distance travelled and typical work rates, there are about 10 full time equivalent A737-300s working the UK sector.

Table 5.5 Example of the Estimation of Marginal Abatement Costs for an Intervention to Reduce CO_2: Retro-fitted Winglets on a A737-300.

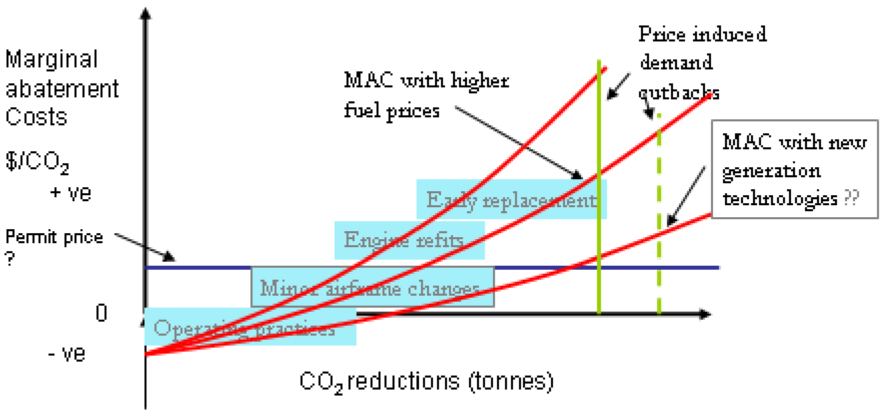
Intervention costs: **winglets**

Extra annual operating costs				
ORM costs				
	airframe	2%	% of P	8000
	engines	0	% of P	0
	other	0	% of P	0
	extra ORM £/year			8000
Fuel costs				
	saving		kg	158481
	fuel price		£/kg	0.41
	costs		£/year	-64766
Crew costs				
	extra		block hr/ye	0%
	rates		£/block hr	400
	costs		£/year	0
Other costs				
	navigation			0
	training			0
	misc			0
Total extra annual operating costs				-56766

Capital cost	**(P)**		£	400000
investment life	year	10		
interest rate	per year	10%		
annuity		6.1446		
Equivalent annual cost £/yr				65098
Extra operating costs				
ORM	0% P			8000
Fuel				-64766
Crew Costs				0
navigation				0
training				0
misc				0
Total Annual costs				-56766
Annual equivalent abatement cost £				8332
Annual abatement		000kgCO2		501
Pv cost £ /000kg CO2 abated				**16.64**
Cost to abate for all	Boeing 737-300			**31988**

Derivation of consolidated MAC estimates– outputs from the preceding analyses were aggregated for a specified year to give (i) total CO_2 abated by intervention and aircraft type (ii) total annual costs by intervention and airplane and (iii) average £/tCO_2 abated per intervention. This was done for years 2007, 2012, 2020 and 2050, allowing for changes in the availability and uptake of abatement options, in the mix of the fleet, and in fuel prices. These estimates were assembled into MAC curves to graphically represent the relative costs of achieving increments in total abatement in a given year by successively adopting interventions in order of least cost. Figure 5.2 shows the concept of the MAC curve for a given year. It should be noted that MAC estimates are sensitive to the price of fuel: higher fuel prices encourage fuel saving and hence reduced CO_2 emissions. Some interventions may offer win-win opportunity in the form of overall reduction in costs, as shown in Figure 5.2. The MAC curve can also be compared with prevailing carbon prices under emissions trading schemes to help determine whether abatement or purchasing/selling permits is attractive. This has not been done here.

Figure 5.2 The Concept of MAC Curves applied to Aviation



The MAC curves in any one year show the total abatement that could potentially be taken up in that year, compared against a fixed year baseline, eg a static 2007 point. This includes any existing abatement options that have already been implemented and any new ones currently available for take up. Thus, the difference between two selected years (say 2007 and 2012) is what was potentially available in the first year plus/minus any changes (costs or performance) in abatements that were available in that year, plus any newly available abatements. MACs, as defined here, give snapshots of what might be achieved for a given year. In this case, this is compared with a moving baseline that allows for increases in air traffic and (unabated) emissions. Hence, for example, interventions in 2012 are considered against the baseline of unabated emissions for 2012, that is before any interventions have been applied. It is important to note that the effects of interventions may not be independent of one another; some interventions may overlap with or substitute for others. The effects of early replacement of aircraft, for example, may substitute for the effects of engine/airframe modifications to older aircraft. Thus, the effects of these interventions may or may not be additive. Furthermore, the extent to which an intervention contributes to the abatement of emissions depends on the order in which interventions are actually implemented.

Implementation Scenarios - assumptions are made to derive estimates of the likely implementation and effectiveness of abatement interventions to reduce CO_2. This involves consideration of three aspects : technical suitability of interventions, actual adoption, and the additivity of effects. These are discussed in turn:

Potential technical and operational feasibility – this reflects the feasibility of implementation of an intervention in terms of technical and practical suitability, that which could be reasonably achieved in the time frame allowing for current circumstances and practices. Table 5.6 shows estimates of the potentially feasible take up of abatement options for 2007 by way of example, where the percentage refers to the proportion of the population of given aircraft types taking up a particular intervention. For example, it is assumed that winglets could be fitted on 90% of the B7373 fleet, if there was a wish to do so.

Table 5.6 Assumed potential technical feasibility of take-up of abatement options, as % of aircraft adopting options in 2007.

abatemment	A319	A320	B7373	B7375	B7377	B7378	B7572	E145	PROP6	PROP7	RJ85
technology											
winglets	0%	0%	90%	50%	25%	90%	25%	0%	0%	0%	0%
riblets	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting- new	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting - existing	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
blended wing	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
aircraft surface - polish	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
engine replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
engine upgrades	25%	25%	50%	50%	25%	10%	50%	25%	10%	10%	25%
open rotors	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
APU - removal	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	100%
APU - tech replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bio-fuels blend (20%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Alternative fuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Optimised aircraft design	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operational											
ATM improvements	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CDA	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Optimise - speed/altitude	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Optimise - LTO practice	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Reduce fuel tankering	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Fleet Management											
Aircraft retirement1&2	0%	0%	100%	100%	0%	0%	100%	0%	0%	0%	0%
maintenance - engine	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - aero	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
maintenance - engine wash	80%	80%	80%	80%	80%	80%	80%	80%	0%	0%	100%
fuel reserves	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
increase turboprop use	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	100%
better use of capacity	60%	60%	60%	60%	60%	60%	60%	75%	75%	75%	75%
reduce APU use	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%

Actual adoption – this allows for take-up below technically feasible levels, due for example, to barriers and inertia, such as embedded practices, and the incentives available to operators to adopt the interventions. Incentives could comprise market drivers such as fuel prices or regulatory requirements such as prescribed emission limits. It is clear for example that higher fuel prices provide greater incentives to adopt fuel saving options. Thus actual adoption of technically feasible options is difficult to predict, and could range between 0% and 100% of technical feasibility. For the purposes here a notional adjustment is made to potential technical implementation accordingly. For the purpose of constructing the MAC curves here, it is assumed that actual adoption is 90% of potential for all interventions for two reasons, namely: (i) to draw attention to the important difference between actual and technically feasible implementation, and (ii) to provide some headroom, albeit small, in the estimates of abatement.

Additivity –this influences the aggregate effects of any set of future abatement interventions. Additivity covers the effects of overlaps and interdependences amongst abatement options, whereby the extra CO_2 reduction attributable to one abatement can be affected by another previously adopted abatement. Thus the scale and the order in which interventions are adopted affect not only incremental CO_2 abatement, but also £/CO_2 abated. For example, increased capacity utilisation that reduces total flights, reduces the incremental affect of other interventions. ACARE compliant aircraft may incorporate and displace a wide range of prior technology options. It might be expected that the most cost-effective (lowest £/CO_2) interventions are adopted first, such that extra savings from subsequent interventions will be less than if they were considered independently.

Allowances could be made for interacting and ordering effects by reducing the abatement gain by a percentage reduction factor. These will for the most part, make successively ordered interventions less attractive than if they were considered independently. But this is a complicated process and falls outside the scope of this study. For the purpose of constructing the MAC curves here, interventions are considered to be independent and non-cumulative in effect. It is emphasised, however, that additivity would need to be considered to reflect real world implementation and will depend on the relative extent and order of implementation of interventions.

The application of these aforementioned adjustment factors has the effect of reducing the initial theoretical estimates of fuel and CO_2 savings as shown in Table 5.3. In the case of winglets applied to a B737-300, for example, the 2% reduction in average fuel burn and CO_2 emissions (Table 5.4) is achieved on 100% of the UK B7373 fleet (Table 5.6) and then multiplied by 90% to allow for actual adoption. Thus, in this case, the 2% emission reduction is weighted by 90% to give a likely actual reduction in emissions of 1.8% attributable to this intervention for the airplanes concerned.

Thus, the volumes of emission reduction presented here for the MAC curves are 90% of the theoretical abatements shown in Table 5.3. These adjustments allow for the fact that theoretical potential is rarely achieved in practice. No allowance is made for additivity effects.

Sensitivity and breakeven analysis – Estimates of MAC are dependent on critical ‘supply side’ factors such as fuel prices, discount rates, investment life and fleet mix. MAC estimates are particularly sensitive to estimates of future aviation fuel prices. Table 5.7 shows the alternative fuel price estimates used to derive MAC.

Table 5.7 Future Oil Prices used to assess MAC for UK Aviation.

	BERR estimates								**IATA**
year	low		central		high		very high		forecast
2007	73	(0.33)	73	(0.33)	73	(0.33)	73	(0.33)	104
2012	45	(0.21)	65	(0.29)	85	(0.38)	107	(0.48)	85
2020	45	(0.21)	70	(0.31)	95	(0.43)	150	(0.68)	95
2030	45	(0.21)	73	(0.33)	100	(0.45)	150	(0.68)	100
2050	45	(0.21)	75	(0.34)	105	(0.47)	150	(0.68)	105

all prices in US $/barrell, then (£/litre).
converted at 159 litres/barrel; US$;£ at 1.86

MACs are also affected by possible changes in ‘demand side’ factors associated with changes in traffic demand (including responses to higher ticket prices) and revenue from ticket sales. Some abatement measures, such as reduced APU use or increased capacity utilisation, might be linked with lower average ticket prices, adding a demand side penalty which should, as far as the industry is concerned, be included as part of the cost of abatement. This goes beyond the scope of the current assessment and has not been investigated.

Where appropriate the change in fuel price necessary to achieve a breakeven zero cost for a particular abatement is identified. Similarly, the implication of alternative carbon permit prices is also considered.

Results

The aforementioned procedure was applied to derive estimates of MAC for the years 2007, 2012, 2020 and 2050. The results are presented below in summary form, and the full range of MAC diagrams are presented in Appendix 5. Further information is contained in supporting spreadsheets. It is emphasised that the estimates are indicative and require cautious interpretation. They are based on incomplete information and many assumptions (see Appendix 6 for a listing of major assumptions by intervention), the validity of which need to be further assessed. They indicate the potential contribution and cost of measures that can be taken to abate the CO_2 emissions of the UK domestic aviation sector.

UK Domestic Aviation MAC for 2007

Following the methods explained earlier, the estimates in Table 5.6 above show the assumed potential implementation of abatement options for 2007, which is the take-up of individual interventions categorised by type of aircraft. It should be noted that a nominal adjustment for actual adoption is applied to the estimates in Table 5.6, as explained above, such that 90% of what is a technically and operationally feasible volume of abatement is assumed in most cases.

Table 5.8 shows the MAC for CO_2 for UK Domestic Aviation 2007, assuming the prevailing fuel price of £0.33/l (US$73/brl). It shows, for the assumptions made, the incremental abatement of CO_2 for each successive abatement option introduced in order of increasing abatement cost (£/tCO_2). It is noted that each intervention is considered independently. Table 5.8 shows the potential annual abatement attributable to each intervention expressed as a percentage of total annual UK domestic aviation CO_2 emissions considering each intervention. Eight abatement options have potential to achieve emission abatements at negative net cost, that is offering overall financial benefit. Most of them are operational interventions, which seek to reduce fuel expenditure. Indeed, there is evidence, collected during stakeholder consultation, that many of them are being adopted in 2008 in response to high fuel prices (these recent introductions have not been included in the base line estimates). It is noted however that some, such as better use of capacity and reduced APU use, can have a demand-side affect through modifying the ‘product service’, with possible implications for revenue and hence MAC. The increased use of turbo props appears to offer advantage given the amount of short haul traffic. Table 5.8 suggests that abatement options when considered independently are associated with a reduction of up to 12% of the sector’s 2007 CO_2 emissions, however, when additivity effects between abatement options are taken into account these savings will necessarily decrease.

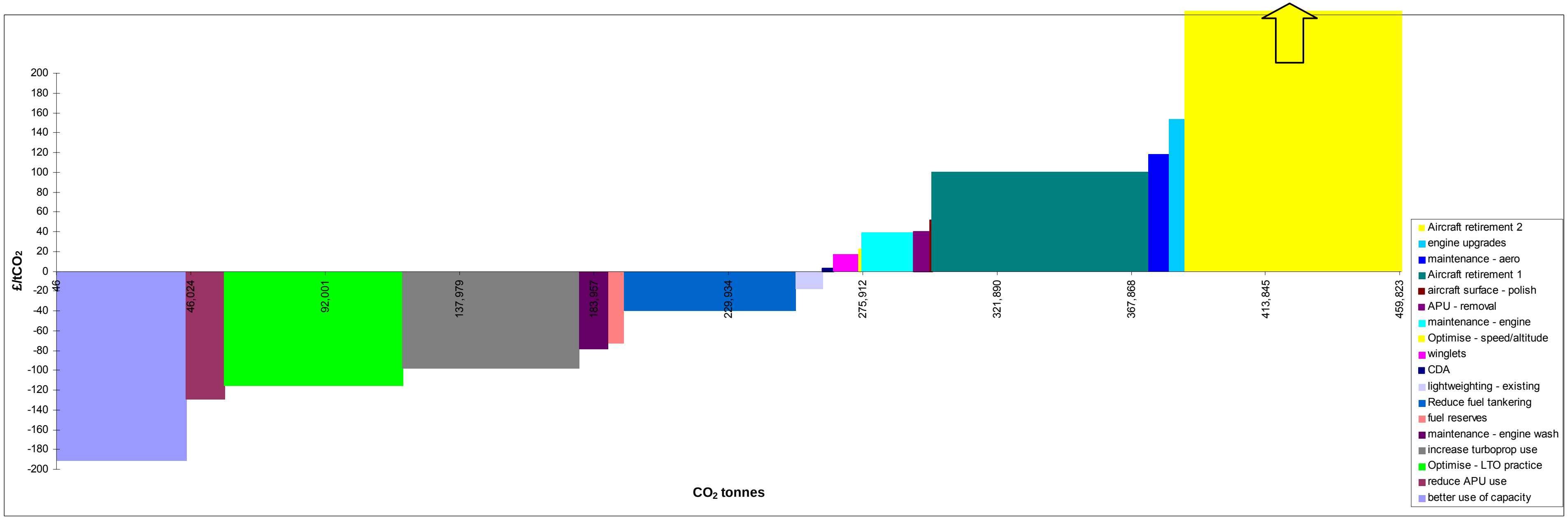
Table 5.8 UK Domestic Aviation Illustrative MAC for 2007 (fuel price £0.33/ltr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
🟨	F8	better use of capacity	44399	-8521803	-192	2.18%
🟩	F9	reduce APU use	12902	-1668614	-129	0.63%
🟩	O4	Optimise - LTO practice	61102	-7057190	-115	3.00%
🟩	F7	increase turboprop use	60393	-5932666	-98	2.96%
🟩	F5	maintenance - engine wash	9927	-782888	-79	0.49%
🟨	F6	fuel reserves	5363	-389202	-73	0.26%
🟨	O5	Reduce fuel tankering	58814	-2352602	-40	2.88%
🟨	T4	lightweighting - existing	9137	-166266	-18	0.45%
🟨	O2	CDA	3836	10202	3	0.19%
🟩	T1	winglets	8773	154116	18	0.43%
🟨	O3	Optimise - speed/altitude	624	13707	22	0.03%
🟨	F3	maintenance - engine	18064	712471	39	0.89%
🟨	T10	APU - removal	5622	225747	40	0.28%
🟨	T6	aircraft surface - polish	677	34914	52	0.03%
🟨	F1	Aircraft retirement 1	74143	7464747	101	3.64%
🟨	F4	maintenance - aero	6924	820440	118	0.34%
🟨	T8	engine upgrades	5393	829286	154	0.26%
🟨	F2	Aircraft retirement 2	74143	30014421	405	3.64%

NB: Assumed annual emissions without interventions = 2 039 000 tCO_2

Figure 5.3 contains (based on Table 5.8) a MAC curve showing the incremental cost of increasing abatement by successive interventions. The win-win opportunities under prevailing fuel prices are apparent. Marginal costs of abatement rise steeply beyond the point where the MAC curve crosses the breakeven point (at 0 £/tCO_2) indicating that achieving further reductions in CO_2 becomes relatively expensive

Figure 5.3 UK Domestic Aviation Illustrative MAC for 2007 (fuel price £0.33/ltr)



UK Domestic Aviation MAC for 2012

Table 5.9 shows the assumed potential implementation of abatement options for 2012, categorised by type of aircraft. The range and depth of the implementation of interventions is increased from that assumed for 2007, for example, riblets are assumed to have been brought to market and potentially taken up by 25% of all aircraft types. The same adjustment for actual adoption is applied.

Table 5.9 Assumed potential technical feasibility of take-up of abatement options, as % of aircraft adopting options in 2012.

abatemment	A319	A320	B7373	B7375	B7377	B7378	B7572	E145	PROP6	PROP7	RJ85
technology											
winglets	0%	0%	90%	75%	50%	90%	50%	0%	0%	0%	0%
riblets	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
lightweighting- new	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
lightweighting - existing	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
blended wing	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
aircraft surface - polish	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
engine replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
engine upgrades	25%	25%	50%	50%	25%	10%	50%	25%	10%	10%	25%
open rotors	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
APU - removal	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
APU - tech replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bio-fuels blend (20%)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Alternative fuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Optimised aircraft design	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operational											
ATM improvements	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
CDA	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Optimise - speed/altitude	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Optimise - LTO practice	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
Reduce fuel tankering	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
Fleet Management											
Aircraft retirement1&2	25%	25%	100%	100%	25%	25%	100%	0%	0%	0%	0%
maintenance - engine	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
maintenance - aero	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
maintenance - engine wash	85%	85%	85%	85%	85%	85%	85%	85%	0%	0%	100%
fuel reserves	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
increase turboprop use	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	100%
better use of capacity	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
reduce APU use	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%

Table 5.10 shows the MAC for CO_2 for UK Domestic Aviation in 2012, assuming the central fuel price of £0.31/l. A similar pattern to 2007 is apparent – the same eight abatement options have potential to achieve emission abatements at negative cost, that is offering win-win opportunity. It is noted that no new major technological development are expected by 2012, with only small improvements in ATM through CDA by that time. Table 5.10 suggests that, considering interventions independently, up to 14% of the sector's 2007 CO_2 emissions could be abated with potential financial benefit in 2012. However, when additivity effects between abatement options are taken into account these savings will necessarily decrease

Table 5.10 UK Domestic Aviation Illustrative MAC for 2012 (central fuel price £0.29/ltr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
🟨	F8	better use of capacity	46740	-8277680	-177	2.03%
🟩	F9	reduce APU use	14881	-1714597	-115	0.65%
🟩	O4	Optimise - LTO practice	79776	-8037779	-101	3.47%
🟩	F7	increase turboprop use	68428	-6694757	-98	2.98%
🟩	F5	maintenance - engine wash	11554	-741404	-64	0.50%
🟨	F6	fuel reserves	6000	-341090	-57	0.26%
🟨	O5	Reduce fuel tankering	79351	-2737677	-35	3.45%
🟨	T4	lightweighting - existing	11817	-22730	-2	0.51%
🟨	O2	CDA	10683	205450	19	0.46%
🟩	T1	winglets	9876	243835	25	0.43%
🟨	T10	APU - removal	8235	240259	29	0.36%
🟨	O3	Optimise - speed/altitude	708	27157	38	0.03%
🟨	F3	maintenance - engine	21475	1151997	54	0.93%
🟨	T6	aircraft surface - polish	3790	256382	68	0.16%
🟨	T2	riblets	4477	340483	76	0.19%
🟨	F1	Aircraft retirement 1	95111	11214219	118	4.14%
🟨	F4	maintenance - aero	8232	1039829	126	0.36%
🟨	T8	engine upgrades	5413	908946	168	0.24%
🟨	F2	Aircraft retirement 2	95111	41295773	434	4.14%

NB: Assumed annual emissions without interventions = 2 299 000 tCO_2

Figure 5.4 contains (based on Table 5.10) a MAC curve showing the incremental cost of increasing abatement by successive interventions. The win-win opportunities under prevailing fuel prices are apparent, and the interpretation is similar to that of the 2007 MAC curve. Abatement costs rise steeply beyond the breakeven point where MAC equals zero. Early retirement of aircraft (shown separately for replacing 5 (F1) and 10 year (F2) old aircraft respectively) offer considerable abatement potential, but at relatively high cost (replacing younger aircraft benefits from higher aircraft resale value).

Figure 5.4 UK Domestic Aviation Indicative MAC for 2012 (Central Oil Fuel price £0.29/ltr)

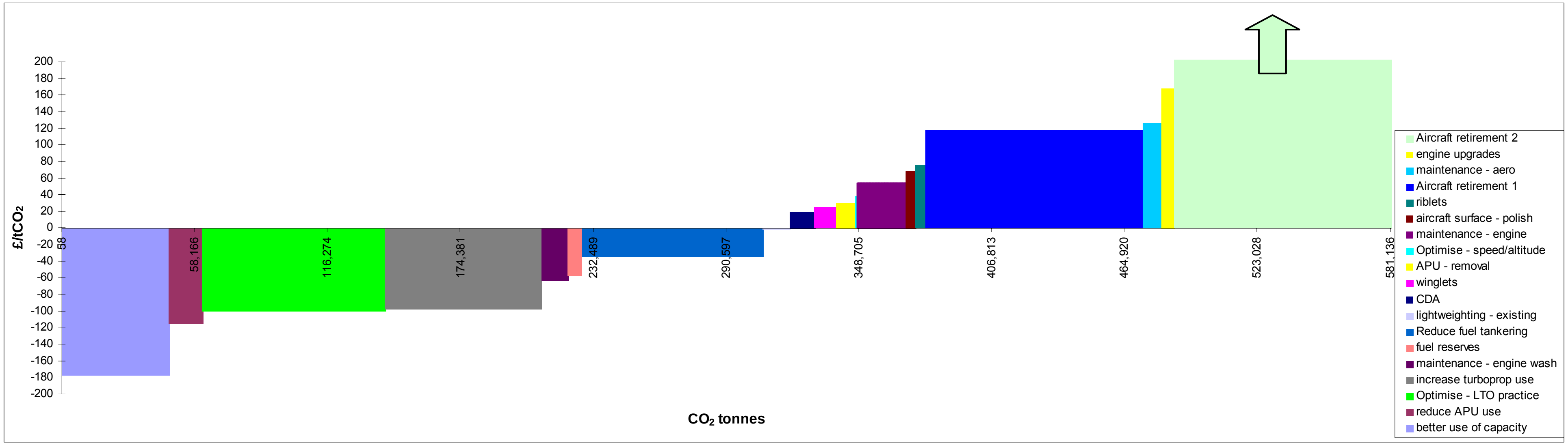


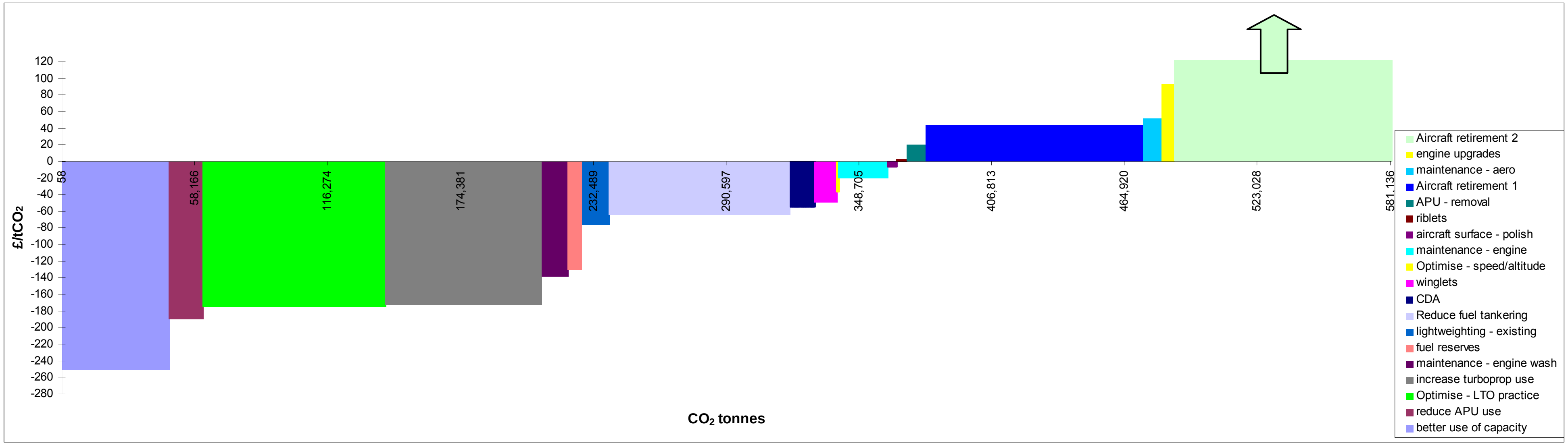
Table 5.11 shows estimates of MAC for 2012 for the range of fuel prices shown in Table 5.7. Interventions above the continuous horizontal lines in the columns can be adopted at negative or zero cost (for the assumptions made). Higher fuel prices make all interventions absolutely more attractive. There are some changes in the relative costs and ranking of interventions in response to fuel prices, but the overall pattern remains much the same. The highest fuel price assumed in Table 5.11 appears to be sufficient to induce abatements associated with up to about 17% of total annual sector CO_2 emissions, when interventions are considered independently. However, when additivity effects between abatement options are taken into account these savings will necessarily decrease. Early retirement/replacement of aircraft (where F1 in table 5.11 indicates replacement at 5 years old) offers considerable scope for abatement and appears more attractive under high oil price scenarios.

Table 5.11 Estimates of UK Domestic Aviation MAC for 2012 by Alternative Oil Price Scenarios

	Oil price scenario	low		central		high		very high
	US$/Brl Oil	45		65		85		107
	£/l aviation fuel	0.21		0.29		0.38		0.48
Interventions								
F8	better use of capacity	**-142**	F8	**-177**	F8	**-213**	F8	**-252**
F9	reduce APU use	**-80**	F9	**-115**	F9	**-151**	F9	**-190**
O4	Optimise - LTO practice	**-65**	O4	**-101**	O4	**-136**	O4	**-175**
F7	increase turboprop use	**-63**	F7	**-98**	F7	**-133**	F7	**-172**
F5	maintenance - engine wash	**-29**	F5	**-64**	F5	**-100**	F5	**-139**
F6	fuel reserves	**-22**	F6	**-57**	F6	**-93**	F6	**-131**
O5	Reduce fuel tankering	**-20**	O5	**-35**	O5	**-49**	T4	**-76**
T4	lightweighting - existing	**33**	T4	**-2**	T4	**-38**	O5	**-65**
T10	APU - removal	**34**	O2	**19**	O2	**-16**	O2	**-55**
O2	CDA	**55**	T1	**25**	T1	**-11**	T1	**-50**
T1	winglets	**60**	T10	**29**	O3	**3**	O3	**-36**
O3	Optimise - speed/altitude	**74**	O3	**38**	F3	**18**	F3	**-21**
F3	maintenance - engine	**89**	F3	**54**	T10	**25**	T6	**-7**
T6	aircraft surface - polish	**103**	T6	**68**	T6	**32**	T2	**2**
T2	riblets	**111**	T2	**76**	T2	**40**	T10	**20**
F1	Aircraft retirement 1	**153**	F1	**118**	F1	**82**	F1	**43**
F4	maintenance - aero	**162**	F4	**126**	F4	**91**	F4	**52**
T8	engine upgrades	**203**	T8	**168**	T8	**132**	T8	**93**
F2	Aircraft retirement 2	**469**	F2	**434**	F2	**399**	F2	**360**

For illustration, the MAC curve for the very high price scenario for 2012 (£0.48/l) is contained in Figure 5.5

Figure 5.5 UK Domestic Aviation Illustrative MAC for 2012 (very high fuel prices at £0.48/ltr)



UK Domestic Aviation MAC for 2020

Table 5.12 shows the percentage of aircraft assumed to be taking up various abatement options in 2020, categorised by type of airplane. The range and intensity of the adoption of interventions increases, where appropriate, from that assumed for 2012. For example, ATM improvements are assumed to be fully implemented, with 90% of each aircraft type taking advantage of the associated benefits. Some new interventions emerge, such as the availability of Bio-fuels, with an assumed 10% of all aircraft types using Bio-fuels as a blend with aviation fuel (Appendix 6 provides further details of assumed Bio-fuel use scenario).

Table 5.12 Assumed potential technical feasibility of take-up of abatement options, as % of aircraft adopting options in 2020.

abatemment	A319	A320	B7373	B7375	B7377	B7378	B7572	E145	PROP6	PROP7	RJ85	acare1	acare2	acare3
technology														
winglets	0%	0%	100%	0%	75%	100%	75%	0%	0%	0%	0%	0%	0%	0%
riblets	50%	50%	50%	0%	50%	50%	50%	50%	25%	25%	50%	0%	0%	0%
lightweighting- new	15%	15%	15%	0%	0%	15%	0%	0%	10%	10%	0%	0%	0%	0%
lightweighting - existing	100%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%
blended wing	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
aircraft surface - polish	80%	80%	80%	0%	80%	80%	80%	80%	80%	80%	80%	0%	0%	0%
engine replacement	10%	10%	0%	0%	10%	10%	0%	0%	0%	0%	10%	0%	0%	0%
engine upgrades	50%	50%	50%	0%	50%	25%	50%	50%	0%	0%	25%	0%	0%	0%
open rotors	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
APU - removal	70%	70%	70%	0%	70%	70%	70%	70%	70%	70%	70%	0%	0%	0%
APU - tech replacement	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Bio-fuels blend (20%)	10%	10%	10%	0%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Alternative fuels	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Optimised aircraft design	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Operational														
ATM improvements	90%	90%	90%	0%	90%	90%	90%	90%	90%	90%	90%	100%	100%	100%
CDA	60%	60%	60%	0%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
Optimise - speed/altitude	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Optimise - LTO practice	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	80%	80%	80%
Reduce fuel tankering	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
Fleet Management														
Aircraft retirement1&2	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	0%	0%	0%
maintenance - engine	90%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
maintenance - aero	90%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
maintenance - engine wash	90%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
fuel reserves	75%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
increase turboprop use	15%	15%	15%	15%	15%	15%	0%	100%	0%	0%	100%	0%	0%	0%
better use of capacity	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%	60%
reduce APU use	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%	0%	0%	0%
ACARE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%

Table 5.13 shows the MAC for CO_2 for UK Domestic Aviation in 2020, assuming the central fuel price of £0.31/l. The pattern of abatement continues from 2012, with the introduction of new interventions, such as ATM improvements associated with the implementation of The Single European Skies programme, offering opportunities for greater abatement. ACARE compliant aircraft are just beginning to appear in the domestic fleet, representing the embodiment of major changes in aircraft technology but they are relatively few and costly. At the central fuel price of £0.31/litre, eight interventions are shown to offer opportunity for abatement at negative or zero cost. These abatement options are associated with about 24% of the sector's 2020 CO_2 emissions when considered independently of one another. It is noted that ATM

improvements account for around a third of aggregate abatements. The adoption of ATM improvements, which reduce journey time, would reduce the potential gain from other interventions that reduce fuel consumption per km travelled for a given payload. This illustrates that when additivity effects between abatement options are taken into account the identified savings will necessarily decrease.

Table 5.13 UK Domestic Aviation Illustrative MAC for 2020 (central fuel price £0.31/ltr)

health	id	intervention	total abated (CO_2 tonnes)	total cost (£)	unit cost (£/tCO_2)	% of total annual sector emissions
🟨	F8	better use of capacity	51999	-9704109	-187	2.00%
🟩	F7	increase turboprop use	126623	-16648737	-131	4.88%
🟩	F9	reduce APU use	17052	-2118428	-124	0.66%
🟩	O4	Optimise - LTO practice	88025	-9604244	-109	3.39%
🟨	F6	fuel reserves	8202	-489513	-60	0.32%
🟨	O5	Reduce fuel tankering	90710	-3624691	-40	3.50%
🟩	F5	maintenance - engine wash	17016	-516800	-30	0.66%
🟥	O1	ATM improvements	221426	-4385865	-20	8.53%
🟩	T1	winglets	11502	179144	16	0.44%
🟨	O2	CDA	28449	458230	16	1.10%
🟨	T10	APU - removal	9139	216237	24	0.35%
🟨	T2	riblets	9789	344085	35	0.38%
🟨	O3	Optimise - speed/altitude	1583	56663	36	0.06%
🟨	T4	lightweighting - existing	41685	1612494	39	1.61%
🟨	F3	maintenance - engine	27225	1163387	43	1.05%
🟨	T6	aircraft surface - polish	6724	425789	63	0.26%
🟨	F10	ACARE	1900	185015	97	0.07%
🟥	F4	maintenance - aero	10436	1108017	106	0.40%
🟨	T8	engine upgrades	8433	961501	114	0.33%
🟨	F1	Aircraft retirement 1	291836	36047672	124	11.25%
🟨	T3	lightweighting- new	16232	2633668	162	0.63%
🟨	T12	Bio-fuels (20% blend)	28777	4781513	166	1.11%
🟨	T7	engine replacement	8826	1819194	206	0.34%
🟨	F2	Aircraft retirement 2	291836	144970902	497	11.25%

NB: Assumed annual emissions without interventions = 2 595 000 tCO_2

Table 5.14 shows estimates of MAC for 2020 for the range of fuel prices shown in Table 5.7. As before, interventions above the continuous horizontal lines in the table columns can be adopted at negative or zero net cost (for the assumptions made). Higher fuel prices extend the range of win-win abatement options, and the proportion of the sector's emissions that could be adopted at zero or relatively low net cost.

Table 5.14 UK Domestic Aviation Illustrative MAC's for 2020, compared by Oil Price Scenario

Oil price scenario		**low**		**central**		**high**		**very high**
	US$/Brl Oil	45		70		95		150
	£/l aviation fuel	0.21		0.31		0.43		0.68
Interventions								
F8	better use of capacity	**-142**	F8	**-187**	F8	**-231**	F8	**-328**
F7	increase turboprop use	**-87**	F7	**-131**	F7	**-176**	F7	**-273**
F9	reduce APU use	**-80**	F9	**-124**	F9	**-169**	F9	**-266**
O4	Optimise - LTO practice	**-65**	O4	**-109**	O4	**-153**	O4	**-251**
O5	Reduce fuel tankering	**-21**	F6	**-60**	F6	**-104**	F6	**-202**
F6	fuel reserves	**-15**	O5	**-40**	F5	**-75**	F5	**-172**
F5	maintenance - engine wash	**14**	F5	**-30**	O1	**-64**	O1	**-162**
O1	ATM improvements	**24**	O1	**-20**	O5	**-59**	T1	**-126**
T10	APU - removal	**28**	T1	**16**	T1	**-29**	O2	**-126**
T1	winglets	**60**	O2	**16**	O2	**-28**	T2	**-107**
O2	CDA	**60**	T10	**24**	T2	**-9**	O3	**-106**
T2	riblets	**79**	T2	**35**	O3	**-8**	T4	**-103**
O3	Optimise - speed/altitude	**80**	O3	**36**	T4	**-6**	O5	**-99**
T4	lightweighting - existing	**83**	T4	**39**	F3	**-2**	F3	**-99**
F3	maintenance - engine	**87**	F3	**43**	T6	**19**	T6	**-79**
T12	Bio-fuels (20% blend)	**107**	T6	**63**	T10	**19**	F10	**-44**
T6	aircraft surface - polish	**108**	F10	**97**	F10	**53**	F4	**-36**
F10	ACARE	**142**	F4	**106**	F4	**62**	T8	**-28**
F4	maintenance - aero	**150**	T8	**114**	T8	**70**	F1	**-18**
T8	engine upgrades	**158**	F1	**124**	F1	**79**	T10	**9**
F1	Aircraft retirement 1	**168**	T3	**162**	T3	**118**	T3	**20**
T3	lightweighting- new	**207**	T12	**166**	T7	**162**	T7	**64**
T7	engine replacement	**250**	T7	**206**	T12	**225**	F2	**355**
F2	Aircraft retirement 2	**541**	F2	**497**	F2	**452**	T12	**356**

The effect of fuel prices on the cost of and therefore the incentive to adopt abatement measures is apparent in Figure 5.6 that shows the 2020 MAC curves for central (US$70/brl, £0.31/l) and very high (US$150/brl, £0.69/l) aviation fuel prices respectively. Higher fuel prices make nearly all interventions more attractive. There are some changes in the relative costs and ranking of interventions in response to fuel prices, but the overall pattern remains much the same. A notable exception is aviation Bio-fuels, which, for the assumptions made, are negatively impacted by increased oil prices (see appendix 6 for further details). The win-win abatements at very high prices are associated with about 40% of the sector's 2020 CO_2 emissions when considered independently of one another. Again, when overlapping effects between abatement options are taken into account these savings will necessarily decrease

Figure 5.6 UK Domestic Aviation Illustrative MAC’s for 2020 (central and very high fuel prices).

(a) Central: US$70/brl, £0.31/l aviation fuel

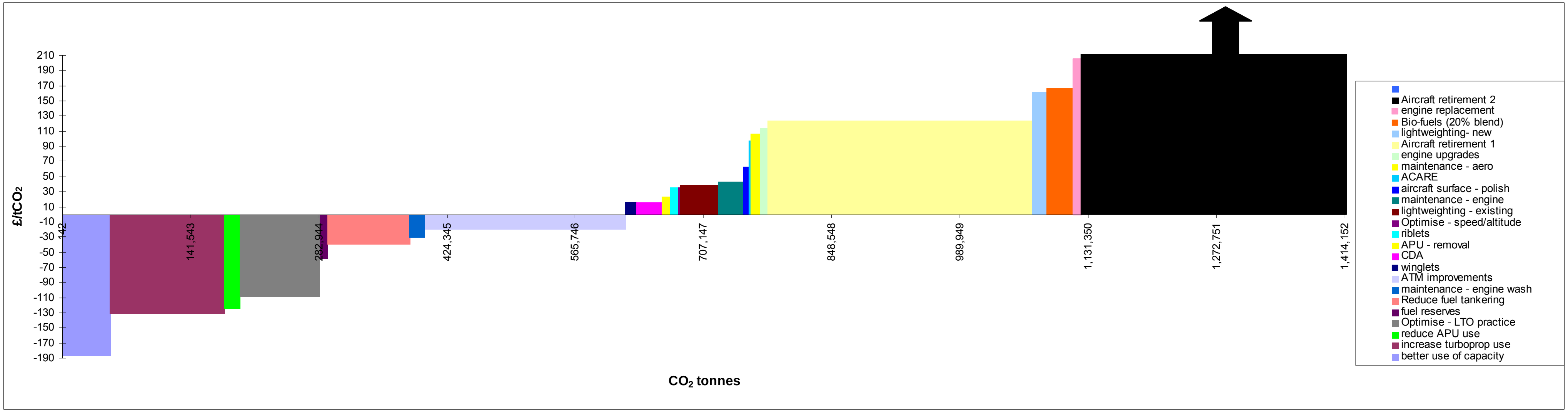
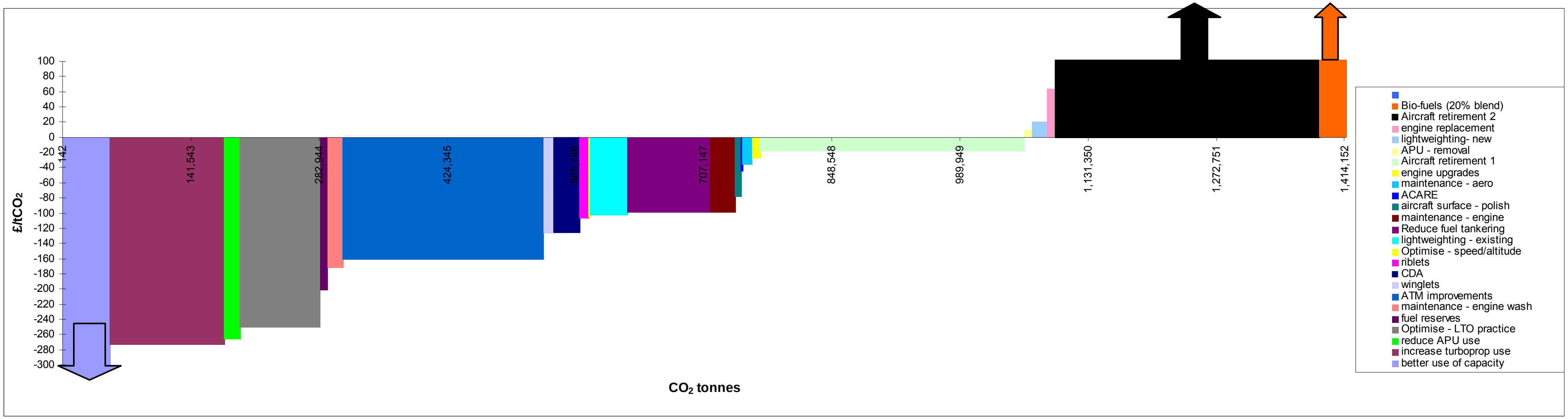


Figure 5.6 UK Domestic Aviation MAC, 2020 for Central and Very High Oil and Fuel Price Scenarios.

(b) Very High: US$150/brl, £0.69/l aviation fuel



UK Domestic Aviation MAC for 2050

At the time of writing it has not been possible to produce an internally consistent estimate of MAC for 2050. Beyond 2020, most improvement in aviation fuel efficiency is perceived to be linked to operational improvements and technologies embedded within ACARE compliant airplanes. These are commonly assumed to each deliver about 25% improvements in fuel efficiency per SKO; 50% in total by about 2030.

Thus, many of the abatement options identified for 2020 continue through to 2050 in the form of operational and ACARE type improvements. A number of long term technological options were identified in section 4 above, including synthetic fuels, fuel cell technologies, composite materials, enhanced engine designs, new propeller technologies and new airframe/engine configurations particularly suited to the short haul UK domestic sector. Some of these options were explored, including the scope for the development of new families of engines, including improved turbo propeller units. It has not been possible to derive reliable estimates of development costs and of likely capital and operating costs for these long term options.

Given the recent fluctuations in oil prices, expectations of future high fuel prices could encourage the aviation industry to pursue the technological, operational and fleet management options identified here. Drawing on the methods used above, Table 5.13 contains some very rough estimates of MAC for ACARE type airplanes delivering 25% reduction in fuel usage per SKO and for ATM delivering 10.5 % reduction through improved routing and associated benefits. The estimates of additional capital costs for ACARE planes and increased navigation charges for ATM are shown, together with the ceilings for additional capital costs at selected fuel prices.

Table 5.13 Indicative MAC estimates for ACARE and ATM Interventions by Oil Price Scenario for 2050

Oil price scenario			**low**	**central**	**high**	**very high**
US$/Brl Oil			45	70	95	150
£/l aviation fuel			0.21	0.34	0.48	0.68
Interventions						
		Extra capital Cost /unit				
	seats					
ACARE 1	70	20%	268	217 (6.5%)*	182	119 (13%)
ACARE 2	150	25%	145	104 (13%)	60	-4 (26%)
ACARE 3	200	35%	127	85(20%)	41	-22 (40%)
ATM	incr nav costs	30%	39	114	-47	-110

* brackets show increase in capital cost to break even at 10% over 25 years

Sensitivity of Interventions to Fuel Prices

As already shown, the cost of abatements is very sensitive to oil and fuel prices. Table 5.14 shows the percentage change in fuel prices from the central estimate required to make the cost of an intervention equal to zero, that is breakeven. A doubling of oil and fuel prices from their 2007 levels, as experienced during 2008, make technological and fleet management options associated with early replacement/retirement much more attractive.

Table 5.14 . Sensitivity of Abatement Options to Changes in Oil and Aviation Fuel Prices

ID	Intervention	% change in central fuel cost to breakeven 2007	2020
Technology			
T1	winglets	15%	10%
T2	riblets		25%
T3	lightweighting- new		120%
T4	lightweighting - existing	-15%	30%
T6	aircraft surface - polish	40%	45%
T7	engine replacement		155%
T8	engine upgrades	120%	85%
T10	APU - removal	160%	170%
T12	Bio-fuels		positive
Operational			
O1	ATM improvements		-20%
O2	CDA	3%	10%
O3	Optimise - speed/altitude	20%	25%
O4	Optimise - LTO practice	-90%	-90%
O5	Reduce fuel tankering	-80%	-75%
Fleet Management			
F1	Aircraft retirement 1	80%	90%
F2	Aircraft retirement 2	310%	380%
F3	maintenance - engine	30%	30%
F4	maintenance - aero	90%	80%
F5	maintenance - engine wash	-60%	-30%
F6	fuel reserves	-65%	-50%
F7	increase turboprop use	-75%	negative
F8	better use of capacity	negative	negative
F9	reduce APU use	negative	negative
F10	ACARE		70%

Central fuel price

oil price	$/barrel	67
aviation fuel price	£/litre	0.33

NB negative = always negative cost
positive = always positive cost

Discussion and Conclusions

The preceding analysis draws on multiple sources of information, including research and practitioner knowledge, to construct estimates of the marginal cost of CO_2 abatement by the UK domestic aviation sector abatement over the next 50 years. This involved two interrelated challenges, namely: first to devise a framework to systematically assess MAC for the UK sector, and second to populate this with available data. Numeric estimates of MAC have been derived for 2007, 2012 and 2020, together with a qualitative assessment of options for 2050. A combination of methodological challenges and limited available data on which to reliably predict the performance and cost of abatement measures requires that the estimates must be regarded as indicative at this stage.

In broad terms the analysis points to a number of conclusions:

A range of measures, comprising technological, operational and fleet management options, can be taken to reduce CO_2 emissions associated with the use of aviation fuel. The cost to the industry of adopting these is very sensitive to the price of oil and aviation fuel.

A range of interventions have been identified that when considered independently are associated with the abatement of about 14% of the UK aviation sector's CO_2 emissions at negative or zero net cost by 2012. This estimate rises to about 17% if fuel prices rise to assumed 'very high' levels. After this point, MAC appear to rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at relatively low cost. By 2020, assuming no major technological breakthrough in airframe or engine performance and central fuel prices, abatement options at or below zero net cost are associated with about 24% of total annual sector CO_2 emissions for the assumptions made. This estimate rises to about 40% if fuel prices rise to assumed 'very high' levels. Within this, ATM improvements have the potential to contribute a 8.5% reduction in CO_2 emissions. It must be highlighted that all the above estimates of reductions in emissions consider interventions individually. Emissions savings will necessarily decrease when additivity and overlapping effects between abatement options are taken into account.

The most cost effective intervention measures appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short hauls of the UK sector (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance.

The analysis shows that high fuel prices are likely to promote further changes in airframe and engine technology. These are embedded in the concept of ACARE compliant planes, assumed capable of achieving 25% improvements in fuel efficiency. There is insufficient available information to reliably assess the feasibility and costs of achieving ACARE targets. Analysis shows that high fuel prices and potential efficiency gains from new generation aircraft are likely to encourage early replacement of existing fleets.

A number of methodological issues are worthy of comment, besides data limitations. The estimates of MAC involve an iterative process whereby interventions are first considered independently to determine a hierarchy of least-cost. The order of adoption affects the efficacy of interventions – the earlier adoption of engine and airframe upgrades for example could for example reduce the net gain from early retirement of aircraft, with implications for double counting. This would affect the width of the abatement measure on the horizontal (x) axis of the MAC curve (CO_2 t abated). Building this additivity factor into MAC calculations was outside the scope of this study, but would need to be considered to reflect real world implementation. For this reason, the approximations here are not estimates of cumulative abatement potential.

The analysis here focussed on ‘supply-side’ costs of implementing abatement measures. Some interventions may have demand-side implications as they affect perceived user value and willingness to pay for air transport services. For example, consolidation of flights to increase utilisation, reduced APU use, and possibly increased use of slower turbo props might affect ticket prices and sales, thereby increasing MAC (changing the height of the abatement measure on the vertical (y) axis (£/tCO_2)). This demand-side aspect is under reported here, and is worthy of further attention.

Obtaining information to construct MAC estimates has been challenging. It would be beneficial to re-engage with the aviation community to scrutinise and strengthen the estimates, as well as achieve ‘buy-in’ into the process.

Summary

The key points arising from this chapter are :

- Drawing on multiple sources, and working with generally limited quantitative data, indicative estimates of MAC for the UK domestic aviation sector have been constructed.

- A range of interventions could, when considered individually, enable the UK aviation sector to abate up to 14% of its CO_2 emissions at negative or zero cost by 2012, up to 17% if fuel prices rise to 'very high' levels. After this point, MAC appear to rise steeply, with limited opportunity at central oil price forecasts to achieve abatement at costs below £20/ t CO_2, the benchmark provided by the current price of CO_2 ETS permits (and the prevailing social cost of carbon).

- By 2020, assuming no major technological breakthrough in airframe or engine performance, the potential for abatement at or below zero cost, with intervention abatement calculated individually, appears to be about 24% of the annual sector total at central fuel prices, with improvements in ATM providing a large share of these benefits.

- These estimates of reductions in emissions consider interventions individually. Emissions savings will necessarily decrease when additivity and overlapping effects between abatement options are taken into account.

- The most cost effective intervention measures in the short to medium term appear to be those associated with: increasing the use of capacity (through for example increased occupancy and consolidation of flights), reducing take-off weight, adopting in flight fuel-saving practices, matching airplanes to the short hauls of the UK sector (through for example increasing use of turbo-prop planes), employing in-situ engine wash maintenance technologies and, by 2020, introducing European-scale ATM improvements that reduce travel distance.

- High fuel prices are likely to encourage early retirement and replacement of airplanes with those that incorporate improved airframe and engine design for fuel efficiency.

- It is difficult to predict the efficacy of intervention measures beyond 2020 that are associated with ACARE compliant standards.
- The estimates derived here should be re-examined for robustness, engaging the aviation community in the process.

Appendix 1 Literature Review

The literature on Aviation and Environment falls under three main aspects, covering: aviation and environmental emissions; costs and benefits of controlling aviation emissions; and the potential inclusion of aviation in a carbon trading regime. The latter necessarily includes reference to the former two aspects.

This appendix uses the recent Omega project 14 literature review as a starting point and adds recently identified additional material of potential relevance to the DfT aviation abatement costs study found to date. The literature review identifies overall objectives, summarises key findings and focuses on material on aviation abatement costs.

Aviation and Emissions trading

CE Delft, "Giving wings to emissions trading", 2005

The study carried out for the European Commission examined the feasibility of including international aviation in the EU ETS in order to mitigate the climate change impacts from this sector. Its objectives included the design of viable policy options and an assessment of their impact.

The design elements included options regarding:

Coverage of climate change impacts – the metrics and policy instruments to address the CO_2 and non-CO_2 effects of aviation.

Geographical scope – the coverage of countries eg intra-EU flights only or all flights departing from EU airports

Trading entity – who would be allowed to trade eg airline, airport, fuel supplier

Allocation rule – whether allowances are set at the EU or member state level.

Interplay with Kyoto Protocol – how aviation can be integrated into the ETS.

Allocation method – whether initial distribution is through grandfathering, benchmarking or auctioning.

Monitoring method – how emissions are measured and reported.

Three policy options were selected for analysis, involving different combinations of these design parameters.

In assessing the economic and environmental impacts of these policy options, allowances prices of \$10 and \$30 per tonne CO_2 were fed in as exogenous assumptions. It was assumed that aviation would be a net buyer of allowances owing to its high abatement costs, with the cheapest emissions reductions available from non-aviation sectors, who sell their surplus allowances to the aviation sector. Consequently the scale of emissions reductions within the aviation sector in comparison with the amount of allowances purchased from other sectors, though their relative share increases somewhat as the allowance price increases.

The study identified emissions abatement measures that the industry might be incentivized to implement, including

- Fleet mix changes – accelerated fleet renewal and purchase of lower emissions aircraft.
- Technical measures ranging from retrofitting winglets, riblets and engines to longer term development of more fuel efficient airframes and engines.
- Operational measures at the individual flight level (eg changes to flight path and speed) or at the network level changes to frequencies, destinations and load factors.
- However the study did not include explicit estimates of the cost of these measures and their viability at different allowance prices.

If the cost associated with emissions abatement or purchase of permits are passed on through higher ticket prices, demand side impacts will arise. These will include an overall reduction in demand and inter-modal switch.

The strength of the supply side incentives will vary according to the policy option under consideration, with the coverage of climate impacts, geographical scope and the allocation method important in determining overall environmental effectiveness.

The results show that the largest share of emissions reductions (ranging from 80% to 99% depending on option and permit price) would be achieved through emissions reductions in other sectors from which allowances would be bought, with only a minor part due to demand and supply-side responses within aviation. In the longer term, CE Delft consider that with stronger supply side responses from technical developments by manufacturers, a somewhat larger share of CO_2 reductions could be achieved within the aviation sector, with a correspondingly lower amount of allowances bought from other sectors.

Potential economic distortions through impacts on the competitiveness of different airlines were considered but judged to be relatively small. It was also found that the potential impact of the inclusion of international aviation on the level of allowance prices would be small.

European Commission, "Inclusion of aviation activities in the scheme for greenhouse gas emission allowance trading within the Community," 2006

This impact assessment builds on the feasibility study by CE Delft and an initial impact assessment produced by the Commission by considering specific design options and policy choices for the inclusion of aviation in the EU ETS. The recommendations cover the scheme architecture, geographical scope, allocation methodology, timing and economic impact. The impact assessment includes no consideration of abatement options within aviation, with the sector assumed to be a net buyer of allowances owing to its relatively high marginal abatement costs.

RCEP, "The environmental effects of civil aircraft in flight: Special report", 2002

This was a response to the DfT consultation paper of 2002 on the future development of air transport. Concerns that environmental problems posed by aircraft may not be given sufficient attention in the forthcoming White Paper form the background to this report. The report considers ways in which these impacts might be avoided or mitigated.

The main findings were as follows:

- It expressed concerns about the contribution that aviation emissions will make to climate change if projected growth was unchecked.
- Ambitious targets for technological improvements represent aspirations as opposed to projections, and in any event will not offset the effects of demand growth;
- Short-haul passenger flights make a disproportionately large contribution to the global impacts of air transport;
- Air freight is more environmentally damaging than other transport modes;
- Policy measures to reduce the environmental impact of air travel included emissions charges, restricted airport development, modal shift with rail promoted as a competitor to short-haul flights, support for technological development and the inclusion of aviation in emissions trading.

The report contains discussion of technological and operational possibilities included blended wing bodies which offered the prospect of fuel savings up to 30% and air traffic management improvements which might produce fuel savings of around 10% from reduced delays and more optimal routeings. It sees kerosene remaining the fuel used for air travel for the foreseeable future. However the report contains no discussion of the likely cost of such improvements.

ICF Consulting, “Including Aviation in the EU ETS: Impact on EU allowance price, 2006

The objective of this study commissioned by DEFRA was to provide a quantitative assessment of the impact on allowance prices of including aviation in the EU ETS.

The study takes as its starting point the CE Delft report, which concluded that the carbon market impacts from including aviation were expected to be relatively small, but potentially larger beyond 2012 with the continued growth of aviation. ICF use their proprietary carbon market model to assess the impact aviation sector trading could have on carbon prices. Using three alternative carbon market scenarios, price forecasts were generated. The results indicated that any increase in demand coming from the aviation sector would cause no detectable change in the price of carbon allowances over the period up to 2012, but noted that with the continued projected growth of the industry, the longer term price impacts could be more significant.

The carbon pricing model draws up demand and supply curves for carbon. The demand side analysis includes emission forecasts by country and sector under various scenarios and compares these against emissions cap applicable to trading sectors for each country. For the supply side analysis, marginal abatement cost analysis is used to provide information about emissions abatement potential and costs for each sector. To derive results to feed into the model, marginal abatement cost curves are aggregated across sectors, with a single abatement cost curve drawn up using abatement options across multiple sectors. Points on the curve were generated using discounted cash flow analysis to estimate the initial capital cost, continuing operating costs and revenue impacts of alternative options. Marginal abatement cost curves are derived by ranking carbon reduction options in ascending order of cost per tonne of carbon equivalent. Points corresponding to a zero or negative unit cost represent measures that pay for themselves. These will include measures with net financial benefits to companies from fuel savings, but which have not been introduced because of technical or institutional barriers. Other measures with positive costs will only be implemented if incentives are offered through tax or other incentives or under a carbon trading regime where permit prices exceed the cost of abatement.

The study notes the dearth of information on the marginal cost and emission reduction potential of aviation sector abatement options, which limits the scope for_considering the scope for mitigation action. However it supports the conclusions of CE Delft indicating that abatement potential does exist within the sector, with the potential for finding cost effective solutions expected to increase over time. Further analysis in developing estimates of the cost and abatement potential of mitigation options available to the aviation sector is recommended.

ACARE (Advisory Council for Aeronautics Research in Europe) “Strategic Research Agenda,” October 2004.

The ACARE initiative identified research and technology opportunities for meeting efficiency, safety, security and environmental objectives within the air transport industry. The original ACARE Strategic Research Agenda (SRA1), published in 2002 identified the following voluntary environmental goals to be achieved by 2020.

- 50% cut in fuel consumption and CO_2 emissions per passenger kilometre .
- 80% cut in NOx emissions.
- 50% reduction in perceived external noise

ACARE envisaged contributions towards the 50% CO_2 reduction target of 20-25% from airframes, 15-20% from engines and 5-10% from optimising ATM. Evolutionary improvements in airframe technology were seen as including aerodynamics, weight reduction and configuration improvements, but more radical measures would include new aircraft concepts. Engine research includes improvements in thermal efficiency and increased bypass ratios as evolutionary measures, but breakthrough technologies might lead to new generation engines, including radical new combustor designs to meet the NOx targets. It saw evolutionary developments likely to deliver less than half the improvements required to meet these ambitious targets, with technological breakthroughs, likely to be both high cost and high risk, necessary to achieve the necessary step change improvements in environmental performance. It pointed to the risk that increased public awareness about the need to protect the environment and the growing contribution of air transport to global climate change, local air quality and noise could result in measures being taken to constrain the growth of air traffic in the absence of effective action to meet the environmental challenge. The reports prepared by ACARE contain considerable detail of potential new technologies applied to airframes, engines and ATM that might contribute towards these goals, but do not address their likely costs. However unlike the other economic studies which focus on abatement options currently available, ACARE addresses potential longer term technological breakthroughs that would be required to achieve these 2020 targets.

A number of steps are recommended to achieve these ambitious goals. These include increasing the efficiency of research programmes, with more collaborative research associations, additional funding from industry and the public purse and appropriate financial incentives to stimulate research.

Frontier Economics “Economic considerations of extending the EU ETS to include aviation, 2005

This report was commissioned by the European Low Fares Airlines Association (ELFAA). It focuses on design issues and impacts of particular relevance to low cost airlines, but in doing so addresses abatement options and their potential environmental benefits. The objective of the study was to provide an objective assessment of the economic issues related to the inclusion of aviation in the EU ETS.

In its assessment of economic impacts, the report argues that a cost benefit framework should be used to assess the case for environmental policy being targeted towards aviation. Once it has been determined that its inclusion in the ETS is the best option, careful design is necessary to ensure that it is included in a way that encourages efficient abatement at the lowest cost. It argues that abatement in other sectors should take higher priority than in aviation, but goes on to add that too little is known about_the shape of the overall marginal abatement cost curve to inform any assessment of the likely effect of the inclusion of aviation on allowance prices. Claiming that by 2030 the aviation share of total EU emissions will be around 5%, it points to the danger of disproportionate attention being paid to aviation. It notes the significant contribution to employment and GDP in the EU made by the aviation industry, with further knock-on implications for other sectors, and expresses concerns about the consequences of environmental measures such as this for new Member States.

Aviation is seen as facing strong commercial pressures to reduce fuel burn due to high fuel prices, with inclusion in the ETS having only a marginal effect in strengthening this. An EU allowance price of €27 per tonne of CO_2 would be equivalent to a 28% increase in fuel cost (2004 prices). Opportunities for abatement are estimated at 17% of all emissions generated by EU flights in the short term, but with half of this attributable to ATM improvements, where the ETS would have no effect, it recommends that the Commission should focus its attention on ATM modernisation initiatives.

Regarding design features, it calls for the scheme to have wide coverage and not be restricted to EU flights in order to maximise its environmental impact and limit distortions to competition. The scheme should be based on robust science, with no attempt to apply arbitrary multipliers to fuel burn to reflect non-CO_2 environmental impacts. Allocation should not be based on grandfathering, but on the basis of benchmarking of industry averages or best practices.

The report assesses likely impacts on airline competition. Because of its higher price sensitivity, the impacts on aviation demand are seen as being larger than other sectors. With their greater price sensitivity the effects on low cost airlines would be larger with demand reductions of 7.5 – 12%.

Abatement opportunities amounting to a one-off benefit of 17% are shown in Table 1. In addition new aircraft replacement would lead to a 1% pa improvement in fuel efficiency to 2010, but with much larger effects from renewals of specific old aircraft. For example Ryanair have estimated a 30-40% fuel saving from replacing their B737-200 fleet with B737-800s.

ATM	8.4%
Airline operational decisions	3.8%
Airline strategic decisions	5.2%

The key factors determining allowance prices are identified as:

- The marginal cost of abatement
- Options available for abatement and the shape of the abatement curve
- Price of other commodities
- The environmental target and the stringency of initial allowances.

Allowance prices may rise significantly above current levels, and may need to in order to promote sufficient abatement activity to meet the Kyoto targets. The impacts of the inclusion of aviation into the ETS are seen as uncertain. If there are many abatement opportunities available, the marginal abatement cost curve will be quite flat, with the allowance price relatively insensitive to the supply of allowances, but if abatement options are limited, allowance prices will be more sensitive.

STRATUS Consulting, "Controlling CO_2 emissions from the aviation sector," November 2005

This study commissioned by the US EPA as an input to the economic analysis carried out in CAEP/5 developed a model to evaluate the costs of a range of policy options to reduce greenhouse gases from aviation. The spreadsheet model developed combined a total abatement curve which ordered the cost effectiveness of emissions control measures in increasing order of costs with a global demand curve for air traffic.

An emissions abatement curve was constructed using assumptions about 9 different emissions control options: their costs, fleet characteristics, CO_2 savings and fleet characteristics. The cost effectiveness of options (cost per tonne of CO_2 reduced) was calculated by aircraft type, size and age. Annual costs and CO_2 reductions were calculated for each emissions control option and plotted according to cost effectiveness, with 7000 observations in total. A demand curve was constructed to enable the impact on airline travel arising from emissions control options to be calculated.

The emissions control options considered were as follows:

- Technological
    - early retirement of aircraft
    - engine replacement
    - retrofitting existing engines
    - installation of winglets
- Maintenance
    - added maintenance
    - reduced maintenance intervals
    - polishing aircraft instead of painting
- Operational
    - reduced fuel tankering
    - reduced flight speed

Two economic instruments, a fuel levy and open emissions trading were considered under alternative emissions targets, involving 10%, 25% and 50% reductions on projected CO_2 growth between 1990 and 2010. For the emissions trading option, permit prices of \$5, \$15, \$25 and \$100 per tonne of CO_2 were assumed.

Some measures were found to be cost effective in their own right in the absence of any policy measures, with the financial savings to airlines from reduced fuel burn exceeding the costs of implementation. Such measures included more frequent maintenance and the installation of winglets on some aircraft. With emissions trading airlines add control options up to the point where their cost exceeds that of purchasing permits from other industries. This level of abatement leads in turn to a demand reduction in response to the additional costs passed on in higher fares. If these emissions reductions arising from abatement and resulting demand impacts fall short of the emissions reduction target, airlines purchase permits from other sectors to bridge this gap.

The results showed that only a small fuel levy would be required to meet the most modest emissions reduction target because 29% of the measures were cost effective in their own right and 85% could be added at zero net cost with a fuel levy. With this target under emissions trading, the permit costs are more than offset by financial savings to airlines with permit prices of \$5 and \$15. Even under the more stringent emissions reductions scenarios, the costs to airlines were much lower under emissions trading compared with a fuel levy. This was because of the ability to purchase permits from other sectors at a lower cost than taking abatement action within the aviation industry.

Babekan, Lukachko and Waitz, Journal of Air Transport Management: "The Historical fuel efficiency characteristics of regional aircraft from technological, operational and cost perspectives" 2002

This article focuses on the impact of regional aircraft on the US aviation system and examines the technological, operation and cost characteristics of turboprop and regional jet (RJ) operations. Regional turboprop aircraft are 40-60% less fuel efficient than larger jets, while RJs are 10-60% less fuel efficient. Since regional aircraft fly shorter stage lengths and spend more time on the ground than larger aircraft, operating costs are higher. In addition they incur higher rates of fuel burn and operate at lower load factors.

While not directly relevant to abatement costs, the results of this study may provide useful inputs to the proposed typology of aviation activities.

Jamin, Schafer, Ben-Akiva and Waitz, Transport Research: "Aviation emissions and abatement policies in the United States: a city-pair analysis", 2004

The background to this article is the rising concern over the contribution of aircraft emissions to local and global air pollution due to increased demand. The city –pair model applied to US domestic routes is used to analyse the change of emissions resulting from three abatement policies: a more aggressive restriction in NOx emissions through technology improvements, the substitution of some short-distance air travel with high-speed rail and the replacement of hub-and-spoke operations with direct flights.

The results show that improved NOx technology could halve the projected growth of NOx emissions to 2030 from 58% to 27%, though with a small CO_2 penalty. The substitution of high speed rail for short haul flights would lead to only modest reductions in emissions. The reduction in emissions from using more direct routeings was found to be limited.

This study throws some light on the feasibility of some abatement options but includes no cost information. The increased use of low NOx engine technology is clearly an important long-term measure. The scope for reduced emissions from substitution from air to rail is likely to be larger in Europe than the US.

Williams, Noland and Tuomi, Transport Research: "Reducing the climate change impacts of aviation by restricting cruise altitudes", 2002

This study identifies the creation of carbon dioxide emissions and high-altitude controls as the key climate impacts of air travel. The formation of contrails could be reduced by limiting cruise altitude, thought this would result in a 4% increase in CO_2 emissions and could result in airspace capacity constraints, particularly in Europe.

ICAO Committee of Aviation Environmental Protection (CAEP). Cost Benefit Analysis of tighter regulating standards for noise and NOx emissions.

Over the past 15 years, a number of cost benefit analysis of options to tighten ICAO regulatory standards governing aircraft noise and NOx emissions have been conducted. These have been used to inform policy recommendations by the CAEP.

Cost benefit analysis has been conducted by comparing the change in the discounted value of costs to airlines with the environmental benefits, estimated by changes in the number of people within the noise contours of changes in the total volume of NOx emissions.

Traffic and fleet forecasts were developed to provide forecasts of numbers of aircraft by generic seat size category. The passenger and freighter fleets were compared against the various stringency options to determine the number of aircraft, or engines non-compliant with each of the options.

For the cost assessment, it was possible to identify whether each individual aircraft or engine passed or failed each of the stringency proposals, based upon its current certified noise or NOx level. The methodology assumed that all non-compliant aircraft would be "fixed" to meet each policy option under consideration. To accomplish this fix, manufacturers estimated the extent of technology development required. Capital and operating cost penalties were estimated. In the case of unproven technologies , operating cost changes were judged to arise from fuel burn penalties, increased maintenance and higher landing charges from additional aircraft weight.

Benefits have been assessed in terms of reduction of pollutants concerned. Emissions reductions have been assessed during the landing and take-off cycle in the context of aviation's contribution to local air quality and for total operations to address climate change impacts. Noise benefits have estimated by number of people removed from the noise contours around airports.

Costs and benefits have been brought together through cost benefit ratios, giving costs per person removed from the noise contours or cost per tonne of NOx reduced. This enables options to be ranked. Sensitivity tests have been applied to consider the impact of changes in key assumptions on the ranking of options.

Holmgren, K. et. al., Swedish Environmental Research Institute, “Greenhouse gas emissions trading for the transport sector”, 2006.

This study focuses on the inclusion of the EU transport sector within the EU ETS. An economic analysis is provided of the impacts of several types of trading scheme on both the transport sector and the industrial sector, incorporating differing levels of sectoral integration. Transport sub-sectors are analysed for the implications of varying choices of ETS design parameters.

In developing sample marginal abatement curves for the transport sector the study assumed that abatement costs were always higher than for the industrial sector. Supporting this was an analysis of tax levels as a driver for emissions abatement, with present taxation for transport at a level of magnitude greater than for industry. Further evidence is provided through reference to a study of the emissions abatement costs for petrol engine cars. Uncertainties in abatement costs were highlighted as an issue, with uncertainty increasing with higher levels of emissions reductions.

No individual aviation emission abatement techniques were specified, but direction was taken from ACARE, DfT and EU sources. The study identified administration costs as cheaper for including aviation in an ETS than for introduction of fuel taxes, although both could result in same cost to aviation sector.

Wit and Dings, C.E. Delft, “Economic incentives to mitigate greenhouse gas emissions from air transport in Europe”, 2002.

This report focuses on economic incentives, other than an ETS, to mitigate greenhouse gas emissions from European air transport. Two types of scheme were identified;

An environmental charge – Under this methodology an aircraft would incur a charge proportional to the volume of greenhouse gas emissions it discharged in the airspace of the European Union. Revenues of €1-9 billion were predicted, along with a 4.4% reduction in emissions through technical/operational improvements, and 4.5% reduction due to drop in demand for air travel.

A performance standard incentive (PSI) - Under this methodology the better an aircraft performed relative to a ‘performance standard’, the more money it would receive, and the worse it performed, the more it would pay. This incentive was designed to be revenue-neutral, with the sum of payments and revenues equalling zero. It was predicted costs may distort air travel prices due to differing impact across market segments. An emissions reduction of 5% by 2010 was predicted from technical and operations improvements.

The legal framework around these incentive schemes was examined, with no barriers to their implementation being identified.

Several sections provide information that is directly applicable to the DfT carbon reduction futures study. Appendix E.6 provides a methodology for the study detailing the generation of direct operating costs, examining the difference between data sources and international charging regimes. Appendix F “supply side measures in greater detail” covers a range of interventions applicable to the UK sector, providing information and references utilized, where possible, in this study.

Arthur D Little, “Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK,” November 2000

This study, commissioned by DfT to inform the 2003 Air Transport White Paper, considered the potential for new technology in enhancing airport capacity and mitigating environmental impacts.

Technology developments until 2030 were predicted to materially reduce the global and local environmental impacts of aviation. Developments of new technologies for improved aerodynamics, materials and engines could offer global and local reduction in emissions, with additional benefits from ATM other operational procedures such as CDA. These technological and operational improvements were forecast to offer fuel efficiency improvements of 2% pa until 2030, though it was noted that these would not sufficient to offset the increase in environmental impacts from the forecast growth in traffic.

The study predates ACARE but contains broadly similar estimates of the potential fuel saving benefits, which are considered by broad category of measure (ie airframe, engine, operational). Unlike the DfT traffic and CO2 forecasts published in 2007, which considers the drivers of and barriers to technological opportunities, this study is more bullish about the take-up of technological opportunities. The study recommends a range of Government policy measures, including emissions trading, environmental charges and tighter regulatory standards for noise and NOx, designed to accelerate the take-up of these technologies. The study does not provide estimates of the cost of environmental abatement measures as this fell outside its scope.

Appendix 2 Emissions from UK domestic flights

Domestic flights have been defined as sectors operated wholly within the UK by airlines having traffic rights on such sectors. The source of data for the following analysis is the OAG for May 2008. This gives all the current sectors operated by airline and aircraft type.

Flights by aircraft type

Table A2.2 ranks the flights by seats offered and by aircraft type. The first 10 types accounted for 83% of total flights and 20 aircraft types accounted for 95% of the total. Table A2.1 focuses on the top ten by seat-kms which accounted for 88% of the total capacity. All these aircraft were jets with the exception of flyBe's turbo-prop Dash 8s. The jets were operated over average sector lengths of between 379km and 470km, and the turboprop over 355km.

Table A2.1 Top 10 aircraft by seat-kms offered, May 2008

Equipment	Seats-kms	Sector kms
A319	402,568,926	470
Dash 8-400	179,325,848	355
B737-800	122,411,920	441
B737-700	96,301,055	421
B737-300	84,733,804	387
A320	94,261,937	460
A321	74,307,110	442
Embraer 195	69,332,681	486
Embraer 145	57,960,356	407
B737-500	45,931,720	379

The largest capacity aircraft in the above table was Ryanair's 189 seat B737-800, with the smallest the regional jet Embraer 145 with only 49 seats. The Dash 8 was operated with 78 seats. In terms of fuel efficiency, the turbo-props in general achieve much higher seat-kms per gallon of fuel, and the larger Dash 8 more efficient than the smaller turbo-props.

In the jet category, economies of scale mean that the B737-800 is much more fuel efficient than the smaller B737-500. In low-cost airline configuration the efficiencies will also be higher due to greater seating density (eg the BA B737-300 offered 121 versus bmibaby 148 seats).

TableA2.2: UK Domestic scheduled air services (May 008)

Equipment	**Flights**	**Seats**	**Seats/flight**	**% seats**
A319	5,967	856,249	143	
Dash 8-400	6,471	504,738	78	
B737-800	1,470	277,830	189	
B737-700	1,537	229,013	149	
B737-300	1,496	219,194	147	
A320	1,286	204,918	159	
A321	913	168,262	184	
Embraer 195	1,209	142,662	118	
Embraer 145	2,878	142,394	49	
B737-500	1,068	121,136	113	83.1
SAAB 340	2,473	84,082	34	
RJ100	567	56,682	100	
Jetstream 41	1,932	56,028	29	
Dash 8	1,196	44,232	37	
ATR72	573	37,885	66	
SAAB 2000	622	31,100	50	
B737-400	189	27,783	147	
BAe 146-300	248	27,280	110	
Fokker 50	437	21,845	50	
Sikorski 61	838	21,788	26	95.0
BNT	1,373	20,786	15	
Jetstream 32	1,004	19,076	19	
Rj85	200	18,964	95	
ATR42	282	18,612	66	
Embraer 135	460	15,180	33	
Dash 8-300	290	14,500	50	
Dornier 328	456	14,136	31	
Twin Otter	694	12,970	19	
B737-300 Winglets	54	7,992	148	
Jetstream 31	385	6,930	18	
LET 410	351	6,669	19	
Dornier 228	341	6,138	18	
Dash 8-200	158	5,688	36	
BNI	530	4,240	8	
BAe 146	9	765	85	
B767-300	1	266	266	
Cessna	17	136	8	
Total	**39,975**	**3,448,149**	**86**	**100**

Flights by airline

The top six airlines accounted for 91% of UK domestic seat-kms in May 2008. The next largest airline was Eastern Airways, which provided only 2% of total UK capacity. Table A1.3 shows that the top three, easyJet, BA and flyBe, accounted for almost two-thirds, with both the first two having broadly similar average stage lengths of around 450 kms. This corresponds to a little in excess of the sector Birmingham/Glasgow, which is scheduled to take 1:10 hours in a regional jet and 1:15 hours in the turbo-prop Dash 8.

Table A2.3: Top 10 aircraft by seat-kms offered, May 2008

Airline	Seat-kms	Sector kms	% seat-kms
easyJet	316,664,909	457	22.6
British Airways	300,672,640	440	21.4
flyBe	285,067,274	377	20.3
bmi British Midland	158,705,042	427	11.3
Ryanair	122,411,920	441	8.7
bmibaby	90,179,792	395	6.4

Table A2.5 looks at the aircraft types operated on domestic services by these top six airlines. easyJet reported that their total fleet currently average only 2.7 years. Their A319s are very new and the most fuel efficient in the required size category. Their B737-700s are older and have not been equipped with winglets. However, easyJet have reported that they intend to return these to various operating lessors over the next 18 months. They have 30 of these aircraft most of which are operated internationally within the EU, with ages ranging from 3.9-7.2 years. They have been leased from a number of different operating lessors including GECAS and Babcock & Brown, and in two years time will all be leased to airlines around the world, mostly likely outside the UK.

The B737-700s incorporate the latest technology available, although they are thought to be slightly less fuel efficient than the A319s over the routes that easyJet operate. They could be fitted with winglets, but easyJet do not own the aircraft and have no incentive to make such an investment (in which the lessor may only wish to take a small share) for the limited time available in their fleet. Domestic routes account for only 16.3% of the seat-kms flown by easyJet's A319, so environmental instruments only applied to domestic capacity or traffic are unlikely to be very effective.

British Airways operate a diverse fleet on domestic sectors, but the largest part is with relatively new and fuel efficient A319s and A321s. Leaving aside their turbo-props which have short field capability which the jets do not have, it may wish to rationalise the fleet regardless of high fuel prices. Domestic routes account for only 5.6% of the seat-kms flown by BA's A319, so environmental instruments only applied to domestic capacity or traffic are unlikely to be effective.

bmi operate B737-300s ranging from 8.1 to 15 years old. This might benefit from winglet installation, since they still have 10-15 years of economic life remaining. However, they are all on operating lease from various lessors and it may be difficult to agree with these companies on the split of investment when the lease term is only assured for another 3-5 years.

flyBe is the most fuel efficient operator of UK domestic routes with a large part of capacity flown by turbo-prop Dash 8s. Domestic routes accounted for 70.7% of total seat-kms flown with this type. It also uses Embraer 195s, which are relatively new and should be best-in-class for this size of aircraft. Clearly larger Boeing and Airbus aircraft are more fuel efficient, but an adequate frequency is necessary on routes with a sizeable business component. A comparison of fuel efficiency by aircraft type for a typical sector length of 450-500km.

Table A2.4: UK Domestic scheduled capacity, May 2008

Airline	**Seats**	**% seats**
easyJet	693,581	20.1
British Airways	682,703	19.8
flyBe	755,452	21.9
bmi British Midland	371,625	10.8
Ryanair	277,830	8.1
Bmibaby	228,272	6.6
Eastern Airways	87,128	2.5
Aurigny Air	50,466	1.5
Air Southwest	43,512	1.3
Aer Lingus	41,586	1.2
EuroManx	40,180	1.2
jet2.com	34,040	1.0
Air France	31,202	0.9
Blue Islands	23,496	0.7
British International	21,788	0.6
VLM	21,600	0.6
Manx2	15,435	0.4
Isles of Scilly	9,082	0.3
Thomsonfly	7,992	0.2
Highland Airways	4,438	0.1
Loganair	4,240	0.1
flyGlobespan	888	0.0

OLT	765	0.0
Atlantic Faroe	582	0.0
Zoom	266	0.0
Total UK Domestic	***3,448,149***	***100.0***

Table A2.5: Top six UK domestic airlines in terms of seat-kms and their fleets (May 2008)

Airline	Aircraft	Seat-kms	% all aircraft
easyJet	A319	220,363,854	15.7
	B737-700	96,301,055	6.9
British Airways	A319	101,846,500	7.3
	A320	29,120,386	2.1
	A321	71,262,714	5.1
	B737-300	5,359,620	0.4
	B737-400	12,648,059	0.9
	B737-500	27,657,568	2.0
	RJ 100	30,736,343	2.2
	RJ 85	288,747	0.0
	SAAB 340	21,134,133	1.5
	Twin Otter	618,570	0.0
flyBe	DHC8-400	179,325,848	12.8
	EMB 195	69,332,681	4.9
	EMB 145	30,116,569	2.1
	Fokker 50	82,798	0.0
	SAAB 340	904,458	0.1
	BAe146-300	3,511,605	0.3
	ATR 72	1,793,315	0.1
bmi British Midland	A319	80,358,572	5.7
	A320	44,194,229	3.2
	A321	677,210	0.0
	EMB 135	5,631,244	0.4
	EMB 145	27,843,787	2.0
Ryanair	B737-800	122,411,920	8.7
bmibaby	B737-300	69,538,454	5.0
	B737-500	18,274,152	1.3
	A321	2,367,186	0.2

Appendix 3 Environmental Abatement Costs for the Aviation Sector

CONSULTATION WITH STAKEHOLDERS

ON THE UK DOMESTIC SECTOR

Background

There is much current interest in helping UK industries to reduce their potential effect on climate change in the most cost effective ways. As part of this, we are researching the scope for actions that can be taken by the aviation sector to reduce its emissions of CO_2 and other greenhouse gases. We are undertaking two parallel studies as follows.

The first study is being undertaken by Cranfield University, under the Omega aviation programme, and is entitled "A framework for estimating the marginal costs of environmental abatement for aviation". This is assessing the cost effectiveness of abatement measures that can help aviation meet its medium and longer term goals. The study held a workshop with key stakeholders in March that considered the applicability, feasibility and effectiveness of a range of abatement measures identified in the literature.

The second study, involving Manchester Metropolitan University (MMU) and Cranfield University, takes forward some further related work for the Department for Transport (DfT). This work again examines abatement options, but focuses on carbon dioxide emissions within domestic UK aviation sector. This work will run alongside the Omega study, utilising some of the contacts, findings and methodology that study has developed.

Purpose

Building on the Omega workshop held at Cranfield University on 6th March, this document aims to further consult stakeholders to address the following issues;

i) to confirm the statements made at the Omega workshop with a wider range of stakeholders,

ii) to seek additional information on the likely magnitude of emissions savings and costs associated with intervention options, and

iii) to seek information on the applicability of abatement options to the UK domestic aviation sector specifically.

Abatement options

The range of abatement interventions presented in this document has been identified from applicable reference sources and review with expert stakeholders. They are grouped into the following broad categories:

- Airframe and engine technology
- Operational improvements
- Fleet management
- Other developments

At the Omega workshop in March, the following criteria were identified in judging the effectiveness of techniques to reduce environmental emissions from aircraft:

- Impact in reducing emissions
- Capital and operating cost of abatement measure
- Impact on safety, airworthiness and reliability
- Operational practicability
- Industry familiarity with the measures
- Customer acceptance

In applying these criteria to the various abatement options identified, the Omega workshop generated a body of knowledge. Reports detailing the workshop outcomes can be found on the Omega website at http://www.omega.mmu.ac.uk/estimating-the-marginal-costs-of-aviation-environmental-abatement-measures.htm

UK Domestic Aviation Sector

In consulting stakeholders again we are **focusing specifically on the UK domestic sector and its CO_2 emissions.** The UK domestic sector is taken to include all scheduled flights which are contained within the UK (including Northern Ireland, the Channel Islands, etc.), as defined by the Kyoto protocol.

Six main operators provide 83% of seat journeys;

- flyBe, Easyjet, British Airways, bmi British Midlands, Ryanair and bmi Baby.

Ten aircraft types provide 83% of seat journeys;

- A319, A320, A321, B737-300, B737-700, B737-800, EMB95, EMB-145 and Dash 8-400.

Stakeholder Dialogue

We realise that different respondents have different experience and knowledge of the sector and we would like you to focus on those topics for which you feel most able to answer. Stakeholder views are sought regarding the following questions:

- **How relevant is this abatement option to your operations, both now and in the future?**

  May be specific to aircraft type or market segment.

- **What is the potential fuel efficiency improvement from this option?**

  Low <0.5% Med 0.5% - 2% High >2%

  If you can provide more specific quantitative data this would be appreciated.

- **What level of costs are associated with employing this option?**

  Estimate Low / Med / High for both capital and operating costs. Again, where possible more specific quantitative data this would be appreciated.

- **What is the likely adoption timescale?**

  Low (next 5 years), medium (by 2022) or high (by 2050) term.

- **What are the likely commercial drivers and their importance?**

  e.g. Fuel costs, market demand.

- **What are the barriers that may work against adoption?**

  e.g. Safety, technical readiness.

- **Are there synergies or interdependencies with other options?**

  e.g. Re-engining limited by airframe type, continuous decent depends on ATM changes.

- **What are the significant knowledge gaps and areas of uncertainty?**

  e.g. technical performance, market conditions.

The attached consultation document contains summary descriptions of selected abatement options and a table for responses to the above questions. This table format is not prescriptive and we welcome feedback in freeform text. We are also keen for details on other relevant issues as you see fit.

Project timescales dictate that we would very much like to receive completed responses by 15th June 2008, or earlier if possible.

If you have any questions regarding this consultation, please contact either

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CONSULTATION DOCUMENT

Airframe and Engine technology

Improvements to existing airframes. - These include the retrofitting of winglets and riblets which are capable of giving modest reductions in fuel burn. Workshop participants considered that the effectiveness of winglets depended on the type of aircraft and the nature of routes flown, with fuel savings from 1 to 4% feasible. This option was viewed as a feasible measure to reduce emissions. Riblets have been trialled on the A340 and were viewed as relatively expensive, but higher fuel prices might make this more cost effective. Also tail cone replacement on older aircraft may improve efficiency. Stakeholder views are sought on the applicability of these and other airframe improvements to the aircraft fleet operated on UK domestic services.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Re-engining. - Stakeholders argued that this option had not been widely used, as there were significant up-front costs of up to 20-25% of the cost of a new aircraft, resulting in the net present value of such an intervention being higher than the cost of acquiring a new aircraft. Re-engining could be effective where new engines were put on relatively new airframes, but even this was costly. Fuel efficiency improvements depend on the relative age and the degree of changes in engine technology, with costs between $5 M and $15 M per engine. Re-engining was viewed as not presenting a viable abatement option at present, but could not be ruled out altogether for the future. It seems likely that these findings apply to aircraft operated on both international and domestic services, but the views of stakeholders are invited.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Engine Retrofits. - This method is often associated with hush kits fitted to meet noise levels standards. However, retrofitting could be used for fuel saving technologies which increase engine efficiency using increased pressure ratios, larger bypass fans, reductions in bleed air and the introduction of lighter materials. Fuel efficiency improvements of up to 3% have been quoted, with costs typically between $0.5 and $1 M per engine. Omega stakeholders considered that retrofits could be profitable over the lifetime of aircraft, with savings in maintenance costs as well as increases in residual values from compliance with environmental standards. Your views on this are sought for domestic services, where it is unclear whether engine retrofits offer a potentially viable option.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

New airframe technology. – A range of technologies are in development that could be employed in airframes to improve fuel efficiency. In the short and medium term alternative materials will allow the light weighting of aircraft interiors and the wider use of composites in fuselage construction, as typified by the B787. A more long term option is the adoption of blended wing technology in passenger aircraft design. Stakeholders are invited to comment on the feasibility, likely timescale for introduction and scale of fuel efficiency improvements associated with developments in airframe technology, including their suitability for domestic flights.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

New engine technologies. - Two alternatives to the current turbofan jet engine technology are turboprop regional aircraft and open rotor engines. Both these technologies offer the prospect of fuel savings of around 20%. Open rotors would involve R&D costs to develop a suitable airframe and manage noise, but the increase to journey times on short-haul flights would be relatively small, making them potentially suitable for domestic operations. Turboprops would involve limited R&D expenditure but the greater journey time penalty means that a balance needs to be struck between lower aircraft utilisation and fuel savings. These issues were only touched with stakeholders at the recent Omega workshop, but views on their potential application to domestic services are invited.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	

Any other comments	

Operational Improvements

ATM improvements - ATM improvements from measures such as Single European Sky offer the prospect of reductions in CO_2 , by allowing more direct routing and reducing delays in EU airspace. However despite delays in implementation, this option is current policy and should be regarded as part of the baseline. Furthermore there is some evidence to suggest that these ATM improvements have had most impact in releasing airspace capacity constraints, resulting in limited reductions in CO_2 and other emissions. We would like to explore with stakeholders the scope for more rapid introduction of ATM improvements on domestic services.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Reduced fuel tankering - Fuel tankering which results in increased aircraft weight and fuel burn is driven by fuel price differentials, fuel quality, the availability of refuelling facilities at airports and turnround times. Omega stakeholders considered that there was scope for significant fuel savings from reduced tankering, which was more prevalent on short-haul services. However it was recognised that the need for rapid turnround times and the resulting pressure on airport refuelling processes represented a barrier to implementation. A fiscal measure, such as a tax on MTOW was felt necessary to discourage fuel tankering, but this falls outside the scope of the study, and in any event may well lead to limited environmental effectiveness if applied to UK domestic flights, resulting in aircraft refuelling at nearby continental airports. The views of stakeholders on the feasibility of this option for domestic services are invited.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐

Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Continuous descent approach - This was viewed by stakeholders as a practicable and acceptable option that will be more popular in the near to medium term. Although this will result in reductions in CO_2 and NOx, stakeholders argued that it could be problematic for some airports with local air quality problems. Further comments are invited on the applicability of this option to domestic flights.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Changes to flight speed and altitude - Stakeholders considered that flying lower or slower was not a viable option for existing aircraft, except at the margins, as they were designed to fly at optimal altitudes and speeds to minimise fuel burn. However there was scope for minimising deviations arising from pilots operating outside optimum fuel burn altitudes and speeds, and there might be some benefits from defining climb speeds that optimised fuel burn (though these would be limited with 90% of fuel consumed outside the LTO cycle). Further views on the applicability of this option to domestic services are invited.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	

Uncertainty	
Any other comments	

Fleet Management

Early retirement of aircraft - This involves replacing old generation aircraft with modern cleaner aircraft. The financial viability of this option depends on relative capital and operating costs of old and new aircraft over their lifetimes. Increasing fuel prices and tighter environmental standards or charging regimes will increase the attractiveness of this option, where old and new aircraft differ considerably in fuel consumption, performance and ability to comply with regulations. Stakeholders felt that for many passenger airlines, this would be a preferred option to extending the life of the existing stock through refits and upgrades. The viability of the option was sensitive to second-hand values of aircraft, and in the view of Omega stakeholders, may need assistance with funding or fiscal mechanisms to reduce the net cost of replacement. Views are invited on the scope for fuel savings and other benefits from the early retirement of aircraft operated on domestic services.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Reduced maintenance intervals - Stakeholders considered that this intervention would be more relevant with increasing fuel prices. Also the abatement of emissions is becoming an issue for manufacturers as part of the service provided. Fuel savings of 2-3% have been quoted for halving maintenance intervals. However engine maintenance is difficult to plan, with up to 80% of repairs/maintenance activities unscheduled. Views are sought on the applicability of this option for domestic flights.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐

Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Reducing required fuel reserves - Stakeholders had mixed views on the feasibility of this option. Some felt that with aircraft more fuel efficient than when fuel reserve regulations were introduced, they could be made less conservative, while others opposed any change on safety grounds, arguing that it was necessary in the event of emergencies. In the light of these conflicting views, further comments are invited for domestic flights.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Use of turboprops - This is considered in new engine technologies, but since the technology exists, it is also included as a fleet management issue. The financial viability of this option will involve balancing savings from reduced fuel consumption against utilisation penalties from lower speeds, which will feed through into lower earning potential. This is a potentially relevant option for some domestic services and views are invited.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Better use of capacity - This option covers measures available to airlines to better match capacity with demand on individual routes, through maximising payload and minimising non-revenue earning flights. In respect to payload, the options of reducing quantities of passenger baggage and goods for sale on flight have been identified as desirable and achievable. Another more fundamental change would be consolidating passengers from competing carriers onto larger aircraft, which would increase load factors, enabling service levels to be maintained at reduced CO_2 emissions. Stakeholders should comment on the feasibility and effectiveness of this option for domestic services.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Other developments

Biofuels - Biofuels are the only viable alternative currently available to the baseline fuel of kerosene with the potential to reduce carbon and NOx emissions. There are concerns that the manufacture of the current generation of biofuels could have adverse environmental effects resulting in increased GHG and global warming, in addition to its implications for agriculture and food prices. Any detailed consideration of these wider environmental impacts falls outside the scope of this study. The feasibility of biofuels for domestic aviation will be explored with stakeholders. This will include the risk of freezing, considered to be less of a problem for short flights and the inter-operability of biofuels with petroleum based fuels. Views on the suitability of this option are sought.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
Adoption timescale	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
Commercial drivers	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Other alternative fuels - Synthetic fuels made from gas or coal, while feasible, do not appear to be viable options, as they would result in increased carbon emissions. Hydrogen is a potential long term alternative to kerosene beyond 2022, but faces considerable technical challenges and would require a life cycle comparison of its global warming effect. The potential for alternative fuels was only touched on at the Omega workshop, so views are invited, particularly on the potential applications of alternative fuels to domestic services.

Operational relevance	
Fuel efficiency gain	Low (<0.5%) ☐ Med (0.5%-2%) ☐ High (>2%) ☐
Extra Costs	Capital – L ☐ M ☐ H ☐ Operating - L☐ M ☐ H ☐
A**doption timescale**	Short (5 yrs) ☐ Med (by 2022) ☐ Long (by 2050) ☐
C**ommercial drivers**	
Barriers	
Interdependencies	
Uncertainty	
Any other comments	

Any other interventions or changes?

Appendix 4 Applicability of Abatement Measures to UK Aviation

This Appendix reviews selected and technology and fleet management options for the abatement of CO2 emissions. It focuses on their potential relevance for the UK domestic aviation sector. Particular attention is given to the early replacement of aircraft.

Improvements to existing airframes: blended winglet retrofit

Not all aircraft can benefit from winglet retrofit. Amongst short/medium-haul aircraft the following are the most popular Boeing aircraft conversions:

- B737-300/400
- B737-700/800
- B757

Airbus A320 family aircraft are delivered with wing tip fences, and further improvements from retrofitting advanced winglets are not viable, mainly because of the lighter structure of the wing (compared to Boeing aircraft).

Aircraft suitable for winglet retrofit, May 2008

	Seats-kms	%
B737-700	96,301,055	6.9
B737-300	84,733,804	6.0
B737-500	45,931,720	3.3
B737-400	12,648,059	0.9
Total above	239,614,638	17.1
Total all aircraft	1,402,009,117	100.0

Source: OAG

The above table does not include any B737-800 aircraft because all the aircraft operating on UK domestic sectors have already have winglets (either retrofitted or on newly delivered aircraft). All the B737-700s are operated by easyJet and all these will be returned to operating lessors over the next two years, to be replaced by A319 family aircraft. They are thus clearly not worth converting.

This leaves only 10% of UK seat-kms served by other Boeing 737 variants. Of those the B737-500 is no longer manufactured and although winglets are available few have been taken up.[20] Almost all the B737-300s are operated by bmibaby on operating lease, with an average age (mid-2008) of almost 13 years. Retrofitting these aircraft faces three problems:

- The payback period would on average only be 7-10 years
- Boeing offers a replacement aircraft with much better fuel burn
- Most operating lessors have installed winglets pre-delivery and not mid contract; there are contractual issues regarding the share of cost each party pays

Finally there remains the crucial question as to whether sufficient fuel savings will be available to justify the investment. Although the aircraft were only operated by bmibaby over a domestic network that averaged around 380km, the airline's domestic B737-300 operations only accounted for 18% of its total seat-kms. Thus most sectors would be considerably longer than the domestic average and winglets might be justified by longer sector EU services. However, if winglets were fitted, the domestic flights alone would scarcely provide much fuel saving, given the weight of the winglets and resultant increase in fuel used and the short distances over which cruise fuel savings could be accrued.

The overall conclusion from the above analysis is that winglets offer negligible savings in fuel on domestic UK sectors, mainly because of the operations of new fuel efficient jet aircraft (some already fitted with winglets), and the use of turbo-props on many shorter sectors.

Improvements to existing engines: replacement engines

Jet aircraft are initially offered with one or more engine types. This is particularly true of long-haul aircraft such as the B767, which is certificated with three different engines made by three different manufacturers. However, short/medium haul aircraft are usually offered with one or two engine types at most. The A320 family can be operated with either CFM56 or IAE V2500 engines. The B737 aircraft on the other hand are only offered with CFM56s.

Decisions on which engine to choose will depend on many factors including the use of specific engine types on other aircraft in the fleet. Some engines perform better over shorter sectors, and the airline may have emissions charges at its main base that leads them to invest in a specific low NOx engine.

If an airline operates an aircraft on a short-term lease it will often have no choice of engine, and changing the type would be prohibitively expensive. Even if it is owned outright, a change in engine type subsequent to purchase is likely to be expensive and the fuel or other savings possible unlikely to be significant enough to be economic.

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[20] The B737-500's replacement the B737-600 is offered both with and without winglets.

Improvements to existing engines: engine upgrades

Various engine upgrades are available which modify existing engines to improve performance. One example is the CFM Tech insertion package for their -5B and -7B engines. These were available from 2007 and promised lower fuel burn, improved NOx and lower maintenance costs. For UK operators this only applied to easyJet's A319 fleet (see table below), but its engines already incorporate this technology

Jet engine types operated by major domestic airlines, July 2008

British Airways	737-300	CFM56-3B-1
		CFM56-3B-2
		CFM56-3C-1
	737-400	CFM56-3C-1
	737-500	CFM56-3C-1
	A320-200	V2527-A5
	A319-100	V2522-A5
	A321-200	V2533-A5
easyJet	A319-100	CFM56-5B5/P
	737-700	CFM56-7B-20
		CFM56-7B-24
bmibaby	737-300	CFM56-3B-1
		CFM56-3B-2
		CFM56-3C-1
	737-500	CFM56-3B-1
		CFM56-3C-1
bmi British Midland	A319-100	V2522-A5
	A320-200	V2527-A5
	A321-200	V2533-A5

Early retirement of aircraft

Three factors will be important in determining whether emissions can be reduced in the short/medium term by early retirement and replacement of owned aircraft: first the availability and efficiency of replacement aircraft, and second the age of existing aircraft. The first assumes that the retired aircraft will be replaced, and the airline is not merely downsizing. The second depends on the aircraft having completed a sufficient number of hours and cycles to be able to spread the fixed costs of acquiring the aircraft type, and the relationship between the replacement aircraft price and the residual value of the retired aircraft.

Aircraft on operating lease can in theory be retired upon expiry of the lease term without penalty, although the lessor will normally try to offer an attractive lease rate to extend the lease period. Furthermore, high fuel prices and emissions charges and taxes will tend to push up lease rates for fuel efficient aircraft and depress less efficient types such as the B737-300/400s.

In terms of the efficiency of the replacement aircraft, the Boeing jets operated in the UK fall into two categories: the so-called ‘classics’ and the ‘new generation’ aircraft (NGs). Broadly, each of the classics has a NG equivalent: B737-600 is close to the older B737-500, the B737-700 replaces the B737-300 etc. Southwest operated B737-300s and B737-700s in 2006, both with 137 seats. Its -300 consumed 763 gallons of fuel per block hour, 7% more than its -700s, but operating over somewhat shorter sector lengths.[21] Thus the improvement from this smaller step change in technology is only between 5-10%. What airlines like SAS are waiting for is the larger step change from its MD-80s (roughly equivalent to older B737-300s) to the B737NG/A320 replacement aircraft expected between 2015 and 2020. This should give a further gain in fuel efficiency of 15-20%, giving an improvement over the MD-80 of around 20-25.

Jet aircraft fleet average age at 30 April 2008

Airline	Aircraft	Average age (years)*	% of total seat-kms
easyJet	A319	2.5	16
flyBe	DHC8-400	2.9	13
Ryanair	B737-800	2.7	9
easyJet	B737-700	5.5	7
British Airways	A319	7.6	7
bmi British Midland	A319	2.8	6
British Airways	A321	2.6	5
bmibaby	B737-300	12.6	5
flyBe	EMB 195	0.9	5
bmi British Midland	A320	6.7	3
Total above			75

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[21] The Airline Monitor, Vol.20, No.3, August 2007 (based on US DOT Form 41 data).

From the above table it can be seen that only the following airline's fleet averaged over three years:

bmibaby's B737-300s: 12.6 years
British Airways' A319s: 7.6 years
bmi British Midland's A320s: 6.7 years
easyJet's B737-700s: 5.5 years

Excluding easyJet's B737s which are to be phased out over the next two years these only accounted for 15% of total UK domestic seat-kms. bmibaby's B737-300s are almost all on operating lease and could theoretically be switched at the end of the contracts, but at a cost. Since they operate in a very competitive market that is almost entirely driven by cost, this could be unacceptable, especially since they do not have the very low aircraft costs that easyJet and Ryanair obtained by timely orders of large numbers of aircraft. Furthermore, replacing them with B737-700s might only give them a 10% increase in fuel efficiency at best, probably less on the short domestic sectors.

The A319s and A320s in the above table do not have more economical replacements available.[22] By the time a replacement can be delivered, say in 2018, they would both be 3-8 years away from the normal retirement age of 20-25 years. Earlier retirement would depend on the timing and economics of the replacement aircraft for the A320/B737NG families. Using a simple fleet planning model, the net present value cost advantages of replacement were estimated over 15 years, with the following assumptions on the oil price:

Oil and fuel price assumptions

	Base year (08)	*2010*	*2015*	*2020*	*2025*	*2030*
Oil price: US$ per barrel	107	85	90	95	100	105
Aviation fuel: US$ per US gallon	3.41	2.71	2.87	3.03	3.19	3.35
Percent pa change			1.1	1.1	1.0	1.0

This base case was the high scenario from the BERR forecasts with the 2008 price taken from IATA's latest estimate for the average aviation fuel price for the full year 2008.

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[22] Newer aircraft of the same type would not give much advantage in terms of fuel efficiency.

Assumptions for operation of existing A320/B737 family aircraft

	Base year	***Year 1-5***	***Year 6-10***	***Year 11-15***	***Year 16-20***
Aircraft related:					
Capital value	Market value				
Value depreciation pa	As graph				
Annual hours pa/change	3,000	0.0%	-1.5%	-1.5%	-2.0%
Fuel costs:					
US gallons/hour	767				
Fuel burn deterioration		0.0%	0.5%	0.5%	0.5%
Fuel price (US$/gallon)	3.41				
Fuel price escalation pa		1.1	1.1	1.0	1.0
Maintenance costs:					
Cost per block hour	821				
Maintenance cost escalation pa		1.0%	2.0%	3.0%	4.0%

The above assumptions reflect cost increases for ageing aircraft. The decline in hours operated per year compared to the new or replacement aircraft (see below) is made up by wet leasing aircraft to operate the missing hours. This ensures that the same market can be served by the two options.

Assumptions for operation of replacement aircraft

	Base year	***Year 1-5***	***Year 6-10***	***Year 11-15***	***Year 16-20***
Aircraft related:					
Capital value	Market value (US$77m excluding spares etc)				
Value depreciation pa	As per graph				
Annual hours pa/change	3,000	0.0%	0.0%	0.0%	-0.5%
Fuel costs:					
US gallons/hour	-25%				
Fuel burn deterioration		0.0%	0.0%	0.0%	0.5%
Fuel price (US$/gallon)	3.41				
Fuel price escalation pa		1.1	1.1	1.0	1.0
Maintenance costs:					
Cost per block hour	663				
Maintenance cost escalation pa		0.5%	0.5%	1.0%	2.0%

It can be seen in the above table that the base case fuel efficiency improvement was taken to be 25%, in line with ACARE and other predictions. The table below presents possible future net present value cost benefits of replacing existing fleets 5, 10 and 15 years into their useful life. This is then compared to the net capital cost for the new aircraft. It can be seen that the newer aircraft is actually cheaper on a present value cash basis because of the higher cash value of the existing aircraft that can be sold or traded in against the replacement cost. This is sensitive to second hand aircraft values that have been based on Graph X (to be supplied). This takes into account past price behaviour, including the impact of new more efficient aircraft on existing values (eg the B737NGs on the B737 classics). However, it may not adequately take into account any step change in technology that the replacement aircraft might have. In this respect the ACARE targets do incorporate such a step change (eg blended wing designs) but this is unlikely to be available by 2020 or even 2030.

Assumptions for operation of replacement aircraft

Present values (US$m)	*@5 years*	*@10 years*	*@15 years*
Cash operating expense: new	172.8	172.9	172.9
Cash operating expense: old	194.3	199.9	201.0
Difference	21.5	27.0	28.1
CO_2 emissions saved (tonnes)	26,837.0	28,266	30,071
Capital cost less residual value $m			
New aircraft (incl. spares/training)	82.5	82.5	82.5
Old aircraft	56.7	38.5	19.3
Net cash required	25.8	44.0	63.2
NPV cost $m	4.3	17.0	35.1
Abatement US$ per tonne	161	601	1,168
Abatement UK£ per tonne	82	306	596
Exchange rate US$ per £	1.96	1.96	1.96
Annual av. cost/seat-km (US cents)			
New aircraft	7.9	8.0	8.0
Old aircraft	8.4	9.0	8.8
Percent difference	-5.5	-11.1	-9.1

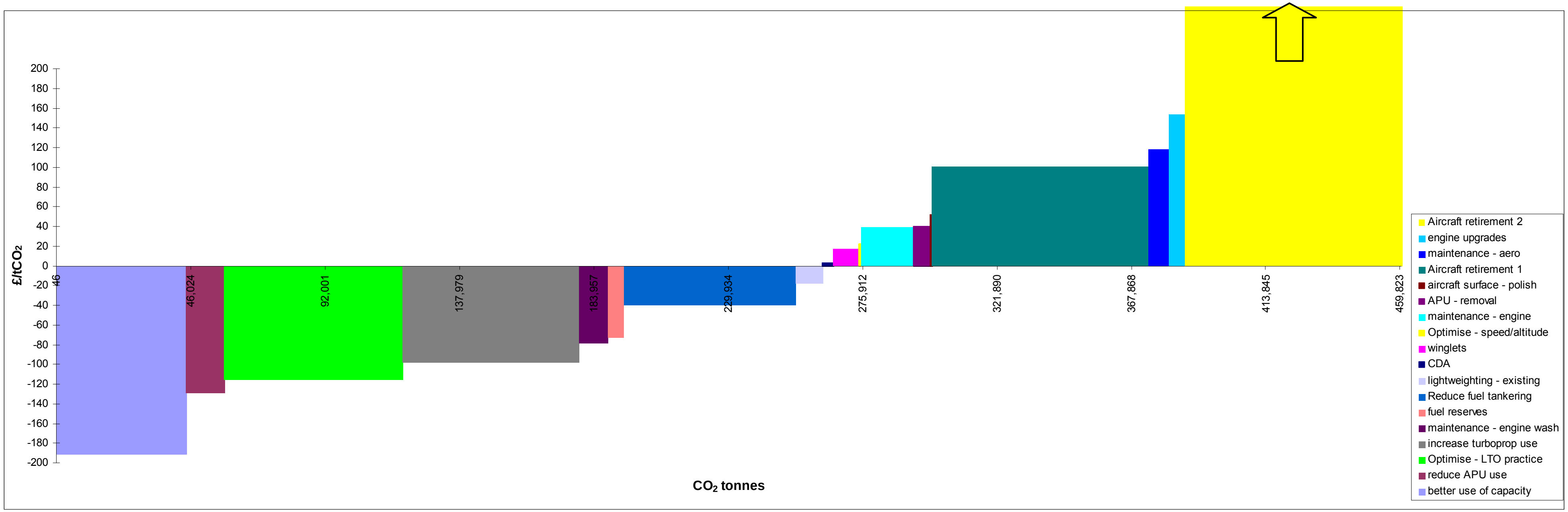
Replacement of jets with turbo-prop aircraft

Given that sector lengths on UK domestic routes average less than 500 km, the substitution of turbo-props could give significant emissions benefits with little economic penalty to operators. This could be done by replacing regional jets with no frequency change, or larger jets with important implications for frequency.

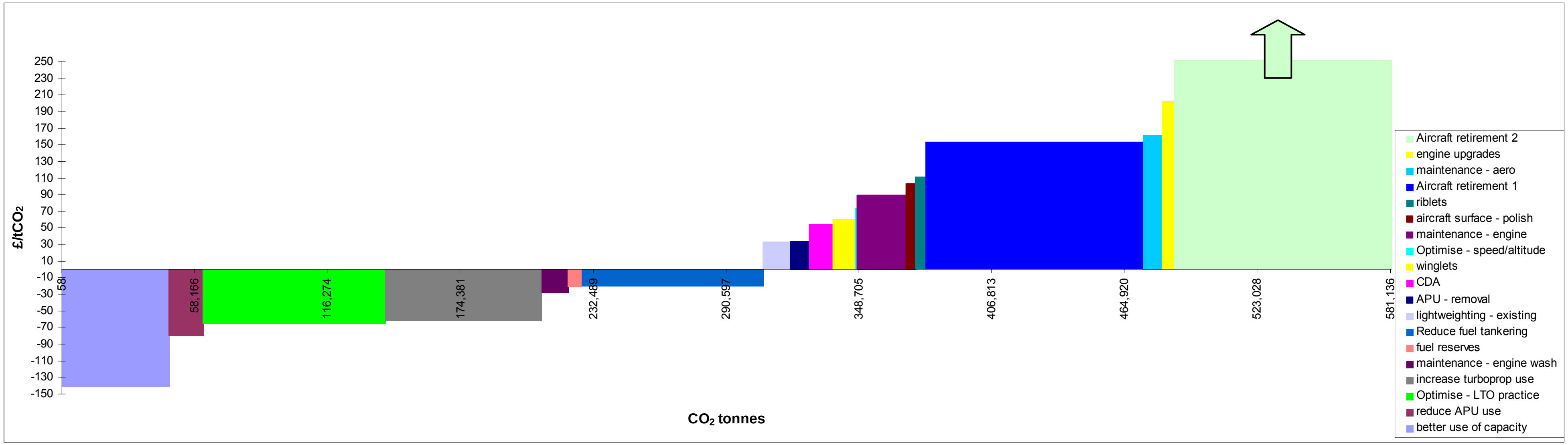
Regional jets of less than 50 seats only accounted for 5% of total seat-kms (Embraer 135s and 145s). These were operated by bmi and have average ages of between 6-8 years. Disposing of them in the near future would thus result in a large economic penalty, especially since other operators may also be sellers of the same type

Appendix 5 : MAC Curves for UK Domestic Aviation Sector, by year and oil price scenario

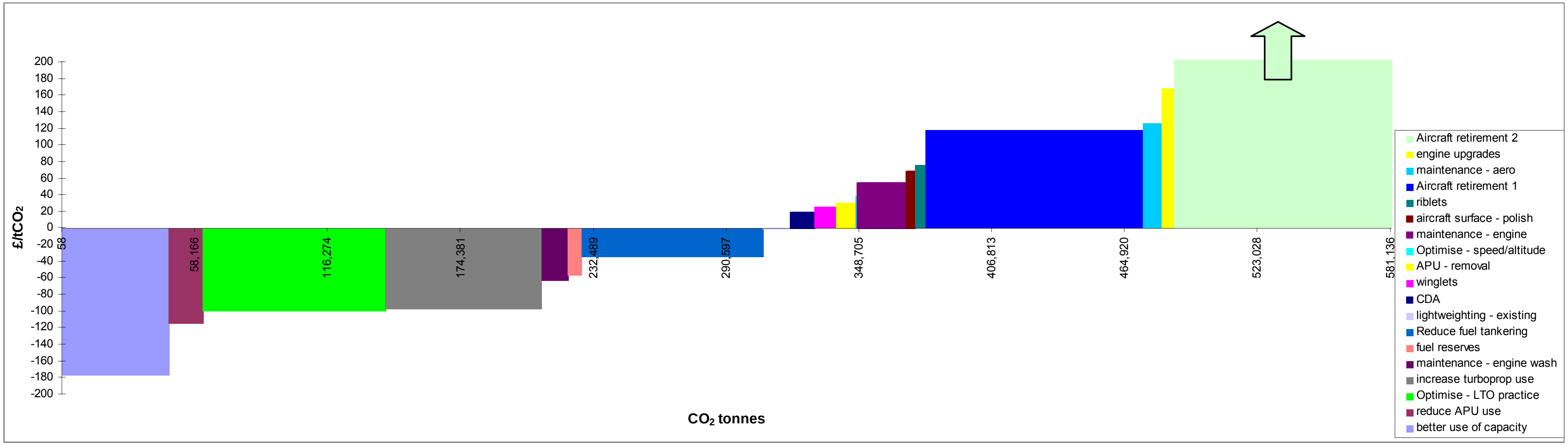
2007: prevailing oil prices : US$73/brl



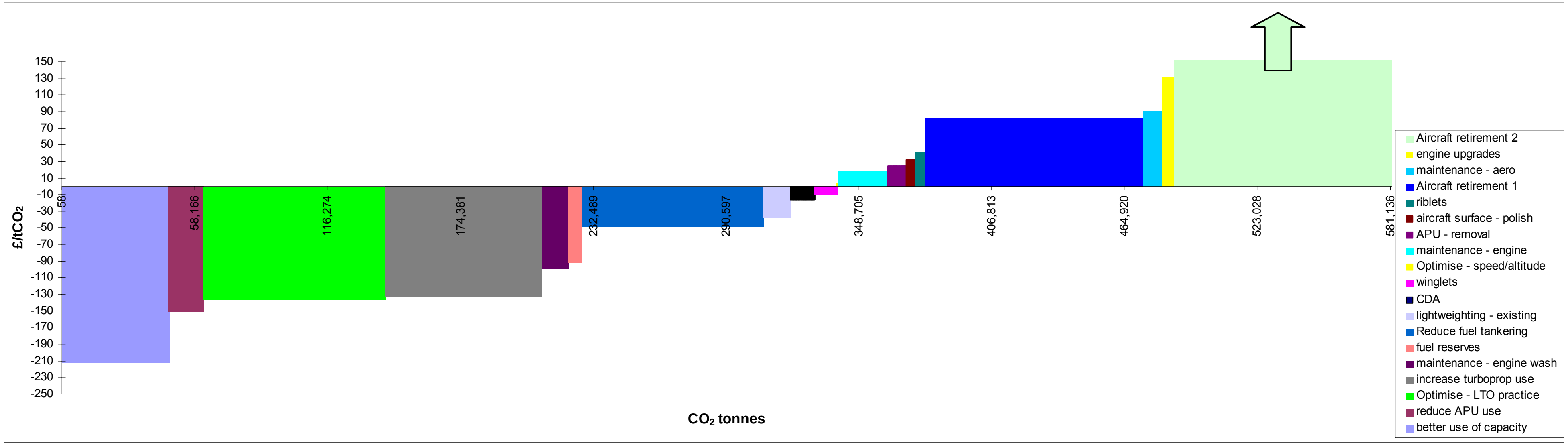
2012 low oil prices: US$45/brl



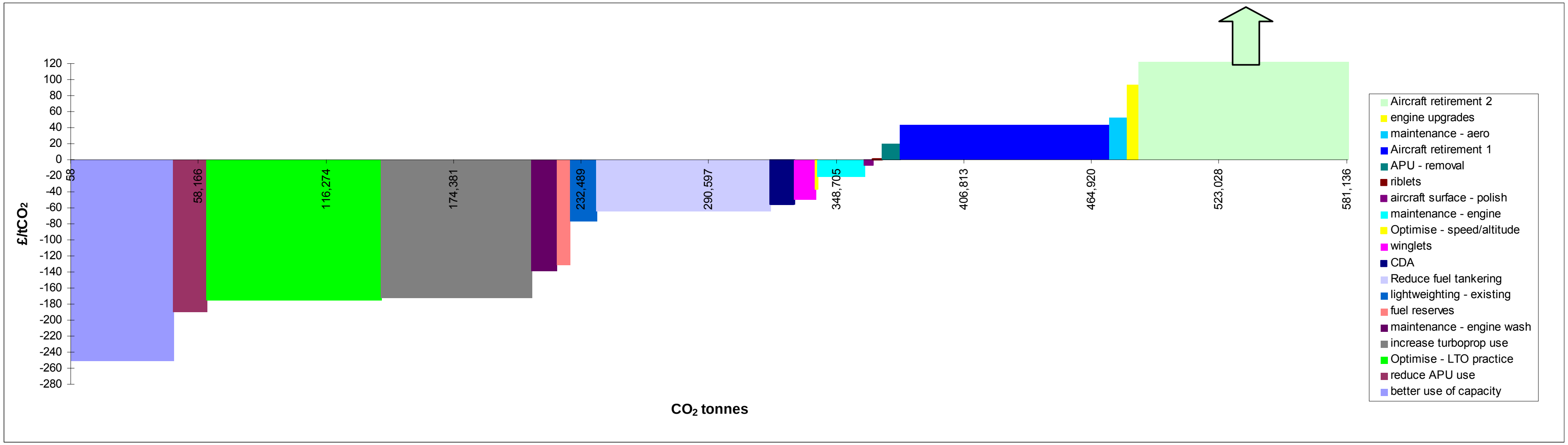
2012 central oil prices: US$67/brl



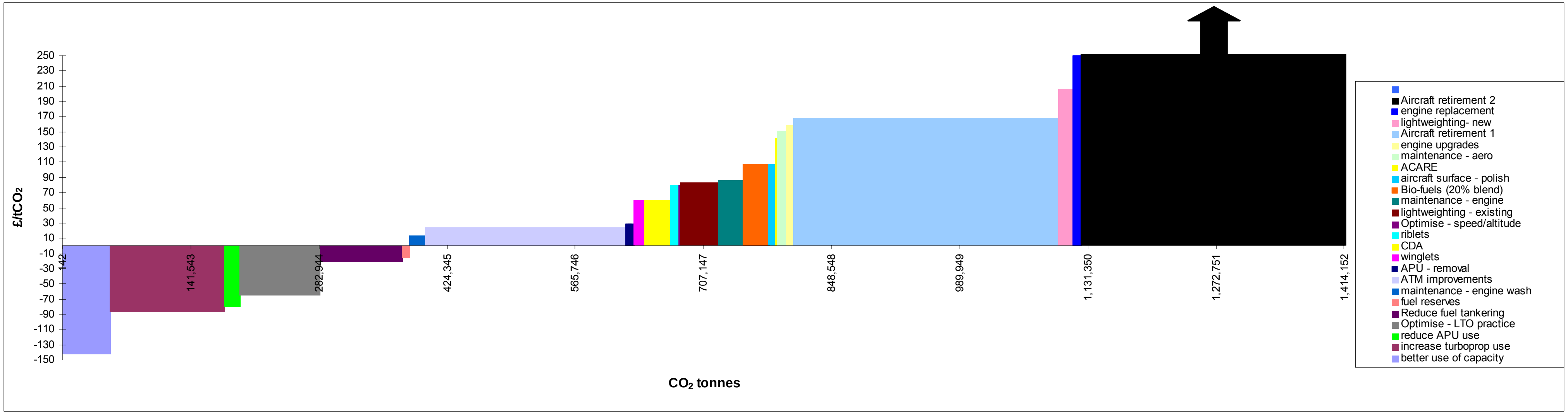
2102 high oil prices: US$87/brl



2012 very high oil prices: US$116/brl



2020 low oil prices: US$45/brl



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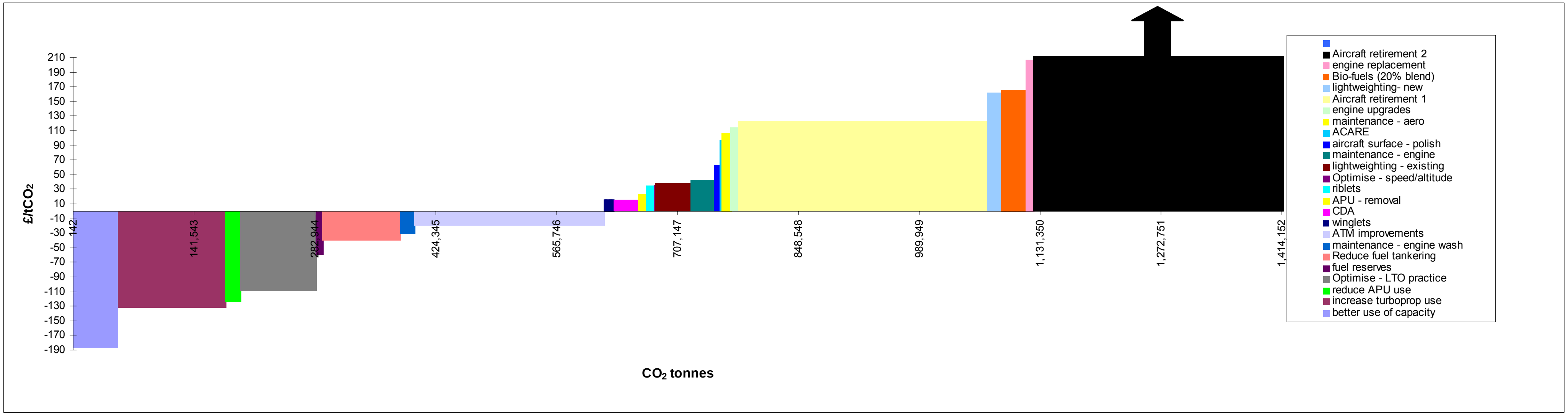
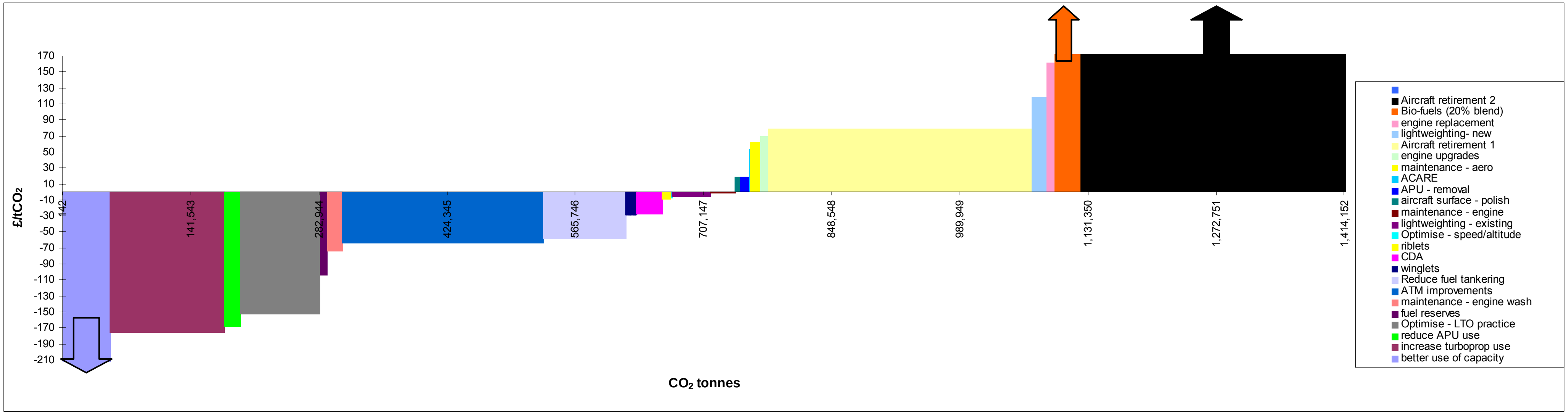
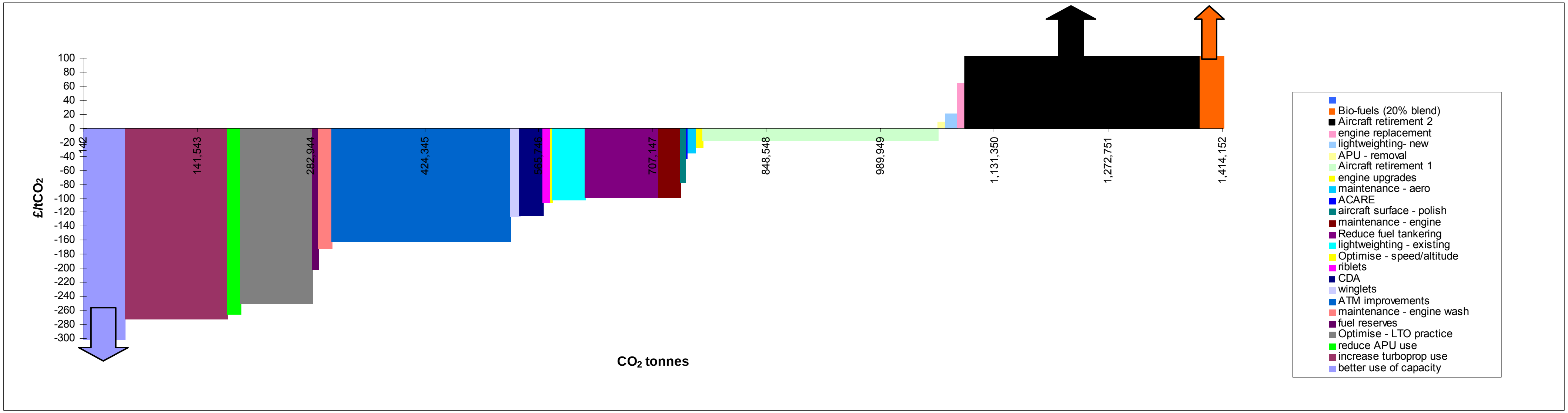


2020 high oil prices: US$95/brl



2020 very high oil prices : US$150/brl



Appendix 6 : Abatement Interventions: technical knowledge and major assumptions.

This appendix provides detailed information about the abatement interventions used in the study. Each intervention has relevant information highlighted in a series of bullet points. The first points are technical information identified as agreed knowledge, the second set of points are assumptions made on the intervention for the purpose of study. Due to the often-sparse nature of information availability, many assumptions are made within the study and can relate to the effectiveness, applicability and/or costs. Source references are supplied where applicable, and are collated in a reference list at the end of the appendix.

Technology based interventions

Winglets

- The addition of wingtip extensions to wings in order to reduce drag.
- Technology is now available as both an option and original fit to new aircrafts, dependent on type, whilst retrofit to some existing aircrafts with an aftermarket upgrade.
- A developing range of Boeing aircraft can accept winglet upgrades, however Airbus are still conducting research development into winglets due to their aircrafts need for additional wing strengthening.
- Winglet principles are now embodied into aircraft wing design by most manufacturers as standard practice
- Effectiveness is focused to cruise phase of flight, limiting overall carbon reduction for shorter domestic sector journey lengths, where cruise flight phase is often very short.

Assumptions

- Capital costs of £400 000 and maintenance increase of £8 000 per year (Aviation partners Boeing, 2008).

- Take-up includes leased aircraft being fitted with winglets as opportunities allow.

Riblets

- Aftermarket adhesive film suitable for aircraft surfaces which reduces drag of aircraft by providing small linear grooves along outer surfaces which reduces air turbulence (Viswanath, 2002).
- Riblet coatings are in development by 3M, with previous trials in conjunction with Airbus showing long term maintenance issues, with an expected life span of 3 years.
- Research development being revisited at present in light of high fuel prices.
- Effectiveness is focused to cruise phase of flight, limiting overall carbon reduction for domestic sector journey lengths.

Assumptions

- Would be fitted to 50% of aircraft surface
- Weight taken as twice that of paint for same area, and reduces efficiency gain accordingly.
- Cost £200/m^2 and linked to OEW for calculations
- Maintenance costs at 10% of capital cost per year

Lightweighting- new aircraft

- The increased use of lightweight materials and systems, such as composite airframe materials and replacement of hydraulic with electrical systems, built in at the design stage for new aircraft.
- Expected to be future manufacturing standard, and presently represented in military aircraft and commercially by Boeing 787 ‘dreamliner’.

Assumptions

- Extra 10% on aircraft capital cost

- Increase to 65% composite use by 2020, represents a 10% weight reduction on OEW (Greener by Design, 2005).

Lightweighting – existing aircraft

- In-service aircraft can have onboard systems modified to incorporate lighter components, eg. seats, galley (remove/minimise/new design), trolleys, carry less water for tiolets, carpets and at more extreme level galleys and cabin fittings (Stakeholder interview, 2008).
- Fleet makeup and operator type (low fair airline) determine the potential and desire for range of measures to be employed, eg. inclusion of first class demands larger heavier seats and supporting galley services.

assumptions

- 2kg/passenger light weighting achievable now. Includes seats (1,35kg each), trolleys (60kg total/aircraft), carpets and magazines. Costs were taken as an additional £500/passenger, assuming they are done at the same time as scheduled refit (Carlsson, 2008).
- 5kg/passenger light weighting achievable in from 2020. This includes measures stated previously and also special light weighted galleys and developments in seats and cabin. Costs were taken as an additional £1750/passenger, assuming they are done at the same time as scheduled refit.

Blended wing

- Long term future development of aircraft integrating the fuselage with the wings, for increased volume efficiency.
- Not applicable to short haul flights and not used in this study

Aircraft surface – polish

- Reducing paint on plane to protective minimum and polishing the remaining aluminium to reduce weight and maintain optimum drag (Green Sky, Apr 2008).

- Average 0.2% increase on net DOC's, at 1998 fuel prices, for polished aircraft, due to increased maintenance from polishing (increased washing and up to 3 polishes/year).

- Decision to paint or polish will be highly influenced by the operator's policy on marketing and branding.

Assumptions

- Weight reduction from maximum polished surface is 0.2% of OEW for single isle short haul aircraft (Hansen, 1999).

- 1.5% increase in annual airframe maintenance costs, to reflect washing and polishing.

- For average single aisle aircraft (A320) capital cost of strip and lacquer £40 000, with other aircraft linked to this cost by passenger numbers.

- Drag improvements were unidentified and not included in calculations.

Engine replacement

- Limited range of engines applicable to aircraft in present fleet, with little difference in standard performance (Air Commerce, 2008).

- Many aircraft leased and would need special financial arrangement to make worthwhile.

Assumptions

- This intervention represents replacement worn engines with similar type new engine, requiring no airframe modification.

- Capital costs of replacement are 6% of initial aircraft purchase price.

- Benefits from reduction in engine maintenance costs of 15% and reduction in fuel burn by 5%.

Engine upgrades

- Upgrades to engines are often supplied through service packages, further hiding costs as separate figure.

- Upgrades can be focused to benefits other than fuel use reduction, such as noise or NOx reduction.

- Through the lifetime of an engine family the manufacturer will introduce several ‘upgrades’, to introduce latest technology, enhance performance and extend engine family lifespan.

Assumptions

- On average upgrades provide 1% reduction in overall fuel burn.

- Capital costs of upgrade taken as 15% of new engine costs.

- Upgrades lower engine maintenance costs by 5%.

Open rotors

- Mid term future engine development that promises fuel burn reductions over present turbofan engines of 30% (SBAC, 2008).

- Problems with noise and fracture risk from external blades.

- Expected to increase journey time, but still highly suitable for domestic/European markets.

Assumptions

- Annual engine maintenance costs increase by 10% of capital cost, £400 000.

- Development costs drive an increase in capital cost for single aisle turbofan aircraft of £4 000 000.

- Crew costs will increase by 25% due to extended journey times.

APU – removal

- The APU is a small turbofan jet engine, usually in the tail of the aircraft, used to provide power when main engines are not running, or back up whilst main engines run (US FAA, 1995).

- The general use for APU is to provide electricity and air conditioning whilst at the airport gates with main engines off, and to start the main engines.

- Airports can supply electricity and pressurised air, either directly to the gate or by portable generators brought to the gate, however, these facilities are not presently widely available.

Assumptions

- Aircraft APU can be removed, with no detriment to the aircraft ability to fly and with airports providing the required power at gate.
- The average weight saved on removal of APU is 195kg, which includes oils and fittings.
- Carbon savings will be generated from weight removed only, as carbon will still be used to generate the power taken from the airport gate.
- Annual engine maintenance decreases by 1%.
- Airport charges will rise by 10%.

APU - tech replacement

- Research is underway to replace the APU turbofan engine will alternative technology; hybrid and fuel cell concepts.
- Insufficient information was available on the performance of these alternatives and the intervention was not used in this study.

Bio-fuels

- Bio-fuel uses grown or waste biological matter, which takes up CO_2 in its growth phase, making these fuels effectively carbon neutral.
- Various generations of bio-fuel are in development, and classification is dependent on the base ingredients and production method.

Assumptions

- The bio-fuel used could involve so-called first generation-type fuels (based on conventional crops such as cereals and sugar beet), second generation-type (such as purpose grown miscanthus/switch grasses) and third generation-type based on controlled bacteria and algae production. In the long term , these latter sources are predicted to make the greatest contribution to sustainable bio-fuels.

- The bio-fuel would be blended with present carbon based aviation fuel, and would not require any special modification of the aircraft engine, other than possibly demanding increased maintenance.
- Bio-fuel is created from a renewable resource and its use is assumed to be carbon-neutral. The emissions from fuel manufacture are not included and are covered by other sectors.
- Aviation fuel will start to be adopted by 2020, with fuel available incorporating an assumed 20% bio-fuel blend.
- Bio-fuel is more expensive than aviation Jet-A fuel, with a 50% price up lift on the bio-fuel fraction of the bio-fuel blend aviation fuel.
- Bio-fuel has a lower energy value for equivalent volume of 35 MJ/kg, against the 44 MJ/kg of aviation Jet-A fuel.
- Factoring in the extra fuel weight necessary to carry out the same amount of work, due to reduced overall fuel energy value, the net saving in carbon is 12.3%.

Alternative fuels

- Whilst concepts for alternative fuelled aircraft exist, such as supersonic high altitude hydrogen aircraft, they are at a very early stage.
- Small scale development testing is assessing concept technologies, but lacks any clarity on expected performance or costs.
- This intervention was not included in the study due to lack of applicable information.

Optimised aircraft design

- Present short and medium aircraft, of the types used in the domestic market, have a maximum range that is much greater than utilised. This means that the airframe and engines are overdesigned for their end use, with the resultant extra weight carried on flights reducing fuel efficiency.

- Turboprop engines have been shown to have better fuel efficiency than turbofan engines, with up to 30% less fuel burn (Babikian et. al., 2002). This benefit is balanced against their increase on flight time and engine maintenance costs.

- It has been suggested by stakeholders and the aviation press that in light of recent fuel prices their exists the potential market for new single aisle aircraft, carrying approx. 150 passengers, with a design focused to short haul distances and utilising appropriately sized turboprop engines (Flight International, 2008).

Assumptions

- The optimised aircraft would achieve a fuel burn reduction of 30%, through both airframe and engine design choices.

- Development costs would be reflected in an addition on purchase price of 25% over equivalent present aircraft.

- This aircraft would be available for service by 2020.

Operational based interventions

ATM improvements

- Future major improvements in ATM will be brought to the UK domestic sector through the introduction of the Single European Skies (SES) program (Chesneau et. al., 2002).

- SES is scheduled to be introduced over 2013-2020, at an anticipated cost of €30 billion.

- The expected benefits for reduction in overall fuel burn range from 6-17%, depending on source (Penner et. al., 1999), but include:

    - 4D trajectories – facilitating direct routing and continuous decent to time specific landing slots.

    - Required Navigational Performance (RNP) – adoption of aircraft technology that enables SES participation.

    - Provision of more direct routing, reducing fuel burn.

- Reduced space between traffic, allowing for flight at more fuel efficient altitude.

Assumptions

- SES and ATM benefits will be operational and effective by 2020
- Overall fuel burn reduction achieved will be 10.5%, taken from Eurocontrol figures.
- Capital costs of £250 000 would upgrade avionics, with annual upgrade costs of £25 000.
- Navigation costs will rise by 30%.
- Annual training costs of £20 000.
- Block hour costs will be reduced due to less flying time.

CDA

- Some CDA activities can be conducted without waiting for SES to be fully implemented (Clarke et. al., 2006).
- Requires that airport and aircraft have requisite technology, and airport is not in very busy airspace.

Assumptions

- Potential fuel burn reduction of 38% only relates to the descent phase of flight.
- Capital costs of £75 000 relate to the aircraft
- Extra operating costs include maintenance, training, block hours and monitoring.

Optimise - speed/altitude

- Any aircraft has an optimum speed and altitude to achieve the best fuel consumption.

- Demands to meet landing slot times or requirements from ATC on flight plan work against this optimum.

- Due to rising fuel prices it is becoming standard practice for pilots to program their aircraft FMC for the most cost effective route.

Assumptions

- Potential benefits across climb, cruise and descent reflect limited scope for improvement in present high fuel cost environment (Henderson, 2005).

- Costs are generated from increase in crew training and from the increase in journey time effecting block hour costs.

Optimise - LTO practice

- Various techniques exist to reduce emissions from the LTO cycle (Pilot interviews, 2008), which include:

    - Single engine taxi, starting engine 4 minutes before take off thrust.

    - Reduced thrust take-off, dropping from 100 to 85% thrust.

- The adoption of these practices requires pilot training and technically capable aircraft.

Assumptions

- The amount of fuel saved from these practices was estimated using ICAO engine performance data to identify an average saving for a range of applicable engines.

- Associated costs are due to crew training and slight increase to journey time.

Reduce fuel tankering

- Fuel tankering is the practice of carrying enough fuel for a continued set of journeys, avoiding the need to take on more fuel at destinations. However this practice adds weight and increases fuel needed for journey distances.

- Fuel tankering is undertaken for several reasons (Cames, 2006; Pilot inteviews, 2008):

- high airport fuel prices, driven by poor supply infrastructures and monopolies
- a desire to your aircraft fill fleet from one depot which contains cheaper hedged fuel.
- to facilitate a quick turn around at destination airport.

Assumptions

- Reducing tankering will reduce the fuel an aircraft carries by 25%, with the overall reduction in journey fuel burn calculated based on the associated weight saving.
- Extra associated costs come from the premium on the replacement fuel bought at the destination airport and an increase in block hour operating costs due to increase turn around time.

Fleet Management based interventions

Aircraft retirement

- The retirement of an aircraft from that operator at an earlier than usual schedule and replacement with a more efficient, new aircraft.
- Aircraft retirement 1 replaces after 5 years service, and aircraft replacement 2 replaces after 10 years service.
- These interventions were based on knowledge from experts, covered in more detail in Appendix 4.

Assumptions

- The replacement aircraft would provide a saving in fuel of 15% before 2020, and of 25% from 2020 onwards, reflecting the availability of ACARE compliant aircraft.
- The replacement aircraft would bring an associated reduction in maintenance costs.

Maintenance – engine

- Increasing the regularity of engine maintenance will limit the degradation of engine fuel consumption, reducing overall fuel burn.

Assumptions

- Fuel burn reduction of 1.2% achieved through increased engine maintenance.(Henderson, 2005)
- Extra costs are incurred from both direct and indirect maintenance, and extra downtime.

Maintenance – aero

- More frequent airframe maintenance will reduce aerodynamic deteriation, and through the effects of drag, will limit the degradation of fuel consumption, reducing overall fuel burn.

Assumptions

- Intervention aerodynamic maintenance will move from major overhauls every 6-8 years, to be conducted twice as often and only represents minor maintenance actions, resulting in annual fuel saving of 0.46% (Henderson, 2005).
- Extra costs are incurred from both direct and indirect maintenance

Maintenance - engine wash

- Washing turbofan engines to minimise internal dirt build up prolongs the engines fuel efficiency and increases time before full maintenance needed by reducing the exhaust gas temperature (EGT).
- Previously engine wash has only been used to postpone expensive maintenance, due mainly to the need to transport the aircraft to a maintenance area and the associated downtime and costs.
- A range of engine wash services are now available that can be conducted over night at an airport gate; specifically EcoPower from Pratt & Whitney and Cyclean offered by Lufthansa technik (GreenSky, 2008).

- EcoPower claims fuel burn reduction of up to 1.2% for a clean of <6 hours, 2 or 3 times a year, with Cyclean claiming up to 0.75% for 1 hour operation.

Assumptions, based on supplier information

- On average a single aisle aircraft employing EcoPower will use 3.5 washes per year, at a cost of £1700/engine, reducing fuel burn by 0.75%. (Pratt & Whitney, 2008)
- Engine wash services can be conducted at an airport gate overnight, and will be widely available across all UK airports.
- Extra cost benefits are an average 2% reduction in annual engine maintenance bills.

Fuel reserves

- Legal minimum fuel reserves are 4.5% of aircraft TOW, between this reserve and the flight fuel, is another amount of buffer fuel, called 'thinking time' fuel.
- Excessive thinking time fuel has a weight penalty that is reflected in increased journey fuel use.
- Operators are attempting to reduce this thinking time fuel, but must balance between cost reduction and infringing aviation safety laws. (SF Chronicle, 2008)

Assumptions

- Thinking time fuel amounts to a further 0.5% of aircraft TOW, with the intervention reducing this amount to 0.25% of TOW.
- Crew training and extra monitoring costs are £3000/year/aircraft.

Increase turboprop use

- Turboprop aircraft are more fuel efficient than equivalent sized turbofan aircraft, by approx. 30% (Babikian et. al., 2002).
- Turboprops aircraft have greater engine maintenance costs than turbofans, and longer journey times.

- The aircraft market offers turboprop aircraft that have similar capacity and journey suitability as regional jets.

Assumptions

- The capability exists to replace regional jets with similar sized turboprops, with no significant impact on flight frequency.
- Additional costs will be incurred, due to increased maintenance and journey time and are calculated through block hour operating costs.
- In the future, circa 2020, larger turboprop aircraft will be available to directly replace single aisle 150 seat turbofan aircraft (Flight International, 2008).

Better use of capacity

- Assuming that increased numbers of passengers are carried by each aircraft, the overall number of aircraft operated can be reduced to meet the same seat demand.

Assumptions

- A general increase to 80% capacity on all flights leads to an overall reduction in aircraft of 5%.
- The effects of increased passenger weight and fuel use were factored in, along with a corresponding increase in block hour costs.
- Savings are accrued from the proportionate aircraft removed from service, providing a net saving in depreciation costs and fuel use in flight.

Reduced APU use

- Their exists a significant difference in operating times for the APU, between different aircraft operators and airports.
- All APU are presently small turbofan engines, using aviation fuel and producing CO_2 emissions.
- Reducing APU use from average times to the minimum possible would have impacts on the service provided to passengers, mainly through lack of cabin air conditioning whilst at the airport gate.

Assumptions

- For the representative aircraft used in this study the average fuel consumption rate of the APU is 119 kg/hour (US FAA, 1995).
- The standard APU operation time for a single flight is 48 minutes (AEA, 2007)
- A leading European low fare airline operates its APU for 12 minutes per flight.
- Savings and costs were presented based on a reduction in APU use of 48-12=36 minutes per flight.

ACARE

- An ACARE intervention was introduced to capture the reduction in fuel burn represented by the aircrafts adoption of technological interventions.

Assumptions

- The ACARE would provide a 25% fuel burn reduction.

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