A MARGINAL ABATEMENT COST CURVE MODEL FOR THE UK AVIATION SECTOR

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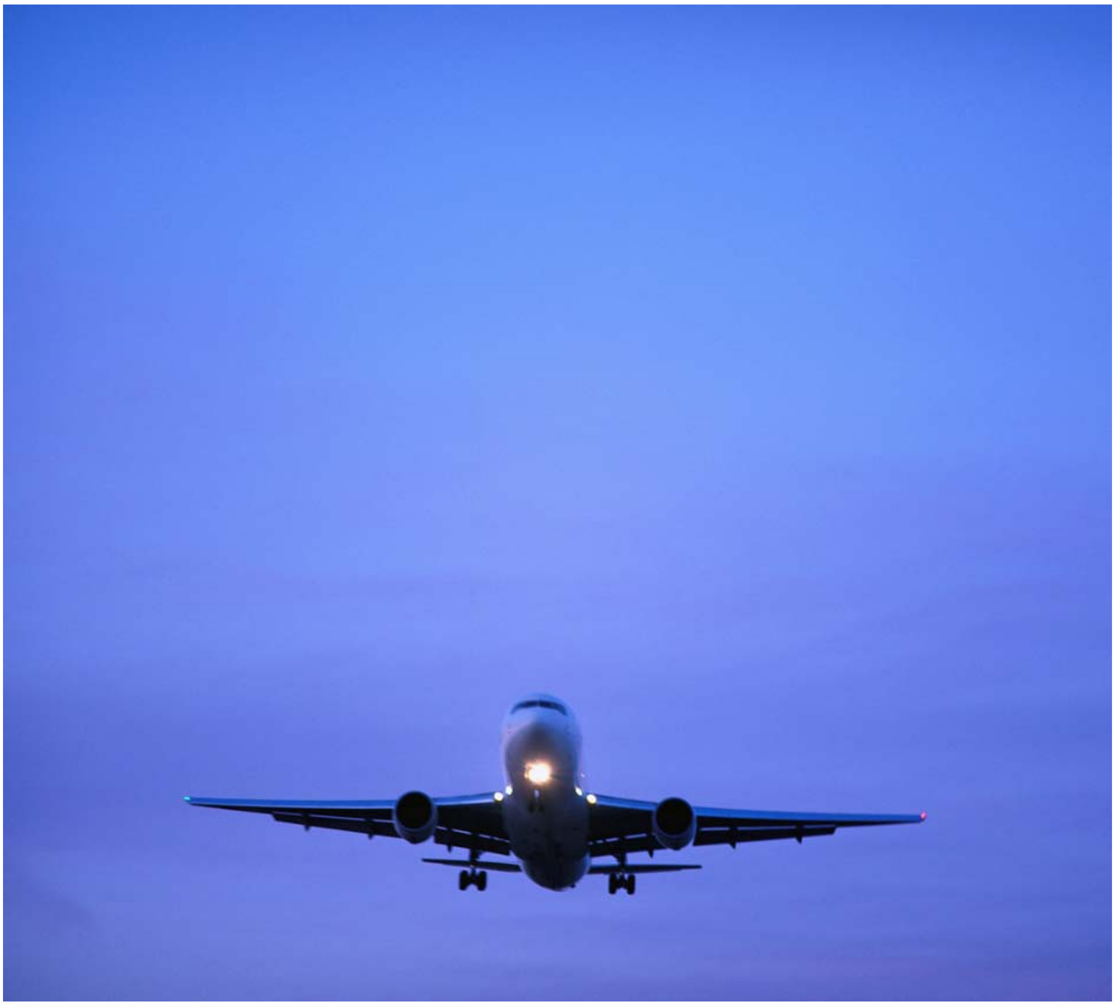
Technical Report: Final



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Executive Summary

Objectives

The primary objective of this research was to develop marginal abatement cost (MAC) curves for the UK aviation sector out to 2050, based around a series of policy levers aimed at reducing carbon dioxide (CO_2) emissions. It is intended that the analysis presented here will provide a platform for broader discussion alongside two companion reports, the first being the DfT (Department for Transport) response to the UK aviation report by the Committee on Climate Change (CCC, 2009), the second being a report on the development of the baseline scenarios used here and in other modelling carried out in-house by DfT (2011). "UK aviation" is defined for the purpose of this analysis as all domestic flights and all international departures from the UK.

Previous analysis in the UK has considered the marginal abatement costs of interventions by the aviation industry to reduce emissions, quantifying against a short-medium timescale to 2025. Here, we have considered the marginal abatement costs of potential policy initiatives instead, and quantified out to 2050. This research therefore breaks new ground in two very important ways.

Levers considered

The levers considered relate to the following. For ease of reference the short names in brackets are used in the report:

Aviation technology

- A potential CO_2 Standard introduced under the International Civil Aviation Organization's Committee on Aviation Environmental Protection (ICAO-CAEP) [regulatory CO_2 standard]
- Regulation/ incentive to accelerate fleet turnover [Early fleet retirement]
- Support for the achievement of the ICAO-CAEP fuel-burn goals [Achieve CAEP goals]
- Support for retrofitting more fuel-efficient technologies to existing fleet covering engine-related and other options [Retrofitting]

Aviation operation

- Capacity constraints with respect to airport slots [Airport capacity]
- Action to reduce inefficiencies in Air Traffic Movements and Air Navigation Service Provider (ATM and ANSP) related operations [ATM efficiency]
- Incentives to reduce inefficiencies in air carrier operations leading to better matching of aircraft type to mission [Operational incentives]

Biofuels

- Supporting biofuels demonstration plant covering fuel production, refining and demonstration [Biofuel demonstration plant]

- Regulation to mandate biofuels uptake in aviation (subsidised or unsubsidised) [Mandatory biofuels]

Behavioural change

- Promotion of behavioural change aimed primarily at the leisure market [Behavioural change]
- Promotion / incentivisation of remote meetings including Webinar and videoconferencing, aimed primarily at the business market [Videoconferencing]

Some future developments, specifically the inclusion of aviation in the EU Emissions Trading System (EU ETS) from January 2012 and further development of high-speed rail in the UK, are covered under the baseline scenarios adopted for the research. Further fiscal measures were excluded from the analysis.

The fact that UK government has commissioned this research should not be interpreted as meaning that it is considering acting in isolation of other governments and international bodies, when multilateral action may provide greater benefit and avoid negative interactions. Whilst some of the policy levers are potentially UK-specific and led, many of the others assume a reliance on international initiatives that the UK would be acting in harmony with. Indeed, many of the levers would be impossible to drive from one nation such as the UK, acting alone. The work considers how policy in different areas could contribute to emission savings from aviation, but does not take a detailed position on how such policies might be implemented.

Modelling approach

A set of baseline forecasts to represent low, central and high demand scenarios has been developed by DfT in conjunction with the project team, using assumptions about the composition of the air fleet, fuel prices, fuel efficiency improvements and so on. Estimates were then made of the costs of action and potential emission savings of the policy levers listed above, drawing on available literature and expert judgement where necessary. Low, mid and high estimates were derived for the policy cases showing differences in effect according to variation in the extent to which levers could be applied. Together with the three baseline demand cases this generated a set of nine combinations of demand and policy.

The DfT aviation models then quantified the extent of emission savings associated with each lever from 2010 to 2050. They also provided cost data in some areas (for example, results on producer and consumer surplus that were relevant to the costing of levers that affect demand for aviation). Supplementary cost analysis was performed in other cases, and MAC curves were assembled.

Further consideration was given to the way that levers may interact with one another, and secondary impacts, for example on noise, local air quality, and non-CO_2 greenhouse gases. Interactions can be extremely important. For example, a combination of retrofitting with achieving the ICAO-CAEP fuel burn goals could bring additional benefits in that the technologies available for retrofit may be better than they would have been without the support for research. Many other interactions, however, may not be positive.

Key results

Given data limitations, the analysis contains many assumptions, so results require cautious interpretation. The costs are illustrative and intended only to indicate broad orders of magnitude. However, they provide a useful guide towards the relative cost-effectiveness of the potential levers studied.

Table (i) summarises estimated emissions for each baseline case, together with estimated aviation emissions following implementation of all levers. The growth in baseline emissions from low to high demand demonstrates uncertainty in forward projections.

Table (i) Estimated emission savings in 2050 under each demand baseline/policy case.

Demand	Forecast 2050 emissions under each baseline, Mt CO_2/year[1]	Policy	Estimated 2050 UK aviation emissions after all levers implemented, Mt CO_2/year
Low	40.2	Low	32.1
Low	40.2	Mid	25.1
Low	40.2	High	15.9
Central	49.2	Low	37.9
Central	49.2	Mid	29.1
Central	49.2	High	18.5
High	58.8	Low	36.6
High	58.8	Mid	30.4
High	58.8	High	18.6

Table (ii) takes this further to show the estimated emission savings associated with each lever over the full time period considered (i.e. to 2050). Green shading highlights the levers associated with the largest emission reductions over the period considered, pink shading highlights those linked with the smallest emission reductions.

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[1] These baseline forecasts differ very slightly from those reported in DfT's UK Aviation Forecasts, August 2011. DfT's revised estimates include improvements in the forecasting of freighter emissions after 2030 that slightly lower the estimate of baseline emissions. The differences in emission savings are small, <1% of total savings in 2050, and do not materially affect any of the results of the MAC analysis

Table (ii) Estimated emission savings over the period 2010 to 2050 from "UK aviation" by policy lever ($MtCO_2$).

Demand baseline	**Low**			**Central**			**High**		
Policy	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Regulatory CO_2 Standards	0	9	10	-ve	9	11	-ve	11	13
Early fleet retirement	0	1	33	1	19	59	20	41	84
Achieve CAEP goals	4	25	44	7	40	66	8	53	84
Retrofitting	1	2	4	1	3	4	1	3	5
Airport capacity	13	14	18	37	37	13	159	77	88
ATM efficiency	12	23	33	15	27	38	16	30	41
Operational incentives	59	92	139	69	108	162	77	120	180
Biofuel demonstration plant	11	20	44	13	23	51	14	26	58
Mandatory biofuels	39	66	108	34	68	118	23	64	125
Behavioural change	0*	11	19	0*	37	43	0*	12	27
Videoconferencing	0*	0	5	0*	-ve	7	0*	17	1
Total savings	**139**	**263**	**457**	**177**	**371**	**572**	**318**	**454**	**706**

Key: * lever defined as having no impact for the demand/policy case. –ve: model reports increase in emissions for the lever in question over the period. For explanation of shading, see text.

The levers associated most consistently with the largest emission reductions over the full period considered are operational incentives and mandatory use of biofuels. A second tier of levers covers constraints on airport capacity, the achievement of CAEP goals, ATM efficiency and biofuel demonstration plant. The weakest measures for emission savings from "UK aviation", according to the assumptions followed here, are regulatory CO_2 standards, retrofitting and promotion of videoconferencing.

Table (iii) provides a similar overview of levers, but this time in terms of cost-effectiveness. Here, however, there is a rather clear distinction between levers that apply to aircraft and engine design and those that deal with improving the efficiency of aircraft movements, biofuels and demand reduction (as indicated by the shading used in the table). Two levers are consistently in the category of most cost-effective:

- Improvements in ATM efficiency
- Support for biofuel demonstration plants

Also amongst the most cost-effective levers in some cases are:

- Behavioural change under the central and high demand baseline cases
- Constraints on airport capacity under low demand baseline
- Mandatory use of biofuels, particularly under the high demand baseline cases

Operational incentives also appear to be relatively cost-effective in comparison to the others considered.

There is therefore some consistency in the results of Tables (i) and (ii) with respect to the measures that appear most promising for emission savings and those that appear most cost-effective.

Table (iii) Cost-effectiveness of measures, net cost (£) per tonne of CO_2 saved.

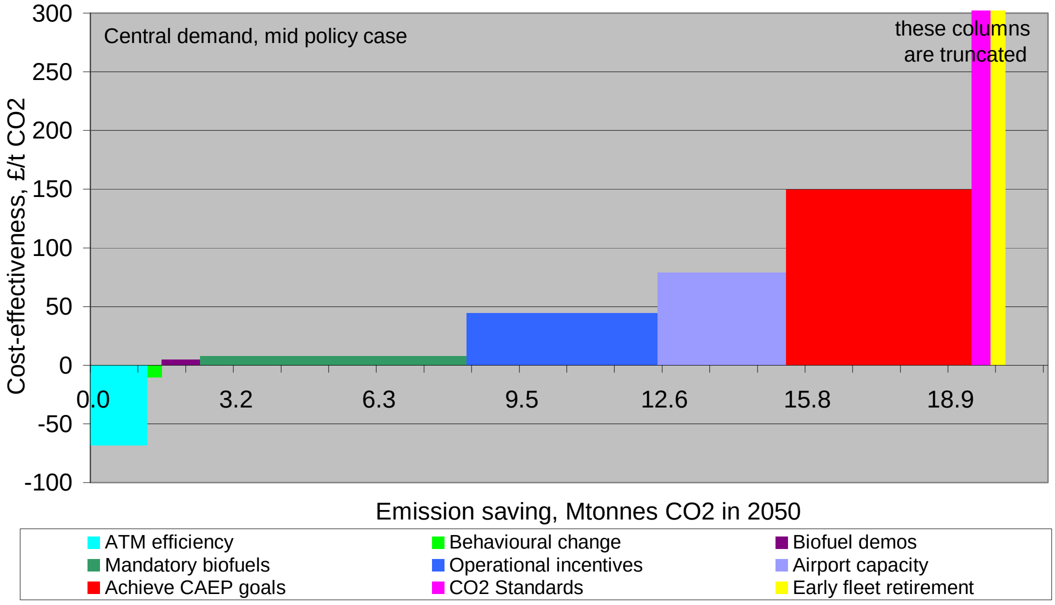
Demand baseline	**Low**			**Central**			**High**		
Policy	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Regulatory CO_2 Standard	n/a	1702	1430	n/a	1080	1553	n/a	927	1390
Early fleet retirement	1257	9999	1443	6667	1645	1044	1187	1385	1226
Achieve CAEP goals	968	338	401	500	150	197	355	11	58
Retrofitting	394	470	2319	274	377	2056	135	239	1770
Airport capacity	-53	-45	-27	39	79	196	53	148	155
ATM efficiency	-25	-14	1	-79	-69	-56	-159	-150	-138
Operational incentives	31	44	45	31	45	46	30	43	44
Biofuel demonstration plant	5	4	5	4	5	4	6	4	4
Mandatory biofuels	67	65	65	8	8	7	0.1	0.1	0.1
Behavioural change	n/a	18	20	n/a	-10	-12	n/a	-16	-28
Videoconferencing	n/a	n/a	50	n/a	n/a	31	n/a	12	544

Key: n/a: lever does not produce emissions savings in 2050 and therefore the cost-effectiveness has not been estimated. For explanation of shading, see text.

These results are specific to the air fleet that serves the UK, where aircraft ages are, by international standards, low. Some of the aviation technology levers may be significantly more effective in other parts of the world than they are in the UK.

Figure (i) shows the cost curve for the year 2050 for the central demand baseline / mid policy case. Two measures, early fleet retirement and the setting of regulatory CO_2 standards, are shown to be substantially more expensive per unit of abatement than the others (£1,080 and £1,645/tonne CO_2 respectively). Indeed, their costs are sufficiently high that Figure (i) was truncated for these two measures. At the other extreme, net benefits are forecast for improvements to ATM efficiency and actions to promote behavioural change in the leisure market for the central demand / mid policy case. The figure does not include retrofitting, as this is forecast to no longer have an impact by 2050.

Figure (i) MAC curve for the central demand baseline / mid policy case.



Robustness of the analysis

It is acknowledged that there are significant uncertainties in seeking to model technologies and economic impacts on a 40 year future time horizon. For some of the levers there is scant information available for quantification of the costs, and for quantifying emission reductions that may follow from a given level of expenditure. The report acknowledges these uncertainties and has sought to limit them where possible. A view has been taken that it is better to provide some quantification of costs and effects than not, in order that future debate can be more focused than would be the case if only a qualitative assessment was provided.

Table (iv) brings together results from the analysis and seeks to provide an overview of confidence in the outcomes as to which levers are estimated to be most and least cost-effective. Emission savings are summarised as the average over the full time period for the nine demand baseline / policy cases. Similarly, cost-effectiveness is described as the average over the nine cases. This averaging is intended to provide a simple grading scheme for the levers; it is important to recognise that it would not be appropriate to apply these averages for other purposes. The final column then provides some guidance, based on expert judgement, on the overall balance of uncertainties on the information given on emission savings and cost-effectiveness. For some levers, retrofitting being a good example, we have a high level of confidence that emission savings will be low and the cost-effectiveness poor so far as the UK air-fleet is concerned. Hence, whilst the uncertainty in the results may be quantitatively large, we conclude that it is not so great as to change our view that a lever to encourage retrofitting is not a cost-effective option for the UK air fleet. On the other hand, we consider it possible that uncertainties in quantification of the effects and costs of the promotion of behavioural change in the leisure market could influence conclusions on the suitability of the lever quite substantially. The table cites two reasons why this may be the case.

Table (iv) Overview of the estimated emission savings and cost-effectiveness of each lever, and confidence in conclusions reached from the analysis. For key, see foot of table on the next page.

Description	**Total emission savings, 2010 to 2050**	**£/t CO_2 Cost-effectiveness**	**Confidence: key issues**
Regulatory CO_2 standards	9	>1000	Limited abatement potential from the UK fleet due to young average age of operational UK aircraft. This policy is expensive due to the required level of fleet replacement. There are uncertainties over the form and application of any Regulatory CO_2 Standard.

Description	**Total emission savings, 2010 to 2050**	**£/t CO_2 Cost-effectiveness**	**Confidence: key issues**
Early fleet retirement	29	>1000	Moderate opportunity for emission savings, but at a high price. Limited potential for the UK fleet due to young average age of operational UK aircraft. This policy would be expensive due to the required level of fleet replacement.
Achieve CAEP goals	37	331	Confidence in the quality of ICAO-CAEP independent experts' fuel efficiency goals work is high. There is some uncertainty connected to the extrapolation of technology timescales (i.e. this work pushed the timescales beyond those of the CAEP goals work). The cost estimates have the largest uncertainty due to paucity of available high quality data.
Retrofitting	3	892	Limited potential for the UK fleet.
Airport capacity constraints	51	61	Significant apparent savings, but in some cases moderately expensive. No account taken in the costings of offsetting emissions increases from displacement of traffic to continental hubs and surface transport modes and of losses to the UK economy if people are discouraged from travelling to the UK.
ATM efficiency improvements	26	-77	Difficulty in linking investment to specific levels of efficiency improvement.
Operational incentives	112	40	Good estimated level of savings at moderate cost, with information obtained during the research suggesting that this could be an attractive option for operators. However, there are uncertainties with the costing assumptions, that may be conservative, and there are other barriers to the introduction that are hard to quantify.
Biofuel demonstration plants	29	5	Difficulty in forecasting effect of demonstration plant on wider uptake of biofuels. However, conservative assumptions have been followed here, leading to reasonable confidence in the performance of this lever relative to others.
Mandatory use of biofuels	72	24	Good estimated level of savings at relatively low cost, but high sensitivity in results to the assumed differential between the cost of kerosene and biofuels.
Behavioural change	25	-5	Difficulty in attributing change in emissions to investments to provide information on CO_2 from aviation or to promote holidays in the UK. No account taken of burdens imposed through alternative use of money saved by avoiding foreign travel.

Description	**Total emission savings, 2010 to 2050**	**£/t CO_2 Cost-effectiveness**	**Confidence: key issues**
Videoconferencing	6	159	Difficulty in attributing change in emissions to investments to promote remote meetings. It is questionable how much government intervention would substantially influence take-up of videoconferencing beyond what businesses may undertake for cost-savings.

Key

	Emission savings	**Cost-effectiveness**	**Confidence**
Good	>50 Mt CO_2	<£10/t CO_2	Expert judgement
Mid	10 to 50 Mt CO_2	£10 - £100/t CO_2	Expert judgement
Poor	<10 Mt CO_2	>£100/t CO_2	Expert judgement

Contents

1 Introduction

1.1 Objectives

The overall aim of the project was to produce a robust set of Marginal Abatement Cost (MAC) curves that illustrate the full social cost and (cumulative) abatement potential through the use of policy levers to reduce UK aviation emissions of CO_2 out to 2050. "UK aviation" is defined for the purpose of this analysis as all domestic flights and all international departures from the UK.

It is inevitable that results from modelling over a period of 40 years are prone to uncertainty. Consider, for example, the situation 40 years ago. That was a time before the first oil crisis, low cost air travel did not exist[2] and the first aircraft produced by Airbus would not enter service until 1974. The assessment therefore needs to recognise uncertainties where they exist and to take realistic account of them. Similarly, readers should appreciate the constraints facing an analysis such as this.

1.2 Policy levers for consideration

The following list of policy levers was agreed for the study, with the short name given to each lever in much of the rest of the report given in square brackets:

Aviation technology

- A potential CO_2 Standard introduced under the International Civil Aviation Organization's Committee on Aviation Environmental Protection (ICAO-CAEP) [regulatory CO_2 standard]
- Regulation/ incentive to accelerate fleet turnover [Early fleet retirement]
- Support for the achievement of the ICAO-CAEP fuel-burn goals [Achieve CAEP goals]
- Support for retrofitting more fuel-efficient technologies to existing fleet covering engine-related and other options [Retrofitting]

Aviation operation

- Capacity constraints with respect to airport slots [Airport capacity]
- Action to reduce inefficiencies in Air Traffic Movements and Air Navigation Service Provider (ATM and ANSP) related operations [ATM efficiency]
- Incentives to reduce inefficiencies in air carrier operations leading to better matching of aircraft type to mission [Operational incentives]

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[2] Southwest Airlines in the US began services in June 1971, the same month that Laker Airways in the UK submitted its application for 'Skytrain', a daily low cost service between London and New York, though services would not commence until 1977.

Biofuels

- Supporting biofuels demonstration plant covering fuel production, refining and demonstration [Biofuel demonstration plant]
- Regulation to mandate biofuels uptake in aviation (subsidised or unsubsidised) [Mandatory biofuels]

Behavioural change

- Promotion of behavioural change aimed primarily at the leisure market [Behavioural change]
- Promotion / incentivisation of remote meetings including Webinar and videoconferencing, aimed primarily at the business market [Videoconferencing]

The impacts of aviation joining the EU's Emissions Trading System (EU-ETS) are included within the baselines. Similarly, assumptions are made on the development of high speed rail in the UK in the baseline scenarios and are not examined specifically here[3]. The use of fiscal measures (i.e. taxation) is outside the remit of the present study.

1.3 Meaning of the term 'Policy Levers'

MAC curve development typically focuses on a series of well-defined measures for which there is information on costs and effectiveness from existing studies and technology assessments. In some cases, technologies will be commercially available already and the development of the curves simply considers how they may be further deployed, at what cost and with what effect on emissions.

The present case deals with more generic 'levers' rather than precise measures, reflecting the uncertainty in developments to 2050 and the fact that we have not considered the exact specification and design of potential policy measures. Hence, when we consider improving the efficiency of ATM, a broad-brush approach is applied, looking at the improvement associated with a given level of investment in more advanced ATM systems, rather than reducing the 'lever' to a series of specific activities. Similarly, with biofuels, we do not speculate about the exact processes that will be used for biofuel production, but take a view on the likely costs and effectiveness of the lever through a general review of the available literature.

1.4 The levers and UK government policy

The levers addressed in this research have been selected to provide government with a suitably broad overview of what may be possible and at what cost, to permit identification of available opportunity, and conversely, to identify approaches that are likely to be of little benefit in reducing greenhouse gas emissions from the aviation sector.

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[3] It is assumed in the baselines that new high speed lines are developed from London to Birmingham, and from there to Manchester and Leeds.

This analysis should not be interpreted as the UK government considering acting in isolation of other governments and international bodies, when collaboration may provide greater benefit and avoid negative interactions. The purpose of the report is to provide information on a range of policy options, as background material for a wider debate on the efficacy of the levers considered. It is not the intention of this report to pre-empt, predict or advise on the decisions of other bodies. For example, whilst a view is taken here on what a regulatory CO_2 standard may achieve and the levels of stringency that may be applied, the positions adopted here are not a formal UK proposal.

A further issue to remember when reading this report is that the analysis and results presented are based on information regarding the composition and operation of the air fleet that serves the UK. Results for particular levers may be quite different to what may be expected from analysis in other countries for which there may be significant differences in the way that the aviation industry is structured and the composition of the fleet.

1.5 Previous studies

The UK's Committee on Climate Change (CCC) has produced two reports which discuss aviation emissions. The first (CCC, 2008) highlighted the significance of aviation for the UK's emission inventory, suggesting that if the UK achieved an 80% cut in greenhouse gas (GHG) emissions by 2050 whilst aviation emissions were maintained at current levels, aviation would account for 25% of the UK inventory in 2050. The second report (CCC, 2009) was produced in response to a request from government to explore options for controlling emissions from aviation. This followed the then government's decisions to set a target for UK aviation emissions (that by 2050 they should not exceed 2005 levels, despite anticipated growth in the sector) and to expand Heathrow Airport with a Third Runway (a decision that has been reversed since the election of the present government).

The 2009 report presented three scenarios ("likely", "optimistic" and "speculative") which projected aviation emissions out to 2050 under different sets of assumptions about fuel efficiency improvements, the uptake of biofuels and behavioural change (including mode switching to high speed rail). Given the assumptions used in the "likely" scenario (such as annual improvements in fuel efficiency of 0.8% per annum and 10% biofuels penetration), the CCC estimated that an increase in passengers of around 60% on 2005 levels by 2050 could be compatible with aviation emissions returning to 2005 levels by 2050. The authors noted that, using a different set of assumptions, increases in the number of passengers beyond 60% may be possible, but warned against basing current policy on speculative assumptions on technology development.

Morris et al (2009a) present a framework for estimating the marginal costs of environmental abatement for aviation. The study involved extensive consultation with aircraft and engine manufacturers, researchers and trade associations to explore the feasibility and sources of information on abatement options. Two case studies were presented, addressing:

- CO_2 emissions from the UK domestic sector
- CO_2, nitrogen oxides (NOx) and selected other pollutants from the Europe-based sector including long-haul international traffic.

An important conclusion from this work was that "*although there is considerable interest in estimating MAC for aviation in order to determine the most cost-effective ways of reducing emissions, there are considerable gaps in data and methods to enable this to be done with confidence. It is particularly difficult to estimate MAC for medium and long term technological changes that require considerable upfront investment in research and development and possible changes in behaviour, both by service providers and users*." This conclusion is not surprising, given the timescales involved. As a result, the case studies presented in the analysis provided MAC curves to 2025, but only a qualitative assessment to 2050. Analysis highlighted the potential for win-win interventions to promote efficiency of aviation operations, by operators and by Air Traffic Control.

Morris et al (2009b) sought to determine the scope for and costs of UK aviation emission reductions from 2007 to 2050, though the MAC curves generated in the study go only so far as 2020 because of concerns about the quality of data going beyond that time. Analysis considered three types of option, improvements to engine and airframe technology, operational improvements and fleet management. Much caution was expressed around the results in the MAC curves generated by the work ("*The costs presented are therefore necessarily illustrative and intended to indicate broad orders of magnitude only*"). Abatement measures were considered independently of one another. This meant that it was not possible to calculate total emission savings as this would have required measures to have been introduced in a cumulative fashion.

The most cost-effective intervention measures in the short to medium term were concluded likely to be:

- Better use of capacity through increased occupancy and consolidation of flights
- Reducing take-off weight
- Adopting in-flight fuel-saving practices
- Matching aircraft to the short hauls of the UK sector
- Employing in-situ engine wash maintenance technologies
- Introducing European-scale ATM improvements that reduce travel distance.

It was also noted that high fuel prices would encourage the replacement of older aircraft with more fuel efficient types.

A number of other studies (e.g. Frontier Economics, 2006; ICF, 2006) have also commented on the dearth of information on marginal abatement costs for aviation.

The present report goes beyond these earlier studies in two important ways:

- By analysing out to 2050
- By considering the marginal abatement costs from the perspective of policy interventions.

When interpreting the results of the research reported here, it is clearly appropriate to consider the caution exercised by previous authors with respect to the confidence in the precise estimates made.

1.6 Structure of this report

Chapter 2 of the report provides an overview of the methods adopted here. Further detail on methods is provided in the chapters describing the policy levers (Chapter 3 for levers affecting aviation technologies, Chapter 4 for operational measures, Chapter 5 for biofuels and Chapter 6 for behavioural change). Results are described in Chapter 7 covering cost-effectiveness by policy lever, emission savings and a qualitative assessment of broader environmental impacts of the policy levers that covers emissions of noise, local air quality and so on.

The main text is supported by a series of appendices, as follows:
Appendix 1: Summary of baseline assumptions.
Appendix 2: Usage of metrics to account for non-CO_2 climate effects of aviation.
Appendix 3: Full set of MAC curves, for all years and demand/policy cases.
Appendix 4: Technology Readiness Levels.
Appendix 5: Glossary of acronyms and abbreviations.

2 Methods

This chapter provides a broad overview of the methods used in the analysis. More detail is provided in the following chapters in the discussion of the individual levers.

2.1 Overview

The first step in the analysis was the definition of the baseline scenarios, including appropriate assumptions on the composition of the air fleet, fuel prices, fuel efficiency improvements and so on. To reflect uncertainty in the baseline it was necessary to define low and high demand baseline cases around a central case. These baselines form the DfT's updated UK aviation CO_2 emission forecasts. An overview of the assumptions made in the baselines is presented in Appendix 1. A more complete description of the assumptions used can be found, along with a comprehensive description of the methods that DfT uses to produce its aviation forecasts, in the DfT Report *UK Aviation Forecasts, 2011*.

Policy levers were then defined, drawing on available information and expert review. The impact of the different levers is clearly a function of the extent to which they are applied, so again, low, mid and high cases were described. For the modelling that followed, a total of nine cases were considered, bringing together the low, central and high demand baseline cases with the three cases for policy strength. No intermediate situations were considered, where, for example, one set of levers were applied at a low level and others at a mid or high level against a particular demand baseline.

Definition of the levers provides information on the extent to which improvements in performance relative to CO_2 emissions may be possible over the period 2010 to 2050, and the consequent impact on emissions and costs. Judgements were also made on the date of possible implementation of each lever. Conclusions reached were then applied within the DfT models for all domestic flights and all international flights departing from UK airports over the studied period, to generate estimates of emission savings. In cases where levers affected passenger numbers (the levers dealing with behavioural change, videoconferencing and constraints on airport capacity), the DfT models also provided the associated costs. Costs for other levers were generated outside of the DfT models.

Given data limitations, the analysis contains many assumptions, so results require cautious interpretation. The costs are illustrative and intended only to indicate broad orders of magnitude. However, they provide a useful guide towards the relative cost-effectiveness of the potential levers studied.

Finally, MAC curves were generated by ranking levers in terms of their cost-effectiveness expressed in £/tonne of CO_2 saved. This was calculated by taking the net present value (NPV) of each lever to 2050 and dividing by the total emission savings over the period. The cost-effectiveness of airport capacity constraints was modelled slightly differently, with the period extended to 2080, consistent with DfT's transport appraisal guidance[4] that states that a period of 60 years shall be applied from the scheme opening year for projects with indefinite lives.

2.2 Specific issues

2.2.1 Order of introduction of measures to the DfT models

The order of introduction of measures is one determinant of the relative cost-effectiveness of those measures. To illustrate, consider two measures, individually capable of reducing uncontrolled emissions by 50% that can also be applied together. Applying the first naturally reduces emissions by 50%. Applying the second reduces the remaining emissions by a further 50%, leaving 25% of the original level of emissions. The cost-effectiveness of the second measure expressed as £/tonne pollutant saved will change when the two measures are applied together, as the quantity of pollutant on which the second measure has an impact is halved.

From an economic perspective, measures should be introduced to the cost curve simply by reference to their cost-effectiveness, with those with the lowest cost per unit emission abated being introduced ahead of those with successively higher costs. However, this implies the following conditions:

1. The economic assessment has succeeded in describing the full costs (to all stakeholders, including externalities) of the measures that are identified.
2. The effectiveness and cost-effectiveness of all policy levers are subject to a similar level of uncertainty.
3. The deliverability, feasibility, political and public acceptability of the measures varies in a similar way to cost-effectiveness.

Further to this, the cost-effectiveness of levers could only be estimated following their application within the DfT models. Hence it was necessary to define an ordering for introduction of the levers. A somewhat arbitrary decision was taken to broadly integrate technology levers first and those that affect demand last, in the following order:

- Regulatory CO_2 Standards
- Achieve ICAO-CAEP fuel burn goals
- Operational incentives
- Early fleet retirement
- Retrofitting
- ATM efficiency
- Biofuel demonstration plant
- Mandatory biofuels
- Behavioural change
- Videoconferencing
- Airport capacity

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[4] Available at http://www.dft.gov.uk/webtag/documents/expert/unit3.5.4.php

We acknowledge that this will have an impact on estimated emission savings and hence cost-effectiveness for individual levers, although it would not affect the total estimated emissions savings from all measures together. However, in the context of the current study, other uncertainties are likely to be more important.

2.2.2 Treatment of impacts

The costs of carbon are factored into the analysis through the EU-ETS carbon price using DECC's (the Department of Energy and Climate Change) projections of the traded price of carbon. Welfare impacts on passengers and effects on producer surplus for the industry are modelled within the DfT SCAB (Social Costs and Benefits) Model for levers where demand is affected (as noted above, the levers dealing with behavioural change, videoconferencing and constraints on airport capacity).

There has, however, been no quantification of other environmental impacts, such as changes in emissions of noise or local air pollutants. The effect of the levers on these effects is, however, described qualitatively. These effects on other environmental impacts are described only in terms of 'direction', not the magnitude. Thus, for example, if a co-benefit is identified, it should not be inferred that this is necessarily significant. Co-benefit and dis-benefit quantification was beyond the scope of this work.

2.2.3 The Effect of Airport Capacity Constraints

A feature of the capacity lever scenarios and all policy scenarios using the high demand baseline, is that at some point before 2050 the national airport system has in effect reached capacity and additional demand cannot be accommodated. The figure below analyses the erosion of spare passenger capacity over the forecast period at the 10 busiest airports in terms of their ATMs in 2010[5]. The airports considered account for 75% of base ATMs. The low and central demand baselines still retain some reserve capacity at the end of the period. However, the high demand baseline and all the policy cases developed from it run out of capacity before the end of the period.[6]

A consequence is that as system capacity is approached, differences in passenger and ATM throughputs diminish between the scenarios. Hence, for the same capacity lever scenario, the central and high demand baselines may have very similar levels of ATM activity by the mid 2040s.

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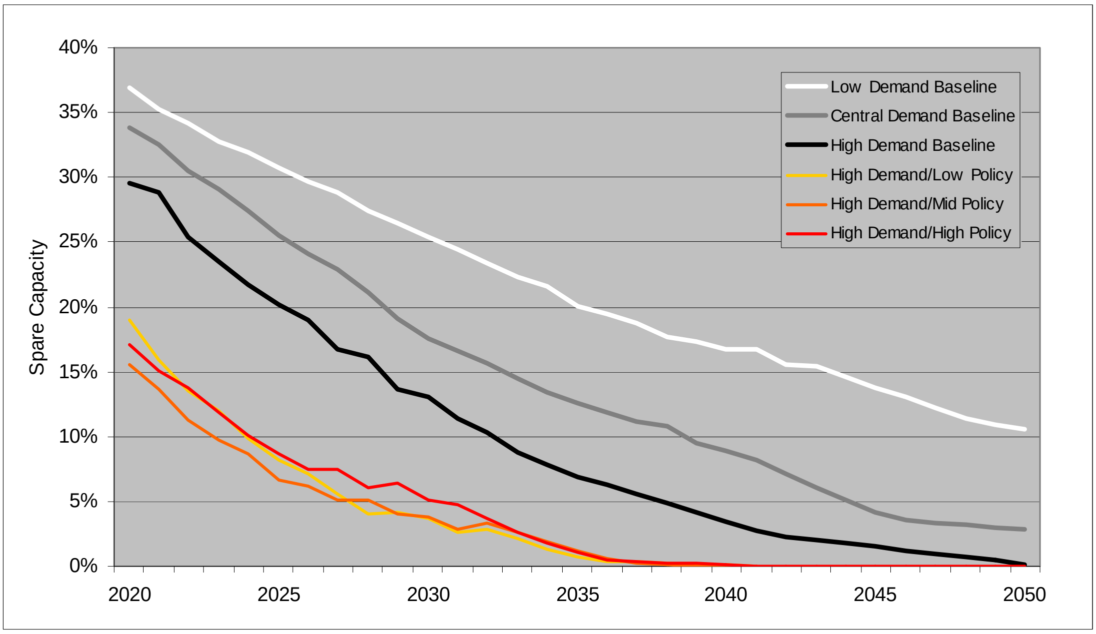
[5] These are all 5 London airports, Birmingham, Manchester, Glasgow, Edinburgh and Aberdeen

[6] Figure 10 is only indicative of the lever results presented later because it includes just the busiest airports.

Figure 1. Trends in reserve capacity at 10 airports under the alternative demand baseline/policy cases.



A further consequence as the overall system nears capacity, with significant levels of demand unable to be accommodated at suitable airports, is that the model results will increasingly be subject to 'noise' or instability. The model works by assigning passengers on a route-by-route basis. Once a settled allocation of passengers to airports has been made, the demand for ATMs is calculated to give an indication of the type of aircraft (seat band class) required to service the demand on each viable route at each airport in each forecast year. Checks are then made against runway and terminal capacities. The model then iteratively searches for an equilibrium solution across the entire system in which no airport is more than a specified tolerance over its input capacity. This is normally with +/- 3% of runway or terminal capacity (or an absolute passenger variance at smaller airports) and depends on which of runway or terminal capacity is "binding" and rules are applied to prevent unnecessary switching between runway and terminal constraints. In highly constrained situations, as model runs reach their end, these tolerances are frequently invoked and can result in slightly different detailed allocations of ATMs at airports for essentially the same combinations of demand and capacity. If very small changes are made in model inputs, clear model signals can eventually be swamped by this noise in the last few years before the search for an equilibrium solution is abandoned.

When the run cannot complete, i.e. it cannot find a convergent equilibrium solution after a preset number of iterations,[7] then it is necessary to extend the results by means of extrapolation. This technique and its effects are discussed in Annex E of the DfT's *UK Aviation Forecasts,* August 2011.

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[7] Usually 250-400.

2.2.4 Calculation of the Net Present Value (NPV)

The first step in quantification of the NPV for each lever is to describe the stream of costs (including cost savings) in each year for the period of assessment. There are typically several components to the cost in any year. Taking a relatively simple example, for ATM improvements it is necessary to quantify the costs from investing in new technologies to improve ATM systems and the cost savings that arise from reduced fuel use. The values for each year are then discounted in line with Green Book guidance, to provide an estimate of 'present value' in each year. This stream of values is then summed to generate the NPV. As already noted, the period of assessment is based on DfT Transport Project Appraisal Guidance[8].

The following, in particular, should be noted:

- Positive numbers denote a net cost
- Negative numbers denote a net saving (benefit)
- Cost savings from reduced fuel consumption take into account reduced purchase of EU-ETS allowances
- Following from this, the monetised value of potential emission savings is not factored into the analysis, as to do so would double count carbon impacts.

Cost-effectiveness, expressed in £/tonne of CO_2 avoided, is calculated by dividing NPV by the total reduction in emissions over the period of the assessment.

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[8] Available at http://www.dft.gov.uk/webtag/documents/expert/unit3.5.4.php

3 Levers affecting aviation technologies

3.1 Regulatory CO_2 standard

3.1.1 Lever description

Baseline assumptions for the low, central and high demand baseline cases for this lever and the others described in this Chapter are provided in Appendix 1.

This lever covers the potential impact of a regulatory aircraft CO_2 standard. This would most likely be an international standard set by ICAO. Currently, work is underway within ICAO-CAEP to determine the measurement metric, certification procedures and regulatory level(s), as well as the applicability, of any proposed standard. A large number of potential CO_2 metrics remain under consideration. The metric chosen within this study (see Equation 1) is consistent with previous ICAO goals work (ICAO-CAEP, 2010) and reflects a possible outcome of the debate within ICAO-CAEP:

$$\textit{Mass of fuel burned} / (\textit{Load x Distance flown}) \quad [1]$$

Selection of this metric is not intended to pre-judge the outcome of ICAO-CAEP, but simply provides a basis for the analysis that follows. This metric was chosen to provide this study with a reasonable estimate of CO_2 reductions and the resultant aircraft rankings. Other CO_2 metrics under consideration by ICAO-CAEP) may give different results (e.g. aircraft ranking), and this would have an impact on which aircraft types pass or fail the CO_2 Standard.

Whether such a metric should be calculated from a complete flight stage, or a single point (e.g. during cruise, giving a SAR (Specific Air Range) based metric) is yet to be agreed. For this study, the regulatory parameter associated with the standard is defined as the minimum value of the CO_2 metric from analysing a range of flight distances. Furthermore, to describe the transport capability of the aircraft (and the physics of moving the entire aircraft) Maximum Take off Weight (MTOW) is chosen as a correlating parameter. The selection of MTOW as a correlating parameter also allows the CO_2 metric to be implemented across many aircraft sizes. The CO_2 Standard is assumed to apply from 2018 with stringency improvements (reductions in the permitted regulatory levels) every six years. This assumption is based on the history of the noise and NOx standards (ICAOa, b).

The applicability of the CO_2 Standard is also under consideration within ICAO. It has already been specified that the standard will not be applied retrospectively to in-service aircraft. It will certainly be applied to new (i.e. future) aircraft types, but whether it will also be applied to in-production types is still being considered. A subtle (but important) detail of this decision will be what determines a “new” aircraft type, as opposed to a derivative of an existing in-production type.

ICAO-CAEP currently plans to reach an agreement on a CO_2 Standard in 2013, with possible application within the 2015 to 2020 timeframe. It is also understood that ICAO-CAEP has confirmed that the CO_2 Standard will be developed using the same principles as the previous noise and emissions standards. This focuses the CO_2 Standard on current technology, while "Goals" are used to encourage longer term improvements. A CO_2 Standard would thus focus on limiting the continued production of lower efficiency current and near-term future aircraft types. Based on previous ICAO-CAEP Noise and Emissions Standards, this could have three impacts on future aircraft production:

- New (and possibly existing in-production) aircraft types that do not meet the CO_2 Standard cannot be produced after a certain date. Due to the high economic impact of production cut-offs, the standard is likely to be set at a level that has minimum (and maybe no) direct impact of this kind (i.e. the regulatory level would be set above all current in-production – as opposed to in-service – types). It will, however, prevent the introduction of future "low tech" types that do not meet the CO_2 Standard.

- If a CO_2 Standard is aimed only at new aircraft types, then an indirect effect could be to reduce sales of those in-production aircraft types that do not meet the CO_2 Standard. This would be due to market forces and specifically airlines wanting to future-proof their fleet both practically and from a marketing point of view (their ability to make the claim that their product "meets the latest CO_2 Standard") and with an eye on re-sale residual values. This was a strong market force for standards for noise and other emissions. However, this is yet to be proven for CO_2 due to the existing driver of fuel price and hence overall cost of ownership. Note that this effect is substantially independent from the actual aircraft-type applicability of the CO_2 Standard.

- Indirectly, the threat of future, more stringent, standards could dictate that manufacturers dedicate increased R&D effort to ensuring their products can meet anticipated future CO_2 Standards with some margin.

The unique aspect of a CO_2 Standard, in contrast to noise or other pollutant standards, is that there is already a strong economic driver to improve CO_2 performance through its direct proportionality with fuel burn – and hence to fuel costs. This 'fuel price' driver has historically provided annual improvements in fuel efficiency at fleet level of around 1% per year (±0.5%). The question then is whether the threat of potential future standards exceeds the pressure from fuel price or from other market based measures. If so, the CO_2 Standard can be said to be influencing future aircraft CO_2 performance (i.e. through increased R&D spend). If the Standard (and the threat of potential future Standards) does not accelerate the introduction of new technologies, then its influence will be limited to stopping production of older types (whether through a regulatory production cut-off or through a lack of orders for types which do not meet the Standard).

An alternative to the adoption by ICAO of a CO_2 Standard would be an agreement between the aircraft manufacturers to limit fuel consumption, and hence the CO_2 production of new aircraft (again, this could be just new types or new builds of existing in-production types). Clearly, this could achieve the same effect as the ICAO standard. However, as ICAO is committed to having a CO_2 Standard, it is unlikely that such an agreement would be required. It is expected that a CO_2 Standard will be agreed at a future CAEP meeting, and it would then need to be endorsed by ICAO before it could be implemented as a certification requirement. Thus, it is unlikely that such a standard could be in place before 2015. However, once a certification requirement for CO_2 has been implemented, reductions in the allowable level ("stringencies") would then be expected to be implemented in future years. Thus, the existence of a CO_2 Standard could place a requirement on the aircraft and engine manufacturers to continue developing advanced technology to achieve continuing reductions in fuel burn and CO_2 emissions.

The barriers to the implementation of this policy lever are associated with the international agreement of a suitable fuel efficiency metric and regulatory limit. Although ICAO-CAEP is committed to the development of a CO_2 standard, there is a risk that agreement to either the metric or the regulatory level might not be obtained in CAEP and not implemented by ICAO, or at best, be delayed.

Low policy lever

The CO_2 standard modelled here initially (in 2018) tracks behind the fleet CO_2 metric and is intended to remove only outlying aircraft types (in terms of CO_2 performance). A stringency improvement of 0.75% per annum is used. This Low Policy Lever option represents the possibility that when an ICAO regulation is implemented, it could be set so that most in-production aircraft meet the CO_2 Standard.

Mid policy lever

The CO_2 Standard in 2018 is assumed to be set broadly to the fleet CO_2 metric average with the intention to remove the higher emitting in-production types from supply. A stringency increase of 1.2% per annum is used (implemented every six years). At least one aircraft type always remains in each aircraft seat class. Figure 2 shows the increase in the stringency for this mid policy scenario stringency, overlaid onto the current and future fleet of aircraft types used in this study[9]. The shape of the CO_2 Standard is defined in such a way as to not disadvantage the smaller, generally short range, aircraft when using this CO_2 metric. For in-production aircraft it can be seen that the CO_2 Standard removes some of the older, less fuel efficient, aircraft types. In terms of new aircraft types, the chosen stringency levels do not drive new technology into production. This is emphasised by the positioning of the 2030 ICAO-CAEP fuel efficiency goals (ICAO-CAEP, 2010) (shown by the black dashed lines in Figure 2), relative to the CO_2 stringency improvements out to 2054. The stringency improvements in the regulatory CO_2 standard always (even at 2054) trail the 2030 ICAO-CAEP fuel efficiency goals (in TS1, TS2 and TS3) and so are unlikely to be at the leading edge of fuel efficiency technology developments.

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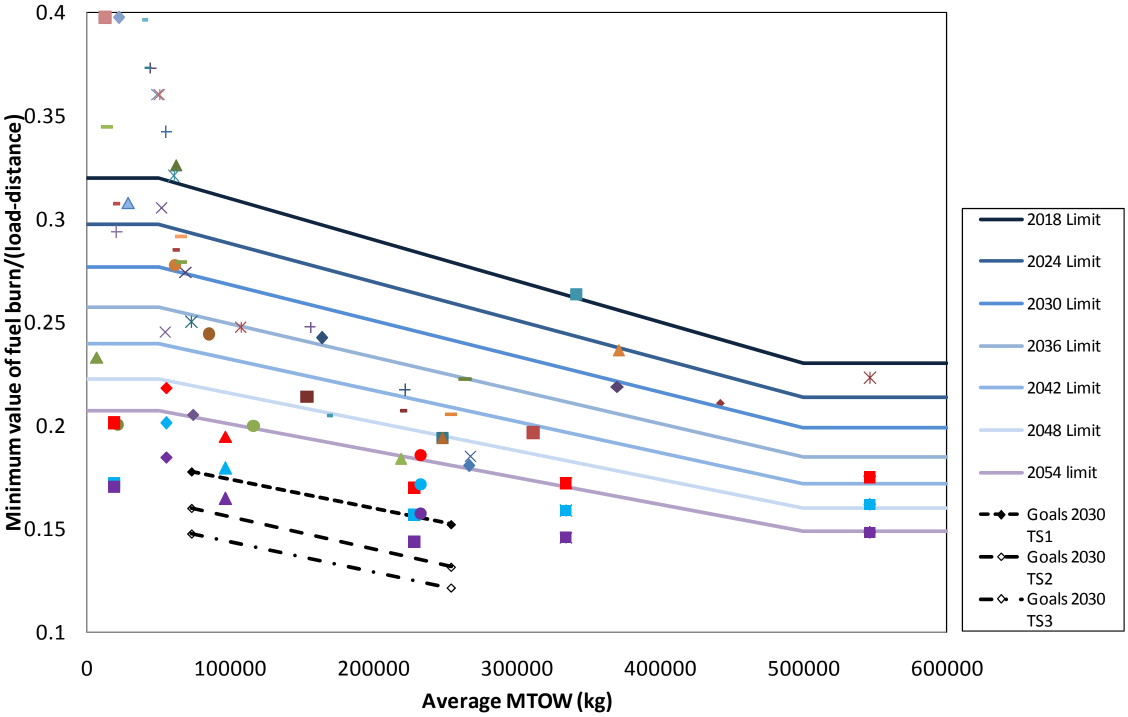
[9] All fuel burn calculations are based on Corinair data (including fuel multiplication factors).

Figure 2. Increase in assumed CO_2 standard stringency (mid case). Each point represents a different (current and future) aircraft type.

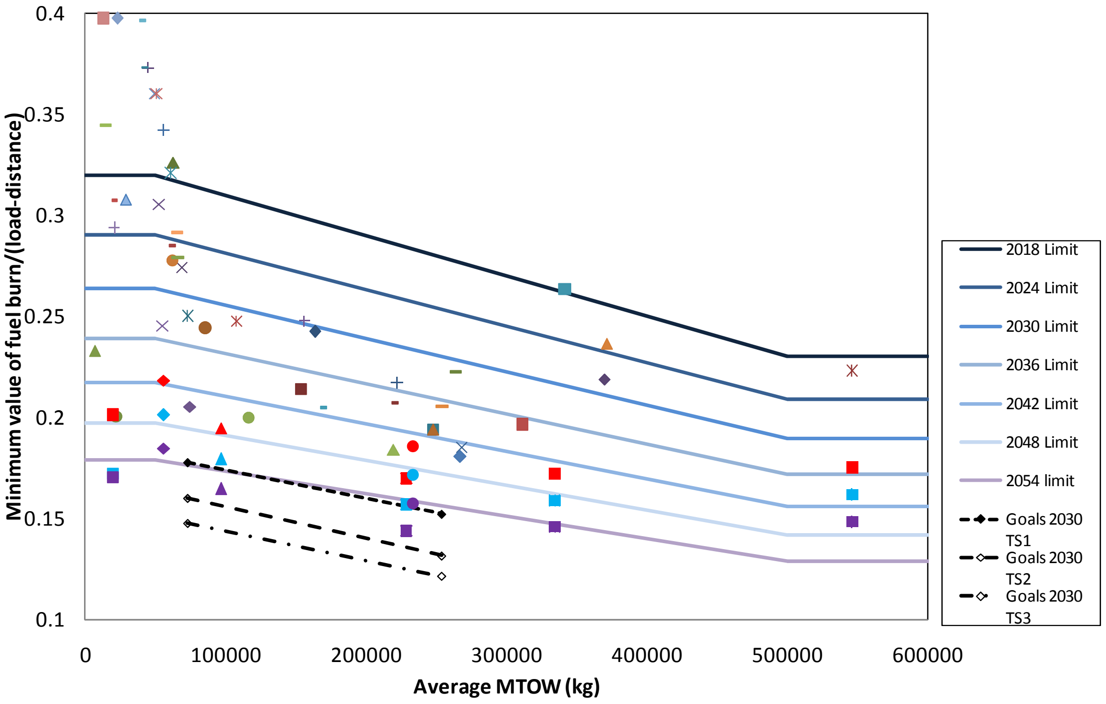


High policy lever

The CO_2 standard in 2018 is assumed to be set broadly to the fleet CO_2 metric average with the intention of removing the higher emitting in-production types from supply. In this high-case the CO_2 Standard enters into force in 2018 at the same level as in the mid-case, though now with a stringency improvement of 1.6% per annum (again, implemented every six years). This level of stringency increase is designed to affect the supply of the new (2020 and 2030) aircraft types, though importantly at least one aircraft type is always compliant in each aircraft seat class.

Figure 3 shows the stringency increases in this high policy scenario, overlaid onto the current and future fleet of aircraft types used in this study. The shape of the CO_2 Standard is again defined in such a way as not to disadvantage the smaller, generally short range, aircraft in relation to the chosen CO_2 metric. In terms of new production aircraft, at this level of stringency the CO_2 Standard does not drive new technology hard (in the same way as the mid-case) and this can be shown by the positioning of the TS1, TS2 and TS3 (all 2030) technology scenario goals. In fact it can be seen that this level of stringency only catches the TS1 (2030) goals compliant aircraft in 2054 though, on the other hand, technology may be indirectly driven further by the greater effect of this level of stringency on in-production types and manufacturers' need for these to be replaced, coupled with the aforementioned wider airline (market) reactions.

Figure 3. Increase in assumed CO_2 stringency (high case). Each point represents a different (current and future) aircraft type.



3.1.2 Modelling approach and results

CO_2 abatement modelling and results

The CO_2 Standard and the stringency levels (the low, mid and high policy cases) were modelled as an aircraft production cut-off. Under this approach, once an aircraft had failed to meet the CO_2 Standard (whether currently in-production or new) then the aircraft type was removed from production and hence the supply pool in the DfT Aviation models. To meet the demand, the remaining aircraft in that seat class were made available in the supply pool in place of the removed aircraft type. In all policy lever cases the CO_2 Standard left at least one remaining aircraft type in each seat class in order to meet the demand.

The estimated CO_2 abatement results from changes to the distribution of aircraft types introduced into the fleet in each year, rather than any changes to the CO_2 performance of individual future types (i.e. through aircraft performance improvement).

Based on the assumptions discussed above, Table 1 shows the estimated CO_2 abatement due to the successful implementation of this policy lever using the central demand baseline.

Table 1. Estimated CO_2 abatement potential from the illustrative regulatory CO_2 standard (2010-2050) as defined for this analysis (Central Baseline)

Policy case	Low	Mid	High
CO_2 abatement, Mt	-0.01	9.1	10.8

For this analysis, the CO_2 standard has been modelled first, before the other potential levers. The Low Policy scenario results in a zero CO_2 abatement because it removes very few aircraft types from production. The CO_2 abatement shown in the mid and high policy scenarios is solely due to the early removal of current and future in-production aircraft from the supply pool, with more fuel efficient aircraft instead procured.

Cost modelling and results

The baseline scenarios do not have a regulatory CO_2 standard and so the direct costs in the baseline associated with this lever are zero. The costing analysis used data from the DfT Aviation model (e.g. for aircraft in-production lives) on the number of new airframes (in-production and future types) entering the fleet under the baseline and the three policy levels (low, mid and high). The costing calculations for this lever were based on the following three major cost elements:

Increase in aircraft list price

It is assumed that a production cut-off increases the list price of newly procured airframes. This applies to both current in-production aircraft types and future aircraft types in the model. For current in-production aircraft types an estimated 2% increase in list price is imposed for each year's reduction in the availability of the type in the supply pool; this accounts for the lost sales revenue to the manufacturers due to the CO_2 Standard. To account for the loss in sales revenue from new aircraft types, a percentage increase in the list price, proportional to the reduced production life, is included (e.g. a 5% cut in production life from 20 years to 19 years would result in a 5% aircraft list price increase). Aircraft are assumed to be procured at list price, and therefore discounts on airframe list prices that airlines might achieve are not accounted for. This is an aviation industry cost (directly to the airlines), and some, or all, of this cost may be passed on to passengers through increased ticket prices, but it is assumed that this would have a negligible effect on demand.

Increased expenditure on R&D for new aircraft types

It is assumed that a CO_2 Standard would affect aircraft types from all manufacturers evenly; thus, the additional R&D costs to comply with the Standard are assumed to be split equally between the EU and the USA. The costs considered in the calculations of cost-effectiveness are the UK share of the additional R&D costs that arise as a result of the application of the policy lever. These costs are also split between UK-Government and non UK-Government sources. Estimates have been made of the R&D costs in the model baseline, where it is assumed that a new aircraft type costs £6-18bn to develop. When (due to the CO_2 Standard) only one aircraft type remains in a seat class it is assumed that half of the costs are to reinstate a competitor type. This is the case even if the DfT model shows one type (particularly the future generic types in the model) in a class, because in reality this is likely to be represented by both Airbus and Boeing aircraft, both with similar performance. The UK government contribution to associated R&D is assumed to be 10% of the UK share (one-fifth of the EU expenditure) in launch investment and other mechanisms.

Increased expenditure on R&D for modifying aircraft types

It is recognised that some aircraft types can be modified to meet a CO_2 Standard. This has been assessed when an individual in-production type fails the regulatory limit (AEA assumptions). When an aircraft type fails the standard it has been assumed (when feasible) that the manufacturers will modify the aircraft model, so that the fuel efficiency performance (at least) matches that of a competitor aircraft that meets the CO_2 standard and in this case additional R&D costs have been included. This cost is assumed to be 25% (based on estimates of the cost to develop the A320 NEO [Airbus A320 New Engine Option] by 2015) of the costs associated with the development of a full new type. The UK government contribution to associated R&D is assumed to be 10% of the UK share (one-fifth of the EU expenditure) via all mechanisms.

Notably, while these three cost elements are considered, only the first element (the increase in aircraft list price) contributes to the policy lever cost. This is because the policy lever does not drive new technology into the UK fleet (either on new or current aircraft types) and therefore there is limited potential to improve aircraft types through additional R&D support. Therefore there are no additional (realistic) R&D costs due to the definition of the policy lever and fleet mix assumptions in the DfT model. The cost calculations are sensitive to the assumed utilisation figure for each aircraft type. These have been derived from aircraft fleet mix and UK Air Traffic Movements (ATMs) data for 2007. The output from the DfT models includes projections of future ATMs, and these have been used, together with derived utilisation values, to determine the number of new airframes entering service under each Policy Lever scenario. Finally, when a new aircraft type has an in-production life of less than 20 years in the DfT model aircraft supply pool it is assumed that it remains in production for use in other regions. Therefore, the minimum in-production life assumed is set at an (estimated) 20 years.

The costs associated with this policy lever for the period 2010 to 2050 are shown in Table 2. Given that the costing method for this lever is one of fleet replacement, the absolute numbers for all cases are large (i.e. > £500bn between 2010 and 2050). However, the change in costs from the Baseline associated with the low policy scenario is small relative to total expenditure. This was expected because very few in-production aircraft types are removed by the CO_2 Standard.

Table 2. The estimated NPV of implementing a regulatory CO_2 standard (2010-2050) (Central Baseline)

Policy case	Central baseline	Low	Mid	High
Aircraft expenditure	514.70	515.22	525.60	532.72
DOC (direct operating cost) fuel saving over baseline (£bn)	0	-0.001	-1.02	-1.20
Total (£bn)	514.70	515.22	524.58	531.52
Change against baseline (£bn)	-	0.52	9.88	16.82

3.2 Regulation/incentive to accelerate fleet turnover

3.2.1 Lever description

A key element in improvements to fleet efficiency is the rate at which new technologies penetrate the fleet. This is the net result of new aircraft replacing old, and new aircraft being purchased to meet any growth in demand. The rate at which old aircraft are retired and the rate of growth of the total fleet both affect the rate at which the fleet efficiency improves, as does the technology level of the new aircraft that are available in the supply pool. Therefore, there is the potential for intervention to accelerate the turnover of the fleet (primarily through early retirement of old aircraft) in order to improve the average fleet efficiency and reduce the CO_2 emissions for the same total demand. However, it should be noted that much of the insertion of new technology in new aircraft types recently has been used to extend the range capability of aircraft (or other aspects of their performance) (ICAO-CAEP, 2010), rather than to reduce fuel consumption on short-haul missions. This means that replacing old aircraft types (like-for-like) with a more modern equivalent might not always give a fuel burn saving over the same mission. Instead the new aircraft type may give an airline more flexibility over which missions it can operate the aircraft.

The intervention could possibly take the form of a subsidy to airlines to retire old aircraft early provided that they are replaced by new build aircraft, similar to the subsidies that have been made previously to encourage the replacement of old cars by new ones. There are then questions as to what happens to a replaced aircraft. Is it scrapped or sold on to a less developed country? If the latter, does it replace an older aircraft there, or increase service capacity? There are also questions as to whether the new aircraft has lower CO_2 emissions or whether the airline replaces an old “short-range” aircraft with a new “long range” type, which may have worse average fuel consumption when employed on the short-haul routes performed by the previous aircraft.

A better form of intervention in terms of its ability to deliver reduced CO_2 emissions would be one which encourages the use of the “best” available aircraft for a particular mission as defined by the stage length and number of seats (see the lever below dealing with incentives to improve operational efficiency). At some airports, this could take the form of a “Green Slots” scheme, where some slots may be allocated solely to airlines which will use the best performing aircraft. At others, where operations are not slot-limited, a landing charge that penalises all aircraft other than the most fuel efficient might be employed. Clearly, either of these two options would require the determination of the best (lowest fuel burn) aircraft for the mission (route and seats combination), which could be contentious. However, assuming that the ICAO CO_2 Standard comes into force in the expected manner, the data required to rate the different aircraft types may be available. If not, the authorities could require that the manufacturers make the relevant data available to them before the aircraft are allowed to operate at a specific airport. Such data would likely be derived from the manufacturers’ models, but the validation of these models would need to be demonstrated to ICAO as part of the certification process. Using such a process, there would be incentives for the airlines to retire their higher CO_2 aircraft and replace them with lower CO_2 ones, hence accelerating fleet turnover and giving lower CO_2 emissions.

Incentives for fleet turnover in the form of subsidies to airlines to acquire new aircraft would need to come from governments, either national or, potentially, the EU. Clearly, the greatest effect would be achieved if the majority of aircraft operating (e.g. in/out of the UK) were included in the incentive scheme. However, a significant proportion of the aircraft that use UK airports are owned by non-UK or non-EU airlines, which might limit the effectiveness of such a policy unless other governments, particularly the US, operated a similar scheme. In the case of a Green Slots mechanism, or penalties for the higher CO_2 aircraft, the responsible authorities could be the airports, though probably with government support. Such measures would have a wider impact as they would apply to all aircraft using the airport, not just those owned by UK airlines.

An incentive to accelerate the turnover of the fleet could be introduced at any time, though it is likely to have most effect when a new generation of technology has been brought into service. It would continue to have a beneficial effect on the fleet for as long as it is in place.

Low policy case

The low policy scenario for this lever sets the maximum retirement age of aircraft in the UK fleet to 22 years. This retirement age limit means that the rate at which new aircraft replace old in the UK fleet is 3.3%, based on the 2010 operations age profile. The retirement rate in the baseline analysis for the year 2010 is 3.0%.

Mid policy case

The mid policy scenario for this lever sets the maximum retirement age of aircraft in the UK fleet to 21 years. This translates to a rate at which new aircraft replace old of 3.7% against the baseline for 2010 of 3.0%.

High policy case

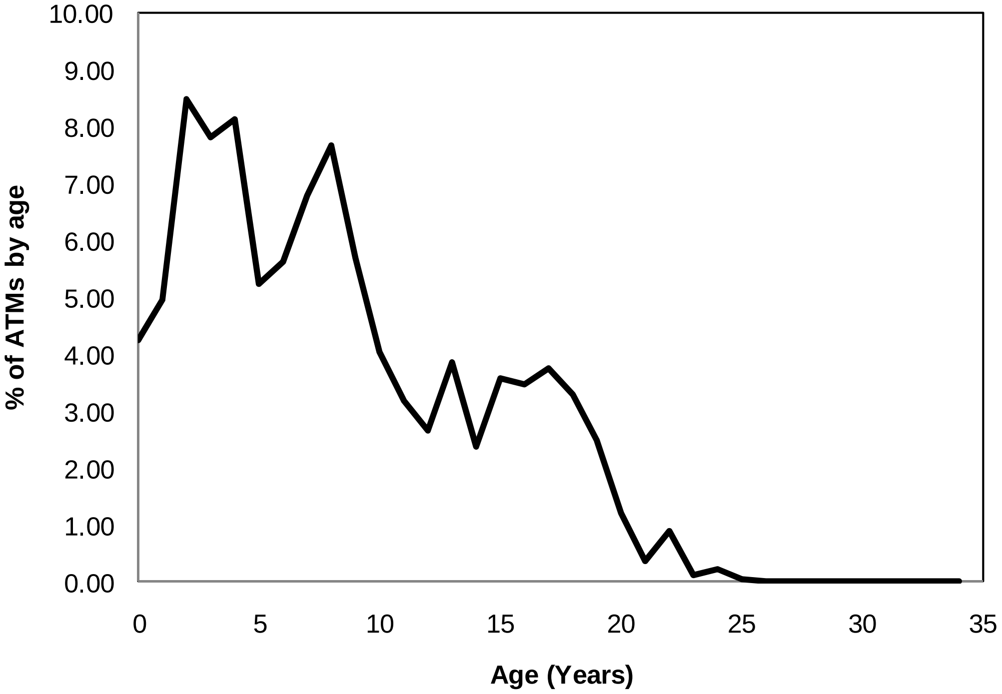
The high policy scenario for this lever sets the maximum retirement age of aircraft in the UK fleet to 19 years. This translates to a rate at which new aircraft replace old of 6.2%, twice the baseline rate for 2010 of 3.0%. Tighter retirement limits (i.e. less than 19 years) were considered but were deemed to be unrealistic, given the very high associated costs.

3.2.2 Modelling approach and results

CO_2 abatement modelling and results

The relatively young average age of the aircraft in the UK fleet is shown by the age distribution from 2007 in Figure 4 using data from the DfT model. Most aircraft are shown to be less than 10 years old. The aircraft retirement rate in the UK fleet is sensitive to the choice of retirement age and to the numbers of each aircraft type (i.e. through the utilisation rate of each aircraft type).

Figure 4. ATMs by age of aircraft for the UK fleet in 2007.



As discussed above, an important aspect of this policy lever is that retirement from the UK fleet does not necessarily mean that aircraft retire from service somewhere in the world. In fact it is realistic to assume that these aircraft will go into service elsewhere. This could either shift the CO_2 burden onto another region or improve that region's CO_2 performance due to the replacement of older aircraft (e.g. an Airbus A320 might replace a Boeing 707). This is not considered in the modelling of this policy lever (which considers emissions from "UK aviation" only) but is an important caveat to this analysis.

Based on the assumptions discussed in this section, Table 3 shows the estimated CO_2 abatement potential from the implementation of this policy lever as defined, using the central demand baseline.

Table 3. Estimated CO_2 abatement potential from accelerated fleet turnover (2010 to 2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	0.6	19	59

Cost modelling and results

The costs for accelerated fleet turnover are based on the output from the DfT Fleet Mix Model calculations, together with the cost of retiring aircraft, the cost of new aircraft and the potential savings in direct operating costs (DOC) due to operating new aircraft types. The costs are derived from analysis of fleet data from the DfT Aviation models, by identifying the aircraft that are removed from the fleet early (due to the three policy scenarios). Using these data the costs of replacing aircraft were calculated using the manufacturers' aircraft list prices (as discussed in relation to setting a CO_2 standard). Additionally, it is assumed that in-service aircraft have a residual value, amounting to 10% of their current list price when they retire from the UK fleet. There are financial benefits of retiring aircraft early and these are taken into account by calculating any direct operating cost (DOC) savings due to operating more fuel efficient aircraft over the period until when aircraft would otherwise have been retired from service. The results of this analysis are shown in Table 4 which shows NPV for the lever over the period 2010 to 2050. The absolute costs of accelerated fleet turnover are large (>£500bn) because this Policy Lever is (as with the setting of a CO_2 standard) about fleet replacement and hence procuring new aircraft.

Table 4. The estimated NPV of early fleet retirement (2010-2050) (Central Baseline).

Policy case	Central baseline	Low	Mid	High
Aircraft expenditure (£bn)	514.57	518.81	547.98	582.22
DOC fuel saving over baseline (£bn)	0	-0.07	-2.06	-6.49
Total (£bn)	514.57	518.74	545.92	575.73
Change against baseline (£bn)	-	4.17	31.35	61.16

3.3 Achievement of ICAO-CAEP fuel burn goals from international collaboration

3.3.1 Lever description

This policy lever is aimed at encouraging the achievement of ICAO-CAEP fuel burn goals technologies (ICAO-CAEP, 2010) through international collaboration, by progressing technology towards entry into service (EIS). This progression of technology R&D can be described using the NASA-TRL (Technology Readiness Level) scale (1 – 9), where TRL 1 means that the basic principles of a technology have been observed and reported, and TRL 9 means that the technology has been qualified through successful mission operations. A full description of the NASA TRL-scale (1-9) is given in Appendix 4 at the end of the report.

The aim of this policy lever is, therefore, to encourage the progression of fuel efficiency technologies towards TRL 9. It requires the UK to promote international R&D collaborations into fuel efficiency technologies, through, for example, UK ICAO-CAEP involvement and technical and industrial leadership. In the longer-term this UK leadership is assumed to cost government a proportion of the civil aviation industry's R&D investment in the UK. The policy lever itself is defined by the potential technologies that could be available (ICAO-CAEP, 2010) given certain levels of R&D investment. Specifically, the low, mid and high policy scenarios are defined in terms of the Technology Scenarios, TS1, TS2 and TS3 as considered by the CAEP independent expert review of fuel burn reduction technology goals exercise (ICAO-CAEP, 2010). Within each TS there are assumed baskets of technologies that will be available to new aircraft products in 2020 and 2030. Table 5 shows the baskets of technologies for TS1, TS2 and TS3 in 2020 and 2030.

The funding for technology R&D comes primarily from the Original Equipment Manufacturers (OEMs) and national and regional governments. For example, the UK research councils (e.g. EPSRC, the Engineering and Physical Sciences Research Council) offer funding for technology research at TRL 1 – 3, which has also been supported by OEMs. The EU, through its framework programmes, has offered funding for airframe and engine research programmes at TRL 1 – 6. Likewise the UK government has funded research at TRL 1 – 6 through funding vehicles such as Applied Research Programmes (ARP) and the Civil Aeronautics Research and Technology Demonstration (CARAD, now closed) programme.

The Clean Sky programme is an excellent example of a current, regionally funded, public-private partnership, with 50% funding from the EU. The OEMs will typically fund the technology development at the higher TRLs, 7 – 9, although EU funding for ancillary items has been available in the past, such as infrastructure development. Any direct funding at these higher TRLs might be considered an illegal subsidy (WTO, 2010) depending on the detailed terms on which it is offered. The one certainty is that, with or without a policy lever, technology R&D support is ongoing, and current fuel efficiency research programmes have timescales (10 —20 years: ICAO-CAEP, 2010) that depend on the technical scope of the research, funding and available resources. While the scope of this policy lever is to accelerate R&D into fuel efficiency technologies, it does not accelerate fleet turnover.

An important ‘real world’ caveat to this lever is that R&D spend alone does not guarantee improvements in aircraft fuel efficiency. Several factors are at play, including external pressures such as those exerted by standards or goals and fuel price. The level of competition between manufacturers is also important – for example the presence of only two closely matched players in the market tends to slow the adoption of new technologies, whereas a third player or entrant would be expected to stimulate a step-change.

Table 5. The baskets of technologies (shown by a '1') in each Technology Scenario. This is adapted from the CAEP independent expert review of fuel burn reduction technology goals (ICAO-CAEP, 2010).

	Single Aisles					Wide Body				
Year	2020	2030	2020	2030	2030	2020	2030	2020	2030	2030
Technology Scenario	1	1	2	2	3	1	1	2	2	3
Propulsion Improvements	16	18	18	20	31					
SFC										
Advanced Turbofan	1									
Geared Turbofan	1									
Open Rotor	1									
UHB										
Variable Cycle										
Inter-cooled Turbofan					1					1
Integrated propulsion										
Buried boundary layer ingesting installation concepts										
BPR										
Increased BPR	1	1	1	1	1	1	1	1	1	1
Propulsive efficiency	1	1	1	1	1		1	1	1	1
Increased propulsive efficiency	1	1	1	1	1	1	1	1	1	1
Active laminar flow										
Variable nozzle										
Suppression of reverse thrust		1		1			1		1	
OPR										
Increase OPR	1			1		1			1	
Increase thermal efficiency	1	1	1	1	1	1	1	1	1	1
Active tip clearance										
Water injection					1					1
Aerodynamic Improvements										
Aero - non viscous										
Improved aero tools	1	1	1	1	1	1	1	1	1	1
Excessence reduction	1	1	1	1	1	1	1	1	1	1
Variable camber with new control surfaces	1	1	1	1	1	1	1	1	1	1
Morphing wing										
Winglets/spiroid wingtips										
Aero - viscous										
Coatings										
Riblets	1	1	1	1		1	1	1	1	
Active turbulence control										
Natural laminar flow	1	1	1	1		1	1	1	1	
Hybrid laminar flow control		1		1			1		1	
Weight reductions										
Wings and empennages										
Optimised geometry										
Reduction of loading	1	1	1	1	1	1	1	1	1	1
New bounding processes (reduced rivets)										
Metallic technologies	1	1	1	1	1	1	1	1	1	1
Composite technologies	1	1	1	1	1	1	1	1	1	1
Multifunctional materials/structures	1	1	1	1	1	1	1	1	1	1
Nanotechnologies		1		1	1		1		1	1
Health monitoring		1		1	1		1		1	1
Active stability										
Cabin and fuselage										
New materials	1	1	1	1	1	1	1	1	1	1
Systems										
Landing gear in Ti	1	1	1	1	1	1	1	1	1	1
MEA		1	1	1	1		1	1	1	1
Fuel cells										

Key: BPR – bypass ratio; MEA – more electric aircraft; OPR – overall pressure ratio; SFC – specific fuel consumption; UHB – ultra high bypass

Low policy case

The policy lever cases are defined through detailed analysis of the ICAO-CAEP (2010) fuel burn Technology Scenarios. In the low policy case the TS1 technologies (see Table 5) are introduced in 2020, whilst in 2040 it is assumed that the TS2 technologies from 2030 are introduced (i.e. 10 years later than in the independent experts' TS2 scenario). A key assumption is that the fuel efficiency benefits associated with technology development become harder to achieve towards 2050. This approach of diminishing returns is used throughout the definition of this policy lever. For this low policy case it means that the technologies available in 2030 offer 2/3 of the efficiency benefit of the improvements over baseline of those available in 2040. The TS1 and TS2 technologies are assumed to enter service on board new and generational developments of civil aircraft up to 2050. Overall, a new aircraft type is assumed to enter service every 20 years with a generational improvement in the intervening 10 year point.

Mid policy case

In the mid policy lever case the TS2 technology goals are assumed to be met in 2020 and in 2030 – defined by the independent experts as the ICAO goals being met. Again it is assumed that fuel efficiency benefits associated with technology development become harder to achieve towards 2050, and so the 2030 TS3 technologies are assumed to enter service in 2040. The (TS1, TS2 and TS3) technologies are assumed to enter service on board new and generational developments of civil aircraft up to 2050. Overall, a new aircraft type is assumed to enter service every 20 years with a mid-life generational improvement in the intervening 10 year point.

High policy case

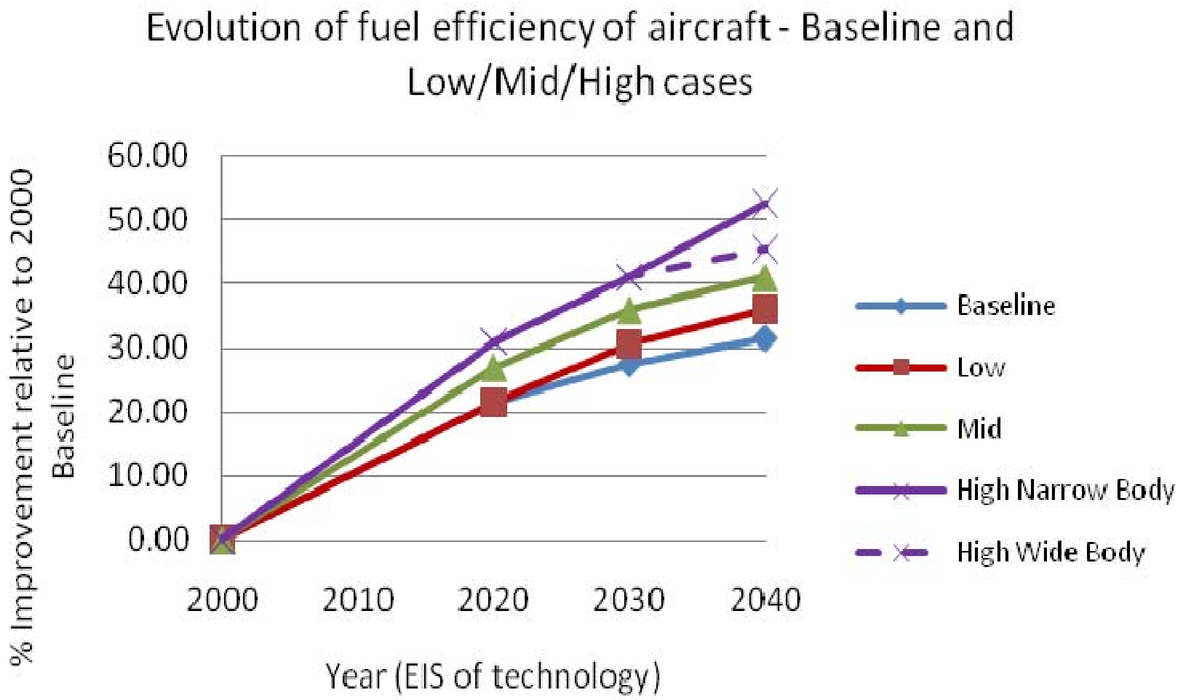
In the high policy lever case it is assumed that the TS2 technology goals are exceeded by 4% in 2020; this represents the width of the Goals range in the Independent Experts report (ICAO-CAEP, 2010). In 2030 the TS3 goals are assumed to have been met. Between 2030 and 2040 the fuel efficiency gains are assumed to be at half of the 2020-2030 rate. In addition, the narrow-body aircraft types are assumed to benefit from the (one time only) additional efficiency improvements embodied in the TS3OR (open rotor) case for 2030. The (TS1, TS2 and TS3) technologies are assumed to enter service on board new and generational developments of civil aircraft up to 2050. As in the other cases, a new aircraft type is assumed to enter into service every 20 years with a mid-life generational improvement in the intervening 10 year point.

3.3.2 Modelling approach and results

CO_2 abatement modelling and results

Based on the preceding assumptions on technology development, fuel efficiency gains for the three policy cases are shown in Figure 5. The rate of fuel efficiency improvement decreases between 2000 and 2040, reflecting the diminishing returns that manufacturers are likely to derive from R&D efforts. The only exception to this is the Narrow Body aircraft in the high policy case, where between 2030 and 2040 the fuel efficiency benefits of an Open Rotor aircraft are assumed to be available. The available fuel efficiency gains due to future R&D (shown in Figure 5) were defined under consensus agreement with industry experts from the study team and using the best available knowledge [ICAO-CAEP]. The team also defined a 2050 fuel efficiency benefit from available technology (e.g. of 35% relative to 2000) although this is not shown here because it cannot influence the 2050 UK fleet, given the timescales involved. This is important when understanding the costing approach discussed below.

Figure 5. Evolution of aircraft fuel efficiency trends through achievement of ICAO-CAEP fuel burn goals' technologies from international collaboration



An important caveat of this study is that the technology developments discussed and shown are associated with EU research funding, and that crucially European manufacturers development is assumed to directly affect the fuel efficiency of up to 50% of the aircraft entering the UK fleet. However, in a competitive situation, it would be expected that other manufacturers (principally Boeing and the US engine manufacturers) would invest, with Government support where needed, in accelerating their R&D programmes to provide competitive products to the European manufacturers. Additionally, in order to achieve the technology developments within TS1, TS2 and TS3, competition between manufacturers is essential. An assumption here is that, as a minimum, the current level of competition is maintained between at least two engine and airframe manufacturers, though as noted previously a third player or new entrant could be expected to result in step-change improvements. Furthermore, it is important that the stagnation currently observed in the development of the new 150 seat class aircraft is not prevalent across the industry. It is also important that other external pressures continue to be exerted to drive the uptake of available technologies on to new platforms.

Based on the assumptions discussed in this section, Table 6 shows the estimated CO_2 abatement due to the implementation of this policy lever for the three policy cases and the central baseline.

Table 6. The estimated CO_2 abatement potential due to support for the achievement of the ICAO fuel burn goals (2010-2050) (Central Baseline).

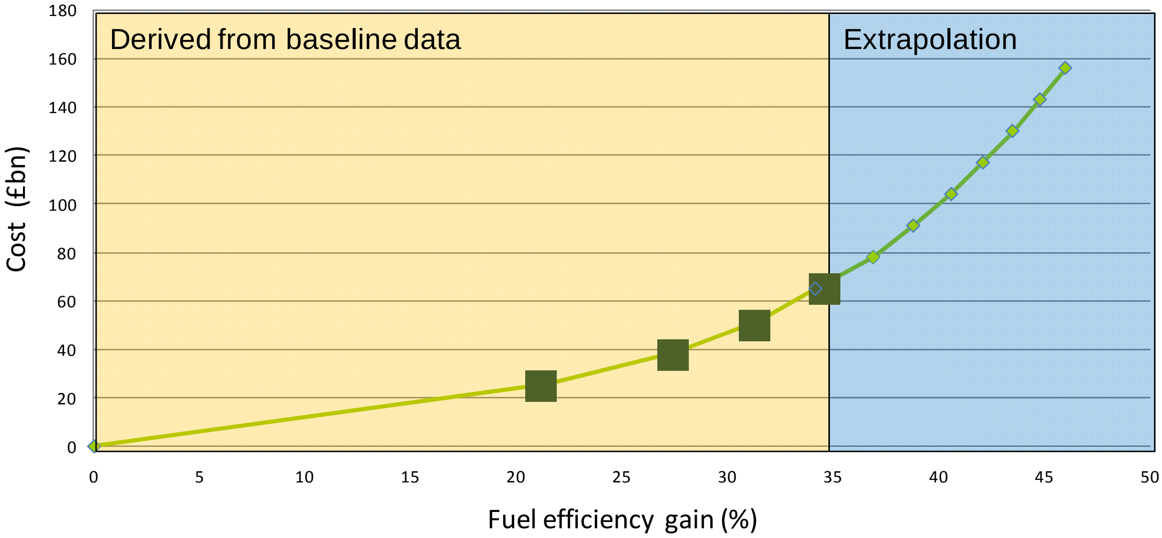
Policy case	Low	Mid	High
CO_2 abatement, Mt	7	40	66

Cost modelling and results

The costs for achieving this policy lever are based on the R&D expenditure to achieve the policy scenarios above the baseline. The three baseline scenarios have the same R&D costs. These baseline costs are calculated (at an EU level) using (at least) the annual R&D cost from Rolls Royce (£580m) (Rolls Royce, 2009), Airbus (£470m) (UK Parliament, 2009), and Clean Sky (£240m) (CleanSky, 2011). The other EU engine manufacturers are assumed to spend £580m per annum, based on Roll-Royce spend. In total the R&D expenditure within Europe is assumed to be around £1.9bn per annum. It is assumed that this amount will be spent per annum (i.e. at a flat rate) to achieve the baseline fuel efficiency gains to 2050. The estimated available fuel efficiency gains to 2040 are shown in Figure 6. In the baseline at 2050 there is an estimated 35% fuel efficiency gain over available technology in 2000. Based on these data (i.e. 50 years of fuel efficiency gains (e.g. ~35%) and 50 years of costs in the baseline (2000-2050) ~£1.9bn/annum) the costs associated with the fuel efficiency gains through the low, mid and high policy lever scenarios have been calculated. This reflects the cost of the harder to achieve fuel efficiency gains through the policy lever scenarios out to 2040 (the last opportunity the model has to influence the 2050 CO_2 abatement using this policy lever).

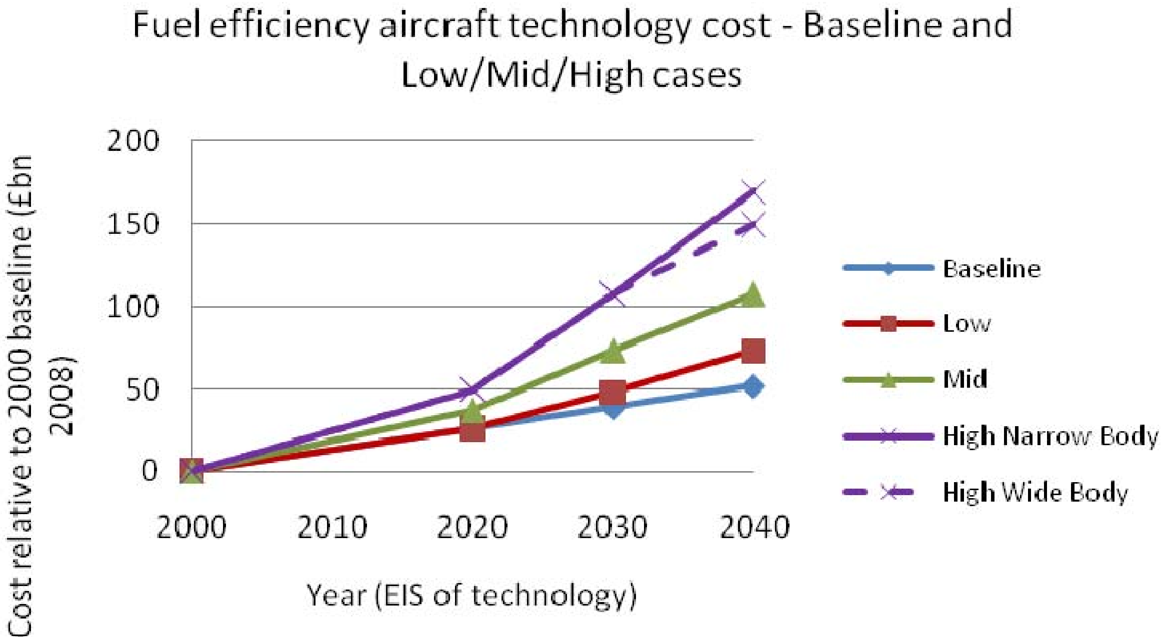
To explain this concept further, Figure 6 shows a cost curve relating cost to fuel efficiency gains from available technologies. The baseline data (2000-2050) are used up to a 35% fuel efficiency gain, and this is extrapolated for fuel efficiency gains towards 50%. The expanded timescale (i.e. 2000-2050) is only used as a basis to calculate the costs for this policy lever. The cost results for this policy lever still represent the 2010-2050 timescale in the same way as the other policy levers in this study. This was due to the availability of historic data from 2000 that enabled cost calculation for the baseline.

Figure 6. Curve relating fuel efficiency gains from technology related to R&D spend. The squares show the baseline data.



Costs for each of the policy scenarios in 2020, 2030 and 2040 were defined (Figure 7). The diminishing return on investment is evident as fuel efficiency goals become more expensive to achieve. Importantly, the ultimate UK Government share of any R&D is assumed to be 10% of the total UK share (which is itself one-fifth of the EU expenditure) in launch aid.

Figure 7. Estimated R&D costs associated with the evolution of aircraft fuel efficiency technologies.



Additionally, the estimated R&D costs associated with one platform development (generational and new) are also included. The R&D associated with a new aircraft is assumed to cost between £6-18bn. The R&D for a generational improvement is assumed to cost 15% of the new aircraft type R&D costs, based on the £1bn development costs for an A320NEO compared to over £6bn for a full A320 replacement[10]. Again, the UK Government share of any platform R&D is assumed to be 10% of the UK share, which is again taken as one-fifth of EU expenditure. An extremely important caveat is that, to achieve any strength (low, mid or high) of this policy lever, UK funding must be matched by EU and US partners and competitors to ensure that all available aircraft types offer the required efficiency improvements.

The DOC savings associated with the use of more fuel efficient aircraft are also included, based on the fuel burn savings calculated by the DfT models for this policy lever and the DECC fuel price forecasts. All of the estimated costs associated with this policy lever (for 2010 – 2050) using the central demand baseline are shown in Table 7.

Table 7. The estimated NPV of support for achieving the ICAO fuel burn goals' technologies (2010-2050) (Central Baseline).

Policy case	Central baseline	Low	Mid	High
Total EU research expenditure (£bn)	42.47	63.04	92.97	142.99
Total EU expenditure on aircraft development (£bn)	54.13	54.13	54.13	54.13
UK share of research expenditure (£bn)	8.49	12.61	18.59	28.60
UK government share of research expenditure (£bn)	0.85	1.26	1.86	2.86
UK share of new aircraft type development (£bn)	10.83	10.83	10.83	10.83
UK government share of new aircraft type development (£bn)	1.08	1.08	1.08	1.08
Total DOC (Fuel) saving over baseline for UK fleet (£bn)	0.00	-0.69	-4.18	-7.03
Change in UK costs (£bn)		3.42	5.92	13.07

3.4 Support for retrofitting more fuel efficient technologies to the existing fleet

3.4.1 Lever description

There is some potential for retrofitting new technologies to the existing fleet giving benefits in fuel consumption, that may be significant but not as great as available from a new aircraft design. The primary technologies showing the potential for retrofit are winglets, riblets and engine replacements. In principle, substantially greater improvements might be achievable through more dramatic upgrades, such as the fitting of laminar flow wings when they become available. However, this would be a very costly upgrade and fuel efficiency would still not be as good as for an optimised, new design, aircraft. Therefore, it is highly unlikely that such large scale upgrades would occur in the baseline.

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[10] Estimate derived using expert engineering judgement and from Flight Global, 2010; and from Flight Global, 1995; Flight Global, 2010; Dow Jones, 2011.

The retrofitting of winglets to existing aircraft, particularly Boeing 737, 757 and 767 models, already occurs. Aviation Technical Services (ATS) claim to have installed over 140 shipsets of winglets on Boeing aircraft (ATS, 2011). These winglet installations have been driven solely by the cost of aviation fuel; however, it would be expected that there would be a wider take-up of such improvements if there were some support to the operators to offset the costs. Flight International (2008) suggested that gains of 4% - 6% were achievable from the fitting of winglets to Boeing 737-700/800 aircraft. Substantial gains could also be made through retrofitting more advanced engines to aircraft.

However, the tendency in engine technology development is to move to higher bypass ratios with larger fan diameters, which restricts the ability to fit the engines to the airframes without substantial modification. There have been examples of engine retrofits to existing airframes. The replacement of RB211-524G/H engines on British Airways' Boeing 747-400s by RB211-524G-T/H-Ts is the most recent example, though in that case the changes to the engines were restricted to the core, with no changes to the external dimensions of the engine. Boeing and Airbus could re-engine the 737 and A320 series, though this would likely be aimed at new airframe builds. In the case of the Airbus aircraft, it is probable that the new engines (Pratt & Whitney PurePower P1000G and CFM Leap-X models) could be fitted to the airframe without any major modifications, so there may be some potential for retrofits to existing airframes in the future. However, the current discussions refer only to new build aircraft, so it is likely that some form of support might be needed to encourage the development of a retrofit option.

The provision of support for retrofitting technologies to existing aircraft would be a Government matter. If it was limited, for example, to the UK Government supporting UK airlines, the ability to implement the improvements would also clearly be limited. A wider application of the measure would require other governments (EU, US) to implement similar measures or to collaborate and provide support through another body, such as ICAO.

The policy lever scenarios all assume that retrofitting occurs to current amenable aircraft between 2015 and 2025. The retrofit of winglet sets and more-advanced engines (including both engine upgrade and replacement) are available within this lever. As noted above, the retrofitting of winglets can be performed now. Retrofitting of more advanced engines to existing aircraft can also be performed now, though there are greater barriers to doing so. Continuing retrofits of newer technology, particularly of more recent variants of the same engine type, may continue far into the future, as it is likely that engines will continue to be developed after their first entry into service, even for new engine families that appear some years in the future.

Low policy case

In the low policy lever case an improvement of 2% fuel efficiency is assumed to be gained from retrofitting winglets[11]. This is assumed to have a maximum take-up across the fleet of 20% of those types to which retrofitting is applicable. This assumes that winglet sets are fitted to appropriate aircraft (so, for example, in 2025 all Boeing 767s still operating have their fuel burns reduced by a factor of 0.20*0.02). This policy lever case could be achieved through UK based airlines only.

Mid policy case

In the mid policy lever case an improvement of 3% fuel efficiency is assumed to be gained from retrofitting winglets and upgrading engine components during overhaul procedures (derived using the same sources as for the low policy lever). This is assumed to have a maximum take-up across the fleet of 50% of those types to which retrofitting is applicable. This policy lever case could be achieved through UK based airlines only.

High policy case

In the high policy lever case an improvement of 4% fuel efficiency is assumed to be gained from retrofitting winglets, and that engines are upgraded to the best available engine within the current family (derived using the same sources as for the low policy lever). This is assumed to have a maximum take-up across the fleet of 80% of those types to which retrofitting is applicable. This case could not be achieved through UK based airlines only, and the involvement of foreign airlines would be essential.

3.4.2 Modelling approach and results

CO_2 abatement modelling and results

The degree to which the fuel burn of an aircraft could be reduced by retrofits clearly depends on the technologies employed. For devices such as winglets, an improvement of 2% has been allowed. For engines, the greatest improvements would be obtained if completely new technology engines were installed, though in the majority of cases, this would be impractical. A further 1% improvement has been assumed (over Winglets) for engine component retrofit and a further 2% (again over winglets) for retrofitting the newest engine family variant available (derived from the same sources as previously listed). Other important assumptions are that in the low and mid policy lever scenarios that the CO_2 abatement is achievable through retrofitting only those amenable aircraft operated by UK airlines. Importantly, in the high policy scenario, support to non-UK airlines would be required to achieve the CO_2 abatement.

A policy of retrofitting has zero CO_2 abatement potential in 2050 due to these retrofit policies assumed to only be in place between 2015 and 2025. All those aircraft involved in a retrofit programme are out of service by 2050 and no future aircraft types are assumed to be retrofitted. Based on the assumptions

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[11] Estimate derived from Aviation Partners Boeing, 2011; Aviation Technical Services, 2011; Airbus, 2011; Farries et al., 2008; Morris et al., 2009b.

discussed in this section, Table 8 shows the estimated CO_2 abatement from implementation of this policy lever using the central demand baseline.

Table 8. Estimated CO_2 abatement potential from retrofitting (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	0.84	2.71	4.46

Cost modelling and results

The number of aircraft amenable to retrofits was calculated using data from the DfT fleet mix model, together with utilisation estimates obtained from data for airframes and ATMs in 2007.

Estimates of cost associated with retrofitting particular fuel efficiency technologies to aircraft have been made. The retrofitting of a set of winglets has been estimated at £800,000[12]. For engine overhauls the cost is assumed to be 10% of a new engine price (~£0.1m to £1.35m)[13]. The retrofit of a new engine (from the current engine family) to an old airframe is estimated to be 8% of the cost of procuring a new aircraft, based on the relative prices of Airbus A320NEO and A320 aircraft[14].

The estimated DOC savings associated with the use of more fuel efficient aircraft are also included, based on the fuel burn savings calculated by the DfT model from retrofitting and the DECC fuel price forecasts. All the estimated costs associated with this policy lever (for 2010 – 2050) using the central demand baseline are described in Table 9.

Table 9. The estimated NPV of retrofitting (2010-2050) (Central Baseline).

Policy case	Central baseline	Low	Mid	High
Retrofit expenditure (£bn)	0	0.33	1.36	9.72
DOC fuel saving over baseline (£bn)	0	-0.10	-0.34	-0.55
Change against baseline (£bn)	0	0.23	1.02	9.16

3.5 Interdependencies between the aviation technology levers

It is clear that there are some interdependencies between the four policy levers discussed above. We have not been able to take account of some of these interdependencies in the modelling of CO_2 abatement and costs, beyond taking account of the emissions savings estimated from implementation of the previous modelled levers. However, it is important to recognise their existence and their potential for affecting the results of actual implementation of the levers.

Support for research and development would be expected to lead to technologies (applicable to retrofitting) being introduced earlier (or greater improvements being achieved), which would result in further tightening of a regulatory CO_2

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[12] Morris et al, 2009b.

[13] Estimate derived using expert engineering judgement and from Farries et al (2008) and Morris et al (2009b).

[14] Flight Global, 2010.

standard having little or no effect. A combination of retrofitting with achieving the ICAO-CAEP fuel burn goals could bring additional benefits in that the technologies available for retrofit may be better than they would have been without the support for research. There is possibly a strong link between application of a CO_2 standard and the ICAO-CAEP goals in that a CO2 Standard (related to the certification of new types) could force technology significantly ahead of where it would be without the Standard. In this case, considerable increases in R&D expenditure would be required to produce the technologies necessary for new types to meet the Standard.

4 Operational Measures

4.1 Capacity constraints including slots

4.1.1 Lever description

The baseline for this lever assumes maximum use of existing capacity, i.e. maximum use of existing runways and associated increase in terminal capacity. It is reported in detail in the DfT report *UK Aviation Forecasts 2011*. Further information is provided in Appendix 1.

This lever examines options for limiting annual airport capacities below the levels of the DfT 'max use' scenario assumed in the baseline. In the max use case no new runways are built in the UK but, where there is no explicit planning prohibition, most airports develop as necessary in the medium term to utilise their current potential runway capacity. This case does imply new consents for terminal expansions beyond the current planning horizons.. The max use baseline scenario is discussed more fully in chapter 2 of DfT's latest report on aviation forecasts.[15]

The policy lever scenarios do not represent Government policy but represent a range of plausible policies for restricting the growth in UK air travel and thereby reducing UK aviation CO_2 emissions.

The policy lever scenarios, with DfT model code, are:

1. **Low: (s01)**: current capacities, except where there is a current planning application in the system. In practice this is simply today's capacities supplemented by proposed expansion at Bristol to handle 10 million passengers per annum (mppa) from 6.5mppa and the proposed lengthening of the runway at Birmingham to allow services to operate to more long haul destinations.

2. **Mid: (s00)**: This is current and permitted capacities only. Like s01, it does include recent planning permissions such as those at Stansted (35mppa) and London City (120,000 ATMs).

3. **High (s0097)**: This scenario assumes that runway capacities are capped at 3% below the level in s00.

Table 10 below shows the assumed runway capacities and terminal passenger capacities by scenario for 2050 (with 2010 data provided for reference). These are the maximum number of passengers an airport's terminal and associated passenger handling infrastructure is assumed capable of serving per annum. Some annual capacities are a little higher than many airports might currently estimate, but this allows for some piecemeal improvements to taxiways and aprons to achieve maximum use of existing runways. It also allows for an

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[15] *UK Aviation Forecasts*, DfT, August 2011, see paragraph 2.88.

increase in off peak and out of season movements as national demand grows. The effect of the high lever capacity scenario used is to reduce all current runway capacities by 3%.

Table 10. Summary of assumed national runway and terminal capacities in 2050

	DfT code:	s02	s01	s00	s0097
Airport	2010	Baseline: Max use	Low Policy: Current planning pipeline	Mid policy: Existing capacity	High policy: Existing capacity reduced by 3%
ATMs (000s) London	1,223	1,254	1,223	1,223	1,186
ATMs (000s) regional	4,834	5,579	4,834	4,792	4,649
ATMs (000s) National	6,057	6,833	6,057	6,015	5,835
Passengers (m) London	181	188	181	181	181
Passengers (m) regional	231	373	231	217	217
Passengers (m) National	412	561	412	398	398

The difference between the low lever and the baseline is largest, because, as described above, the baseline includes airports developing as necessary in the medium term to utilise their current potential runway capacity where there is no planning restriction in place.. The gap between the low and mid levers is very small as it consists of limited improvements associated with planning applications at Birmingham and Bristol airports. There is no change at all in capacities in the London airport system between these two cases. The difference between the mid and high levers by definition equates to 3% of runway capacity everywhere with no changes in the terminal capacity.

For the purposes of the study it is possible to interpret capacity restraints as reflecting the introduction of slot limitations at all airports when they reach their assumed annual runway capacity coupled with limitations on the introduction of additional terminal capacity.

The organisation responsible for initiating such policies would be DfT in consultation with other Government departments, but implementation may need to involve the CAA (Civil Aviation Authority) and the slot coordinators at the airports involved. In practice this would mean that the incumbent airlines at the airports subject to slot restrictions would need to be involved in the allocation of a reduced number of airport slots.

In principle, slot restriction measures could be implemented relatively quickly, subject to legal challenges, and since the restrictions on capacity and traffic throughput would be immediate, resulting reductions in UK emissions should follow rapidly.

4.1.2 Modelling approach and analysis

CO_2 abatement modelling and results

Passenger throughputs are summarised in Table 11 for the policy lever scenarios in the central demand baseline case. The results are generally similar and highlight the relatively small difference between the cases when forecasting is constrained to capacity. The largest change is that between the baseline case of max use and the low policy scenario. Differences are focused on the regions, while in the South East only Luton gains any extra capacity.

Table 11. Forecast passenger throughput (central demand baseline), mppa

		2010	2020	2030	2040	2050
Central baseline (s02)	Max use	209	270	334	403	471
Low policy case (s01)	Current planning pipeline	209	271	330	387	402
Mid policy case (s00)	Existing capacity	209	269	324	375*	388
High policy case (s0097)	Existing capacity reduced by 3%	209	266	317	367*	388

Notes: forecasts rounded to nearest 1 mppa, shading highlights cases where the model run required extrapolation. * 2039 full model forecast as full run terminated in 2040.

The table also illustrates that as capacity is reduced, the passenger allocation process in the detailed National Air Passenger Allocation Model struggles to fit all demand to available capacity and runs terminate earlier as capacity is taken away. Extrapolation of model runs where capacity constraints prevent the DfT models running through to 2050 is explained in the DfT 2011 UK Aviation Forecasts report.[16] By 2050 in both the mid and high policy cases all the significant airports have run out of spare capacity. This is discussed more fully below. In this particular case, although input passenger demand is the same and the high policy case has 3% lower runway capacities, the terminal capacities are the same and therefore aircraft loads increase to allow the same ultimate terminal capacities to be reached.

When an airport reaches capacity in the DfT model, the model calculates the extra cost of using the airport that would reduce excess demand to zero. This 'shadow cost' or 'fare premium' represents the way the market might respond to capacity constraints by increasing the costs faced by passengers of using the over capacity runway or terminal facilities. This fare premium might be captured by either the airline or the airport operator. The main effects of shadow costs being applied at an airport are to cause passengers to divert to less preferred substitute airports and for some passengers not to travel. There are important secondary effects on the nature of passenger and ATM demand as the airport system gets closer to its overall capacity:

1. Where the constraint is runway slots, bigger aircraft tend to replace smaller aircraft as the cost of the slot can be shared between more passengers. Larger aircraft have higher emissions.

2. For similar reasons, long haul routes operated by larger aircraft will tend to be more dominant in competition for slots and therefore emissions can rise with an increase in aircraft-kms. Domestic and short haul services will tend

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[16] See Annex E in *UK Aviation Forecasts*, DfT, August 2011

to be squeezed out of constrained airports as they are generally less profitable.

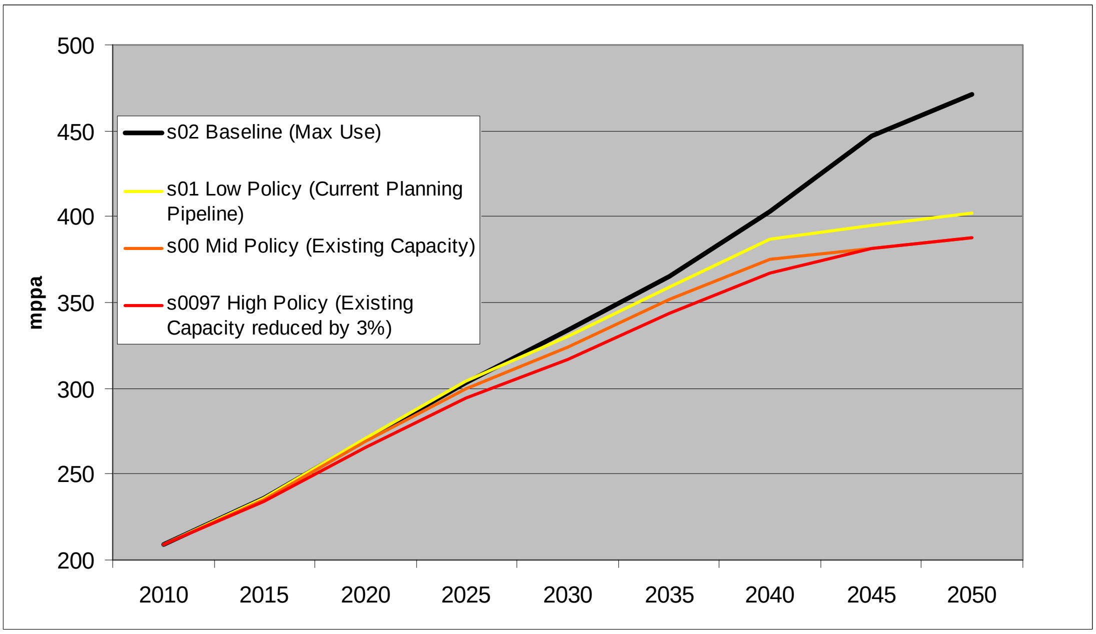
3. Passengers with lower values of time, i.e. leisure passengers, will be more sensitive to shadow costs at constrained airports and therefore more likely to move to less preferred substitute airports or not travel.

4. Transferring passengers at congested hub airports are more likely to disappear because they face a double shadow cost at the hub (a flight into and a flight out of the airport).

When a scenario leads to capacity being largely filled and similar ATM and passenger forecasts, the key difference between the outputs is that the scenarios with higher inputs demand baseline will have higher fare premiums per passenger. This will have effects on the composition of the demand (more long haul, less transfers and so on) within the same overall throughput cap for the reasons described above.

Figure 8 plots the data on forecast passenger throughput under each policy case (using the central demand baseline).

Figure 8. Million passengers per annum under the central demand baseline and the three policy lever cases.



It can be seen that with central demand the difference between the capacity levers as it affects constrained national passenger throughput (and in turn ATMs and CO_2 emissions) is much greater between the baseline and the low lever than it is between the levers themselves. Up to the mid 2030s it can be seen that, quite intuitively, the high policy lever satisfies the least passengers but that the differences are very small. After the mid 2030s the mid and high lever effects become almost indistinguishable in terms of passengers (and therefore ATMs and emissions) [17]. Note that the graph shows the effect of the different capacities on passengers, but also reflects the additional effect of the behavioural change levers (chapter 6) that are applied before the capacity levers.

Data on estimated aggregate emission savings over the period analysed for this study are presented in Table 12.

Table 12. The estimated CO_2 abatement potential due to capacity constraints at UK airports (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	37	37	13

Savings in CO_2 emissions are greatest in the low and mid policy cases because the step from the baseline max use to the low case of the current planning system represents the largest change in capacity between any of the options. The step between the current planning system (low) and current capacity (mid) is very small, concerning only improvements at Birmingham and Bristol airports

Cost modelling

Drawing on the information just presented for CO_2 modelling, costs for this lever take the form of losses of user benefits to passengers no longer able to travel. In addition there would be welfare losses to existing passengers from higher fares, reduced frequencies, service levels and so on. While the higher fares arising from the capacity constraints would impose a cost on existing passengers, there would be offsetting benefits to airlines or airport operators, who would benefit from the greater revenues they receive from these passengers. However, there would be losses of producer surplus to airlines and airports from lower traffic. There would also be benefits in terms of infrastructure costs avoided, that would offset the costs of capacity constraints to passengers. Reduced traffic would also result in exchequer costs through a reduction in APD (Air Passenger Duty) receipts, as well as having impacts on direct taxation, through changes in expenditure elsewhere in the economy, as consumers spend less money on air travel.

These welfare effects are estimated and monetised in the Social Costs and Benefits (SCAB) module of the DfT's aviation modelling framework[18]. Results for the central baseline, low, mid and high policy cases are shown in Table 13.

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[17] Note, as explained above, the only difference between s00 and s0097 capacity inputs is a reduction in ATM (runway) capacity. During the final years aircraft loads increase so that the same total passenger throughput is achieved.

[18] The methods underpinning the calculations in SCAB are set out in TAG Unit 3.18 Aviation Appraisal, published for consultation as part of the Department's Transport Analysis Guidance. http://www.dft.gov.uk/webtag/documents/consultations.php.

Table 13. Summary of estimated costs for capacity constraints (central baseline) £billion.

Description	Low Policy	Mid Policy	High Policy
User Benefits, of which:	105.6	178.9	147.7
transfer from producers	101.4	171.3	142.1
from change in passenger numbers	4.2	7.6	5.6
Producer Benefits, of which:	-105.9	-180.0	-148.1
transfer to consumers	-115.1	-191.4	-158.8
from change in passenger numbers	9.2	11.3	10.7
Government Revenue, of which:	9.4	15.0	13.4
APD revenue	3.9	4.7	3.7
tax changes elsewhere in the economy	5.5	10.3	9.7
Surface Access Carbon	-0.4	0.0	-0.2
Accidents	-0.2	-0.3	-0.2
Capital Costs	-3.3	-3.9	-3.9
NPV	5.2	9.7	8.7

Although the high policy lever assumes the largest reduction in capacity relative to the baseline, it does not follow that the pattern of NPVs will mirror the assumed changes in capacity. This is because the capacity lever is applied after all the other levers being assessed. Most significantly, this lever comes after the application of the videoconferencing and behavioural change levers which would both potentially have significant impacts on the composition and level of passenger demand. The low policy capacity lever is applied to the forecast level of demand in the central baseline, as neither behavioural change nor videoconferencing are assumed to have an impact on demand in the low policy lever case.

However, for the mid policy capacity lever, the central demand baseline is modified by a 2% reduction in business and leisure travel and a further 5% switch from long haul to short haul flights by 2050 as a result of the assumed impact of the behavioural change and videoconferencing levers. In the high policy lever case, the central baseline demand is modified by a 5% reduction in business and leisure travel and a further 10% switch from long haul to short haul flights by 2050. The lower levels of overall demand in the mid and high policy scenarios serve to offset the greater levels of capacity reduction from the capacity lever.

In addition, the assumed switch of long haul traffic to short haul traffic serves to relieve pressure at the most congested airports in the model where long haul routes are concentrated, because short haul passengers are able to use more local airports. This effect also offsets the greater levels of capacity reduction assumed in the mid and high policy scenarios. A key reason why the NPV of the low policy capacity lever is relatively low is that it generates significant benefits in the form of the capital costs avoided by restricting airports from investing in the capacity expansions assumed in the baseline. The capital cost savings associated with the additional capacity restrictions assumed in the mid and high policy levers are relatively small in comparison.

4.1.3 Commentary on capacity constraints

It is likely that capacity constraints will lead to some amount of carbon leakage, as passengers and cargo are forced to reach their destinations via less efficient routes, with a consequential increase in CO_2 emissions. Further to this, there may be a loss to the UK economy if tourists and business people are discouraged from travelling to the UK. On the other hand the UK economy may benefit from UK residents spending more of their incomes in the UK rather than overseas. The high policy case which caps capacity at 3% below the mid policy case could also improve operational performance and recovery from disruption to services. No account is taken of these potential impacts. In addition no account is taken of displaced passengers switching to continental hubs or to road and rail and the effect of this in reducing any UK aviation emissions savings.

It should also be noted that capacity constraints are treated in the NPV analysis differently to the other levers. The DfT’s transport appraisal guidance requires projects to be appraised over their lifetime. For infrastructure projects, where it is generally assumed that there is an indefinite lifetime, the guidance is to appraise costs and benefits over a 60 year period from project opening. For this analysis, the capacity levers have been appraised over the period to 2080. The other levers are assessed only to 2050, this being in line both with the DfT’s transport appraisal guidance and with government practice on CO_2 MAC curves.

4.2 Reducing inefficiencies in ATM & ANSP related operations

4.2.1 Lever description

This lever is not directly in the gift of government or regulators, so it would be necessary to implement it in conjunction with organisations such as NATS (National Air Traffic Services) and EUROCONTROL (the European Organisation for the Safety of Air Navigation). Measures may consist of ATM service providers giving guidance to airlines or airports on the implementation of best practices to improve the performance of the ATM system. These may include fuel saving measures associated with:

- Taxi delays
- Continuous climb
- Direct routes
- Wind routes
- Speed control
- Optimal descents

Description of the policy levers is made with reference work by the Civil Air Navigation Services Organization (CANSO, 2008) which has set aspirational goals for ATM fuel efficiency improvements by 2050 (Table 14). These would be achieved through initiatives such as new operating procedures and institutional changes to reduce airspace fragmentation.

Table 14. CANSO aspirational goals for ATM efficiency improvement.

	Year	Global ATM efficiency
Baseline	2005	92% to 94%
Goal 1	2010	92% to 95%
Goal 2	2020	93% to 95%
Goal 3	2050	95% to 98%

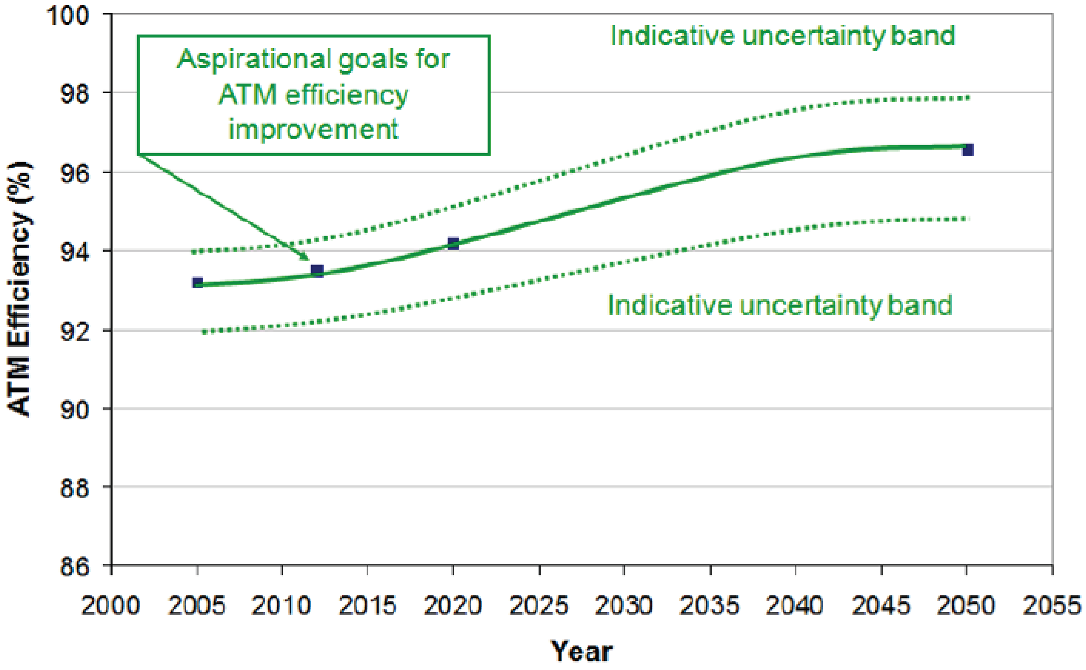
Note: 100% efficiency represents aircraft flying point to point via the optimum trajectory such as the great circle ground track route at the most fuel efficient altitude and speed. Therefore a flight that uses 2% more fuel than the optimum trajectory is considered 98% efficient. In practice 100% efficiency is not possible for a number of reasons such as safety, (i.e. the need to keep aircraft separated by a certain distance or time), weather, capacity, and noise.

CANSO note that forecasts for increased traffic congestion in future years will, without action being taken to increase efficiency, lead to a reduction in efficiency. The apparent improvement from 2005 to 2050 therefore underestimates the true benefit of attaining Goal 3 in 2050 relative to the business as usual position, as a greater level of efficiency would need to be delivered to counteract the reduction in efficiency from increased traffic congestion, to deliver the overall improvements set out in Table 14.

There is no single organisation responsible for implementation of this lever, with most initiatives involving air service providers working closely with aviation stakeholders. For example, the Flight Efficiency Plan is a joint initiative launched in September 2008 by EUROCONTROL, IATA (the International Air Transport Association) and CANSO to drive fuel and emissions savings. Similarly the Single European Sky Air Traffic Management research (SESAR) is the EU’s €30 billion air traffic management modernisation programme, but its implementation involves synchronising the plans and actions of different aviation stakeholders.

The timeframe for these policy levers is governed by the CANSO goals for 2050 but efficiency savings are expected to accrue progressively over this period (Figure 9).

Figure 9. CANSO goals for ATM efficiency (from CANSO, 2008)



The key issue for consideration in conducting any modelling is how much, if any, of these projected CANSO 2050 goals should be included in projecting forward the baseline. Including all these improvements might be considered unrealistic, particularly given the significant barriers to introduction. It is therefore considered realistic to incorporate some shortfall below the achievement of the CANSO goals in the baseline used here. In its 1999 report, the IPCC (the Intergovernmental Panel on Climate Change) estimated that for the 1998-99 worldwide fleet operations, improvements in the ATM system alone could reduce fuel burn per trip by 6-12%, provided that the necessary institutional and regulatory arrangements had been put in place. The CANSO benchmark for 2005 indicates overall inefficiency of the global ATM system of between 6% and 8%, though for Europe the estimates are rather higher with a range of 7% to 11%. The CANSO benchmark represents an update to the IPCC 1999 figure, taking into account improvements put at 4% over the intervening period. CANSO considers that of the remaining inefficiency, half is related to interdependencies and not recoverable, but the CANSO goals aim to recover all the remaining inefficiency.

Taking account of CANSO (2008), in particular, policy levers are defined as follows:

Low policy case

In the low policy lever case it is assumed that there is partial achievement of the CANSO target with an improvement of 2% by 2050 over the CANSO 2005 baseline of 92-94% global ATM efficiency.

Mid policy case

In the mid policy lever case it is assumed that there is full achievement of the CANSO global aspirational target, representing a 4% improvement over the 2005 baseline.

High policy case

The high policy lever case assumes a 6% efficiency improvement is delivered, representing full achievement of the CANSO target and in addition takes account of the fact the European starting point level of ATM efficiency in 2005 is estimated by CANSO to be 2% lower than the global average

4.2.2 Modelling approach and analysis

CO_2 abatement modelling and results

The preceding assumptions on baseline and policy levers have been analysed using the DfT models. Results showing data on estimated aggregate emission savings over the period analysed for this study are presented in Table 15.

Table 15. The estimated CO_2 abatement potential due to improvements in ATM efficiency (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	15	27	38

Cost modelling

The estimated costs associated with the ATM improvements set out in the policy levers have been based on the cost of additional measures to improve ATM efficiency up to 2050. The costs of SESAR and associated initiatives are already subsumed within the baseline, as this represents existing policy, but there would be additional costs to improve ATM efficiency over and above this level. The European ATM Master Plan includes an analysis of the funding, costs and benefits and risk assessment associated with the implementation of Single European Sky. This includes a total investment of €30bn, with a breakdown by stakeholder. Stripping out investment by military and general and business aviation stakeholders, the investment required by airlines, ANSPs and airport operators amounts to €18.3bn. The €18.3bn is additional to the improvements in the baseline from SESAR investment.

We have made a judgement to apply this to our high policy case, with lower investment costs of €4bn and €10bn respectively, to meet the low and mid cases. These lower capital costs reflect an assumption of diminishing returns to reflect the likelihood that the unit costs of achieving progressively higher levels of ATM efficiency will rise. Given the time frame for the analysis these costs are repeated in 2035. Savings from reduced fuel consumption linked to efficiencies in air traffic movements are also factored into the costings but other savings in airline operating costs from reduced delays and more direct routings have not been included. Costs for the period to 2050 under the policy cases and central baseline are shown in Table 16.

Table 16. Estimated NPV for improvements in ATM efficiency as defined (central baseline).

Policy case	Low	Mid	High
NPV, £million	-1,148	-1,872	-2,098

Note: Negative figures denote a cost saving.

The Master Plan identifies a number of key risks to delivery of the efficiency improvements, most of which are classed as "high". These include:

- Governance structure not capable of ensuring successful deployment;
- Future investment by key stakeholders not secured because of long payback periods and uncertainty over commercial returns through customer sales;
- Delays in the availability of new technology; and
- No agreement in reducing fragmentation of European airspace.

It is clear that there is a risk of shortcomings in the delivery of SESAR and the Master Plan identifies mitigation strategies. It notes that an uncoordinated approach could increase the amount of investment required by 5-15%.

4.2.1 Commentary on improving efficiency of ATM and ANSP operations

There are a number of barriers to introduction of this lever. Institutional barriers may limit improvements from reduced fragmentation of airspace while financial ones may constrain improvements associated with infrastructure investment. In addition, 100% ATM fuel efficiency is not achievable as some inefficiencies will remain as a consequence of operating constraints and interdependencies, such as safety, capacity, weather and noise.

This lever comes out as a win-win in most cases because financial savings to airlines from lower fuel costs outweigh the estimated costs of capital investment. However, there are diminishing returns as ATM efficiency approaches a ceiling under the high demand case. There are several caveats:

- It is difficult to attribute ATM efficiency improvements to the level of capital investment assumed;
- There are uncertainties over the level and profile of capital investment required to deliver the ATM efficiency savings modelled;
- The effects of continued traffic growth on airspace congestion could offset to varying degrees the improvements from programmes such as SESAR;
- The estimated cost is very sensitive to the assumed fuel price. Whilst 8 of the 9 cases considered return an estimated net economic benefit from this lever (see Table 30 below), the low demand/high policy case does not, as a result of the assumed low fuel prices that are insufficient to counter the high investment costs;
- No account is taken of other operating costs savings to airlines from reduced delays, use of more direct routes etc. other than fuel cost savings.

4.3 Reducing inefficiencies in air carrier operations

4.3.1 Lever description

This lever would encourage a range of operational and fleet management measures that airlines could implement to reduce inefficiencies relating to operational practices, ground operations and aircraft specification in terms of design range, payload and proportion of maximum payload used. Incentives to optimise fuel use already exist through the fuel price, and these will strengthen as prices increase and after aviation joins the EU ETS in 2012. However, there may be inhibitors such as a lack of alternative aircraft designs, biases caused by large leasing company purchases or information gaps that result in inefficient practices even at current fuel prices.

This lever could be implemented via changes to the slot allocation system, with slots only available to airlines deploying aircraft meeting specified target levels of fuel burn per ATK (Available Tonne Kilometre) or by requiring the use of turbo-prop aircraft on domestic and other short-haul routes until such time as more optimally designed aircraft are available. For the purposes of this study, we have not designed a specific measure. If the lever was applied as a financial penalty to airlines, as opposed to an incentive funded by the Exchequer, the cost would be incurred by airlines and there would be some demand feedback effects. If a financial incentive was applied, there would be broadly similar costs, though these would be incurred by the Exchequer. Clearly there will be financial savings to airlines from reduced fuel burn associated with the implementation of such efficiency improvements. However for the purposes of costing this lever, the offsetting costs associated with implementing these improvements have been estimated, but no account has been taken of fuel costs savings to airlines. These costs provide a reasonable proxy for the cost to either airlines or the Exchequer.

One particular aspect of excess fuel usage arises from poor matching of aircraft types to missions flown in terms of emissions. For example, most aircraft operated on short haul services have considerable unused range and capability for the majority of missions performed. There is therefore potential for fuel savings from reduced sized fuel tanks and wing area. The independent experts advising ICAO-CAEP also remarked on the ‘over-range’ characteristics generally, coupled with over-speed for short haul flights. If a reduction in speed, reduced wing area and wing sweep designs were available for short and possibly medium haul flights, some technologies such as laminar flow and open rotors could be easier to implement. From the manufacturers’ standpoint, many of the issues surrounding greater aircraft optimisation from a CO_2 perspective relate to added complexity of multi-version production runs, so there is a potential overlap with the aviation technology levers discussed in Chapter 3.

A further possibility is that aircraft may routinely travel with excess equipment on board, and that action to correct this could have further fuel savings.

With some form of incentivisation in place, most initiatives to improve airline efficiency will lie with airlines themselves, in conjunction with other aviation stakeholders. For example, measures to optimise the type of aircraft used for particular missions will involve close collaboration between airlines and manufacturers.

Although a number of no frills carriers operating relatively short range services have identified such optimisation as an important measure, network carriers have generally been more ambivalent and manufacturers are likely to be resistant where the introduction of multi-version aircraft may reduce economies of scale from long production runs. On the other hand it is known that some (few) airlines are pushing for a change in manufacturer behaviour, and particularly with respect to the new B737/A320, replacement designs with true shorter range (smaller winged) variants would be welcomed.

Baseline assumptions for the low, central and high demand baseline cases are provided in Appendix 1. No specific account is taken of measures to improve aircraft operator efficiency, so these can be considered as additional to the baseline.

Low policy case
The low policy lever assumes relatively modest penalties (or rewards) based on MTOW and fuel burn that are assumed to result in emission savings of 2% in 2020, rising to 4% in 2030 and 6% in 2040.

Mid policy case
The mid case assumes penalties (or rewards) based on MTOW and fuel burn that are assumed to result in savings of 2% in 2020, rising to 7% in 2030 and 10% in 2040.

High policy case
The high policy lever assumes higher penalties (or rewards) based on MTOW and fuel burn that are assumed to result in savings of 5% in 2020, rising to 10% in 2030 and 15% in 2040.

From the ICAO Independent Expert's report, it seems likely that under the low policy case (6% emission saving in 2040), improvements could be provided mostly through optimising range, which would be relatively easy to do within the present network system. These same improvements would arise under the mid and high policy cases. However, in addition, in the mid and high policy cases we have assumed that optimising for lower speed would contribute 65% of the fuel saving i.e. about 10% of our 15% in the high policy case. In the mid policy case we have assumed much the same improvement from range optimisation, but around half the improvement from lower speeds. The effect on fuel burn of reducing speed is not fully linear. There is an initial portion that is close to linear but then there are steep diminishing returns. For example, supporting work for the ICAO Independent Experts (ICAO-CAEP, 2010) indicated that reducing speed, moving from 0.86 Mach to 0.74, yields an 11.4% saving, but that moving further from 0.74 to 0.7 yields only an additional 1.7%. This would appear to justify stopping short of the full 20% saving from all measures, evidenced in work continued after the IE (Independent Expert) ICAO review, and restricting ourselves to 15% in the high case. It may be possible to squeeze a bit more out of range optimization plus the basket of other factors in the high policy case, though this seems optimistic for the present study.

4.3.2 Modelling approach and analysis

CO_2 abatement modelling

From the previous section, this lever covers operational improvements in three areas:

- More optimized design ranges;
- Optimising for lower speeds; and
- A basket of other factors e.g. take-off field length, climb rate, initial cruise altitude etc

All the above measures can be utilised for any future technology level. The work undertaken by the ICAO/CAEP Independent Experts indicates that in very broad terms under the high policy case, range optimization could contribute 25% of the fuel savings linked to this lever, with 65% from lower speed and 10% from other factors.

Improvements in fuel efficiency are modelled to accrue progressively throughout the period.

Estimated aggregate emission savings over the period analysed using the DfT models for this study for the central demand baseline are presented in Table 17.

Table 17. The estimated CO_2 abatement potential through reducing inefficiencies in air carrier operations (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	69	108	162

Cost modelling

Clearly there is a financial benefit to airlines from lower fuel costs, and these will increase with fuel prices, but if airlines are not currently implementing such measures, these savings must be outweighed by perceived negative cost factors. The approach used includes estimates of these offsetting costs, but does not include the savings to airlines from lower fuel costs. These offsetting costs may, for example, arise from higher maintenance costs associated with reduced fleet commonality and reduced aircraft and crew productivity from lower aircraft utilisation associated with reduced speeds and longer flying times. It is notable that there are currently no airline orders for the reduced range version of the B787.

Estimating these offsetting costs is not straightforward, but we have sought to scope them. If airlines do not optimise for fuel burn in the absence of policy levers specifying fuel efficiency improvements, any fuel burn savings must be outweighed by these negative cost factors. This suggests that any penalty or financial inducement will need to be sufficient to tip the balance, so that some additional incentive or penalty over and above the saving in fuel costs will be needed. For some airlines at the margin where, in the absence of any policy lever, the fuel savings are only just outweighed by the offsetting costs, a small penalty will be sufficient to yield a change in behaviour, so this approach will over-estimate the costs. However, in other cases, it may be necessary to set the penalty or incentive at a level sufficient to cover these offsetting costs, or possibly higher to the extent that there are other costs and barriers that have not been quantified.

There would be cost issues related to having more aircraft types, mostly associated with having more wing and engine variations. It is possible to make some assumptions related to the wing and engines element of total airframe development costs. For example, the wing accounts for around 20% of total airframe development costs. If we assume a 50% increase in this cost element, associated with designing more optimised aircraft with larger wing spans, with these costs passed on to airlines through higher purchase prices, this would result in an increase in fleet costs of 10%, that could be factored into the aircraft depreciation element of airline DOC. With aircraft depreciation accounting for around 4% of airline DOC[19], this would result in a DOC increase of around 0.5%. This estimate does not include the cost of engine variations and the need for increased maintenance, for which we have not been able to find any data. We have therefore illustratively doubled this estimate to a 1% impact on DOC to reflect all aspects of the potential increase in cost.

Turning now to the cost implications of reduced speeds, the evidence referred to above indicates an 8% fuel saving from a 10% speed reduction, until diminishing returns are reached. But there will be offsetting increases in airline DOCs from lower productivity from flying slower. For a fixed utilisation, each aircraft will produce fewer seat miles and therefore more aircraft and crew will be needed for a fixed amount of traffic. Longer flight times will result in a loss of benefits to passengers, and could in principle be estimated by applying values of travel time. However, these are likely to be relatively small over short haul routes at least. The effect would be greater on long-haul flights with a possible side effect that it may impose some restrictions on services as a result of night curfews, particularly on some routes to and from the Far East.

Low policy case
In the low case it is assumed that a penalty or incentive equivalent to 1% of airline DOC is required to encourage range optimisation.

Mid policy case
In the central policy case we have assumed that the contribution from reduced speeds is halved from the high policy case (see below), so that it contributes 5% of the total 10% saving. This reduces the incentive or penalty required to 2.25% (1% from range optimization, 1.25% from reduced speed).

High policy case
Including the 1% DOC impact from range optimization, suggests that any incentive or penalty would need to amount to up to 3.5% of airline DOC in the

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[19] Estimated DOC percentages are taken from CAA airline statistics, 2009.

high policy case (1% from range optimization and 2.5% from reduced speeds) to be sufficient to induce airlines to do things differently. However, this does not include any cost impacts arising from the basket of other factors.

There is some overlap with the levers relating to a CO_2 standard and achievement of the ICAO-CAEP fuel burn goals, as to some extent the scope for operational improvements in the medium term would be facilitated by both as they would be likely to accelerate the introduction of newly designed aircraft which could be optimised from a CO_2 perspective for specific missions. However, since the costs of these technology improvements are already reflected above, they are not included a second time.

Table 18. Estimated NPV for improvements in aircraft operation efficiency (central baseline).

Policy case	Low	Mid	High
NPV, £million	2,152	4,843	7,533

4.3.3 Commentary on improving efficiency of aircraft operations

A number of factors need to be borne in mind when considering the results for this lever. Assessment has focused on two areas of potential improvement: matching aircraft types more closely to missions flown, given that many aircraft have substantial unused range capability for the majority of routes on which they operate, and flying at reduced speeds using existing aircraft such as turbo-props or potential new aircraft types such as open rotors. Reducing the size of wings and fuel tanks and flying at reduced speeds would benefit airlines from lower fuel costs.

It should be recognised that the potential for speed reduction is not the same for short/medium and long haul. There is greater opportunity for emission reductions from short/medium length trips where a greater reduction in speed might be possible. However, travel time and curfews are more significant problems for long haul journeys, so the potential for speed reduction may be less than for short/medium length trips.

However, given that, against the background of rising fuel costs, there is only limited evidence (though not zero[20]) of such operational improvements being made by aircraft operators to reduce their fuel costs, the approach used assumes that there must be some offsetting costs. We have attempted to estimate these by including additional aircraft development costs (e.g. from the introduction of smaller wings) and utilisation penalties from flying more slowly in the form of higher aircraft and crew costs. These costs would need to be translated into a lever that might take the form of a financial inducement or penalty to airlines to stimulate a change in behaviour.

We are more confident about the potential scope for fuel efficiency improvements and hence CO_2 savings, but recognise that there are uncertainties

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[20] The recent death of the market for 50 to 60 seat regional jets and the rebirth of the turboprop market are considered to be directly attributable to the rise in fuel price.

over costs and other barriers to introduction that are not easy to quantify. For example, barriers may arise from:

- The structure of the manufacturing industry, with only 2 major suppliers;
- Airline resistance because of the need for flexibility in fleets even if aircraft only need to be deployed occasionally on long missions;
- Resistance by leasing companies from concerns about implications of more specialised aircraft types on residual values; and
- A greater number of aircraft will be needed to fly the same number of ASKs (Available Seat Kilometres) if the productivity of each aircraft decreases (which has been factored into the costing assumptions), with associated ATM issues (that have not been factored in).

To the extent that there are other barriers such as these not included or hard to quantify, overall costs for the lever could therefore be underestimated, though at the margin, only a small further increase in fuel prices might be needed to tip the balance, with the result that including all these offsetting costs would be an over-estimate. The need for government action in this area is greater at low fuel prices, as at some very high fuel price these optimisations would happen naturally. This lever therefore seeks to speed up these airline reactions ahead of the fuel price trend.

Despite the barriers that exist, the project team is aware of some airlines that are considering such operational improvements for the short and medium sectors at the present time. Although this lever would produce potentially large emission savings and is estimated to be relatively cost-effective, there are major uncertainties associated with its delivery in practice. Translating this lever into a fully designed workable policy would be challenging.

5 Biofuels

Analysis of the policy levers concerning biofuels has been informed by an ongoing study being carried out by AEA for DfT. The AEA work is focused on developing a model that can be used to calculate the cost-effectiveness of different deployment scenarios for biofuels across UK transport covering the time period from 2010 to 2050. The starting point is recent work carried out for DECC that looked at future global and UK biomass supply scenarios, and UK supply scenarios for biofuel feedstocks have been developed from this. The model takes these feedstock supply scenarios and uses conversion efficiency factors to calculate the amount of biofuels that could be available to the UK transport sector between 2010 and 2050. The calculated amounts of biofuels are then used to develop potential deployment scenarios in different modes of transport. The model has a very detailed vehicle stock/activity/energy consumption/emissions module for each of the different road transport modes and relatively simple fuel-based modelling for the shipping and aviation sectors. A simple fuel-based approach can be used for shipping and aviation as biofuels will be “drop-in” fuels for these modes of transport – only fuels that do not require technical modifications to be made to aircraft and ships would be used, and hence unlike for road transport, there is no need to model the penetration in the fleet of new types of aircraft or ships that are specifically designed to operate using biofuel blends.

5.1 Supporting biofuel demonstration plants

5.1.1 Lever description

Baseline assumptions for the low, central and high demand baseline cases are provided in Appendix 1.

There have already been some successful demonstrations of biofuels being blended with kerosene (EBTP, 2010). There are also EC projects on the use of sustainable biofuels in aviation with funding of R&D to map a way forward for the introduction of sustainable biofuels. Beyond the R&D stage, it is necessary to produce sustainable feedstocks in commercial scale quantities to ensure that biofuels for aviation are a viable option. There is scope for incentives for companies to develop processing and refining capacity needed to turn raw feedstock into biojet fuel. Such incentives could take a number of forms, through the provision of subsidies or tax incentives. One possibility is pump-priming measures similar to US part-funding of biofuels demonstration. British Airways intend to start using biofuels for its flights from London City Airport from 2014. These would be produced at a plant to the east of London that would produce 16 million gallons of biofuel from a plant processing 500,000 tonnes of waste (Renewable Energy Focus, 2010). This is likely to exploit existing financial incentives associated with waste management.

The introduction of policy levers for biofuels would be the responsibility of government, with DfT in the lead but with involvement from BIS and Treasury, in the event of fiscal measures. The European Commission also clearly has a role through its research programmes. The timescale for the introduction of the policy lever could be quite short.

5.1.2 Modelling approach

CO_2 abatement modelling
Baseline assumptions are as follows:

- Low demand baseline: Biofuels make up 0% of aviation fuel use by 2050.
- Central baseline: Biofuels make up 2.5% of aviation fuel use by 2050.
- High demand baseline: Biofuels make up 0% of aviation fuel use in 2020; 1% in 2030 and 5% of aviation fuel use by 2050.

Low policy case
This assumes that demonstration projects will accelerate the take-up of biofuels from 0% in 2020 to 1% penetration achieved by 2025. The penetration rate then stays constant at 1% to 2050.

Mid policy case
The mid case assumes that demonstration projects will accelerate the take-up of biofuels from 0% in 2020 to 2% penetration achieved by 2025. The penetration rate then stays constant at 2% to 2050.

High policy case
Assumes that demonstration projects will accelerate the take-up of biofuels from 0% in 2020 to 5% penetration achieved by 2025. The penetration rate then stays constant at 5% to 2050.

Different biofuel feedstocks have different levels of life-cycle emissions. The use of sustainably sourced biofuels in aviation would be expected to result in lower levels of emissions than the use of kerosene, but would not reduce emissions to zero. Guidance from the Intergovernmental Panel on Climate Change is that the use of biofuels as a fuel by the transport sector should be allocated zero emissions for accounting purposes. Any emissions from biofuel production and transportation would count against the emissions of the relevant sectors. This is consistent with the accounting of biofuel use in the UK's carbon budgets and for aviation in the EU ETS. Within this analysis, the use of biofuels by the aviation sector has therefore been allocated zero emissions.

Data on estimated aggregate emission savings using the central baseline over the period analysed for this study are presented in Table 19.

Table 19. The estimated CO_2 abatement potential through supporting biofuel demonstration plant (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	13	23	51

Cost modelling

We have assumed that the cost of a demonstration plant with a 100m litre annual capacity plant would be around $250m, but these costs are expected to fall quite sharply over time[21]. Several important questions arise:

1. How many plant might be subsidised by government?
2. By how much might government subsidise the plant?
3. To what extent would this lever promote the uptake of biofuels in aviation?

These questions have been dealt with as follows. It is assumed that government would provide 25% of the costs of plant development, essentially pump-priming to encourage industry to move in this direction. The number of plant required is calculated from the fuel savings inherent from the CO_2 abatement modelling discussed above, by dividing emission savings by the emission factor (2.5 kg CO_2 per litre of fuel) to generate the quantity of fuel required in the year that this lever has maximum effect. For the central baseline mid policy case this is equivalent to 336 million litres of fuel in 2033. The quantity of fuel required is rounded up in multiples of the 100 million litre assumed capacity of the demonstration plant (roughly accounting for downtime), so it is assumed in this example that 4 facilities would be needed.

This implies that the lever would not stimulate the uptake of biofuels beyond the relatively modest levels assumed to be met by the demonstration plant themselves, and so is clearly a worst case assumption given that the objective of the demonstration plant is to stimulate wider production and use of biofuels. However, we consider it better to use this as a basis for quantifying associated costs than adopt an alternative that might bias the analysis in an indeterminate manner.

Costs to biofuel producers are not included as it is assumed that revenues from produced biofuels are sufficient for them to earn a return on investment (see further comments, below).

Table 20. Estimated NPV for biofuel demonstration plant (central baseline).

Policy case	Low	Mid	High
NPV, £million	54	108	216

5.1.3 Commentary on subsidising biofuel demonstration plant

There are general issues around the sustainable supply and demand for biofuels given that aviation is only one of a number of sectors expressing interest in them and of the full life cycle impact of using biofuels in aviation compared with other sectors, with potentially greater burdens from the requirement to produce a very high quality fuel.

On the other hand, biofuels are one of only a few options that would be capable of reducing emissions from aviation substantially. The same does not apply to surface transport, for which there are other possible fuels for reducing GHG

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[21] Poyry estimates for DfT, 2011

emissions (e.g. electricity from low carbon sources, fuel cells). On this basis it may make sense to prioritise use of biofuels for aviation. However, this may not be necessary if the surface vehicle fleet moves away from oil-based fuels in the coming years (e.g. to electricity or fuel cells, either of which might be feasible on a 40 year timescale). Additionally, the use of biofuels in the aviation sector could help the UK meet its 2020 targets for the deployment of renewable energy in the transport sector, as set out in the European Commission's Renewable Energy Directive.

There are also questions around the interaction between this lever and the mandatory targets for biofuels use for aviation considered in the next lever. The demonstration plant projects would inform more rapid and widespread uptake of biofuels and so it could be considered a precursor to the next lever, taking the form of a mandatory target for biofuel use.

A further factor is that there may already be some government policies in place that could stimulate industry interest in biofuel production facilities. One example is that manufacturing fuels from waste avoids the need to pay landfill tax on waste that would otherwise be sent to landfill – a factor in the proposed development by Solena and BA of a biofuels from waste plant in the east of London[22].

There may also be issues around where such plant might best be located, with the possibility that fuels could be produced more economically outside the UK. However, if funding were to be provided by UK government (e.g. with no funding from European bodies) with a view to reducing UK aviation emissions, it would seem logical to base the plant in the UK, otherwise the benefits to the UK economy and to the environmental performance of UK aviation could be lost.

In undertaking the cost estimates, we have used estimated capital costs for a demonstration plant provided by DfT, coupled with assumptions on the level of Government funding. Clearly the cost-effectiveness of this measure will be sensitive to these assumptions (noting also that funding linked to national and local waste management policies in some way could be considered equivalent to government funding), along with the assumptions of the effectiveness of this measure in reducing emissions by stimulating and accelerating the use of biofuels by aviation.

Further, we have assumed that for accounting purposes, the use of biofuel by the aviation sector would be attributed zero emissions, consistent with the use of biofuel in the rest of the transport sector. However, in practice, there would be some CO_2 emissions associated with the use of biofuel, which would depend on the particular feedstock used (although for this policy to be effective, this would be less than would be associated with the use of kerosene). If these emissions were to be included in the analysis, this would reduce the estimated cost-effectiveness of this policy lever (and the following lever mandating a given level of biofuel uptake).

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[22] Sustainable Construction, 2009

5.2 Regulation or voluntary agreement to mandate biofuels uptake

5.2.1 Lever description

This lever could either be funded by industry or subsidised by the Government. The costs would not vary between the two options, but where the cost would fall would be different – either on aircraft operators (and passed on to consumers in the form of higher fares) or on Government, respectively. As with subsidisation of biofuel demonstration plant, this would be the responsibility of government with DfT in the lead, with possible CAA involvement in its implementation and monitoring. In the event of a voluntary agreement between government and airlines, the airlines would be responsible for its implementation and any monitoring that might occur.

In principle this lever could be introduced relatively quickly, but it might be argued that delay would enable some of the technological and other issues associated with the use of biofuels in aviation, e.g. sustainable sourcing, to be resolved. In addition, a suitable metric for a regulation or voluntary agreement would be needed, unless it simply took the form of an aspirational target. Constraints on production capacity are also problematic. We note that aircraft need specialised fuels created using either the Fischer-Tropsch process or the hydrogenation of vegetable oils, processes that are more expensive than those used and under development for road transport fuels.

Baseline assumptions are the same as for the previous lever with respect to biofuel use in aviation.

Low policy case

For the low policy case it is assumed that there will be 0% penetration of aviation biofuels in 2020, rising to 2% penetration in 2030 and 10% by 2050.

Mid policy case

Here, it is assumed that there will be 0% penetration of aviation biofuels in 2020, rising to 3% penetration in 2030 and 20% by 2050.

High policy case

Finally, for the high case it is assumed that there will be 0% penetration of aviation biofuels in 2020, rising to 6% penetration in 2030 and 40% by 2050.

It is assumed that the levels of biofuel take-up modelled for this lever can be supplied sustainably to the aviation sector. In practice, competing demand from other sectors and issues over the amount that can be supplied from sustainable sources might act as barriers to its effective implementation.

5.2.2 Modelling approach

CO_2 abatement modelling

The lever definitions provided in the previous section have been applied within the DfT models. Estimated aggregate emission savings over the period analysed for this study are presented in Table 21.

Table 21. The estimated CO_2 abatement potential through setting mandatory biofuel targets (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	34	68	118

Cost modelling

Costs associated with this lever arise from any differential in price between kerosene (including the cost of EU ETS carbon allowances) and biofuels. In this analysis, we have used DfT price projections for biofuels and kerosene (based on DECC's projections of fuel prices) out to 2050 and DECC's projections of the traded price of carbon. These are summarised in Table 22 below.

Table 22. Summary of the estimates of fuel costs as applied to the policy cases.

	Fuel price biofuels £/litre	Fuel price kerosene price £/litre	Carbon charge £/litre fuel including ETS	Price differential between kerosene and biofuels taking into account carbon charge
Low demand baseline				
2010	1.03	£0.37	£0.000	£0.666
2020	0.78	£0.27	£0.022	£0.492
2030	0.84	£0.27	£0.089	£0.484
2040	0.84	£0.27	£0.171	£0.401
2050	0.84	£0.27	£0.253	£0.319
Central demand baseline				
2010	1.03	£0.37	£0.000	£0.666
2020	0.78	£0.39	£0.041	£0.346
2030	0.84	£0.44	£0.177	£0.218
2040	0.84	£0.44	£0.342	£0.053
2050	0.95	£0.44	£0.507	£0.000
High demand baseline				
2010	1.21	£0.37	£0.000	£0.839
2020	1.01	£0.82	£0.052	£0.139
2030	1.15	£0.82	£0.266	£0.067
2040	1.33	£0.82	£0.513	£0.000
2050	1.58	£0.82	£0.760	£0.000

Using these assumptions, biofuels are more expensive than kerosene plus the cost of carbon allowances for much of the period, but this flips over from 2044 in the central demand case with biofuels becoming slightly cheaper. However, for the policy cases we assume the demand pressures from aviation coupled with the effect of supply inelasticities result in price increases for biofuels such that once the price differential to biofuels falls to zero it remains at zero (i.e. biofuels never become cheaper than kerosene). Under very optimistic assumptions with widespread use of advanced production techniques, there could be a win-win situation with very limited supply inelasticities and biofuel prices remaining low, resulting in no subsidy required and perhaps some modest cost savings to airlines.

Estimated costs for this lever under the central baseline are shown in Table 23.

Table 23. Estimated NPV for mandated levels of biofuel take-up (central baseline).

Policy case	Low	Mid	High
NPV, £million	286	510	864

5.2.1 Commentary on setting targets for biofuel uptake

This lever involves setting targets for the take-up of biofuels by aviation, achieved through regulation, voluntary agreement or through the use of Government subsidies. Costs would be incurred by either aircraft operators or the Exchequer, depending on how this lever is specified, but in both cases they would be broadly similar. Where the costs are incurred by aircraft operators, there would be likely to be some additional demand feedbacks from higher fares needed to recover the costs, but these have not been estimated.

Costs of the lever are based on the differential between projected biofuel prices and the cost of kerosene plus EU ETS carbon allowances or project credits. In addition we have considered the effect of these mandated penetration rates on the supply of biofuels. There is conflicting evidence on this, but under pessimistic assumptions, high penetration rates by aviation coupled with supply inelasticities could drive up the price of biofuels. On the other hand under a more optimistic scenario with the widespread use of advanced production techniques, any feedback effects on prices would be much more limited.

Key sensitivities for this lever relate to:

- The availability of sustainably sourced biofuels;
- Linked to this, the elasticity of biofuels prices; and
- The projected evolution of prices for biofuels and aviation kerosene.

This is a potentially promising lever with scope for large emissions savings and reasonably good cost-effectiveness. However, there are large uncertainties and with a more pessimistic scenario where high aviation penetration rates coupled with supply constraints drives up the price of biofuels, this would be a less cost-effective lever. The analysis has sought to counter this by assuming that biofuels never become cheaper than kerosene, though this could be a pessimistic view.

6 Behavioural Change

6.1 Promotion of behavioural change

6.1.1 Lever description

There is a range of potential measures to voluntarily reduce the demand for air travel through the promotion of behavioural change that could be targeted at passengers. These include increasing awareness of the carbon footprint associated with air travel, encouraging fewer overseas holidays, switching from long haul to short haul destinations and modal switch to rail.

DfT would take the lead in campaigns to provide advice and practical information to airlines, freight shippers and passengers. It may be appropriate to involve a body such as Visit Britain that is already involved in encouraging people to take holidays in the UK. However, there is also a role for the aviation industry, for example through increased efforts to promote carbon offsetting (acknowledging that some airlines are already proactive in this area).

In part to acknowledge the uncertainties that are present, analysis of this lever has focused on the leisure market. The business market is addressed via the lever below on videoconferencing. No account is taken of air freight.

The baseline assumption (see Appendix 1) is that in the absence of specific and targeted Government actions, there will be no impact on traffic from behavioural change.

Low policy case

For the low policy case it is assumed that this lever has no effect on the behaviour of leisure passengers.

Mid policy case

The mid policy case is modelled on a "what if" basis, such that we have modelled the answer to the question, "what if this lever could reduce total leisure travel by 2% and encourage 5% to switch from long haul to short haul destinations by 2050?".

High policy case

This is treated the same as mid policy case but the percentage changes are increased to 5% and 10% respectively by 2050.

6.1.2 Modelling approach

CO_2 abatement modelling

The DfT models have then been used to estimate the emission reductions associated with this change in demand from leisure passengers.

The lever is forecast to reduce total aircraft-kilometres (Table 24) and this in turn produces a reduction in CO_2 emissions (Table 25).

Table 24. Estimated effect of promoting behavioural change in the leisure market on million aircraft km, 2010-2050 for UK flights.

	Low demand baseline		
	Low policy	**Mid policy**	**High policy**
Baseline	183,219	183,219	183,202
Lever	183,219	181,406	179,492
Lever effect	**0.0%**	**-1.0%**	**-2.0%**

	Central demand baseline		
	Low policy	**Mid policy**	**High policy**
Baseline	207,333	207,333	207,316
Lever	207,333	202,444	199,909
Lever effect	**0.0%**	**-2.4%**	**-3.6%**

	High demand baseline		
	Low policy	**Mid policy**	**High policy**
Baseline	229,159	229,159	229,141
Lever	229,159	225,983	223,118
Lever effect	**0.0%**	**-1.4%**	**-2.6%**

Table 25. The estimated CO_2 abatement potential through promoting behavioural change in the leisure market (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	0	37	43

Cost modelling

To the extent that people are persuaded to change their leisure travel behaviour voluntarily, there should be no losses of consumer surplus from passengers no longer flying. However, aircraft operators and airports would suffer losses of producer surplus from lower traffic and there would be impacts on APD receipts. There could also be some welfare losses to existing passengers if lower demand results in reduced frequencies and level of service provided. Welfare losses are estimated using the DfT model.

There are also further costs associated with government campaigns to promote this lever. For the purposes of illustration we take figures of £5 million, £10 million and £20 million each year, based on data on the costs of the Visit Britain campaign. We consider that an annual investment would be needed to maintain awareness.

Results for the central baseline, low, mid and high policy cases are shown in Table 26.

Table 26. Summary of estimated costs of behavioural change in the leisure market as specified (central baseline), £billion.

Description	**Low Policy**	**Mid Policy**	**High Policy**
User Benefits, of which:	0.00	-4.05	-6.82
transfer from producers	0.00	-3.95	-6.71
from change in passenger numbers	0.00	-0.09	-0.10
Producer Benefits, of which:	0.00	4.00	6.81
transfer to consumers	0.00	4.05	6.71
from change in passenger numbers	0.00	-0.05	0.10
Government Revenue, of which:	0.00	-0.45	-0.77
APD revenue	0.00	0.65	1.56
tax changes elsewhere in the economy	0.00	-1.10	-2.33
Surface Access Carbon	0.00	-0.06	-0.10
Accidents	0.00	-0.02	-0.03
Capital Costs	0.00	0.00	0.00
Costs of promotional campaign	0.00	0.19	0.38
NPV	0.00	-0.38	-0.51

Note: Negative figures denote a cost saving

6.1.3 Commentary on behavioural change in the leisure market

Somewhat counter-intuitively, in particular years this measure has the effect of increasing CO_2 emissions or producing cost savings. The reason for this is that the reduction in demand from leisure passengers who voluntarily choose to fly less or shorter as the lever is pulled, results in other leisure passengers previously displaced by supply constraints temporarily coming back into the market, as lower pressure of demand reduces fares. As well as potentially resulting in cost savings to remaining passengers, there are estimated to be small increases in emissions as a result of longer distances travelled. This effect only occurs as the system becomes heavily loaded. It can be seen in Table 24 where the effect of the policy lever appears weaker in the high demand case. This is because higher demands create higher shadow costs as the system becomes more constrained. As the discussion on the airport capacity lever emphasises, higher shadow costs favour long haul routes and larger aircraft in the competition for airport slots, running counter to the intention of the lever.

It should also be noted that these complex effects are compounded by model noise. As the system becomes heavily constrained and shadow cost rise sharply the model becomes less stable and the signal from the model test increasingly subsumed by model noise as discussed more fully in Chapter 4 on capacity levers.

Leaving aside these modelling uncertainties, there is significant uncertainty about the effectiveness of Government information campaigns in encouraging behavioural change by air passengers. The emissions reduction for the policy cases are modelled on a “what if?” basis, in the absence of any alternative evidence. In addition there is the real concern that even if such campaigns are successful in reducing leisure travel demand, there is so much excess demand in the system that other passengers will take their place, offsetting any emissions savings.

6.2 Promotion of videoconferencing

6.2.1 Lever description

This is similar to the previous lever, but instead of attempting to alter the level of demand from leisure travellers, it is aimed at reducing demand from business passengers. To some extent there are already useful government initiatives in this direction, for example, the government's current intention to make high speed broadband available throughout the country. This together with the pace of technological change should mean that sophisticated video-conferencing facilities will be available to anyone with a good broadband connection within a few years. The challenge therefore is less with the introduction of technology but more in encouraging businesses to use video-conferencing as an alternative to face-to-face meetings.

Promotion of videoconferencing could be done in several ways, for example:

- Financial support for development of videoconferencing facilities.
- Information campaigns about the benefits of videoconferencing and the systems available.
- Government departments using remote conferencing facilities as a default, and hence setting an example to their suppliers with the intention that this will then be further disseminated through the private sector.

Responsibility for such actions would largely rest with DfT, except for the last example just given, which could be rolled out across government.

The lever could be introduced at short notice, but its impact in terms of reducing emissions and over what timeframe is very uncertain. There are two particular uncertainties, concerning the effectiveness of provision of guidance and information and the extent to which business will move in this direction without government intervention as videoconferencing and related technologies become more mature.

Baseline assumptions (see also Appendix 1) are as follows:

- Low demand baseline: 10% reduction in business air travel by 2050, corresponding to the CCC's "optimistic" scenario.
- Central baseline: No change in business travel, consistent with CCC's "likely" scenario.
- High demand baseline: 5% increase in business air travel by 2050, reflecting evidence cited by the CCC that the rebound effect on travel could outweigh any substitution effects.

Given the lack of available evidence relating to the potential impact of this lever, and the limited evidence of market maturity in the business market to date, the assumptions adopted for the low, mid and high policy cases should be regarded as 'what if?' type analysis.

Low policy case
For the low policy case, it is assumed that this lever has no impact on business demand.

Mid policy case
For the mid policy case, it is assumed that the lever generates a 2% reduction in total business travel by 2050, on a 'what if?' basis.

High policy case
Again, this is modelled on a 'what if?' basis, assuming that the lever results in a 5% reduction in total business travel by 2050.

In practice, it is possible that actions already underway to make high speed broadband generally available are the key to extending videoconferencing to the degree suggested by the policy levers. It is also possible that videoconferencing will be taken up voluntarily by industry as associated technologies mature and there is increased familiarity with them. In either case, this would imply that the impact of the associated increase in use of videoconferencing should be included in the baseline cases. It would then be up for debate how much additional take-up of videoconferencing this policy lever could deliver.

6.2.2 Modelling approach

CO_2 abatement modelling
The DfT models have been used to estimate any emission reductions that might be associated with this change in demand from business passengers.

Using these assumptions, the estimated aggregate emission savings over the period analysed for this study using the central baseline are presented in Table 27.

Table 27. The estimated CO_2 abatement potential through promoting videoconferencing in the business market (2010-2050) (Central Baseline).

Policy case	Low	Mid	High
CO_2 abatement, Mt	0	-0.9	7.3

Given the assumptions used for this lever, the model forecasts small emission savings each year up to the mid to late 2030s. Under the mid policy case a small increase in emissions in the final years of the assessment is, however, sufficient to wipe out these savings. The effect overall is very small (a total increase in emissions over all years of less than 1 million tonnes CO_2). It is possible that this is at least in part a function of instability in the model in the later years. A further factor is the potential for this lever to reduce business travel, but free up slots for leisure travel over possibly longer distances.

Cost modelling

This lever involves the promotion of behavioural change by encouraging business passengers to use facilities such as videoconferencing as an alternative to travel. To the extent that people are persuaded to do this voluntarily, there should be no losses of consumer surplus from passengers no longer flying, but aircraft operators and airports will suffer losses of producer surplus from lower traffic and there will be impacts on APD receipts. However, there could be some welfare losses to existing passengers if lower demand results in reduced frequencies and a reduction in the level of service provided. Costs for airlines and travellers have been assessed using DfT's SCAB model and are shown in Table 28.

In the absence of any available evidence on the level of the incentive that might be needed to encourage the take-up of videoconferencing by businesses over and above the baseline to the levels implied by the policy cases, we have not included an estimate of the potential cost to Government.

Table 28. Summary of estimated costs for behavioural change in the business market through the adoption of videoconferencing (central baseline), £billion.

Description	**Low Policy**	**Mid Policy**	**High Policy**
User Benefits, of which:	0.00	-0.41	-2.78
transfer from producers	0.00	-0.41	-2.79
from change in passenger numbers	0.00	0.00	0.01
Producer Benefits, of which:	0.00	0.38	2.94
transfer to consumers	0.00	0.30	3.07
from change in passenger numbers	0.00	0.08	-0.13
Government Revenue, of which:	0.00	0.15	0.14
APD revenue	0.00	0.26	0.54
tax changes elsewhere in the economy	0.00	-0.11	-0.41
Surface Access Carbon	0.00	-0.02	-0.05
Accidents	0.00	-0.01	-0.01
Capital Costs	0.00	0.00	0.00
Government information campaign	0.00	Assumed 0	Assumed 0
NPV	0.00	0.09	0.23

Note: Negative figures denote a cost saving

6.2.3 Commentary on behavioural change in the business market through the promotion of videoconferencing

This measure involves Government encouragement of the use of videoconferencing and remote meetings to reduce the volume of business travel. This could involve information campaigns coupled with Government funding. These measures are assumed to be additional to trends occurring in the baseline forecasts resulting in trends towards maturity in certain market segments. Costs estimated by the DfT model include losses of profit to the aviation industry from fewer passengers, many of whom will be high fare paying, and reduced tax receipts.

The signal from the model runs is that this measure has a limited effect in reducing emissions. The lever is generally estimated to be most effective where shadow costs arising from airports being at capacity are low i.e. in the low demand baseline cases or in the earlier years of the forecasting period for all demand levels. However, as airports become full and shadow costs in the form of slot values and fares rise, the modelling suggests that business flights removed by the lever (that are predominantly short haul) are increasingly replaced by leisure flights which tend to be over longer distances. Typically, 16% of business passengers are on long haul flights, compared to 22% of leisure passengers. For much of the forecasting period the effectiveness of the lever is blunted. Late in the forecasting period no clear signal in either direction emerges as the changes being modelled are too small relative to the effects of model noise, as the model struggles to find an equilibrium solution to the capacity constraints.

As with the previous measure, there are doubts about the effectiveness of Government information campaigns, particularly against the background of rapid changes in technology, that mean that many people (and not only business travellers) have videoconferencing facilities on their laptops or home computers. There is also the possibility that in addition to substituting demand for air travel, increased use of videoconferencing could have the effect of stimulating additional travel for leisure purposes by enabling closer personal relationships between people in different countries.

7 Results

Before describing the combined results of the analysis it is useful to be reminded of some of the caveats around the study. Most importantly, there are some very significant uncertainties in the quantification of the abatement potential and cost-effectiveness of the levers, not least from the need here to extend the analysis to 2050 and beyond. As a result, we warn against putting too much weight on the precise ordering of levers by cost-effectiveness, which will in any case be seen to change between the baseline demand and policy cases considered. That said, we anticipate the overall ordering to be reasonably robust in identifying the set of levers likely to be most cost-effective or associated with the largest emission reductions.

A further issue is that results for some of the levers are very specific to the UK fleet, which is composed of relatively young aircraft by international standards. Hence, where we find that some levers have limited scope for UK aviation emission savings, this may not be true for the fleets serving many other countries. Examples here concern, for example, the benefits from imposition of CO_2 emission standards or the early retirement of aircraft. Results should thus be considered as specific to the UK.

Particular attention is given in this chapter to the low/low, central/mid and high/high baseline/policy cases. Similar results for the other cases are provided in Appendix 3.

7.1 Abatement potential by policy lever

In considering the estimates of abatement potential from this analysis, it should be noted that:

a) assuming the EU ETS continues past 2020 out to 2050, the reductions in “UK aviation” emissions will not automatically result in a reduction in aviation emissions at an EU level, as any emission reductions from the aviation sector will displace emission reductions from other sectors in the EU ETS (rather than being additional); and
b) no account has been taken of the potential impact of the levers on non-“UK aviation” emissions e.g. an international CO_2 standard might be expected to reduce aviation emissions globally, whilst capacity constraints in the UK might not reduce overall aviation emissions (and could conceivably increase them), if flights (and therefore emissions) are simply displaced elsewhere.

With these caveats in mind, Table 29 shows estimated cumulative “UK aviation” emission savings from 2010 to 2050 for each lever. Shading in the table highlights the three levers associated with the largest (green) or smallest (pink) reduction in emissions over this period. The levers that most consistently generate the greatest savings in the UK are:

- Incentives to optimise the efficiency of operations

- Mandatory use of biofuels

Also featuring in the top 3 most effective levers for reducing emissions in some demand/policy cases are:

- Achieve CAEP goals ((low/mid, central/mid and central/high cases)
- Constraints on UK airport capacity (low/low, central/low and all high baseline cases)
- Biofuel demonstration plant (low/high case)

The top three measures taken together for each demand/policy case account for between 56% and 81% of overall emission savings for UK aviation.

At the other end of the spectrum, the levers that are associated most frequently with the smallest change in 'UK aviation' emissions are:

- Application of CO_2 standards
- Retrofitting
- Promotion of videoconferencing

In a few cases these measures are estimated to cause an increase in emissions over the period of assessment: reasons for this are discussed below. The three levers with the smallest effect only account for between 0.7% and 5.7% of total emissions under each of the 9 demand/policy cases considered.

Table 29. Estimated (cumulative) emission savings from "UK aviation" by policy lever, 2010 to 2050 ($MtCO_2$).

Demand baseline	**Low**			**Central**			**High**		
Policy	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Regulatory CO_2 Standards	0	9	10	-ve	9	11	-ve	11	13
Early fleet retirement	0	1	33	1	19	59	20	41	84
Achieve CAEP goals	4	25	44	7	40	66	8	53	84
Retrofitting	1	2	4	1	3	4	1	3	5
Airport capacity	13	14	18	37	37	13	159	77	88
ATM efficiency	12	23	33	15	27	38	16	30	41
Operational incentives	59	92	139	69	108	162	77	120	180
Biofuel demonstration plant	11	20	44	13	23	51	14	26	58
Mandatory biofuels	39	66	108	34	68	118	23	64	125
Behavioural change	0*	11	19	0*	37	43	0*	12	27
Videoconferencing	0*	0	5	0*	-ve	7	0*	17	1
Total savings	**139**	**263**	**457**	**177**	**371**	**572**	**318**	**454**	**706**

Key: * lever defined as having no impact for the demand/policy case. –ve: model reports an increase in emissions for the lever in question over the period. For explanation of shading, see text.

7.2 Cost-effectiveness by policy lever

Table 30 provides a similar overview of levers, but this time in terms of cost-effectiveness. Here, however, there is a rather clear distinction between levers that apply to aircraft design and those that deal with improving the efficiency of aircraft movements, biofuels and demand reduction (as indicated by the shading used in the table). The most consistently cost-effective measures across the 9 cases considered are:

- Improvements in ATM efficiency

- Biofuel demonstration plant

Also amongst the most cost-effective levers in some cases are:
- Behavioural change under the mid and high demand cases
- Constraints on airport capacity under low demand
- Mandatory use of biofuels, particularly under the high demand cases

Although never one of the three most cost-effective levers, operational incentives are also generally competitive against the other levers.

Table 30. Estimated cost-effectiveness of measures, £/tonne CO_2 saved.

Demand baseline	**Low**			**Central**			**High**		
Policy	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Regulatory CO_2 Standard	n/a	1702	1430	n/a	1080	1553	n/a	927	1390
Early fleet retirement	1257	9999	1443	6667	1645	1044	1187	1385	1226
Achieve CAEP goals	968	338	401	500	150	197	355	11	58
Retrofitting	394	470	2319	274	377	2056	135	239	1770
Airport capacity	-53	-45	-27	39	79	196	53	148	155
ATM efficiency	-25	-14	1	-79	-69	-56	-159	-150	-138
Operational incentives	31	44	45	31	45	46	30	43	44
Biofuel demonstration plant	5	4	5	4	5	4	6	4	4
Mandatory biofuels	67	65	65	8	8	7	0.1	0.1	0.1
Behavioural change	n/a	18	20	n/a	-10	-12	n/a	-16	-28
Videoconferencing	n/a	n/a	50	n/a	n/a	31	n/a	12	544

Key: n/a: lever does not produce emissions savings in 2050 and therefore the cost-effectiveness has not been estimated. For explanation of shading, see text.

The results for cost-effectiveness are to some extent dependent on the order in which levers are applied. For example, investments in ATM efficiency will have a greater impact if applied in isolation than if applied after aircraft efficiency measures are in place, although there may also be an impact on costs. However, this is unlikely to have a great impact on the ranking of levers in terms of cost-effectiveness: there will be some changes, but given the orders of magnitude difference in cost-effectiveness shown in the table these are not expected to be sufficient to move a lever several places up or down the ranking. There is greater sensitivity as a result of the order in which levers are applied as to whether the cost-effectiveness results are positive or negative for a few of the levers. Again, we take the example of ATM efficiency improvements, for which cost per tonne abated is negative in most cases (i.e. costs are saved by the investment in ATM being more than balanced by fuel cost savings) but positive in one case (low demand, high policy). For the case with a net cost it is possible that applying the lever earlier in the analysis would increase fuel savings to the point where estimated costs were negative. However, other uncertainties also apply, for example in the attribution of emission savings to a given level of investment, so even in this case the sensitivity of results to the order in which levers are added should not be considered a major factor for the analysis overall.

7.3 UK Aviation Emission savings

Table 31 summarises forecast baseline emissions for each demand case, together with estimated emissions following implementation of all levers under the alternative policy cases.

Table 31. Estimated emission savings in 2050 under each demand/policy case.

Demand baseline	2050 emissions in the baseline[23], $MtCO_2$	Policy case	2050 emissions assuming all levers implemented, $MtCO_2$
Low	40.2	Low	32.1
Low	40.2	Mid	25.1
Low	40.2	High	15.9
Central	49.2	Low	37.9
Central	49.2	Mid	29.1
Central	49.2	High	18.5
High	58.8	Low	36.6
High	58.8	Mid	30.4
High	58.8	High	18.6

Baseline emissions are seen to be almost 50% higher in the high demand case compared to low demand. There is roughly a factor 2 difference in emissions with all levers in place between the low and high policy cases, irrespective of baseline.

The trend in estimated emissions and emission savings to 2050 is illustrated for three cases in Figure 10. The upper line in each case shows forecast emissions in the baseline. Subsequent lines then show the effect of adding in each lever: the greater the distance between the lines the more the emission savings arising from the newly applied lever. The lower line therefore shows emissions once all levers have been applied. The figure shows that:

- It is estimated that there would be a significant decline in baseline emissions from 2035 for the low/low case. The central/mid case shows a similar decline, but starting about 10 years later. Baseline emissions in the high/high case flatten out around 2040, and may be starting to show a decline at the end of the period.
- The time at which levers are assumed to start to generate significant savings can be identified, being marked by a clear fall in emissions from the line above. One of the earliest levers assumed to come through concerns improvements in the efficiency of airline operations, whereas effects from setting mandatory levels for biofuel use and airport capacity constraints are assumed not to appear until around 2030.
- The difference between the three graphs with respect to the spread between baseline emissions and emissions following application of the final lever in the results for 2050 highlights the different ‘strength’ to which levers are applied in the low, mid and high cases.

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[23] These baseline forecasts differ very slightly from those reported in DfT’s UK Aviation Forecasts, August 2011. DfT’s revised estimates include improvements in the forecasting of freighter emissions after 2030 that slightly lower the estimate of baseline emissions. The differences in emission savings are small, <1% of total savings in 2050, and do not materially affect any of the results of the MAC analysis.

Figure 10. Estimated emission savings over time for the low/low, central/mid and high/high baseline/policy cases.

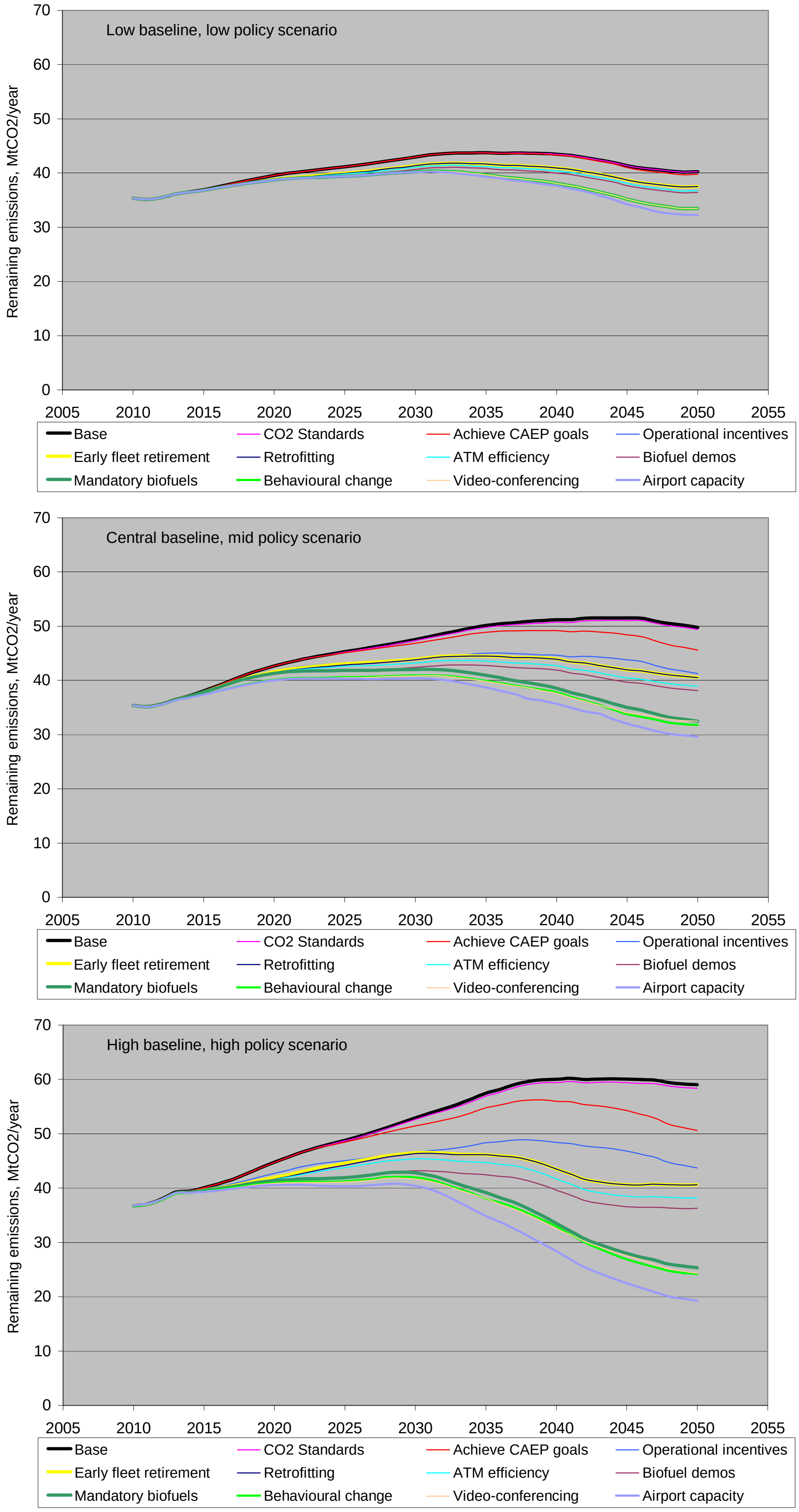

Figure 11 shows the full marginal abatement cost (MAC) curves for 2050 for the same three cases that were considered in Figure 10 (a more detailed version of the same graphs is presented below in Figure 15, showing the costs of the levers towards the left side of the graph more clearly)[24]. These figures suggest the following:

- There is substantial variation in the estimated cost per unit emission reduced between the levers.
- Some levers (e.g. retrofitting) are absent from the 2050 results, as they have no effect at that time.
- The cost per unit CO_2 reduction for two levers (CO_2 standards and early fleet retirement) are estimated to be substantially greater than the costs of the other levers.
- The assessed ordering of levers changes between the different baseline/policy cases. Airport capacity constraints are the most cost-effective measure for the low/low case, as with a low level of baseline demand and the low strength of the policy lever it has a minimal impact on passengers. But this lever moves progressively higher in the curve through the central/mid and high/high cases. Similarly, regulatory CO_2 standards and early fleet retirement swap positions in the central/mid and high/high cases.
- Total estimated emission savings for 2050 double when moving from the low/low case to central/mid, and then roughly double again when moving to the high/high case.

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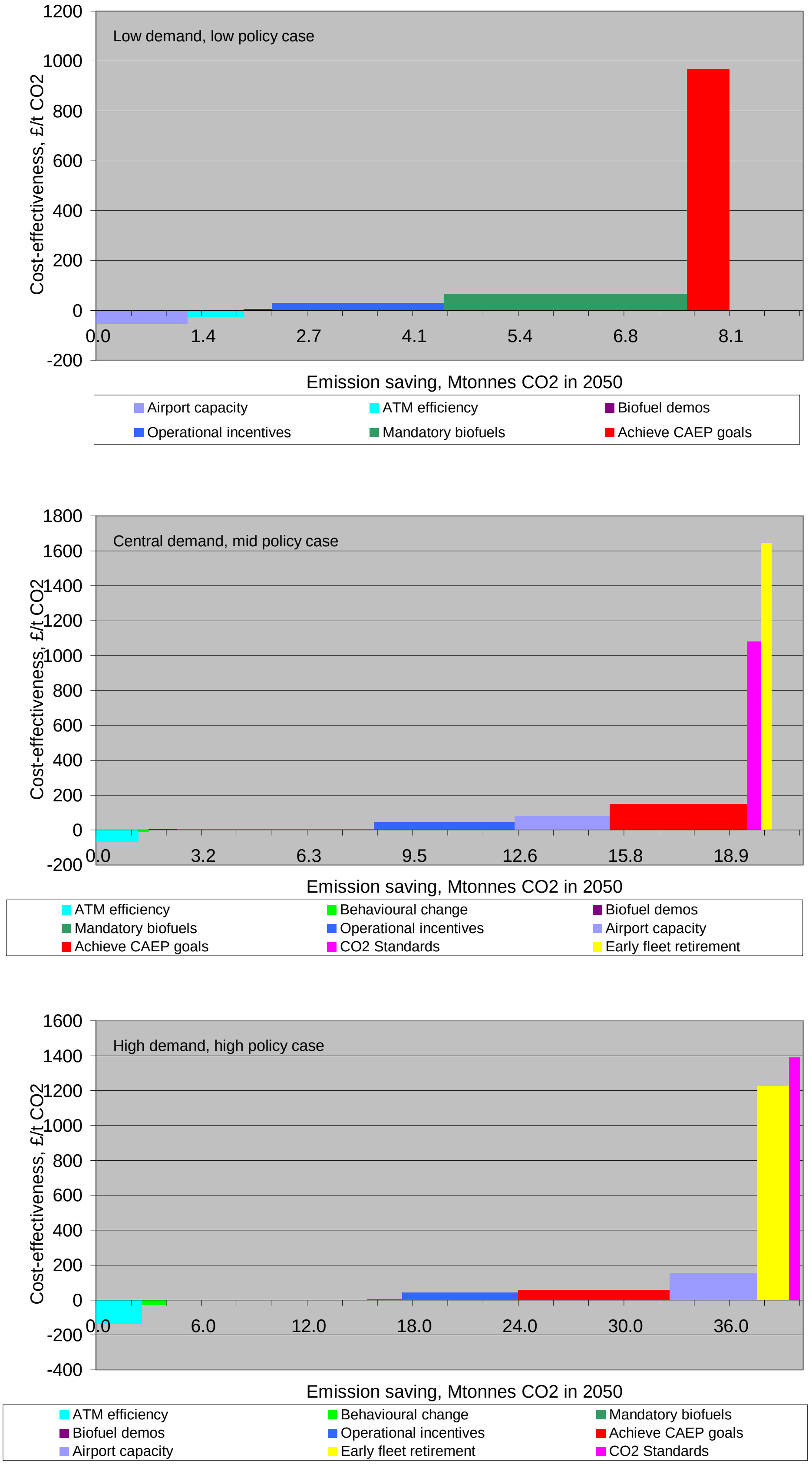
[24] Note that the scale for the x-axis is not uniform through the series of graphs that follow.

Figure 11. MAC curves for the low/low, central/mid and high/high baseline/policy cases in 2050.



The series of graphs from Figure 12 to Figure 15 show the MAC curves for 2020, 2030, 2040 and 2050 respectively, for the low/low, central/mid and high/high cases. To show the estimated costs of measures to the left side of the graphs more clearly the y-axis has been truncated. This loses some detail for the least-cost-effective levers, though cost-effectiveness data for them is presented in Table 30, above.

The figures demonstrate the following:

- Emission savings are estimated to grow over time, and also when moving from the low demand baseline / low policy case up to the high demand baseline / high policy case. Note that the x-axis scale is not consistent between the cases and years.
- The number of levers that contribute to estimated emission savings increases from the low policy to the high policy case.
- The estimated cost-effectiveness of the levers changes from case to case. This results in the levers changing position along the curve, some moving up and some moving down over time. However, these changes are in general insufficient to move levers from the most to the least cost-effective areas of the graphs.

The curves do not take any account of uncertainty beyond the consideration of low, central and high demand baseline cases. These uncertainties apply to both the estimates of cost and of emission savings. Further information on the uncertainties that exist in the data presented is provided above in the sections dealing with each policy lever.

Figure 12. MAC curves for 2020 for the low/low, central/mid and high/high cases

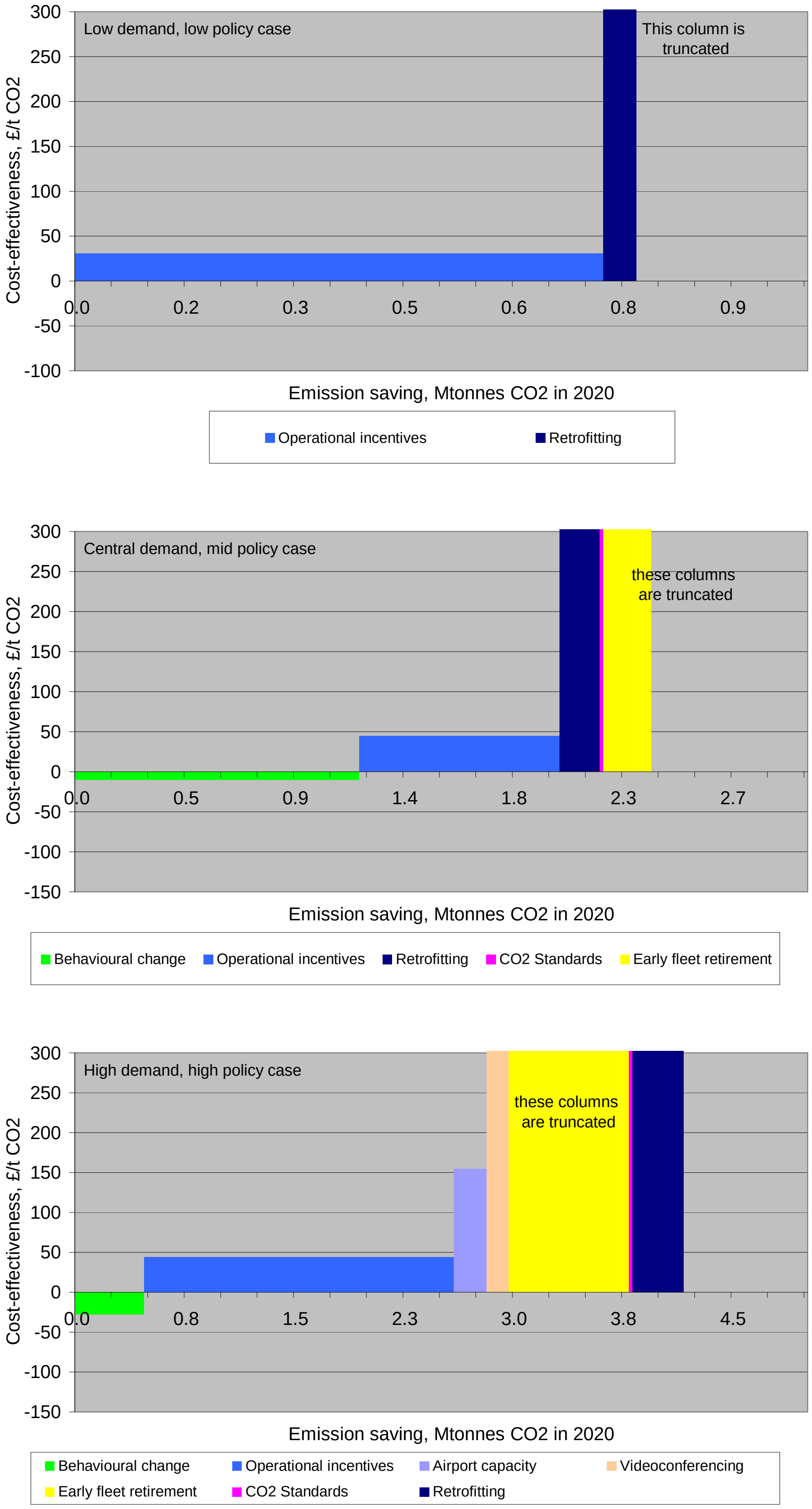


Figure 13. MAC curves for 2030 for the low/low, central/mid and high/high cases

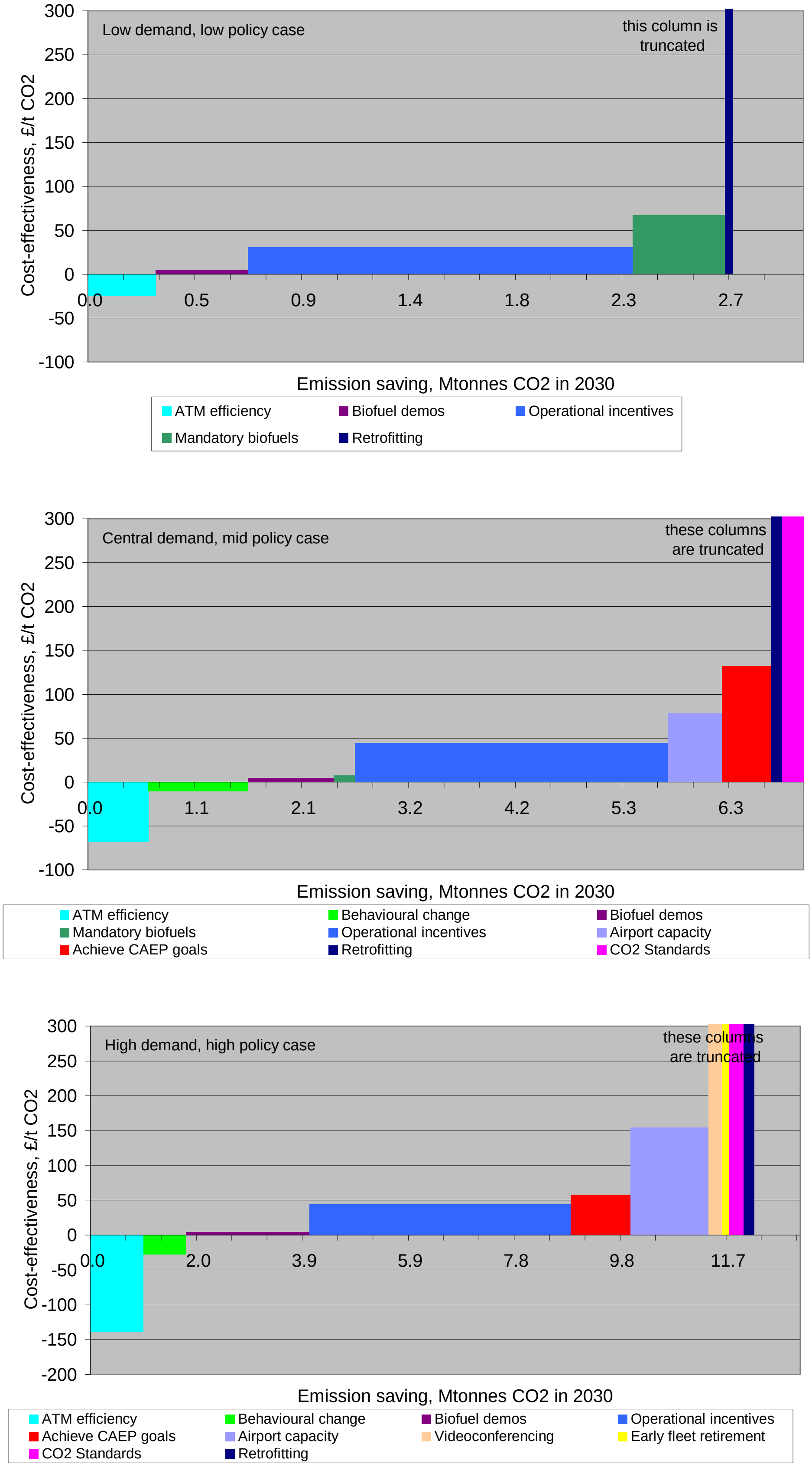


Figure 14. MAC curves for 2040 for the low/low, central/mid and high/high cases

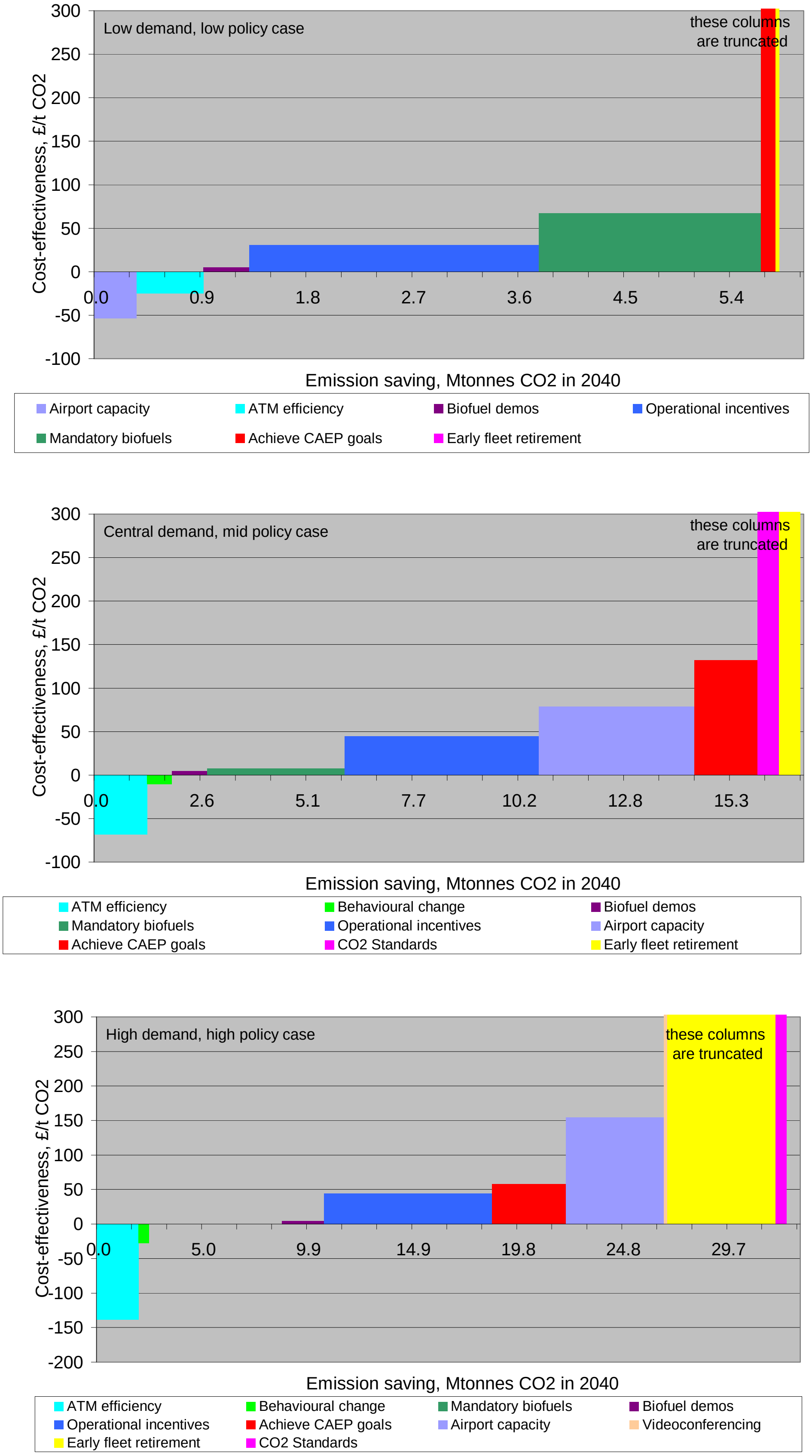
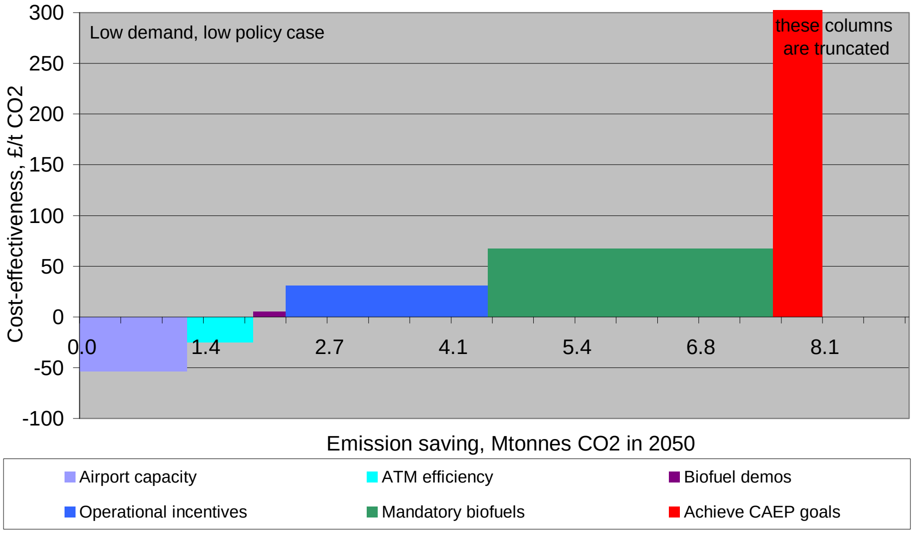
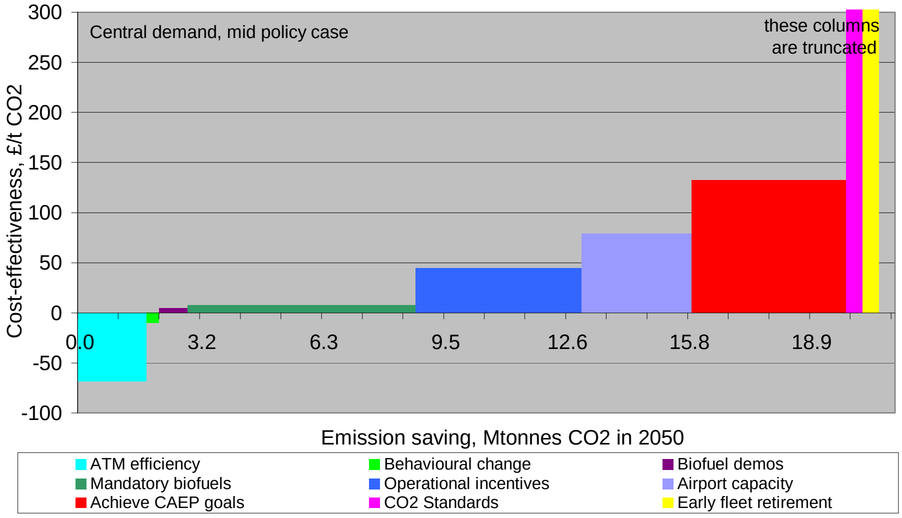
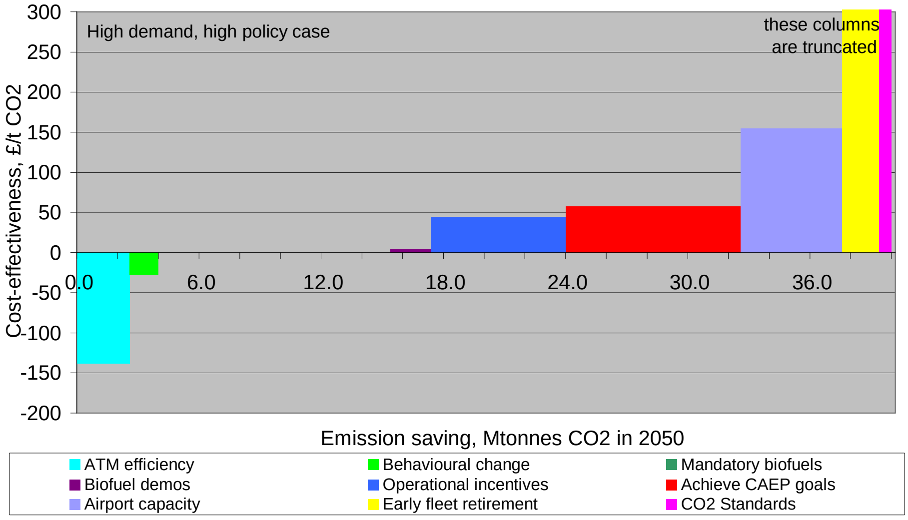


Figure 15. MAC curves for 2050 for the low/low, central/mid and high/high cases







7.4 Exceptional cases

For a small number of cases the results suggest that some levers could lead to a reduction in cost for the aviation sector or an increase in emissions (a very small number of cases for the effect on emissions over the full period under assessment, a larger number for shorter periods). It is important to understand why these exceptions occur. Table 32 highlights the cases where levers are estimated to lead to cost savings, the commentary that follows describes why they might arise.

Table 32. Cases where levers are estimated to reduce costs.

Demand baseline case	Low			Central			High		
Policy case	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
Regulatory CO_2 standard									
Early fleet retirement									
Achieve CAEP goals									
Retrofitting									
Airport capacity	x	x	x						
ATM efficiency	x	x		x	x	x	x	x	x
Operational incentives									
Biofuel demonstration plant									
Mandatory biofuels									
Behavioural change					x	x		x	x
Videoconferencing									

Airport capacity constraints under the low demand scenarios.
With lower passenger demand the costs of constraining airport capacity, in terms of the costs to passengers, airlines and airports of passengers being forced to fly via alternative routes, or to travel by alternative modes or to different destinations, are estimated to be insufficient to outweigh the benefits of the reduction in estimated capital costs.

ATM improvements, all scenarios except for low demand, high policy.
Improved ATM efficiency reduces fuel costs for airline operators. These savings are estimated to offset the assumed level of investment that would need to be made to upgrade ATM systems in all cases except low demand, high policy, for which fuel prices are low and ATM investments high.

Behavioural change under the central and high demand, mid and high policy cases.
This lever is assumed to influence passengers so that they change their travel behaviour voluntarily. This means that there is no estimated cost to those passengers who decide not to travel by air or to travel short haul rather than long haul. The remaining passengers benefit from the reduction in demand leading to lower air fares, but this is almost exactly offset by the cost to airlines and airports in lower revenue. The small net benefits delivered by this lever are driven by the impacts on Government revenue – whilst APD revenue falls, this is more than offset by an increase in tax revenue from across the rest of the economy as passengers who decide not to travel are assumed to switch expenditure to other goods and services. However, the cost estimate does not take account of the congestion and environmental costs associated with

passengers who are persuaded not to travel by air choosing to travel within the UK on road and rail.

Table 33 highlights cases where the introduction of a lever appears to cause an increase in emissions when account is taken of the full period of assessment to 2050. This is estimated to arise only for the regulatory CO_2 standard and the promotion of videoconferencing.

Table 33. Cases where levers are estimated to cause an overall increase in emissions over the period of assessment.

Demand baseline case	**Low**			**Central**			**High**		
Policy case	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
Regulatory CO_2 standard				x			x		
Early fleet retirement									
Achieve CAEP goals									
Retrofitting									
Airport capacity									
ATM efficiency									
Operational incentives									
Biofuel demonstration plant									
Mandatory biofuels									
Behavioural change									
Videoconferencing		x			x				

Regulatory CO_2 standard under the low policy cases for the central and high demand baseline scenarios. In both cases the modelling results suggest that given our assumptions, there is roughly a 10 year period starting in 2032 in which emissions increase as a result of implementation of this lever. However, the maximum annual increase in emissions is only of the order of 5,000 tCO_2. This is related to the removal of some small types of aircraft from the supply pool as a result of the lever and their replacement by larger types (still within the same seat class) that have better performance against the metric but a higher overall fuel burn (due to a higher payload).

Videoconferencing under the mid policy case for the low and central demand baseline scenarios. Given the assumptions used for this lever, the model forecasts small emission savings each year up to the mid to late 2030s for these baseline cases. An estimated increase in emissions in the final years of the assessment is, however, sufficient to wipe out these savings. The effect overall is very small (a total increase in emissions over all years of less than 1 million tonnes CO_2). It is possible that this is at least in part a function of instability in the model in the later years. A further factor is the potential for this lever to reduce business travel, but free up slots for leisure travel over possibly longer distances.

7.5 Qualitative assessment of broader impacts of the policy levers

Table 34 reviews the potential effects of the policy levers on climate via non-CO_2 greenhouse gas emissions, local air quality and noise. We consider that these are likely to be the biggest impacts (beyond changes in CO_2 emissions) associated with the levers that we have considered.

Depending on how a specific policy lever may be defined, the suggested direction of impact under specific demand baseline/policy scenarios may differ to that shown in Table 34. A notable example concerns the promotion of video-conferencing aimed at the business market. For some scenarios this lever has been found to increase emissions, by releasing slots currently taken by short-haul business flights to the long-haul leisure market. The effects described in the table should therefore be regarded as the general consequence of levers acting as intended, rather than actual consequence in all cases.

It is important to note that Table 34 indicates the envisaged direction only of the consequential non-CO_2 effects (in terms of climate, air quality, noise) and not the magnitude. It is possible that the direction could be correct but the effect trivial; equally, there may be a significant effect. This work has not attempted to quantify the magnitudes of these effects since this would be a substantive exercise in its own right, and was beyond the present scope of work.

There are further effects associated with some of the other levers. Those that reduce emissions by acting on demand for aviation (airport capacity constraints, behavioural change and potentially videoconferencing) could also reduce road traffic and hence congestion around airports, which would have a further effect on local air quality (i.e. additional to the airside perspective taken in Table 34). Alternatively, they could lead to an increase in road traffic and congestion (and therefore have a negative impact on air quality) if they resulted in more journeys being undertaken within the UK. The same levers, together with improvements in ATM efficiency, could have some landscape benefits by reducing the presence of aircraft in the sky.

The most contentious levers with respect to additional impacts are likely to be those concerned with biofuel production. There is a presumption that this is done sustainably. In this respect it is important to understand that 'sustainability' is not a narrowly defined concept but brings in a number of factors beyond the immediate consequences of agricultural (etc.) production methods, with possible effects on biodiversity, food security, land rights and so on. There is thus potential for increased demand for biofuels to be beneficial or detrimental in terms of its overall effect in terms of sustainability.

Within the scope of this report it has not been possible to assess implications of levers for economic growth. We simply acknowledge that there is potential for some levers (perhaps achievement of ICAO Fuel Burn Goals) to contribute to the Growth Agenda whereas others could have a negative impact by reducing demand.

Table 34. Qualitative assessment of the effects of the levers on non-CO_2 pollutants.

Policy Lever	Qualitative environmental impacts Non-CO_2; climate	Qualitative environmental impacts: local air quality	Qualitative environmental impacts: noise
Regulatory CO_2 standard	The action of the standard as modelled is to remove older aircraft types from production. In general, more modern types have lower pollutant emissions than older ones, so an overall benefit. Greater propulsive efficiencies of engines could potentially increase contrails/cirrus by a small amount due to lower exhaust plume temperatures.	Newer types will have to have met tighter regulatory standards (assuming ongoing stringencies, particularly for NOx, potentially particulates) (**co-benefit**)	Newer types will have to have met tighter regulatory standards (assuming ongoing stringencies) (**co-benefit**)
Early fleet retirement	Possible small reduction in NOx emissions due to a greater proportion of more modern aircraft/engines in the fleet. More modern engines have greater propulsive efficiencies; could potentially increase contrails/cirrus by a small amount	Better, more modern engines should improve air quality (**co-benefit**)	Better, more modern engines should improve noise (**co-benefit**)
Achieve CAEP goals	If engine overall pressure ratios (OPR) driven up, $EINO_x$ (NOx Emissions Index) may increase without additional efforts to limit NO_x emissions; total NO_x countered by relative reductions in fuel usage. Additional costs may be incurred in combustion development to meet NOx regulations at the higher pressure ratios. Greater propulsive efficiencies of engines would potentially increase contrails/cirrus by a small amount.	If OPRs are driven up, $EINO_x$ may increase without additional efforts to limit NO_x emissions; but total NO_x countered by relative reductions in fuel usage. May be a larger effect than on climate as take-off thrust tends to be dependent on aircraft weight, while cruise thrust can also benefit from improvements in aircraft aerodynamics. No anticipated effects on carbon monoxide (CO), hydrocarbons, smoke	Greater OPRs tend to go hand in hand with lower noise (**co-benefit**). Open rotors would introduce a step-change and would incur additional costs to meet the noise regulations. There may be a limit to future noise reduction for narrow-body/short-range types. En-route noise (well beyond airports) may be a growing issue.
Retrofitting	No significant effects anticipated. Improved NOx performance of newer engines in most cases	Better, more modern engines should improve air quality (**co-benefit**)	Better, more modern engines should improve noise (**co-benefit**)
Airport capacity constraint	Reduced UK aviation emissions, reduced impacts (**co-benefit**)	Reduced UK aviation emissions, reduced impacts (**co-benefit**)	Reduced UK aviation movements, reduced impacts (**co-benefit**)

Policy Lever	**Qualitative environmental impacts Non-CO_2; climate**	**Qualitative environmental impacts: local air quality**	**Qualitative environmental impacts: noise**
ATM efficiency	Reduced emissions, reduced impacts (**co-benefit**)	Reduced emissions, reduced impacts (**co-benefit**)	Reduced movements, reduced impacts (**co-benefit**)
Operational efficiency	Reduced emissions, reduced impacts (**co-benefit**)	Reduced emissions, reduced impacts (**co-benefit**)	Reduced movements, reduced impacts (**co-benefit**)
Biofuel demonstration plant	Non-CO_2 effects would remain unchanged according to current understanding (even with reduction in particle emissions, since contrails will form on background particles taken into engine)	Particle emissions potentially reduced	No change
Mandatory biofuels	Non-CO_2 effects would remain unchanged according to current understanding (even with reduction in particle emissions, since contrails will form on background particles taken into engine)	Particle emissions potentially reduced	No change
Behavioural change	Reduced emissions, reduced impacts (**co-benefit**)	Reduced emissions, reduced impacts (**co-benefit**)	Reduced movements, reduced impacts (**co-benefit**)
Videoconferencing	Reduced emissions, reduced impacts (**co-benefit**)	Reduced emissions, reduced impacts (**co-benefit**)	Reduced movements, reduced impacts (**co-benefit**)

8 Discussion

Previous research has highlighted the difficulty of estimating the costs of reducing emissions from aviation on long time scales. Morris et al (2009b), for example, developed MAC curves only so far as 2020. Whilst we have gone further, we recognise the added uncertainty inherent in doing so. Results are summarised at the end of this Chapter in Table 36, which seeks to provide an overview also of the robustness of the conclusions reached on the relative effectiveness and cost efficiency of the levers that have been considered. Before reaching that point, in view of the concern over uncertainties and some other factors, it is important to be reminded of various issues raised in the course of the report. On a more positive note, however, we believe that by considering these factors it is possible to reach sound conclusions on the relative merits of the different policy levers considered here.

8.1 General considerations on the baseline assumptions

There are a number of general caveats relating to the baseline assumptions that influence the results of this analysis. These include:

- The model does not consider supply side effects of higher fuel or carbon prices in driving technology and airline choice of aircraft.

- The inclusion of a high-speed rail network in the baseline, with links from London to Birmingham and then Manchester and Leeds. On the one hand, this assumes that the network will be established to these locations, and on the other, it assumes that it will not continue further, to Scotland. Extension to Scotland would potentially capture a much larger share of domestic UK air traffic.

- The inclusion of the existing level and structure of Air Passenger Duty in the baseline, though changes in APD and other fiscal measures fell outside the scope of the study.

8.2 Considerations about specific levers

These have been discussed at length in Chapters 3, 4, 5 and 6 so we do not seek to provide further substantive overview here. The following are, however, provided by way of illustration:

- The levers concerning behavioural change and videoconferencing have required assumptions to be made on the link between government action and effects on demand for aviation. This has been modelled on a 'what-if?' basis, as there is a dearth of quantitative evidence to describe precisely how effective given levels of intervention might be. On a similar point, the assumptions used in costing biofuel demonstration plant have taken a pessimistic assumption on the extent to which such facilities would encourage wider use of biofuels in the sector.

- Whilst there appear to be sound reasons in terms of potential fuel savings for airlines optimising their operations by, for example, better matching of aircraft types to mission, there appears to be rather limited interest from the airlines industry. This implies that there are, or there are perceived to be, added costs of adopting such an operations model, for example through reduced commonality of aircraft resource, which could impact on services and maintenance costs. We have sought to factor such issues into the analysis but there are inevitably questions as to the robustness of the cost estimates.

- We have not addressed the question of what could happen outside of the UK following application of the levers. With respect to early fleet retirement, for example, would aircraft removed from the UK fleet be scrapped or bought by airlines in other countries? If the latter, would they be used to expand air services, or replace older and less efficient aircraft? Similarly, if airport capacity in the UK is constrained, would flights be diverted to neighbouring countries with potentially no overall benefit in terms of CO_2 reduction?

Clearly, an awareness of these and other factors is extremely important when interpreting the overall results of the analysis.

8.3 Interdependencies between levers

There are interdependencies between the policy levers discussed above, some of which were discussed specifically in relation to the aviation technology levers in Section 3.5. There are also clear inter-dependencies with some other initiatives not considered in our set of policy levers, such as high-speed rail. The following are provided by way of illustration:

- Support for the achievement for the ICAO fuel burn goals technologies would be expected to lead to technologies being introduced earlier (or greater improvements being achieved), that would result in further tightening of a CO_2 standard having little or no effect.

- A combination of retrofitting and support for the achievement of the ICAO fuel burn goals could bring additional benefits in that the technologies available for retrofit may be better than they would have been without the support for the achievement of the ICAO goals.

- Extension of high speed rail networks beyond London could reduce air travel to at least the nearer European centres, such as Brussels and Paris, reducing the impact of optimising aircraft types to short distance routes.

- Slots made available by reduced business travel as a result of the promotion of videoconferencing could simply switch to the leisure market. If these journeys are over greater distances on average, overall emissions could increase.

- The estimated cost-effectiveness of individual measures is dependent on the assumed order of introduction in the modelling.

8.4 Non-CO_2 effects of the levers

Table 35 summarises information presented in Section 7.5 on the non-CO_2 effects of the policy levers. As before, it simply identifies the likely existence and direction of effects ('+' being beneficial, '-' being detrimental) and makes no judgement on either their magnitude or significance relative to one another.

Table 35. Summary of non-CO_2 effects of the policy levers.

Lever	Non-CO_2 effects	Local air quality	Noise	Road traffic	Landscape	Broader sustainability concerns.
Regulatory CO_2 standards	+/-	+	+			
Early fleet retirement	+/-	+	+			
Achieve CAEP goals	+/-	+/-	+			
Retrofitting		+	+			
Airport capacity constraint	+	+	+	+/-	+	
ATM efficiency	+	+	+		+	
Operational incentives	+	+	+	+		
Biofuel demonstration plant		+				+/-
Mandatory biofuels		+				+/-
Behavioural change	+	+	+	+/-	+	
Videoconferencing	+	+	+	+	+	

8.5 Robustness of the analysis

So far, this discussion has emphasised the complexities of seeking to model aviation demand, technologies and economic impacts on a 40 year future time horizon. It is important, however, to go further, to consider how the uncertainties that have been identified may, overall, influence the conclusions reached in the analysis as to which levers appear to be most and least cost-effective. Table 36 seeks to provide an overview of confidence in the results.

In Table 36, estimated emission savings are summarised as the average over the full time period for the nine demand / policy cases. Similarly, cost-effectiveness is described as the average over the nine cases. This averaging is intended to provide a simple grading scheme for the levers. It is not appropriate to apply these averages for other purposes given their dependence on baseline conditions and the extent to which a policy lever is applied. The final column then provides some guidance, based on expert judgement, on the overall balance of uncertainties on the information given on estimated emission savings and cost-effectiveness. For some levers, retrofitting being a good example, we have a high level of confidence that emission savings will be low and cost-effectiveness poor. Whilst the uncertainty in the results may be quantitatively large, we conclude that it is not so great as to change the view that retrofitting is not a promising option for the UK air fleet. On the other hand, we consider it possible that uncertainties in quantification of the effects and costs of the promotion of behavioural change in the leisure market could influence conclusions on the attractiveness of the lever quite substantially. The table cites two reasons why this may be the case. Overall, it is apparent that the study team has reasonable confidence in the outcomes of the analysis. For only one lever, behavioural change in the leisure market, is it considered that uncertainties are so significant that the levers position relative to others in terms of cost-effectiveness or emission savings could change significantly.

Table 36. Overview of the estimated emission savings and cost-effectiveness of each lever, and confidence in conclusions reached from the analysis.

Description	**Total emission savings, 2010 to 2050**	**£/t CO_2 Cost-effectiveness**	**Confidence: key issues**
Regulatory CO_2 standards	9	>1000	Limited abatement potential from the UK fleet due to young average age of operational UK aircraft. This policy is expensive due to the required level of fleet replacement. There are uncertainties over the form and application of any Regulatory CO_2 Standard.
Early fleet retirement	29	>1000	Moderate opportunity for emission savings, but at a high price. Limited potential for the UK fleet due to young average age of operational UK aircraft. This policy would be expensive due to the required level of fleet replacement.
Achieve CAEP goals	37	331	Confidence in the quality of ICAO-CAEP independent experts' fuel efficiency goals work is high. There is some uncertainty connected to the extrapolation of technology timescales (i.e. this work pushed the timescales beyond those of the CAEP goals work). The cost estimates have the largest uncertainty due to paucity of available high quality data.
Retrofitting	3	892	Limited potential for the UK fleet.
Airport capacity constraints	51	61	Significant apparent savings, but in some cases moderately expensive. No account taken in the costings of offsetting emissions increases from displacement of traffic to continental hubs and surface transport modes and of losses to the UK economy if people are discouraged from travelling to the UK.
ATM efficiency improvements	26	-77	Difficulty in linking investment to specific levels of efficiency improvement.

Description	**Total emission savings, 2010 to 2050**	**£/t CO_2 Cost-effectiveness**	**Confidence: key issues**
Operational incentives	112	40	Good estimated level of savings at moderate cost, with information obtained during the research suggesting that this could be an attractive option for operators. However, there are uncertainties with the costing assumptions, that may be conservative, and there are other barriers to the introduction that are hard to quantify.
Biofuel demonstration plants	29	5	Difficulty in forecasting effect of demonstration plant on wider uptake of biofuels. However, conservative assumptions have been followed here, leading to reasonable confidence in the performance of this lever relative to others.
Mandatory use of biofuels	72	24	Good estimated level of savings at relatively low cost, but high sensitivity in results to the assumed differential between the cost of kerosene and biofuels.
Behavioural change	25	-5	Difficulty in attributing change in emissions to investments to provide information on CO_2 from aviation or to promote holidays in the UK. No account taken of burdens imposed through alternative use of money saved by avoiding foreign travel.
Videoconferencing	6	159	Difficulty in attributing change in emissions to investments to promote remote meetings. It is questionable how much government intervention would substantially influence take-up of videoconferencing beyond what businesses may undertake for cost-savings.

Key

	Emission savings	**Cost-effectiveness**	**Confidence**
Good	>50 Mt CO_2	<£10/t CO_2	Expert judgement
Mid	10 to 50 Mt CO_2	£10 - £100/t CO_2	Expert judgement
Poor	<10 Mt CO_2	>£100/t CO_2	Expert judgement

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Appendix 1: Baseline assumptions

This Appendix provides summary information on the baselines for the modelling work carried out for this study. Further detail is provided in the DfT's *UK Aviation Forecasts* (2011)

Table 37. Key baseline assumptions.

Input assumption	**Low demand baseline**	**Central baseline**	**High demand baseline**
Economic growth	Low GDP (Gross Domestic Product) growth	Central GDP growth	High GDP growth
Trade	Linked to GDP growth	Linked to GDP growth	Linked to GDP growth
Exchange rates	1.54/US$	1.6835/US$	1.8467/US$
Oil prices	DECC oil price scenario 1 ("low global energy demand")	DECC oil price scenario 2 ("timely investment, moderate demand")	DECC oil price scenario 4 ("high demand and significant supply constraints")
Air Passenger Duty	Same as central	Rates announced in 2011 PBR	Same as central
EU ETS carbon price	DECC low traded carbon price projection	DECC central traded carbon price projection	DECC high traded carbon price projection
Market maturity	Low growth market maturity scenario	Central market maturity scenario	High growth market maturity scenario
High speed rail	Same as central	HS2 Y route network (Birmingham, Leeds and Manchester)	Same as central

Table 38. Baseline assumptions relevant to the fuel efficiency levers.

Policy lever	Low demand baseline	Central baseline	High demand baseline
Regulatory CO_2 standard	Same as central	No regulatory CO_2 standard, so no effect on the modelling.	Same as central
Early fleet retirement	All aircraft retirement ages reduced by 1 year from Central Baseline.	Aircraft retirement ages as per the current DfT baseline	All aircraft retirement ages increased by 1 year from Central Baseline.
Achieve CAEP goals	The 2020 generation aircraft are assumed to have a 23.5% improvement in fuel burn (narrow-body) and 19.5% (wide-body) relative to 2000 types; 2030 generation aircraft 28.5% and 31.5%, and 2040 generation aircraft approx 37.0% and 35.0% improvement respectively. Aircraft mix in supply pool as per the current DfT baseline.	The 2020 generation aircraft are assumed to have a 21.5% improvement in fuel burn (narrow-body) and 17.5% (wide-body) relative to 2000 types; 2030 generation aircraft 24.5% and 27.5%, and 2040 generation aircraft approx 31.5% and 29.5% improvement respectively. Aircraft mix in supply pool as per the current DfT baseline.	The 2020 generation aircraft are assumed to have a 19.5% improvement in fuel burn (narrow-body) and 15.5% (wide-body) relative to 2000 types; 2030 generation aircraft 20.5% and 23.5%, and 2040 generation aircraft approx 26.0% and 24.0% improvement respectively. Aircraft mix in supply pool as per the current DfT baseline.
Retrofitting	Same as central	Level of retrofitting as per current DfT baseline	Same as central

Table 39. Baseline assumptions relevant to the levers dealing with operational efficiencies, biofuels and demand.

Policy lever	Low demand baseline	Central baseline	High demand baseline
Airport capacity	Same as central	Max use (i.e. maximum use of existing runways and associated increase in terminal capacity)	Same as central
ATM efficiency	1% improvement in ATM efficiency by 2050 to reflect implications of low traffic growth in easing delays and congestion	Zero trend in ATM efficiency assumed as ATM improvements are offset by the effects of increased congestion.	4% degradation in ATM efficiency by 2050 to reflect the implications of high traffic growth on delays and congestion, and taking ATM efficiency back to the 1999 level, identified by CANSO (i.e. removing the 4% improvement from 1999 to 2005).
Operational incentives	Fuel efficiency growth 0.25% pa higher than central baseline	The fuel efficiency trends used in the DfT forecasts to be used as the baseline	Fuel efficiency growth 0.25% pa lower than central baseline
Biofuel demonstration plants and mandatory biofuels	Biofuels make up 0% of aviation fuel use out to 2050.	Biofuels make up 0.5% of aviation fuel use in 2030 and 2.5% of aviation fuel use out to 2050.	Biofuels make up 0% of aviation fuel use in 2020; 1% in 2030 and 5% of aviation fuel use by 2050.
Behavioural change	Same as central	As implied by model baseline (i.e. little or no impact on traffic)	Same as central
Videoconferencing	10% reduction in business air travel by 2050, corresponding to the CCC's "optimistic" scenario	As implied by model baseline (i.e. little or no impact on traffic) and consistent with CCC's "likely" scenario	5% increase in business air travel by 2050, reflecting evidence cited by CCC of rebound effect on travel outweighing any substitution effects

Appendix 2: Usage of metrics to account for non-CO_2 climate effects of aviation

As is now well known and understood, aviation exerts a number of effects on climate through other emissions and effects other than CO_2. These were first documented in detail by the Intergovernmental Panel on Climate Change (IPCC), in their report 'Aviation and the Global Atmosphere' (IPCC, 1999).

The non-CO_2 effects of aviation are reviewed in detail elsewhere (e.g. IPCC, 1999; Lee et al., 2010) but include:

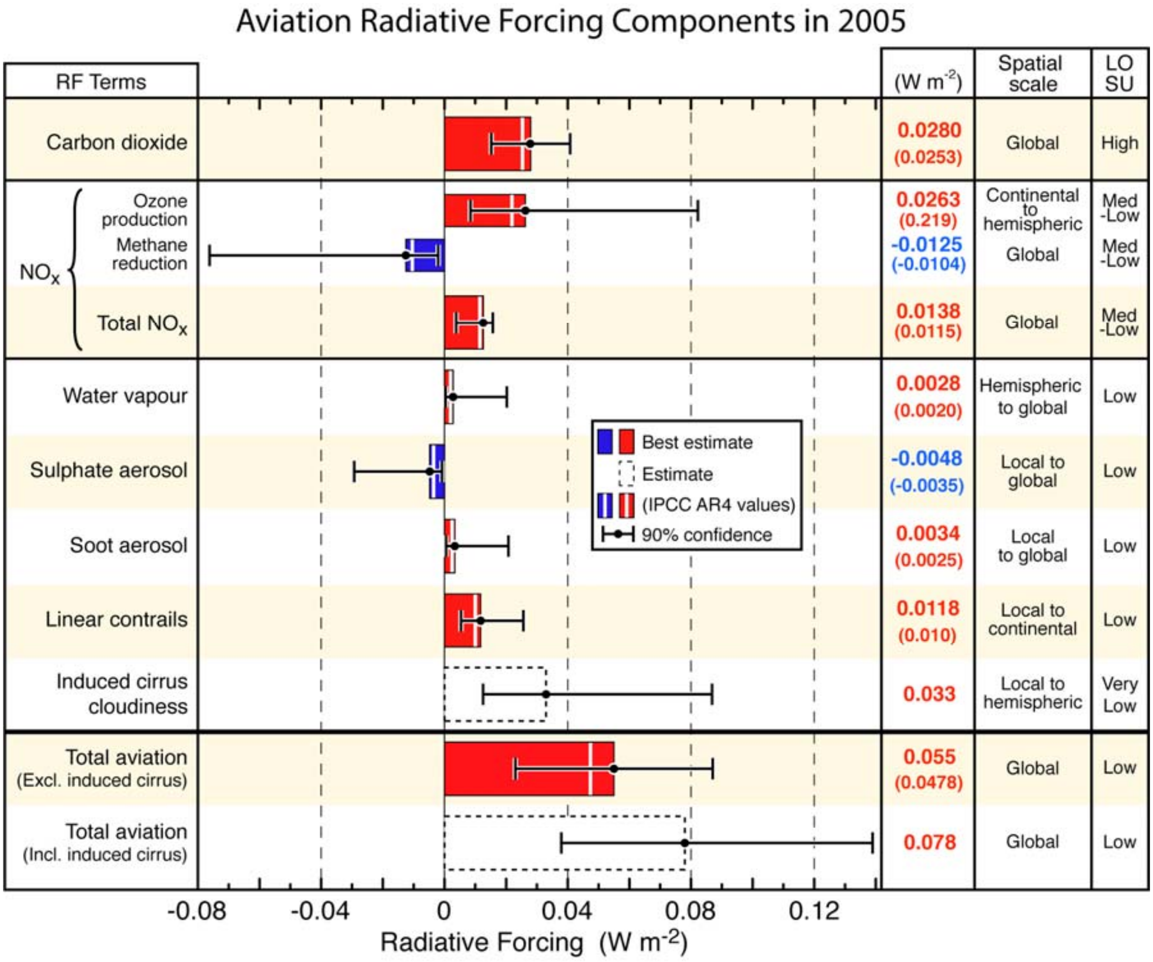
- Warming from the formation of tropospheric ozone (O_3) from NO_x emissions;
- Cooling from the destruction of ambient methane (CH_4) from NO_x emissions (this also induces a secondary cooling effect of reducing O_3 by a small amount over the long-term from reduced CH_4);
- Warming from emissions of water vapour;
- Warming from the formation of linear contrails;
- Warming from aviation-induced cirrus clouds;
- Warming from emission of soot particles;
- Cooling from the emission of sulphate particles.

The most up to date assessment of the scales and magnitudes of these effects is that of Lee et al. (2009) and a chart of the various effects shown below in Figure 16 in terms of radiative forcing (RF).

The IPCC (1999) formulated a simple metric to indicate the scale of current-day non-CO_2 forcing compared with CO_2 forcing alone from aviation, termed the 'Radiative Forcing Index' (RFI), which is the sum of the individual forcings divided by the CO_2 forcing alone.

The formulation of the RFI has given rise to much confusion as to how the metric might be used. For example, the IPCC (1999) assessed the RFI for 1992 to be 2.7. This was taken by many to indicate a factor by which CO_2 emissions should be multiplied to account for the non-CO_2 effects. This is erroneous since the RFI is a ratio of *forcings*, not emissions; and CO_2 forcing is a complex non-linear function of accumulated emissions over time (not a single year's emissions). This has been discussed in a number of publications, including the IPCC's Fourth Assessment Report (Forster et al., 2007).

Figure 16. Radiative forcing components from aviation, 2005 (see Lee et al., 2009 for detailed description).

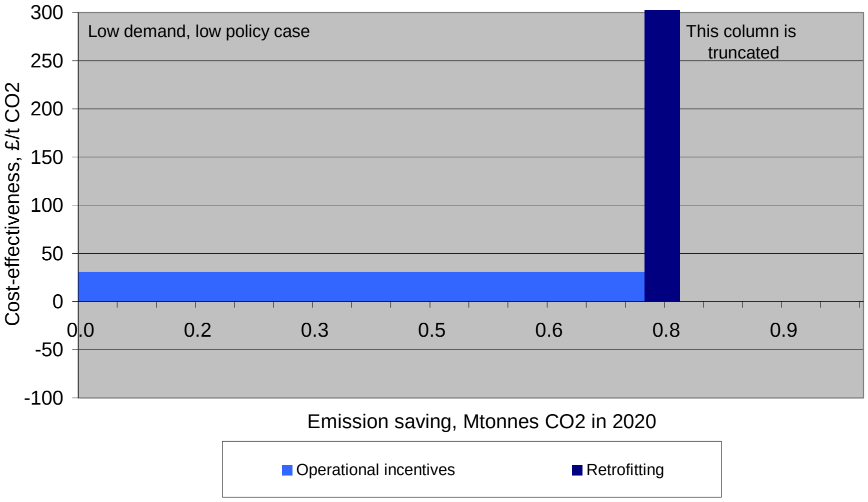


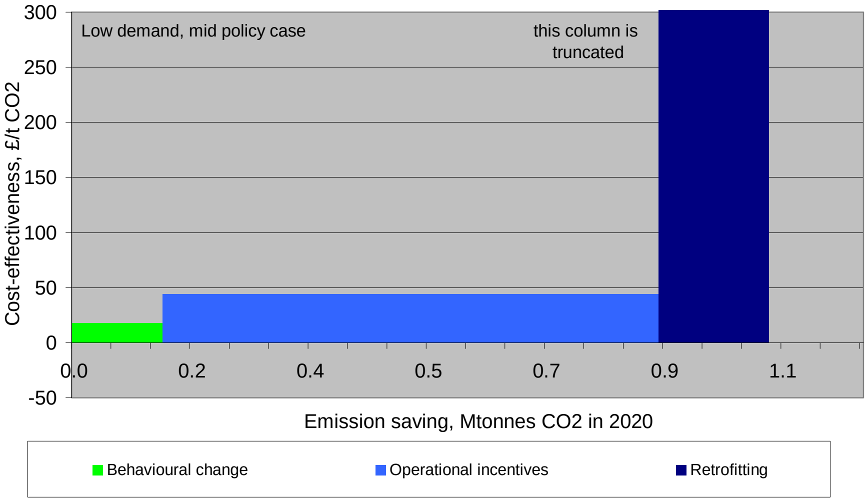
The correct formulation of an emissions metric, by which CO_2 *emissions* can be multiplied to account for non-CO_2 effects is discussed in detail by Fuglestvedt et al. (2010) and applied by Lee et al. (2010) based on the latest available assessments of individual effects. This takes the form of a Global Warming Potential (GWP) or a Global Temperature change Potential (GTP) over some specified time horizon (TH) (e.g. 20, 100, 500 years). The Kyoto Protocol uses a GWP with a TH of 100 years.

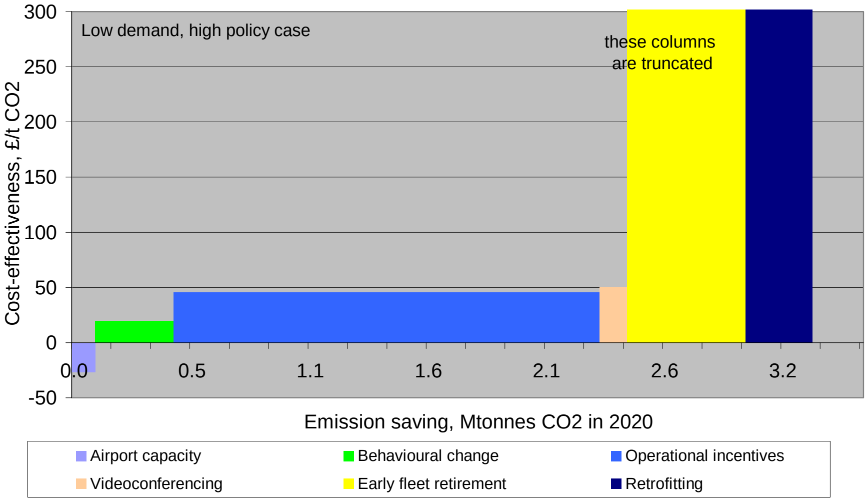
Values of overall GWPs/GTPs for aviation were published by Lee et al. (2010) and reproduced in the UK Committee on Climate Change's aviation report (their Box 6.3, p127), so will not be repeated here. However, if one were to choose an overall aviation GWP with a TH=100 years, the value would be of the order 2.

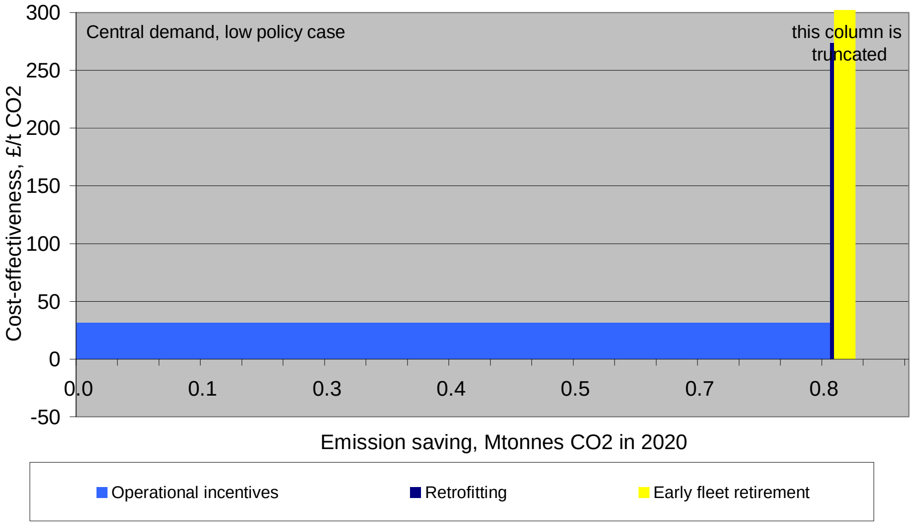
Appendix 3: MAC curves by year

2020





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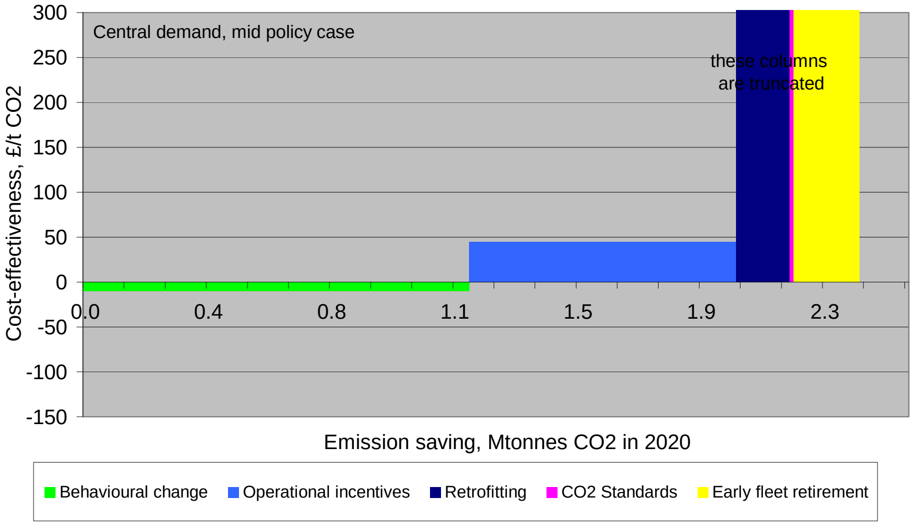
Emission saving, Mtonnes CO2 in 2020
Operational incentives
Retrofitting
Early fleet retirement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Emission saving, Mtonnes CO2 in 2020
Behavioural change
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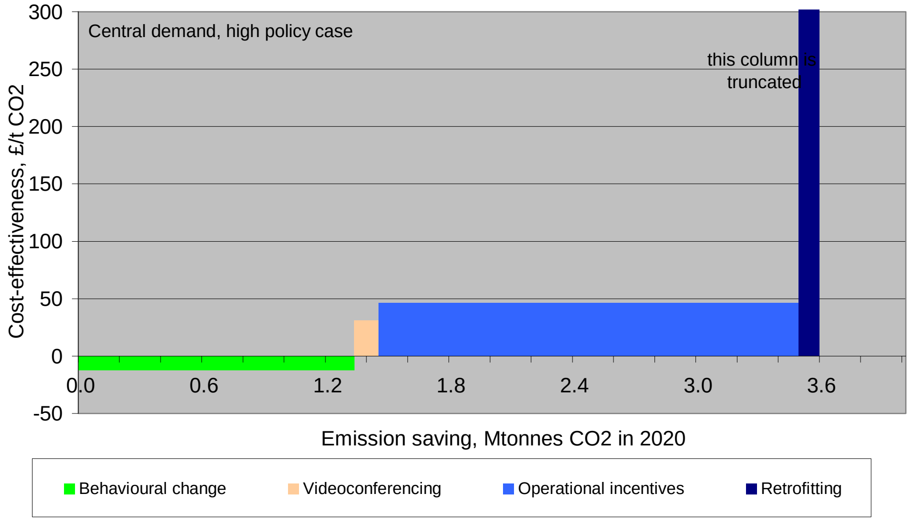
CO2 Standards
Early fleet retirement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Behavioural change
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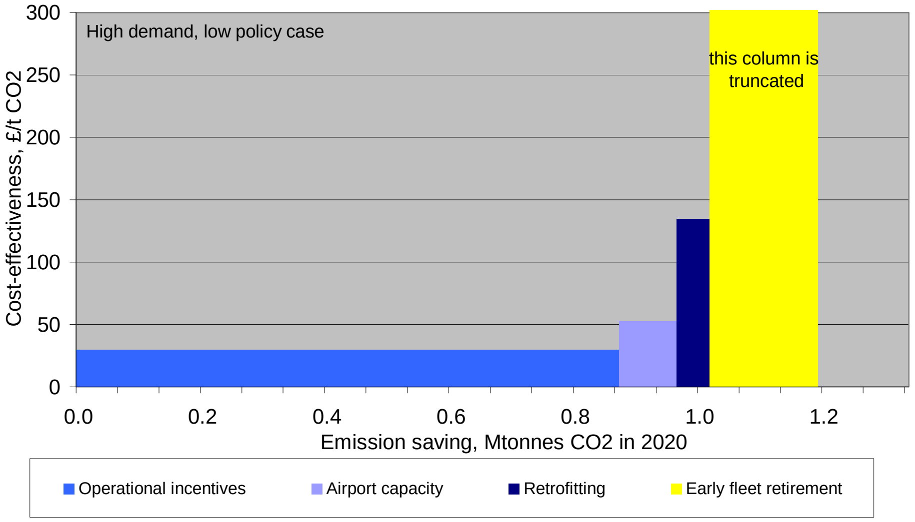
Operational incentives
Retrofitting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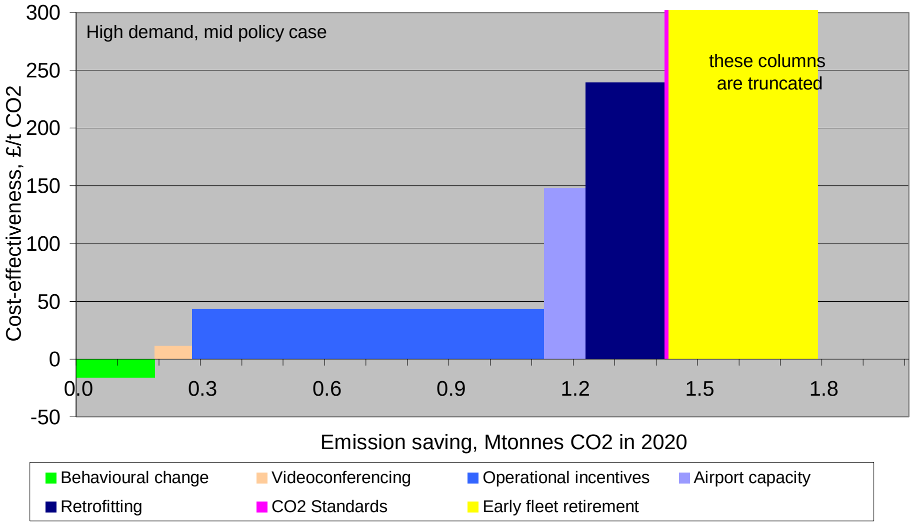
Operational incentives
Airport capacity
Retrofitting
Early fleet retirement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Behavioural change
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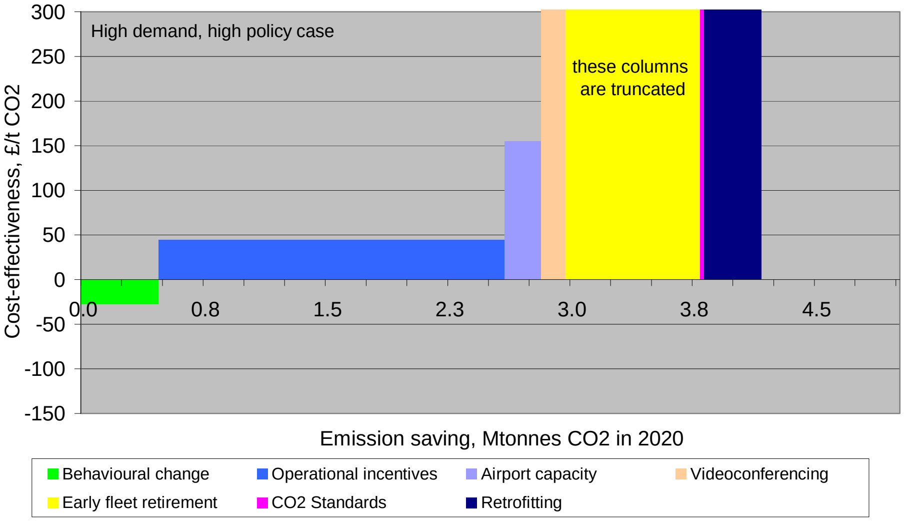
Operational incentives
Airport capacity
Retrofitting
CO2 Standards
Early fleet retirement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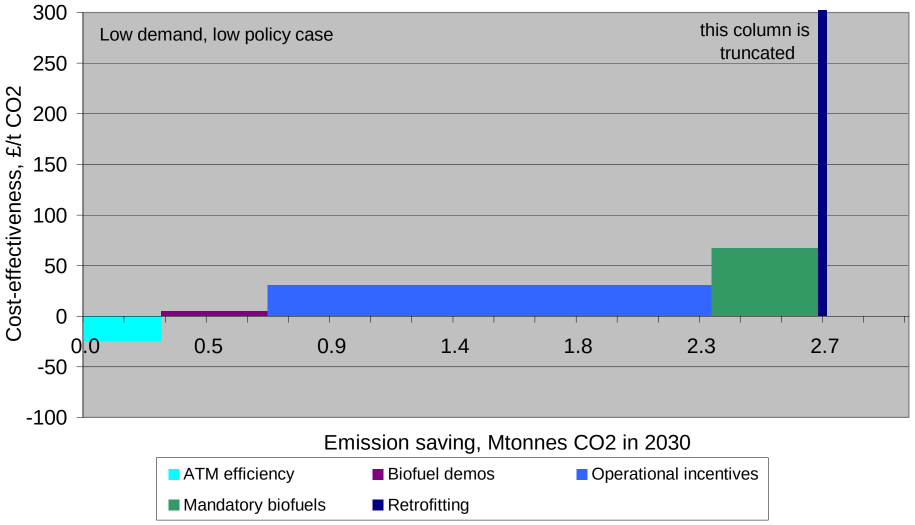
Behavioural change
Operational incentives
Airport capacity
Videoconferencing
Early fleet retirement
CO2 Standards
Retrofitting

2030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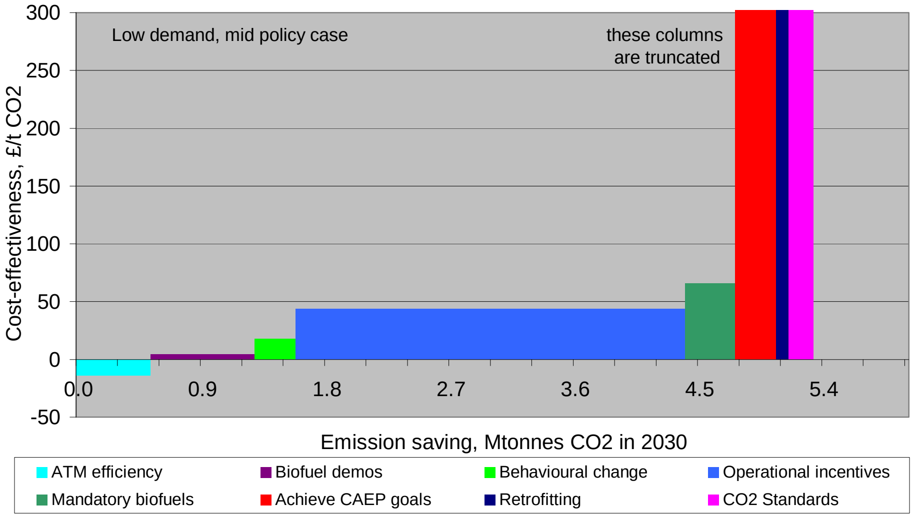
Emission saving, Mtonnes CO2 in 2030
ATM efficiency
Biofuel demos
Operational incentives
Mandatory biofuels
Retrofitting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Emission saving, Mtonnes CO2 in 2030
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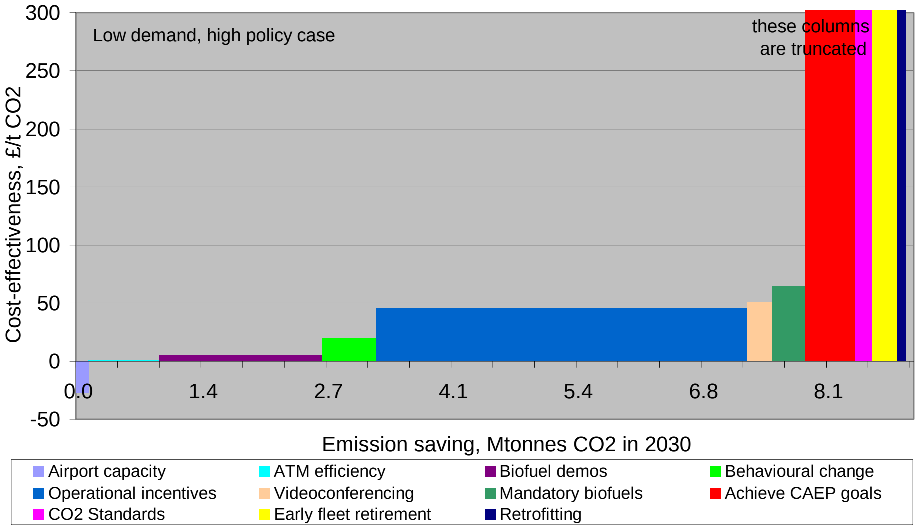
Retrofitting
CO2 Standards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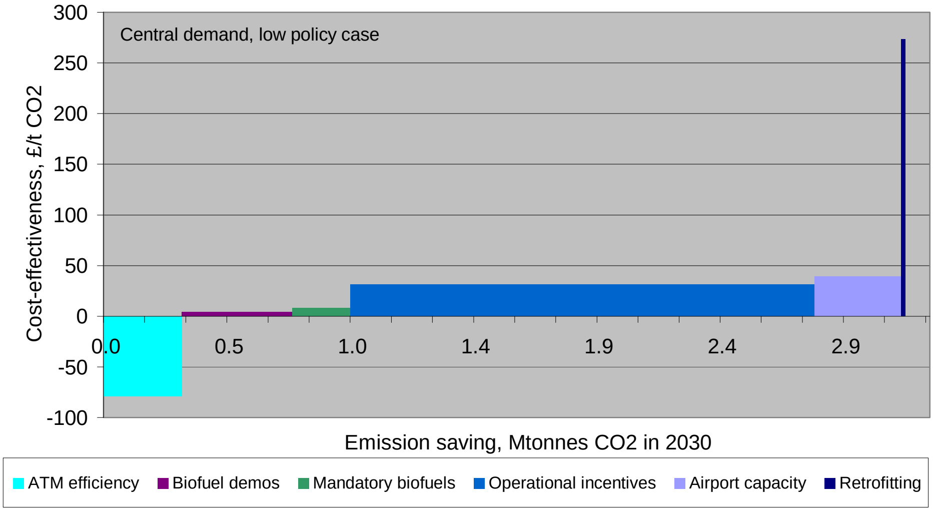
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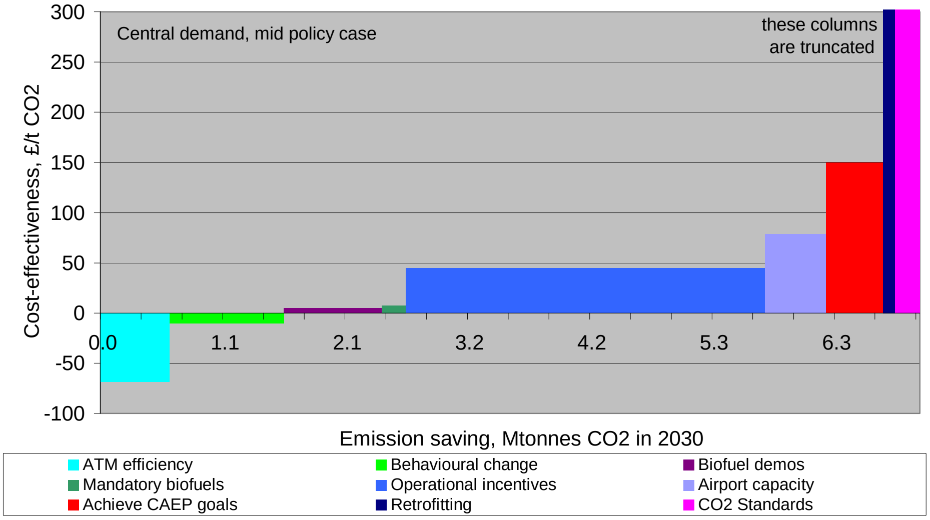
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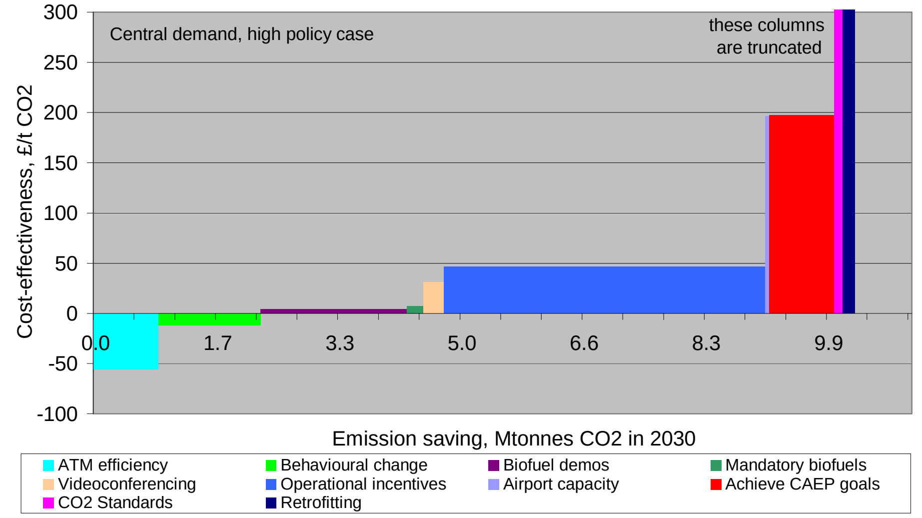
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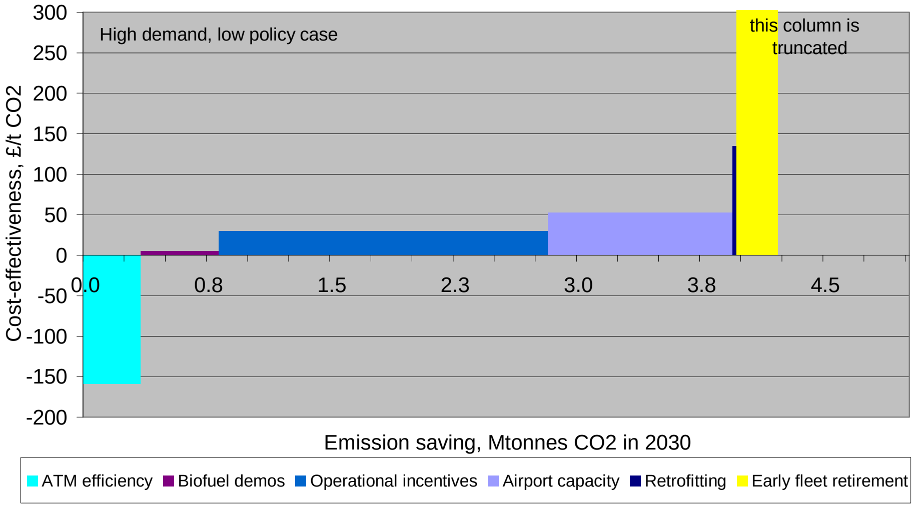
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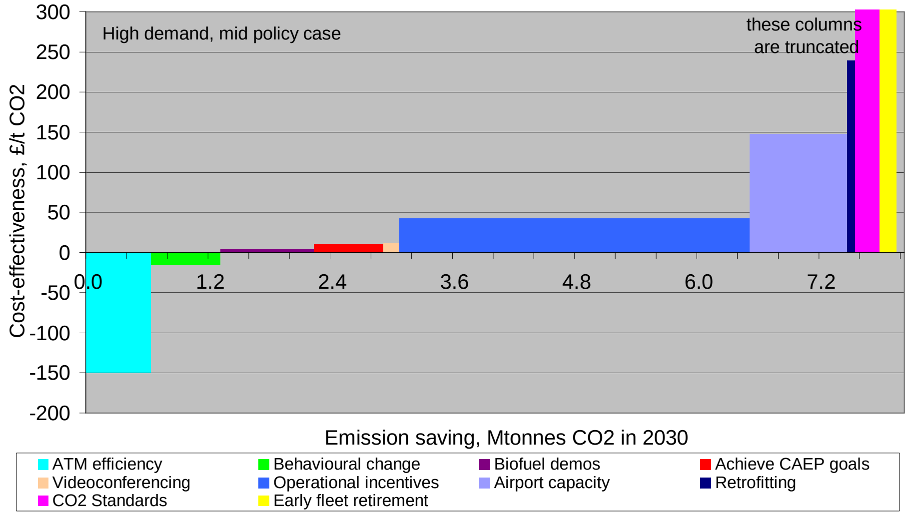
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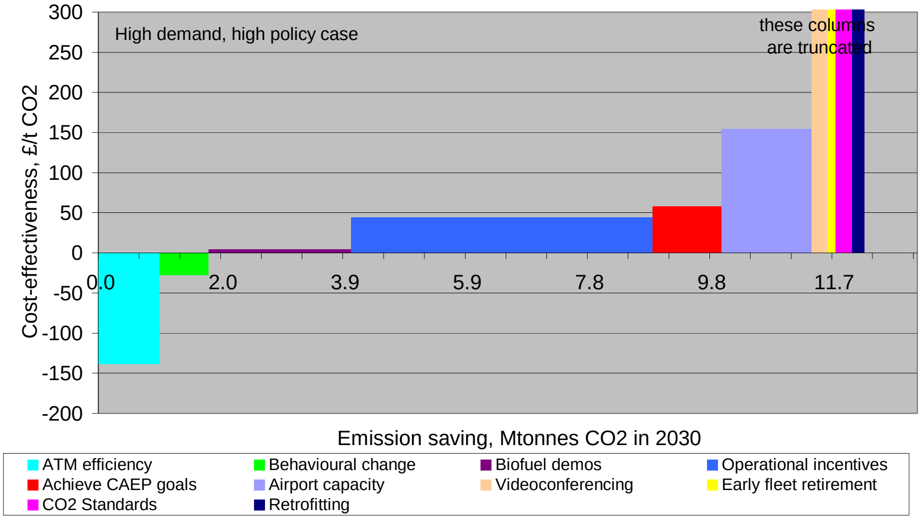
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Retrofitting

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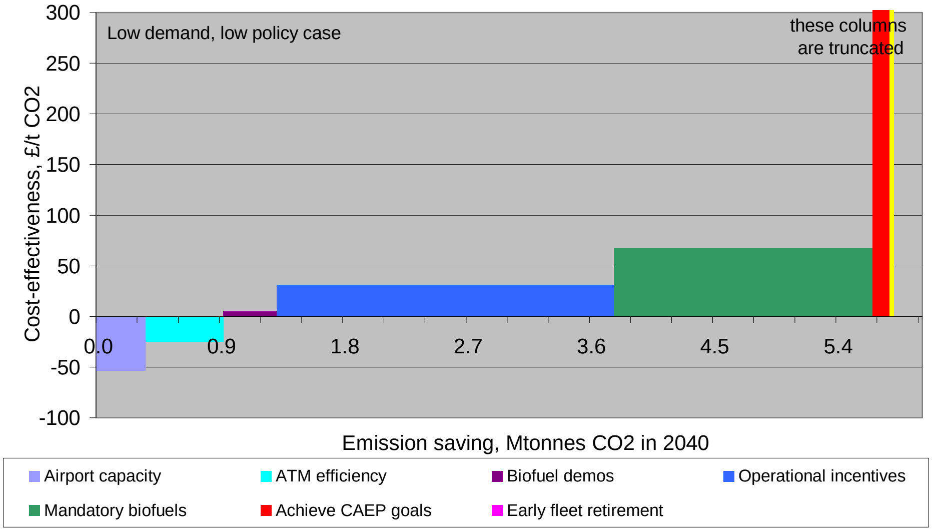
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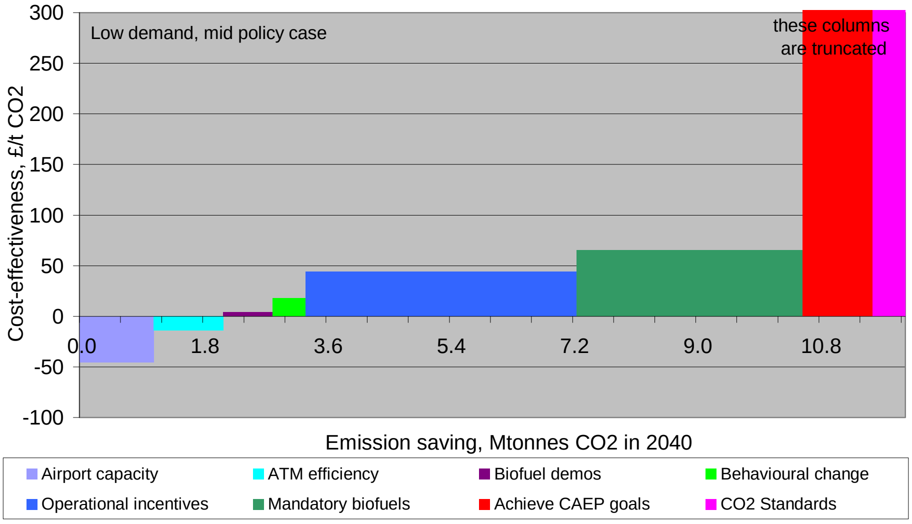
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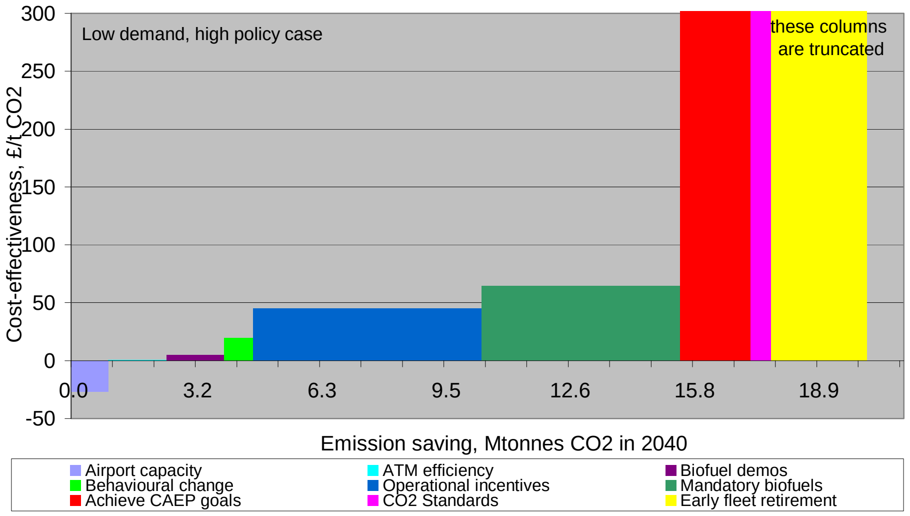
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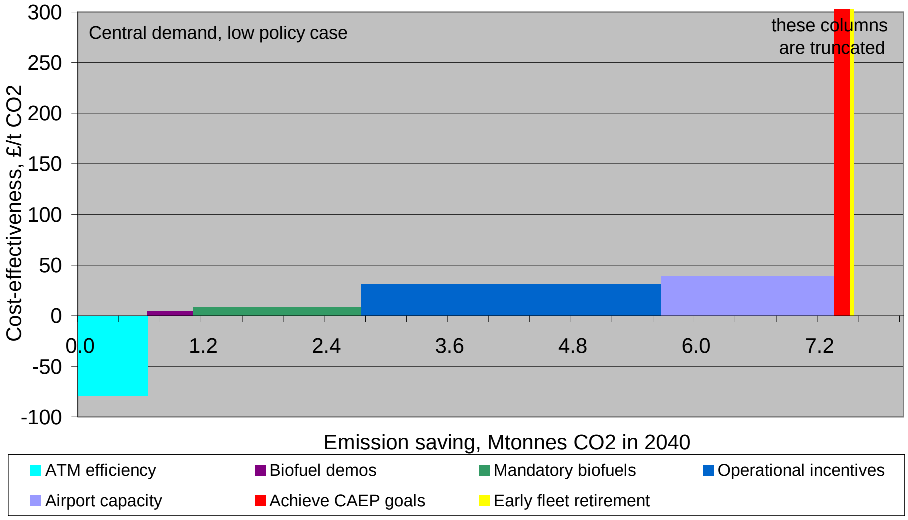
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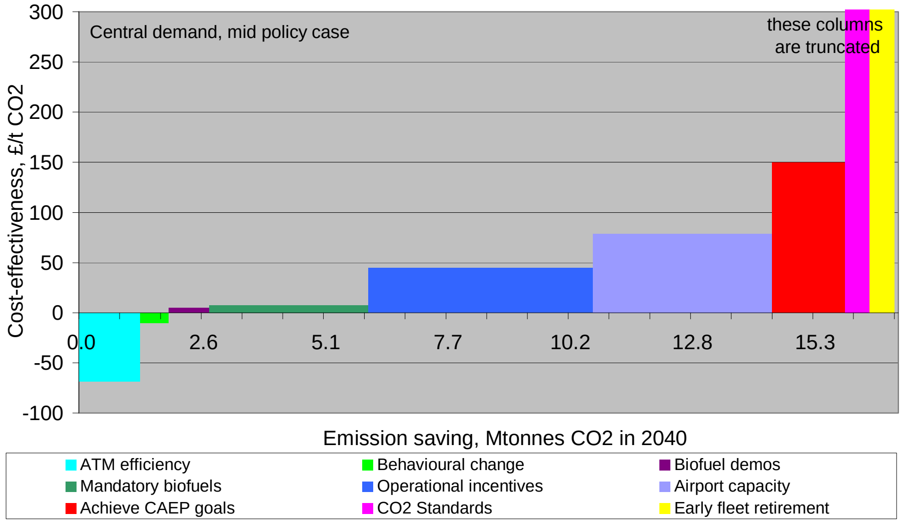
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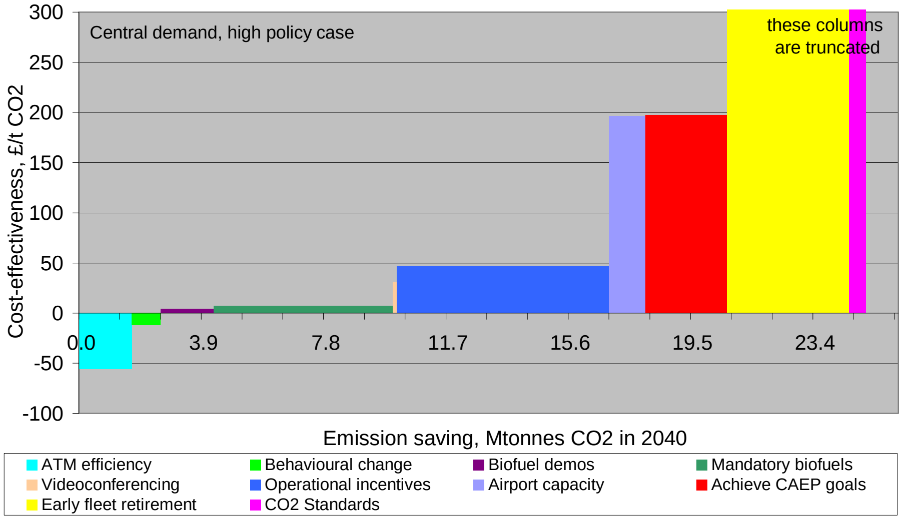
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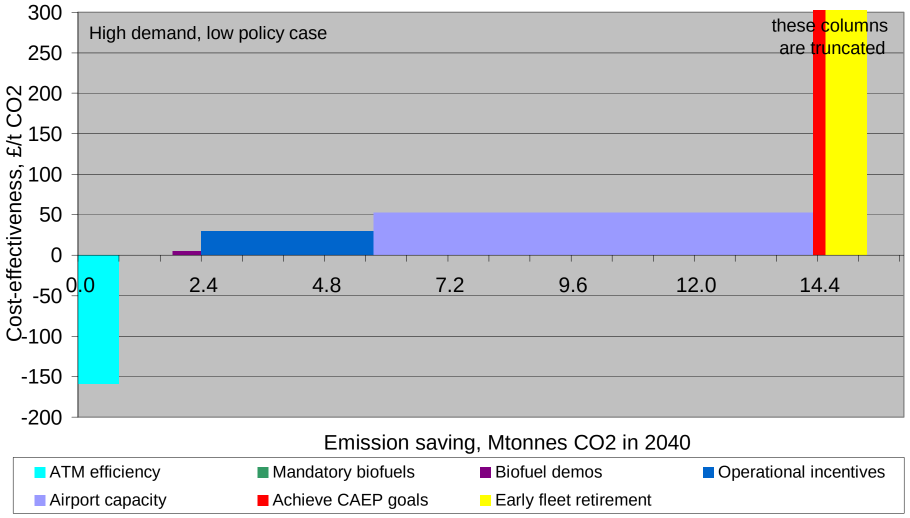
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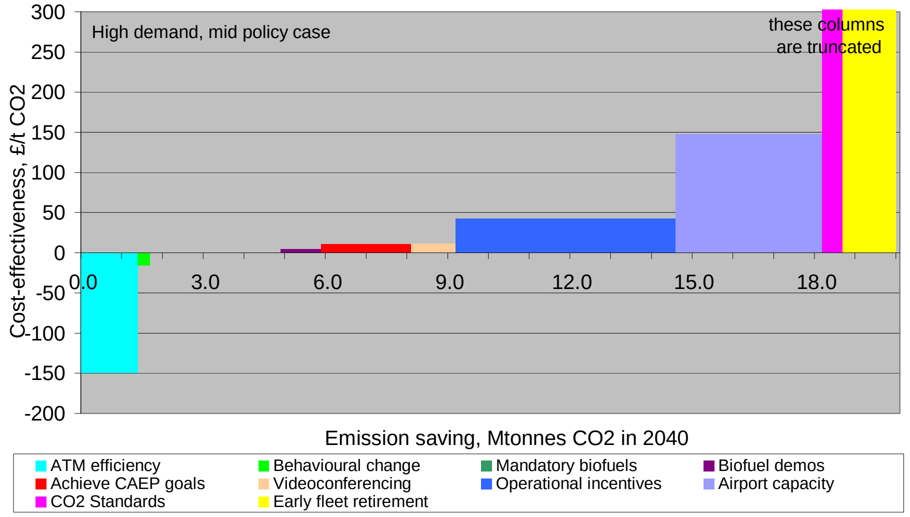
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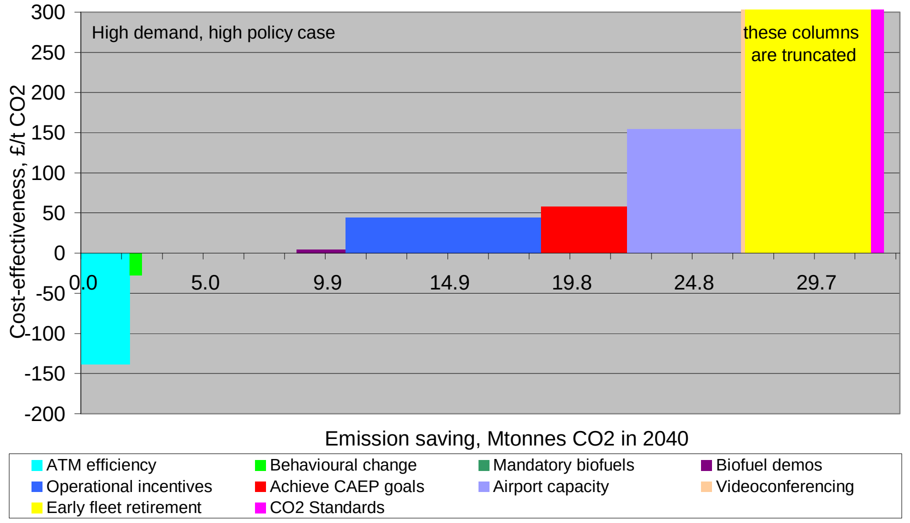
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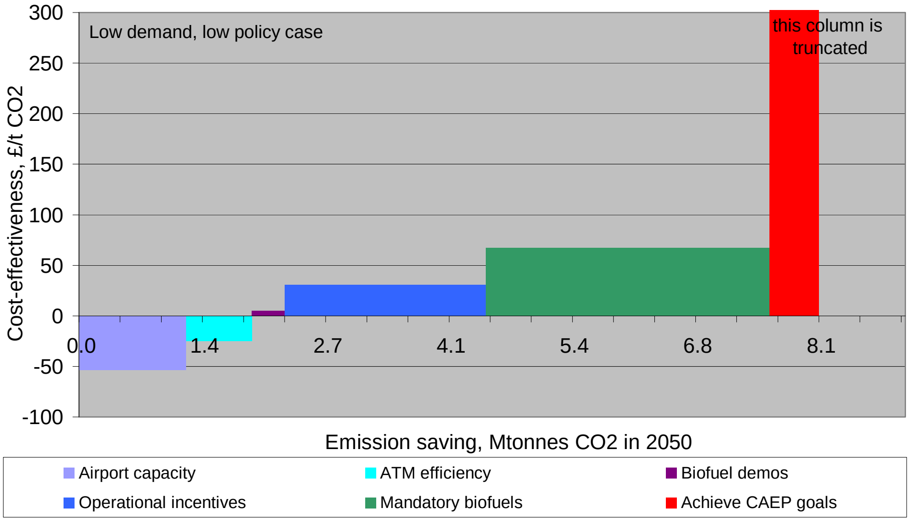
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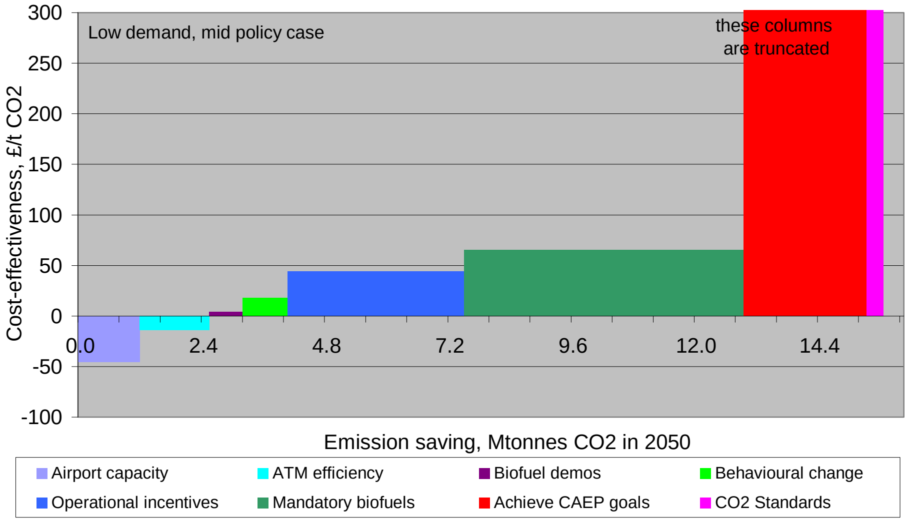
Achieve CAEP goals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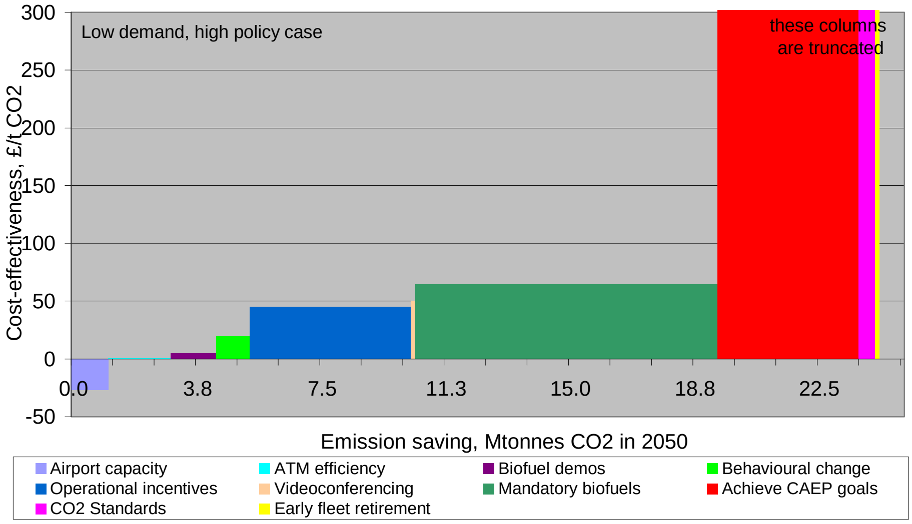
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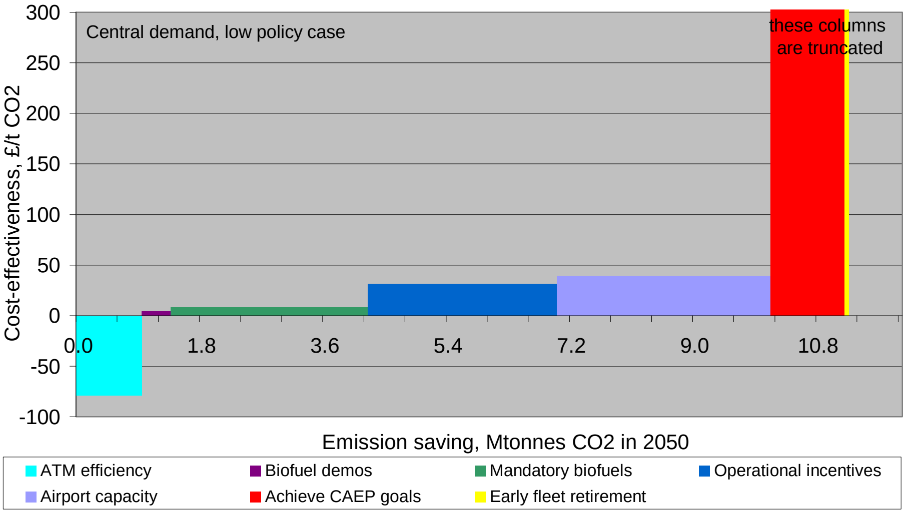
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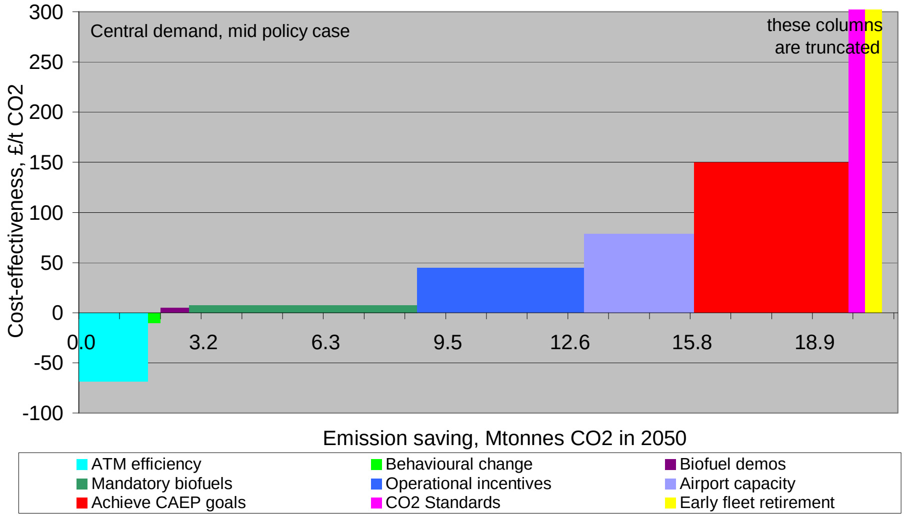
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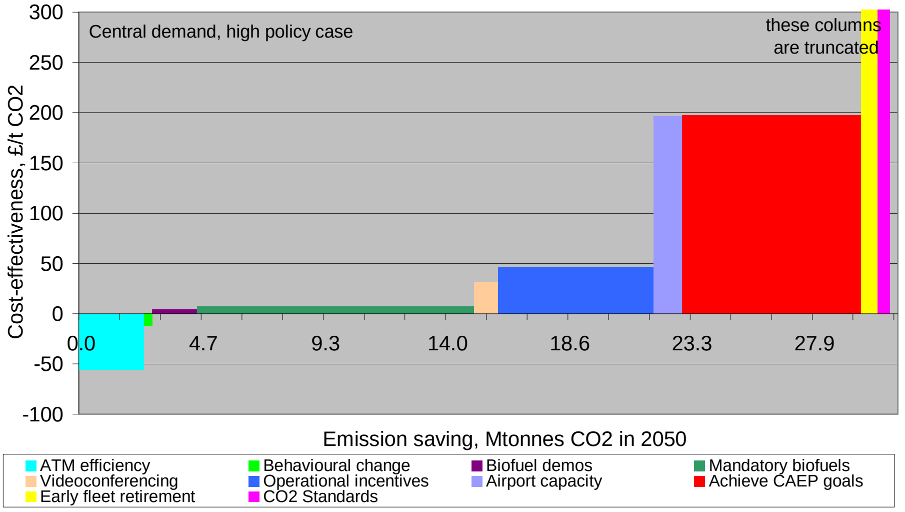
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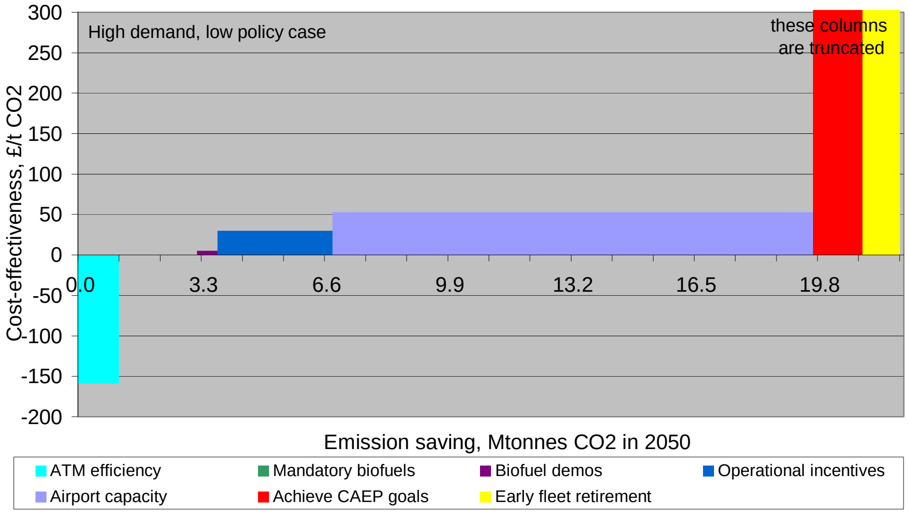
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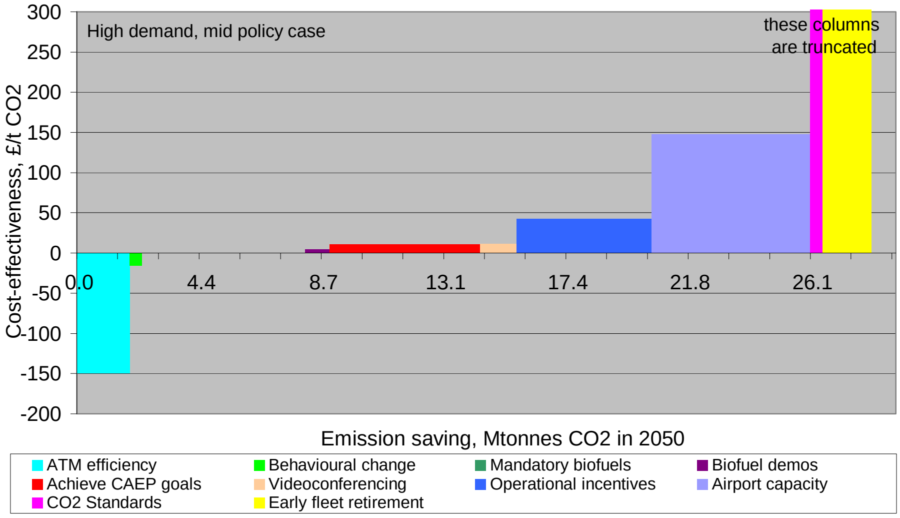
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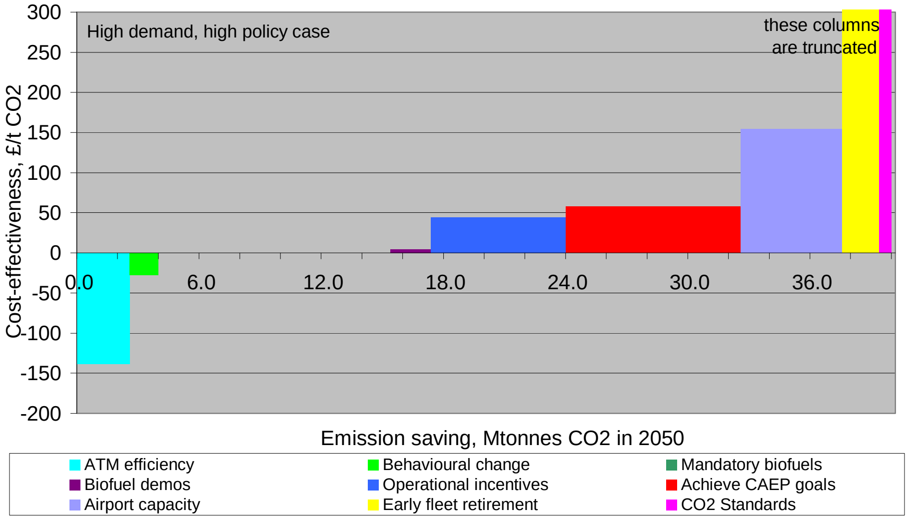
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Operational incentives
Achieve CAEP goals
Airport capacity
Early fleet retirement
CO2 Standards

Appendix 4: Technology Readiness Levels

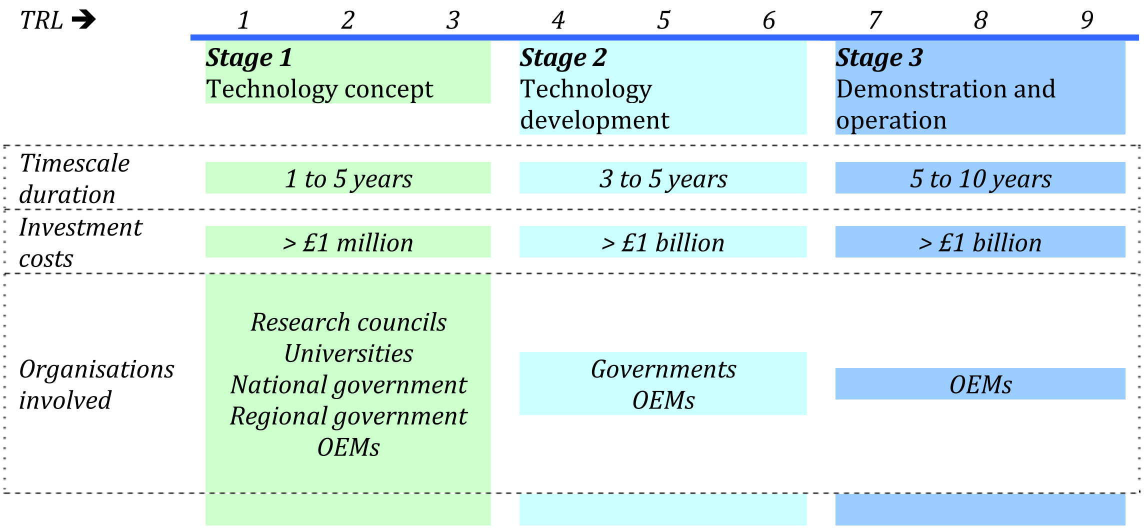
The progression of technology research and development can be described using the NASA-TRL (Technology Readiness Level) scale (1 – 9), where TRL 1 means that the basic principles of a technology have been observed and reported, and TRL 9 means that the technology has been qualified through successful mission operations. A description of the NASA TRL-scale (1-9) is given in Table 40.

Table 40. An overview of the NASA Technology Readiness Level (TRL) scale.

TRL 1	Basic principles observed and reported.
TRL 2	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept.
TRL 4	Technology basic validation in a laboratory environment.
TRL 5	Technology basic validation in a relevant environment.
TRL 6	Technology model or prototype demonstration in a relevant environment.
TRL 7	Technology prototype demonstration in an operational environment.
TRL 8	Actual Technology completed and qualified through test and demonstration.
TRL 9	Actual Technology qualified through successful mission operations.

The support for technology research and development can be divided, in terms of TRL, into three notional stages, as shown by the overview of aerospace technology development in Figure 17. Stage 1 (taking the TRL up to 3) involves proof of concept and may be the result of Ph.D or post doctoral research. This could be funded from various sources including research councils, regional or national government, original equipment manufacturers (OEMs), or a combination of these. At Stage 2 (raising the TRL from 3 to 6) a proof of concept is advanced to the demonstrator stage, and this can be funded by the OEMs and (national or regional) governments. Stage 3 (increasing TRL to 9) involves progressing a technology through to its EIS and this requires OEM investment. The time and cost associated with technology development (anywhere between TRL 1 and 9) is non-linear, with for example flight tests and validation to achieve TRL 7 typically requiring greater capital investment than the initial laboratory testing to TRL 1. Importantly, it is acknowledged that technologies progress at different rates, with some reaching maturity without major difficulties, while progress with others may stall for very many years (ICAO-CAEP, 2010).

Figure 17. An overview of aerospace technology development.



TRL ➔	*1 2 3*	*4 5 6*	*7 8 9*
	Stage 1 Technology concept	***Stage 2*** Technology development	***Stage 3*** Demonstration and operation
Timescale duration	*1 to 5 years*	*3 to 5 years*	*5 to 10 years*
Investment costs	*> £1 million*	*> £1 billion*	*> £1 billion*
Organisations involved	*Research councils* *Universities* *National government* *Regional government* *OEMs*	*Governments* *OEMs*	*OEMs*

Appendix 5: Glossary

A320NEO	Airbus A320 New Engine Option
ANSP	Air Navigation Service Provider
APD	Air Passenger Duty
ARP	Applied Research Programmes
ASK	Available Seat Kilometres
ATC	Air Traffic Control
ATK	Available Tonne Kilometre
ATM	Air Traffic Movements
Blended Wing Body (BWB)	Delta shaped flying wing with passengers seated in the main wing body
BPR	Bypass ratio
CAA	UK Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection
CANSO	Civil Air Navigation Services Organisation
CARAD	Civil Aeronautics Research and Technology Demonstration Programme
CCC	UK Committee on Climate Change
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Composite Floor Beams	Use of lighter materials to reduce airframe component weight
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DOC	Direct Operating Costs
EINOx	NOx Emissions Index
EIS	Entry Into Service
EPSRC	Engineering and Physical Sciences Research Council
EU ETS	European Union Emissions Trading System
EUROCONTROL	European Organisation for the Safety of Air Navigation
GDP	Gross Domestic Product
Geared Turbofans	Conventional turbofan engine with a reduction gear added between the front fan and the turbine driving the fan
GHG	Greenhouse gas
GTP	Global Temperature change Potential
GWP	Global Warming Potential
HC	Hydrocarbons
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEs	Independent Experts
IPCC	Intergovernmental Panel on Climate Change

Laminar Flow	Smooth non-turbulent flow to achieve lower drag
MAC(C)	Marginal Abatement Cost (Curve)
Mach	The scale measuring the speed of an object relative to the speed of sound
MEA	More Electric Aircraft
mppa	million passengers per annum
MTOW	Maximum Take Off Weight
NATS	National Air Traffic Services
NICs	Newly Industrialised Countries
NPV	Net Present Value
O_3	Ozone
OEM	Original Equipment Manufacturer
OPR	Overall pressure ratio
Open Rotor Engines	Engine with no nacelle around the fan and the fan replaced with 2 contra-rotating swept propellers or rotors
RFI	Radiative Forcing Index
Riblets	Small grooves or raised lines on the air-swept surface skin of the aircraft to reduce turbulence and friction drag
SAR	Specific Air Range
SCAB	Social Costs and Benefits Model
SESAR	Single European Sky Air Traffic Management Research
SFC	Specific Fuel Consumption
TRL	Technology Readiness Level
TS1, TS2, TS3	ICAO-CAEP Technology Scenarios
UHB	Ultra High Bypass
VC	Videoconferencing
Winglets	Wingtip extensions designed to reduce cruise drag