Carbon Abatement in UK Aviation

Final Report

Report for Department for Transport
CCCC16B03/CCCC16B05

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Executive summary

A study has been performed by Ricardo Energy & Environment, together with our partners SYSTRA Ltd., Gaia Capital Ltd., Michael Mann, Bethan Owen and Prof. David Lee, to assess policies that could be used to reduce carbon in UK aviation and to provide the cost and abatement data needed for DfT to produce updated marginal abatement cost (MAC) curves for the UK aviation sector.

This is the final report on the study.

The aim of the study was not to recommend future Government policy, but to assess a range of measures that could be implemented in the future depending on the aims, objectives and priorities of the Government at the time. Although the report considers polices that are considered technically feasible, based on discussions with DfT and other Government Departments, and a high level description of each is provided, detailed consideration has not been given to the precise mechanisms by which they would be implemented.

The assessment of the abatement produced by the policy measures used the DfT aviation modelling framework. The assumptions included in the baseline calculations (those representing the case in which there is no further policy action) were reviewed and recommendations were made for updates to be made to the calculation. These were implemented by the DfT and the updated model was used for the baseline and policy measure calculations using the model.

Three baseline calculations were used in the study, based on low, central and high forecasts of oil and carbon prices, as published by BEIS.

A number of policy measures were considered for this study. They were assessed for their feasibility and those that were considered feasible were taken forward to the quantitative analysis. In each case, three levels of policy ambition (low, mid and high) were assessed. The policy measures analysed in this manner were:

- Increased R&D in more efficient engines and aircraft
- Early fleet replacement with more fuel-efficient aircraft
- Improvements to the ICAO CO_2 emissions standard
- Reduced aircraft cabin weight
- Regulation of aircraft types operating from UK airports
- More efficient ground movements
- Increased use of biofuels

The potential impact of these policy measures on the CO_2 emissions from flights departing from the UK was identified and supplied to DfT for inclusion in the aviation modelling framework. The model then calculated the emissions in future years so that the abatement could be derived.

The approach to implementing the impact of the different policy measures included changes to the assumed fuel efficiency of future aircraft types, changes in the assumed retirement ages, changes to the years in which aircraft types were phased out of UK operations and changes to the CO_2 factors applied to the fuel consumption.

The calculation of the costs of the measures included implementation costs (such as the cost of the increased R&D or the increase in aircraft acquisition costs), the change in fuel costs and the change in the costs of carbon. In most cases, the policy measure led to a reduction in fuel consumption, giving negative changes in fuel and carbon costs.

The CO_2 abatement, implementation costs and fuel costs were used to calculate cost effectiveness values for each policy measure. Following guidance published by BEIS, the reduction in the costs of carbon was not included in the calculation of cost-effectiveness. The cost effectiveness values were based on total (discounted) values between 2017 and 2065.

The increased R&D measure was found to have a poor cost-effectiveness. This is primarily due to the UK bearing all the costs of the measure, but only identifying a small part of the benefits (as the more efficient aircraft types would be sold and used globally).

The early fleet replacement and regulation of aircraft types policy measures also gave high cost per tonne CO_2 saved values, due to the high costs incurred by airlines in acquiring additional aircraft. The abatement under the policy measure for the regulation of aircraft types was the highest of all the measures considered, but the airline costs were also very high.

The policy measure related to the increased use of biofuels was found to have a good cost effectiveness if the reduction in the costs of carbon was included in the calculation, but was less good when it was not (in line with BEIS guidance). This was because the biofuels were assumed to be more expensive than fossil-fuel-based kerosene, but they were also assumed to be exempt from carbon pricing.

The policy measure related to an improved ICAO CO_2 standard was found to have a good cost-effectiveness, but there is considerable uncertainty regarding the ability of the UK to unilaterally cause such an improved standard to be agreed.

The policy measures on reduced cabin weight and more efficient ground movements were also found to have good cost-effectiveness as the overall costs are low (or even negative due to the savings in fuel cost) and the abatement of CO_2 emissions is similar to most of the other measures.

As well as having different values of cost-effectiveness, as calculated using the assumptions employed in this study, it is clear that there are differing levels of uncertainty around the implementation and results of the policy measures. The implementation of the increased R&D policy measure would depend on the research community and aerospace industry responding to the policy and increased funding, giving an uncertainty around the ability to implement the aims of the policy. Equally, research is an uncertain process and it is not certain that an increase in research efforts would necessarily deliver the desired improvements in fuel efficiency.

The policy measures that would be implemented through action by airlines, such as the early fleet retirement or the reduced aircraft cabin weight measures, could bring challenges in implementation, especially as many of the airlines that would be affected are not registered in the UK.

Other policy measures, such as the more efficient ground movements or increased biofuels measures, are more likely to deliver the expected results in reduced fuel consumption and/or reduced net CO_2 emissions when implemented. They are also likely to be easier to implement through unilateral policy action by the UK, as they depend less on international collaboration

The cost and abatement results from the analyses have been supplied to DfT for incorporation into updated MAC curves. These updated MAC curves will be reported separately by DfT in a forthcoming report.

This study was guided by a steering group that consisted of members of the DfT and other Government departments and a team of independent peer reviewers. The steering group provided regular feedback on the direction of the study, the policy measures selected, the analysis methodology and the results obtained, as well as on the preparation of this report.

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1 Introduction

Ricardo Energy and Environment, supported by our partners SYSTRA Ltd., Gaia Capital Ltd., Michael Mann, Bethan Owen and Prof. David Lee, have been contracted by the Department for Transport (DfT) to assess policies that could be used to reduce carbon in UK aviation and to provide the cost and abatement data needed for DfT to produce updated marginal abatement cost (MAC) curves for the UK aviation sector[1].

The aim of the study was not to recommend future Government policy, but to assess a range of measures that could be implemented in the future depending on the aims, objectives and priorities of the Government at the time. Although the report considers polices that are considered technically feasible, based on discussions with DfT and other Government Departments, and a high level description of each is provided, detailed consideration has not been given to the precise mechanisms by which they would be implemented. This would be for policy makers and other stakeholders to decide should they wish to purse any of these measures.

A previous study in 2011[2] examined a range of policy measures to reduce emissions from UK aviation and generated a set of MAC curves for DfT. This represented a first application of MAC curves to policy measures, rather than technology developments, for the UK aviation sector.

The request for the current study was to provide detailed descriptions of potential policy measures, together with their abatement potential and costs, for an updated set of MAC curves. The updated MAC curves were to be developed by DfT and, as for the previous study, the CO_2 emissions from UK aviation were to be calculated using the DfT air passenger demand and CO_2 forecast model.

The study includes both technical (e.g. increased research and development of fuel-efficient aircraft) and non-technical (e.g. increased use of biofuels) measures. The policy measures investigated were intended to focus on options that could be pursued unilaterally by UK Government policy action. However, aviation is an inherently international business and it was assumed that UK action would also encourage similar action by other, European and non-European, countries. These aspects are discussed later in the report.

The requirements for the definition of policy measures include:

- Feasibility and capacity to be applied unilaterally by the UK;
- Policy levers that could be used to incentivise/regulate the application of the measure;
- Who is responsible for implementing the measure/lever (‘who pulls the lever?’);
- What would different policy-level abatement scenarios look like;
- Main cost/benefit impact areas;
- Barriers to take up and the cost of overcoming them;
- The timeframe over which the measure would be expected to have an effect;
- Potential for carbon leakage.

1.1 Study quality assurance

The study that culminated in the production of this report was reviewed regularly by a steering group, consisting of members of the DfT and other Government departments and a team of independent peer reviewers. The steering group provided direction to the study, reviewed the policy measures selected, the analysis methodology and the results obtained. Feedback from the steering group was used when preparing this report.

[1] These will be presented in a separate DfT report, subsequent to the publication of this document.
[2] Holland, M., Mann, M., Ralph, M., Owen, B., Lee, D., Horton, G., Dickson, N., Kollamthodi, S., “A marginal abatement cost curve model for the UK aviation sector”, Contract PPRO 4/8/56, 09/08/2011 https://www.icao.int/environmental-protection/Documents/ActionPlan/UK_AbatementModel_en.pdf

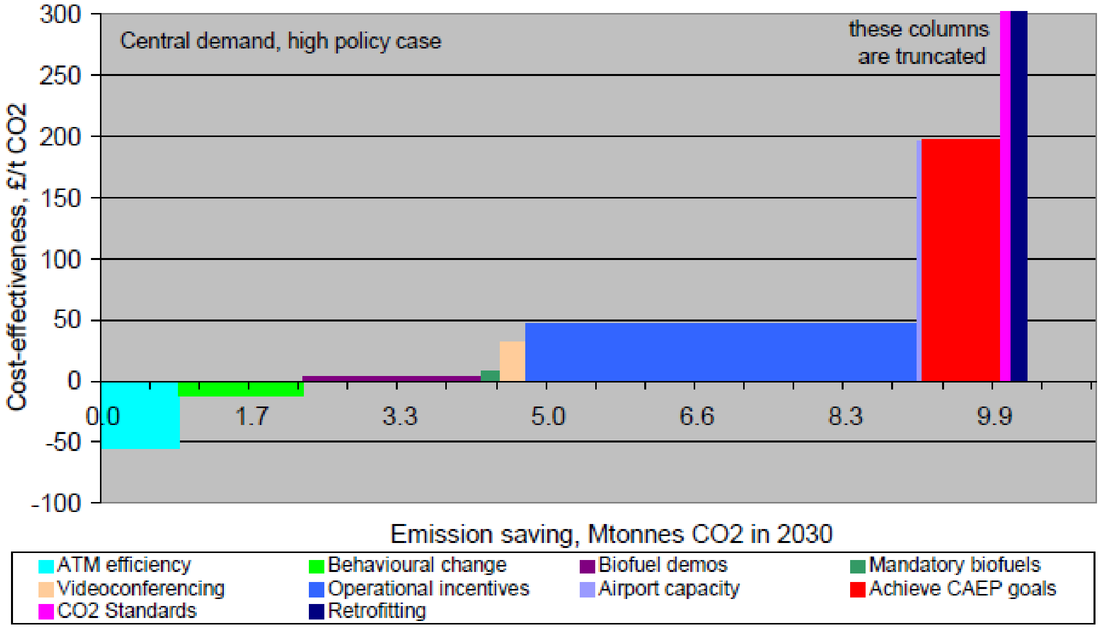
2 Marginal Abatement Cost Curves

The concept of marginal abatement cost (MAC) curves has been developed as a means of comparing and contrasting the costs of different options for reducing emissions. In most cases, though not necessarily all, the emissions that are to be abated are greenhouse gas emissions, most commonly carbon dioxide (CO_2). MAC curves have been applied to the comparison of different technologies and different policy options to achieve the goal of reduced emissions.

The inclusion of the term "marginal" in the MAC curve indicates that it compares the additional costs of achieving additional levels of abatement; therefore, most forms of presentation of MAC curves show the cumulative costs (usually in the form of cost-effectiveness, e.g. in £/tonne CO_2 abated) as further abatement measures are added.

An example of a MAC curve for the UK aviation sector is presented in Figure 2-1

Figure 2-1 Example of policy-related MAC Curve



Source: Holland M. et al. A marginal abatement cost curve model for the UK aviation sector. Technical report: Final, PPRO 4/8/56, 2011[3]

In Figure 2-1, the horizontal width of each "box" represents the additional abatement of each measure when added to that achieved by the preceding measures. Thus, the right hand end of each box represents the total abatement achieved by all the measures to that point. Similarly, the vertical height of each box represents the total cost (in £/tonne CO_2) of achieving the abatement represented by all measures to that point.

As shown in Figure 2-1, it is possible for an individual measure to have a negative cost effectiveness. This occurs when the overall effect of a technology or policy measure is to reduce costs as well as emissions. This may occur, for example, when the (up-front) implementation costs of the measure are small, but its effect is to reduce fuel consumption and hence operating costs over time.

As the MAC curves present the total abatement (and cost) of the set of measures up to, and including, each one, the order in which the measures are presented is important. Conventionally, they are presented in order of decreasing cost-effectiveness. Therefore, the first measure (in the far left of the chart) has the lowest cost per tonne of CO_2 abated, even if the abatement potential of that measure is much smaller than other measures (in which case the width of the box would be small). The last measure (at the right-hand end of the chart) has a high cost per tonne, although it may have a high abatement potential.

When identifying the abatement potential of each measure for presentation in a MAC curve, it is important that they are calculated taking account of the other measures implemented previously. For

[3] https://www.icao.int/environmental-protection/Documents/ActionPlan/UK_AbatementModel_en.pdf

example, in Figure 2-1, the dark blue box, representing "operational incentives" was calculated assuming that all five measures to the left of it on the chart were already in place. Any interactions between measures (e.g. the amount of CO_2 emissions that might be saved through "operational measures" may depend on the impact of the biofuels-related measures that were also implemented) need to be considered when deriving the abatement and costs. In many cases, the measures may be technologically independent, so their percentage emissions reduction is calculated (when the measure is applied in isolation) and that percentage reduction is applied to the emissions that remain after the preceding measures have been implemented.

It is possible for some pairs of measures, both technologies and policies, to be mutually exclusive (i.e. the two measures may not be applied together). In such cases, it is not possible to include both measures in a single MAC curve and multiple MAC curves are required to illustrate the full range of technologies or policies under consideration.

MAC curves are usually derived to cover a specific period of time; for example, from the present day to 2050. The abatement and costs calculated are the total costs through the period, with the costs usually being discounted to take account of preferences regarding spend over time and to present a net present value of those costs. When considering results presented in a MAC curve, it is important to note that emissions abatement may continue for some time after the costs finish (for example, the costs for developing a fuel efficient aircraft type will primarily occur before it enters service, while the abatement will occur during the time the type remains in service, which may be 30 years or more). It is also important to note that a key operating cost (particularly in the aviation sector) is the fuel cost and that reductions in fuel consumption (through fuel efficient technologies) reduce operating costs as well as abating emissions. Under scenarios in which carbon costs may be significant in the long-term (as in the assumptions for this study), those carbon costs may also be expected to reduce in line with fuel consumption. However, in their guidance for the evaluation of energy use and greenhouse gas[4], the Department for Business, Energy and Industrial Strategy (BEIS) specify that such reductions in carbon costs should not be included in cost-effectiveness calculations. Therefore, a similar approach has been adopted in this study.

This report presents the methodology used to estimate the cost and abatement impact of the policies that have been assessed. These will be used by DfT to produce a forthcoming report presenting policy MACC curves for the UK aviation sector.

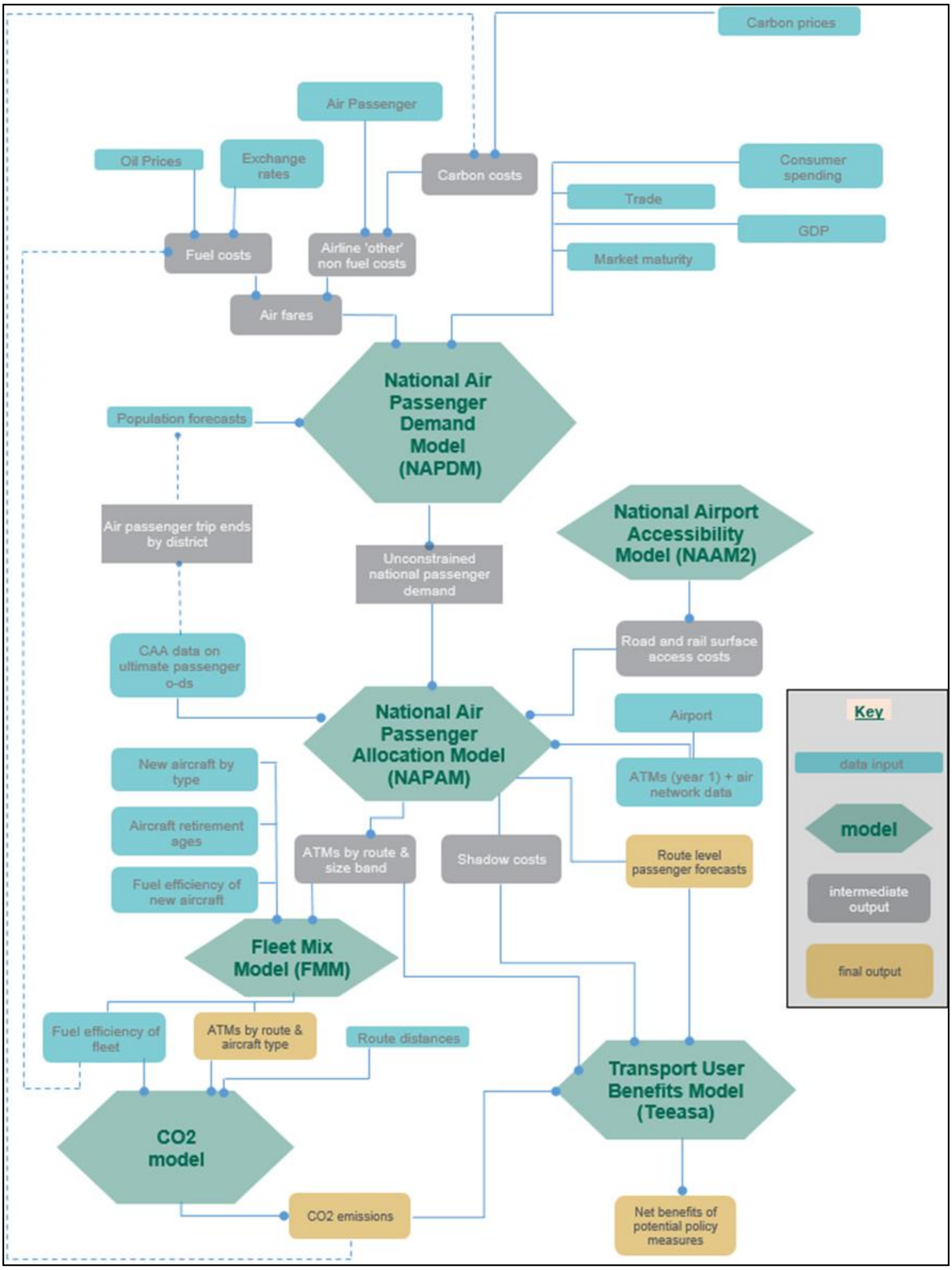
3 DfT's aviation modelling suite

As noted in the introduction, the CO_2 emissions for the study were calculated by the DfT using the modelling system that is used for the air passenger demand and CO_2 forecast analyses. To calculate the CO_2 abatement from the different policy measures, the modelling system was used to calculate future emissions under both baseline (no further policy action) and policy scenarios. The DfT modelling suite is illustrated in Figure 3-1[5].

[4] *Valuation of energy use and greenhouse gas – Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government*, March 2017, available at https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[5] Extracted from the DfT UK Aviation Forecasts, 2017, available athttps://www.gov.uk/government/collections/uk-aviation-forecasts

Figure 3-1 Illustration of the structure of the DfT modelling system



Before commencing the assessments, the baseline assumptions in the DfT model, particularly those related to the Fleet Mix Model (FMM) and the calculation of CO_2 emissions from aircraft, were examined and recommendations made to retain or modify those assumptions. The conclusions from this review are presented below.

In addition to the review of the baseline assumption, a detailed review of the FMM was also undertaken. The FMM is a key element in the modelling system, as it defines the aircraft types used to perform the air traffic movements in future years. The review encompassed the aircraft types included in the model (including generic future types), together with the methodology and assumptions used when populating the future fleet (such as aircraft retirement ages).

Recommendations were also made for future improvements to the model. The review of the FMM has been published as a separate report[6].

3.1 Model baseline assumptions review

The assumptions included in the definition of the existing baseline in the DfT aviation CO_2 model were reviewed and, where appropriate, recommendations were provided for changes to be made for the MAC curve study. The review was based on an existing baseline model (for 2016), using “central” assumptions for parameters such as oil and carbon prices. As the study was to develop inputs to MAC curves for three different baseline scenarios (based on low, central and high fuel price assumptions), the assumptions for those scenarios were discussed and agreed separately.

The review was focused primarily on those assumptions related to the FMM and the CO_2 calculations; input values related to other aspects of the model, such as demand modelling, were also noted for confirmation that they were being updated with the most recent data (DfT confirmed that they were being updated, in preparation for the analysis for the 2017 UK aviation forecasts (TR17)[7]). The full set of assumptions in the baseline are presented in the TR17 report.

The key recommendations were:

- No further amendments were recommended to the definition of future aircraft types in the model.
- The aircraft-level fuel burn modelling should be updated to use the aviation emissions calculator accompanying the EMEP/EEA air pollutant emission inventory guidebook (2016)[8].
- Analyses of the base year data suggested that the aircraft retirement age assumptions (the ages at which aircraft are assumed to be removed from flights to and from the UK) could be updated. However, discussions with DfT identified that the base year data used do not form a robust basis for recommendations for changes to the retirement ages (which have been found to have a significant effect on the results of the model). Therefore, it was recommended that the existing retirement ages should continue to be used for this study, but that a more comprehensive investigation should be undertaken into aircraft ages, and the ages at which aircraft are removed from UK operations (and, potentially, sold to be used elsewhere in the world).
- The existing assumptions on load factors were considered realistic.
- The great circle distance adjustment, used to increase flight distances (over the value for the most direct route) to represent the effects of the need to comply with ATC instructions, deviations due to weather, etc., was reviewed. Evidence from a study by Ricardo indicates that average extra distance flown (above the Great Circle Distance) is between 4.5% and 5% for flights in Europe[9]. Another study by Reynolds[10] indicated that the extra distance flown on North Atlantic routes was 5%, while the extra distance on typical Europe to South-East Asia routes was 7%. Combining the results of these studies, it was recommended that the “Great Circle Adjust” parameter should be set to 5% for flights to Europe (including UK domestic) and 6% for flights to long-haul destinations.
- The existing baseline assumes a 5% penetration of biofuels by 2050, with lifecycle emissions savings of 50% compared to conventional kerosene. Sustainable Aviation (2012)[11] projects a penetration of sustainable biofuels of 25% to 40% by 2050, while E4Tech (2014)[12] states that biofuels may achieve an 80% to 95% reduction in GHG emissions. At the same time, planned biofuel production capacity in the UK will not be developed. Based on the large differences in projected future biofuel use and emission saving potential between the existing DfT assumptions and the E4Tech report, it was recommended that the existing assumptions on

[6] Horton, G., A review of the DfT aviation fleet mix model,, May 2017

[7] DfT UK Aviation Forecasts, 2017, available at https://www.gov.uk/government/collections/uk-aviation-forecasts

[8] https://www.eea.europa.eu/publications/emep-eea-guidebook-2016

[9] https://ec.europa.eu/transport/sites/transport/files/2017-03-06-study-on-options-to-improve-atm-service-continuity-in-the-event-of-strikes.pdf

[10] T Reynolds. *Development of Flight Inefficiency Metrics for Environmental Performance Assessment of ATM*. Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009), 2009 (available at http://www.atmseminar.org/seminarContent/seminar8/papers/p_122_EI.pdf)

[11] Sustainable Aviation *Sustainable Aviation CO_2 Road-Map 2012*, Sustainable Aviation, 2012 (available at http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/SA-Carbon-Roadmap-full-report.pdf)

[12] E4Tech. Sustainable Aviation Fuels – Potential for the UK aviation industry. E4Tech, 2014. (available at http://www.e4tech.com/reports/sustainable-aviation-fuels-potential-for-the-uk-aviation-industry/)

the penetration of biofuels and life cycle CO_2 emission savings should be retained for this study but reviewed for future analyses.

The recommendations arising from the review of the baseline assumptions were provided to DfT and were considered when developing the data for the TR17 analysis. Further details of the baseline review are provided in Annex 1.

3.2 Aircraft-level fuel burn modelling

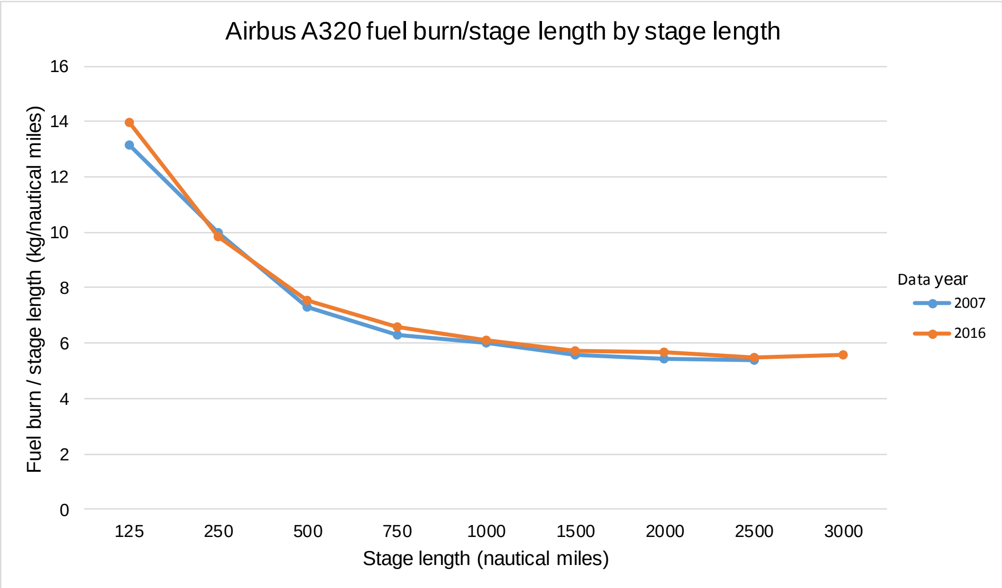
The existing model calculates fuel burn of different aircraft types using a set of curve fits to the previous CORINAIR data (which accompanied previous editions of the EMEP/EEA air pollutant emissions inventory guidebook). The curve fits are for fifth-order polynomial curves for fuel burn/distance (in kg/Nm) as a function of flight distance (in Nm). This provides a flexible approach to the calculation of fuel burn and its continued use is supported.

The CORINAIR data used to derive the fifth-order polynomials are those published in 2007. These were based on analyses performed using the PIANO model. The 'Future Aircraft Fuel Efficiencies' (2010) report[13] (2010) recommended some adjustments to the CORINAIR data for certain aircraft types (based on modelling studies at QinetiQ) and also some approaches for modelling additional aircraft types that were not included in the CORINAIR dataset.

With the more recent editions of the EMEP/EEA guidebook, the CORINAIR data have been replaced by an aviation emissions calculator, based on aircraft fuel burn modelling using the EUROCONTROL Advanced Emission Model (AEM). This includes a wider range of aircraft types than previously.

Some comparisons have been made of the fuel burn data from the 2007 and 2016 CORINAIR versions, for aircraft types that appear in both datasets. Examples are shown in Figure 3-2 to Figure 3-4, below.

Figure 3-2 Comparison of EMEP/EEA fuel burn data for Airbus A320 aircraft type



[13] G.Horton *Future Aircraft Fuel Efficiencies – Final Report*, QinetiQ/10/00473, March 2010, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4515/future-aircraft-fuel-efficiency.pdf

Figure 3-3 Comparison of EMEP/EEA fuel burn data for Boeing 747-400 aircraft type

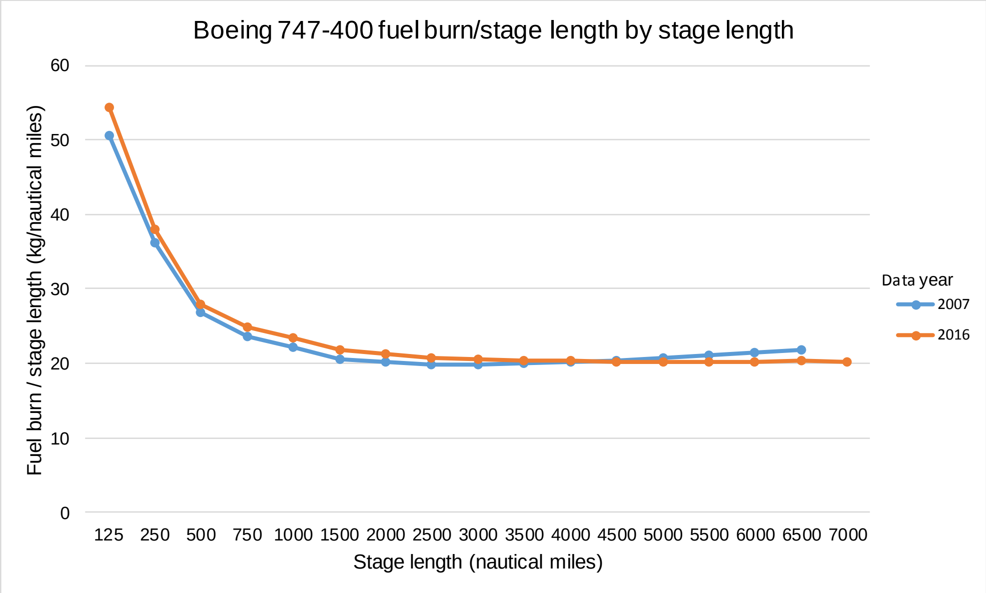
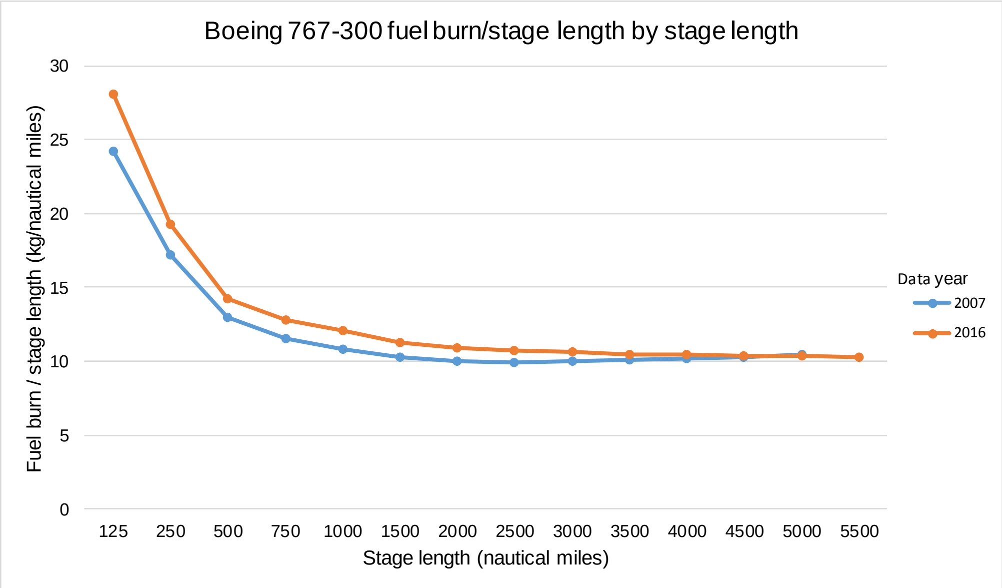


Figure 3-4 Comparison of EMEP/EEA fuel burn data for Boeing 767-300 aircraft type



The agreement between the two data sources is generally very good, though the Boeing 767 does show some significant differences on short stage length. It is notable that the more recent emissions modelling by EMEP/EEA provides fuel burn data for longer stage lengths than are available in the older version.

It is recommended that the fuel burn modelling in the DfT aviation CO_2 model is updated to use data based on the most recent (2016) EMEP/EEA aviation emissions calculator. As well as being based on a model that has been widely used in the International Civil Aviation Organisation's (ICAO) Committee on Aviation Environmental Protection (CAEP) process (including comparisons with other aircraft fuel burn models), it provides data for an extended range of aircraft types, which will reduce the need for modelling using proxy aircraft.

Following the review of fuel burn modelling, recommendations were provided to DfT, specifying which EMEP/EEA aircraft type should be used to model each aircraft type in the latest Fleet Mix Model. For some near-term future aircraft types, and for all post-2030 types, adjustment factors to be applied to the EMEP/EEA fuel burn values were also specified. The full list is provided in Annex 2.

The EMEP/EEA aviation emissions calculator does not include any data for helicopters; therefore, all helicopters were modelled using one of the lightest twin-engined turboprop aircraft (the DHC6 Twin Otter). It is believed that this provides the closest approximation to helicopter emissions using this data source and it is sufficient for analyses in which helicopters form a small portion of the overall movements. However, further consideration of the modelling of helicopters would be required for cases where they form a significant part of the movements.

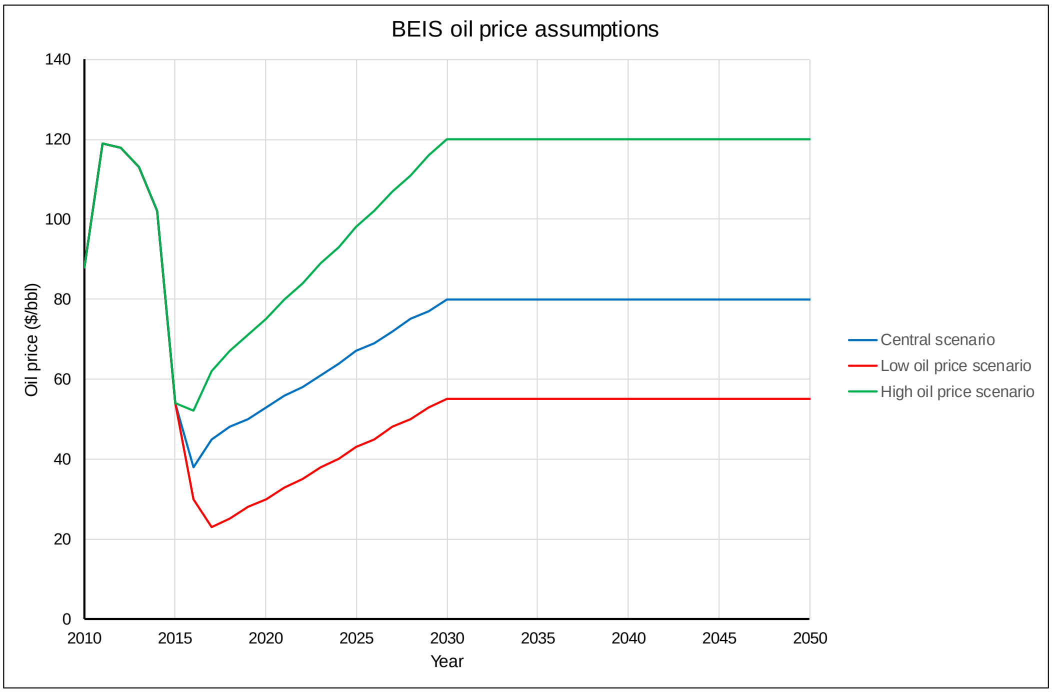
3.3 Baseline definition

The modelling performed for this study included three baseline scenarios. These were intended to provide a “most likely” scenario, together with high and low scenarios as sensitivity scenarios. The three baseline scenarios differed only in the assumptions for oil and carbon price projections. Together, these have been termed low and high “fuel price” scenarios for this study.

The oil price projections were obtained from the BEIS fossil fuel price projections[14]. For this study, it was assumed that all CO_2 emissions from aviation (except those from the consumption of biofuels) are subject to carbon pricing. The carbon prices used were the “traded” values from the BEIS projections for appraisals[15].

Figure 3-5 and Figure 3-6 present the BEIS oil and carbon price projections to 2050, for the central, low and high price scenarios. The oil price is projected to stabilise from 2030, while the carbon price is projected to continue to increase. Under the low oil price scenario, the price after 2030 is similar to that in 2015, while the central and high scenarios show significant increases, with the post-2030 level under the high scenario being similar to the peak in 2011. The oil price chart also shows that the recent drop in oil prices is expected to be short lived and that prices will rise in the future

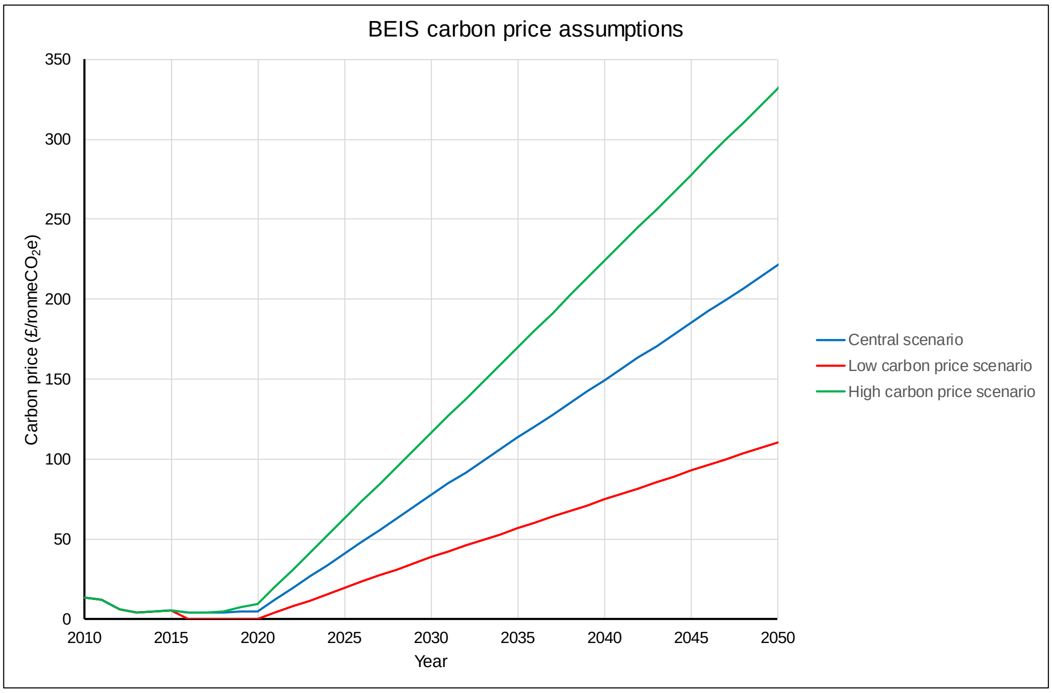
Figure 3-5 BEIS oil price assumptions used in baseline calculation



Carbon prices have recently been very low, so all three scenarios show significant increases in the future.

[14] https://www.gov.uk/government/publications/fossil-fuel-price-assumptions-2016
[15] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

Figure 3-6 BEIS carbon price assumptions used in baseline calculation



The results of the DfT baseline calculations using the above oil and carbon price assumptions are shown in Figure 3-7 to Figure 3-9. Figure 3-7 and Figure 3-8 show the growth in demand over time, in both the number of movements and revenue passenger kilometres (RPK). The low fuel price scenario gives the greatest growth in demand (about 52% increase over 2015 levels by 2050), while the high fuel price scenario gives the least growth in demand (31% increase by 2050). These variations are expected, as the higher fuel costs are passed on to passengers through increases in ticket prices, leading to reductions (or reduced growth) in demand.

Figure 3-7 Variations of air traffic movements over time from DfT baseline calculations

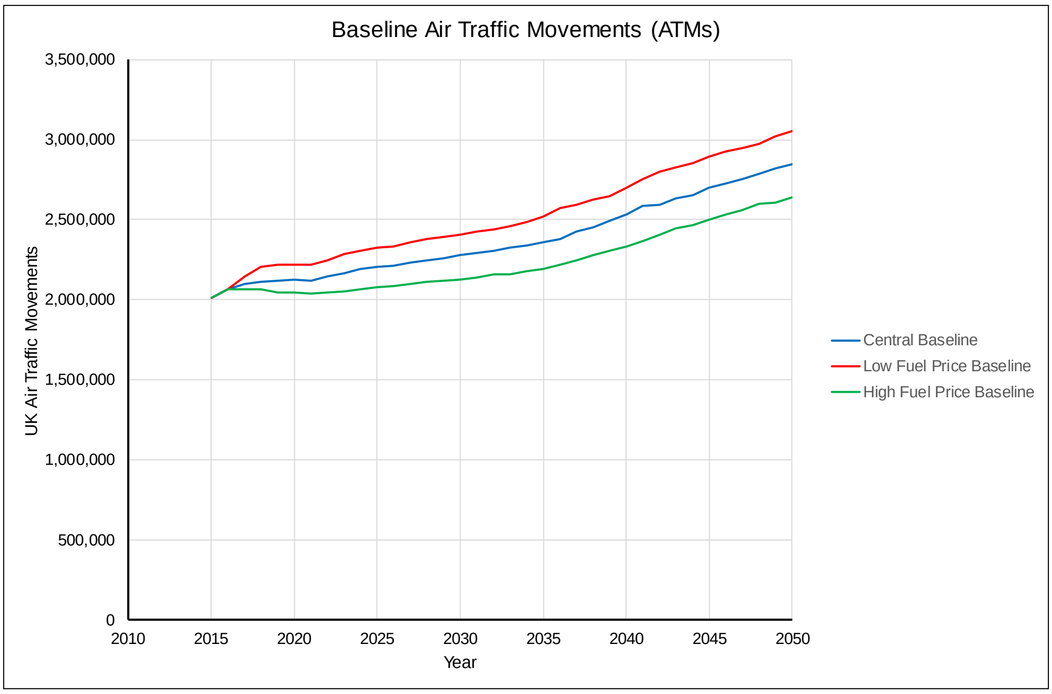
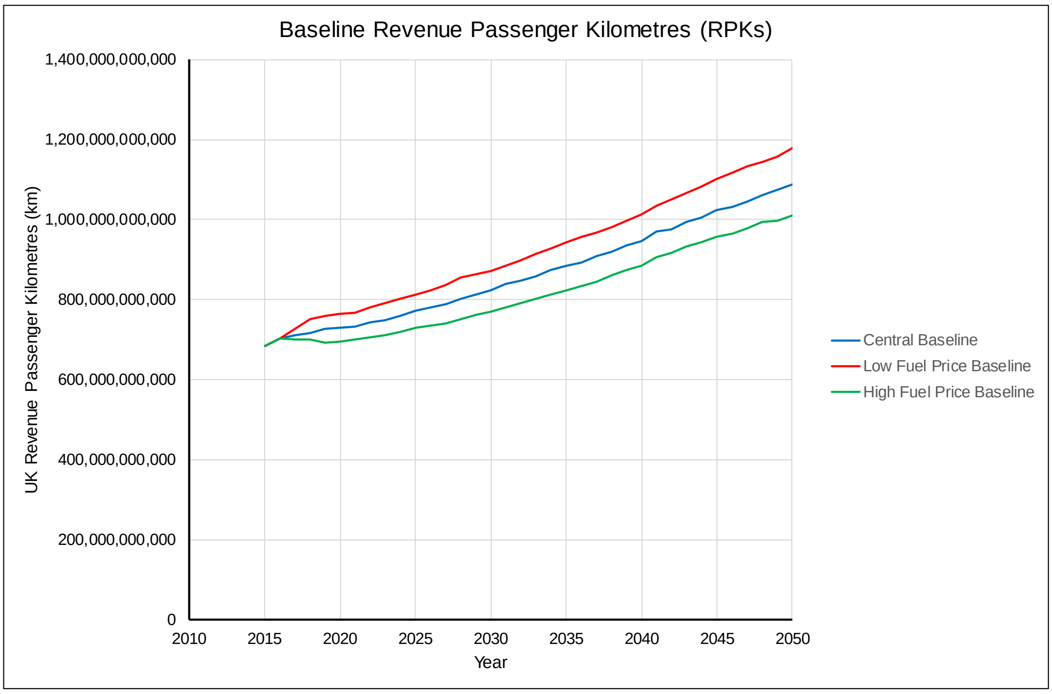
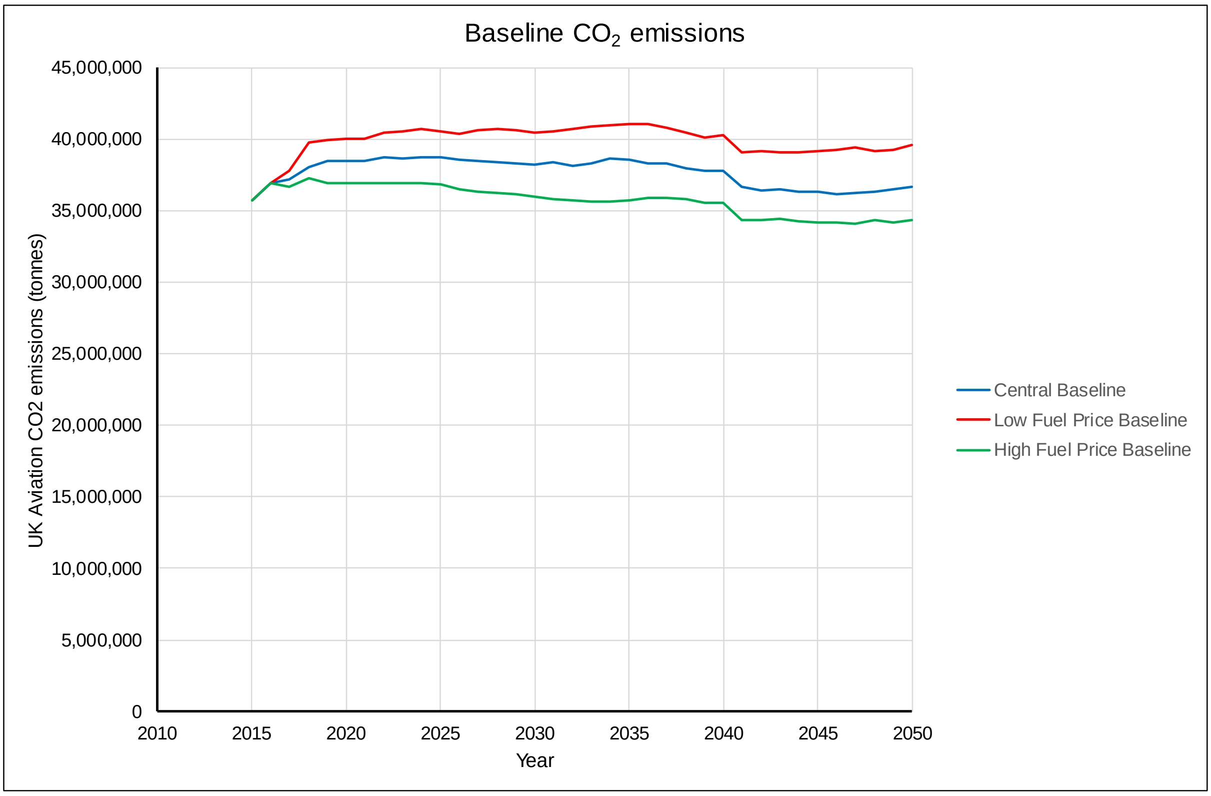


Figure 3-8 Variations of demand (as revenue passenger kilometres) over time from DfT baseline calculations



The improvements in fuel efficiency of aircraft over time, combined with the effects of biofuel penetration, can be seen in Figure 3-9, as the CO_2 emissions stagnate rather than continue to grow in line with demand. The aircraft technologies available, and the biofuel penetration, are assumed to be the same under all three baseline scenarios, so the low fuel price scenario results in the highest fuel consumption and emissions (in line with demand).

Figure 3-9 Variations of CO_2 emissions over time from DfT baseline calculations



An important factor in the baseline assumptions affecting the evolution of CO_2 emissions is the penetration of biofuels. After evaluating the existing DfT baseline and other sources, it was decided to retain the existing estimated future penetration rate which is based on biofuels comprising 5% of all aviation fuels by 2050. It is also assumed that the life cycle emissions associated with biofuels are 50% of the emissions due to using fossil fuels, so the penetration of biofuels reduces aviation CO_2 emissions by 2.5% by 2050.

The other key parameters for the calculation of future emissions are the aircraft types in service and their fuel efficiency. The majority of aircraft types included in the model are current in-production types or near-term future types. The fuel efficiency of these aircraft type is modelled using the EMEP/EEA aviation emissions calculator, as described in Section 3.2. The near-term future aircraft are modelled using the data for similar current types, with adjustments to the fuel burn values to reflect the known or assumed fuel efficiency improvements.

The model also includes some longer-term future aircraft types in each of the seat classes defined within it. These seat classes are used to segregate movements between the different sizes of aircraft. Six seat classes are included in the model, as shown in Table 3-1.

Table 3-1 Definition of seat classes in DfT aviation model

Seat Class	Number of seats
1	0 to 70
2	71 to 150
3	151 to 250
4	251 to 350
5	351 to 500
6	Over 500

The longer-term future aircraft types in the model are defined as being expected to enter service after 2030 and after 2040 (there is also a type in seat class 6 with an entry-into-service (EIS) date of 2026). These generic future types are given assumed EIS dates and fuel efficiency improvements over current types, as shown in Table 3-2.

Table 3-2 Longer-term future aircraft types included in baseline model

Seat Class	Aircraft Name	Assumed EIS date	Assumed fuel efficiency
2020s aircraft			
Seat Class 6	G16	2026	A380 – 17.5%
Post-2030 aircraft			
Seat Class 1	G21	2030	ATR42 - 24.5%
Seat Class 2	G22	2034	B734 - 24.5%
Seat Class 3	G23	2035	B734 - 24.5%
Seat Class 4	G24	2031	B772 - 27.5%
Seat Class 5	G25	2031	(average of A343 and B772) - 27.5%
Seat Class 6	G26	2036	A380 - 27.5%

Seat Class	Aircraft Name	Assumed EIS date	Assumed fuel efficiency
Post-2040 aircraft			
Seat Class 1	G31	2040	ATR42 - 31.5%
Seat Class 2	G32	2045	B734 - 31.5%
Seat Class 3	G33	2045	B734 - 31.5%
Seat Class 4	G34	2041	B772 - 29.5%
Seat Class 5	G35	2041	(average of A343 and B772) - 29.5%
Seat Class 6	G36	2046	A380 - 29.5%

The EIS dates given in Table 3-2 are those assumed when the aircraft is operated on scheduled services. If the same aircraft types are also used on chartered services, they are given assumed EIS dates one or two years after those for scheduled services. For "no-frills carriers" (NFC) services, the aircraft usually have the same EIS dates as for scheduled services.

The CO_2 emissions results presented in Figure 3-9 show a noticeable drop between 2040 and 2041. This drop coincides with the introduction of the new, more fuel-efficient, aircraft types in seat classes 4 and 5, which are key seat classes for long-haul flights.

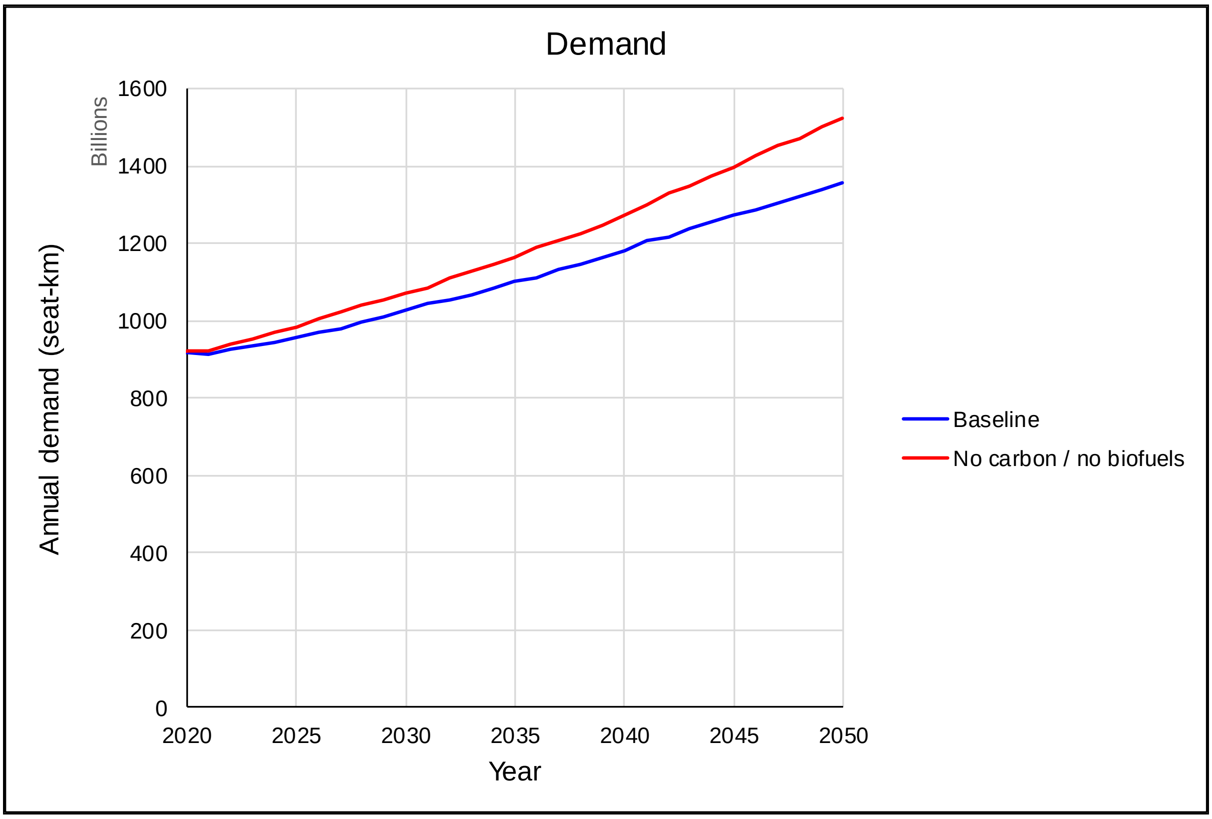
The modelling of the in-service fleet also includes assumed retirement ages. All aircraft operating scheduled or NFC services are assumed to retire at 22 years of age, while aircraft operating chartered services are assumed to retire at 25 years of age. It should be noted that, in this context, an aircraft is not necessarily scrapped when it is retired. It is removed from operations from UK airports, but may be sold (or leased) to airlines flying in other parts of the world.

3.4 No policy-action baseline

The baseline scenarios for the DfT aviation CO_2 model, described above, include assumptions regarding the impact of variations in carbon prices and the penetration of biofuels, which already include some elements of policy action to reduce CO_2 emissions. To illustrate the effects of these "baseline" policy actions on emissions, and to put the impacts of the policy measures described in this report in context, a further calculation has been performed with no carbon price or assumed uptake of biofuels. The baseline assumptions about fleet fuel efficiency improvements remain.

Figure 3-10 shows a comparison of the variation of demand (in terms of seat-km) over time between the two baselines.

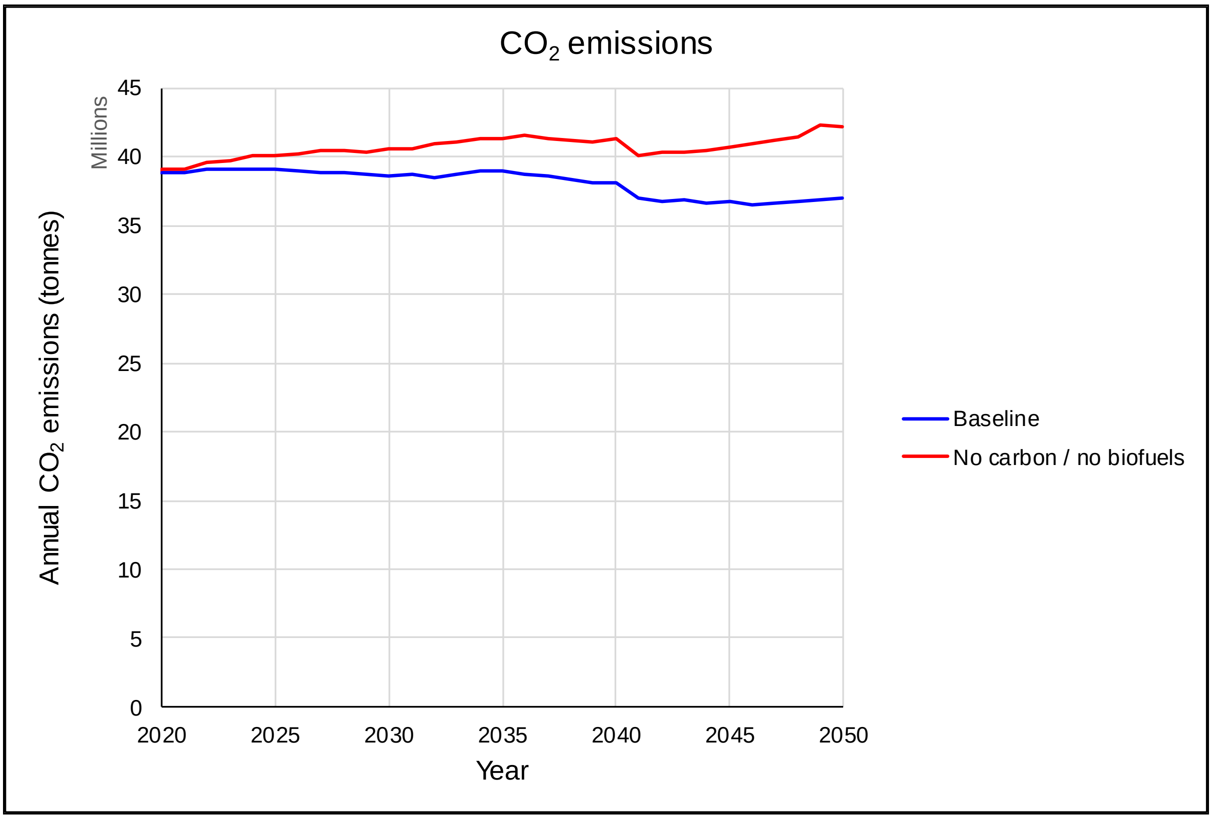
Figure 3-10 Comparison of demand between baselines with and without carbon costs and biofuel penetration



By 2050, the inclusion of carbon costs and biofuels (in the "Baseline" calculation) reduces the demand by 10.9% compared to the case without those actions. This is caused by the assumption that carbon costs will be passed on to passengers through increased ticket prices, leading to a reduction in demand.

Figure 3-11 shows the comparison of the CO_2 emissions between the two calculations.

Figure 3-11 Comparison of CO_2 emissions between baselines with and without carbon costs and biofuel penetration



The results for the Baseline calculation in Figure 3-11 are the same as those shown as the "Central baseline" in Figure 3-9. Whereas the baseline calculation (including the impacts of carbon costs and biofuels) shows a gradual reduction in emissions over time, with the more distinct step in 2040 as discussed above, the results without these policy actions shows a gradual increase. By 2050, the inclusion of carbon costs and biofuel penetration reduces emissions by 12.2% (compared to the case without them). Biofuels are assumed to comprise 5% of fuel in this calculation, with a 50% effectiveness, so the inclusion of biofuel penetration is responsible for 2.5 percentage points of the difference between the two calculations. This indicates that, without biofuels, the inclusion of carbon costs alone would reduce emissions by 9.7%, for the 10.9% reduction in demand. The reduction in fuel efficiency that this implies is related to the modelling of the effects of demand and how it is met in the model, with the lower demand resulting in a combination of lower passenger load factors and a greater proportion of the demand being met by smaller aircraft.

4 Policy measures

This section describes the policy measures that were considered in this study. In addition to a description of each measure and possible levers that could be used to implement it, the following also includes the specification for its implementation in the DfT aviation CO_2 model and the approach for estimating costs.

To capture some of the uncertainty in the overall results, the calculations of CO_2 emissions were performed against three different baselines, which differed in the assumptions for oil and carbon prices (producing the "Low fuel price", "Central fuel price" and "High fuel price" baseline scenarios). The results of the baseline calculations give variations in demand as a result of the changes in fuel price. For this study, it was decided, in consultation with DfT, that the specification of the policy measures should not vary with fuel price (for example, the high fuel price scenario would not lead to any differences in the fuel efficiency of future aircraft types, so the improvements in technology through increased R&D would also not vary with fuel price). The impacts of these policy measure specifications on CO_2 emissions would vary with fuel price (because of the different demand levels), as would the costs (due to the differences in fuel price and demand, and the consequent differences in demand for new aircraft).

The following sections present the differences in the specification of each policy measure under the three levels of policy ambition (“Low”, “Mid” and “High”). The results of the analyses of these policy measures are presented later in this report as full matrices of fuel price and policy ambition.

The analyses of the policy measures were focused on their impacts on “UK aviation emissions”. These emissions are defined as those from aircraft on flights departing from a UK airport, whether to other UK airports (i.e. domestic flights) or overseas destinations. Therefore, the emissions savings reported here are restricted to those flights. The calculated changes in fuel and carbon costs are also restricted to those flights. The implementation costs have been calculated as those needed to implement the policy measure; in some cases (e.g. those leading to improvements in aircraft technology), the results of the policy measure would also benefit other flights, including flights from overseas to the UK and flights between two other countries, that are not accounted for in this study.

The descriptions of the costs in the following sections focus on the implementation costs. These are the costs that result directly from the implementation of the policy measure, such as the increased research and development costs or the increased acquisition costs for purchasing new aircraft. For some of the policy measures, there is no certainty regarding the exact mechanism by which the measure would be implemented, nor about how the costs would be apportioned between stakeholders (e.g. Government and industry contributions to increased research and development costs). Therefore, the descriptions identify the full costs of implementation and do not attempt to apportion them further.

In addition to the costs described below, there would also be some administrative costs, related to managing the implementation of the measure or negotiations with national or international bodies (e.g. for the measure on an improved ICAO CO_2 standard. Although such efforts would be important to the success of the measure, the costs are not addressed here as they would be very much smaller than the main implementation costs. There are also further costs that have not been captured in this analysis, such as those related to additional impacts on the aviation market (beyond those associated with fuel, carbon and aircraft technology) and Government enforcement costs.

Conversely, there are some potential benefits of the measures that are not captured in the current study. The policy measures that relate to the wider use of aircraft technology are likely to deliver improvements in noise and emissions of nitrogen oxides (NOx), as well as CO_2. For the policy measures related to the development of improved technology (the increased R&D in more efficient engines and aircraft and the improved ICAO CO_2 standard policy measures), the issue is less clear, as the greater focus on fuel efficiency and CO_2 emissions could lead to a reduced focus on these other emissions (and hence less progress in the relevant technology), although international standards would ensure that they did not become significantly worse. Conversely, there could be significant benefit at a global level, as the improved aircraft technologies developed as a result of UK action would be available for use globally, giving greater reductions in CO_2 emissions than are achieved in the UK.,. These additional costs and benefits are also not included in the current analysis.

For each policy measure, there would also be implications for the costs of fuel (i.e. A-1 jet fuel (kerosene) or biofuels) and carbon costs. The DfT baseline assumes that carbon pricing is applied to all emissions (e.g. through emissions trading system allowances or offsets); therefore, the reduction in emissions through abatement also leads to a reduction in carbon costs. The changes in fuel costs and carbon costs are related directly to the CO_2 emissions produced (and the assumed penetration of biofuels); therefore they are not described in more detail in this section but they are included in the cost results presented in Section 6).

This section presents the seven policy measures that have been included in the current analysis. Further policy measures were also considered during the study, but it was decided not to include them further, for different reasons. These additional policy measures are described in Annex 3.

4.1 Increased R&D in more efficient engines and aircraft

This measure relates to improving the delivery of fuel efficiency technology from research programmes. The aim would be to increase the level of funding for research and technology development (R&D) available to manufacturers and to the wider research community to deliver further efficiency improvements above those that are included in the assumptions for future aircraft types in the baseline.

Feasibility and capacity to be applied unilaterally by the UK

Historically, aircraft technology has progressed through a range of research programmes, funded either by the aerospace industry (i.e. aircraft and engine manufacturers) or by the state (in the case of Europe, this has now been largely replaced by EU funding). Many of the latter research programmes also require the state-provided funding to be matched by industry. The main regions of funding for civil aerospace research have been Europe and North America (principally the USA, but also Canada and, more recently, Brazil).

The research programmes in Europe and North America have contributed to the improvements in aircraft fuel efficiency and reductions in emissions. It would be expected that the level of funding available presents a limitation on the level of progress that has been achieved and that, therefore, it is feasible that additional funding may accelerate the technology development. Within Europe, the UK has frequently contributed funding (through programmes such as the Civil Aerospace Research and Development (CARAD) programme and Innovate UK) and capabilities (in both industry and academia) to major technology development research projects. Unilateral action by the UK to accelerate technology development would require a considerable investment in funding of research programmes; however, the UK is well positioned to perform the additional research and to exploit the results through companies such as Rolls-Royce, Airbus UK and Bombardier UK. It would be expected that any significant advances in technology developed through such programmes would result in increased funding in other regions, particularly North America, in order to ensure that their industry remained commercially competitive.

Policy levers that could be used to incentivise/regulate the application of the measure

For a purely UK-centric measure, the primary lever would be an increase in funding for UK research programmes (e.g. through Innovate UK and the Aerospace Technology Institute (ATI)). However, greater effectiveness may be feasible if the UK is part of an international collaborative research programme, as this could benefit companies that operate in more than one country.

Who is responsible for implementing the measure/lever?

The principal UK bodies that would be responsible for implementing the policy measure would be the Department for Business, Energy and Industrial Strategy (BEIS) and the organisations that manage the funding of research, such as Innovate UK and the ATI.

What would different policy level abatement scenarios look like?

The effect of implementing this policy measure would be to increase the rate of development for aircraft technologies aimed at reducing fuel consumption and emissions. Enhanced technology might be exploited through improvements to aircraft types that are already in production; however, more significant improvements are likely to be seen in new aircraft types with initial entry-into-service dates after the mid-2020s. The different levels of policy ambition would then give different levels of improvement for the future aircraft types, relative to the types included in the baseline scenario.

Main costs/benefit impact areas

The primary costs under this policy measure would be those associated with the funding of additional aerospace research programmes. The benefits would then be seen through the subsequent development and introduction into service of aircraft types that are more efficient than they would have been without the additional research.

As a UK-centric policy measure, it is assumed that all the costs of the additional research, needed to deliver the improved aircraft technology, would be borne by the UK (Government and industry). However, the more fuel-efficient aircraft that would be produced using these technologies (plus those developed in other world regions as a competitive response) would be sold globally, leading to significantly greater reductions in emissions than would be achieved in the UK alone. As this study relates to the impacts of the policy measures on UK aviation emissions, these additional emissions savings are not captured in this analysis.

Efforts to improve aircraft technology through R&D are not focused solely on CO_2 emissions. They also address other environmental impacts (noise, emissions of NOx and particulate matter), safety, passenger comfort and other aspects of aircraft performance (e.g. range) and operating costs (e.g. maintenance costs). An increased focus on fuel efficiency technology could reduce the focus on these other aspects leading, potentially, to less progress being made in these areas than would otherwise be the case. However, given the international emphasis and regulation of all aspects of environmental impacts and safety, it is felt that it would be highly unlikely that future aircraft would have lower performance in these areas than current types. Equally, commercial pressures from airlines will ensure that aircraft manufacturers retain a focus on all aircraft operating costs when bringing new types to market. These additional impacts have also not been addressed in the analyses reported here.

Barriers to take up and the costs of overcoming them

Apart from the additional funding required for aerospace research, there might be a need to ensure that there is sufficient capacity to perform the required research in the UK, particularly in academia. This could be achieved by re-orienting some capabilities in other areas of engineering to focus on aerospace. Alternatively, if the UK remains part of European research programmes, or joins other international programmes, it could be possible to use additional funding to ensure that aerospace research receives a higher priority.

The timeframe over which the measure would be expected to have an effect

It is unlikely that increased levels of funding for research would impact the technology of new aircraft types entering service prior to the mid-2020s. There would be further improvements in new aircraft types that enter service after this date, through to the new types that enter service in the 2040s (as assumed for the DfT aviation CO_2 model). The improved technology would then gradually lead to reductions in emissions from UK aviation as the new aircraft types penetrate the fleet through normal retirement and replacement processes.

The policy to increase the funding available for R&D on more fuel-efficient aircraft and engines could continue beyond 2040. However, this review focuses on the impacts of the R&D to deliver technology up to 2040, as that is the last date for which there are exploitation routes available in the DfT aviation model used for the CO_2 analyses in this study (i.e. the new, more fuel-efficient, aircraft types introduced in 2040 or soon after).

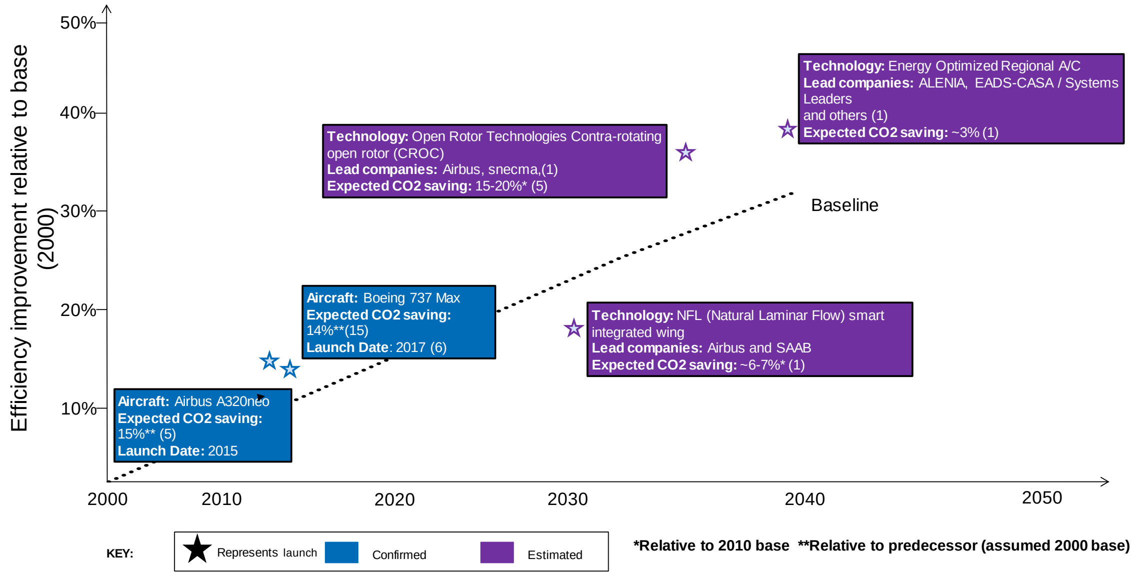
Potential for carbon leakage

The benefits of the advanced technology aircraft would be seen globally through reduced fuel consumption and emissions. There is little likelihood of carbon leakage, unless the improved aircraft are significantly more expensive to manufacture, increasing their price to airlines and potentially causing some to delay the replacement of older, in-service aircraft. Given the balance between operating costs of in-service aircraft and the acquisition costs of new aircraft (with lower operating costs through reduced fuel costs), this is more likely to happen in regions with lower demand or where fares are lower because of lower wealth among the passengers.

4.1.1 Implementation in the DfT aviation model

As described in Section 3.1, the existing baseline in the DfT aviation CO_2 modelling system includes generic future aircraft types in each seat class, with EIS dates of 2026, 2030 and 2040 (or soon after, as the actual EIS date varies with seat class and operator type). The existing assumptions have been reviewed and compared to published information on near-term new aircraft types and expected outcomes of current research and development programmes, as shown in Figure 4-1 and Figure 4-2.

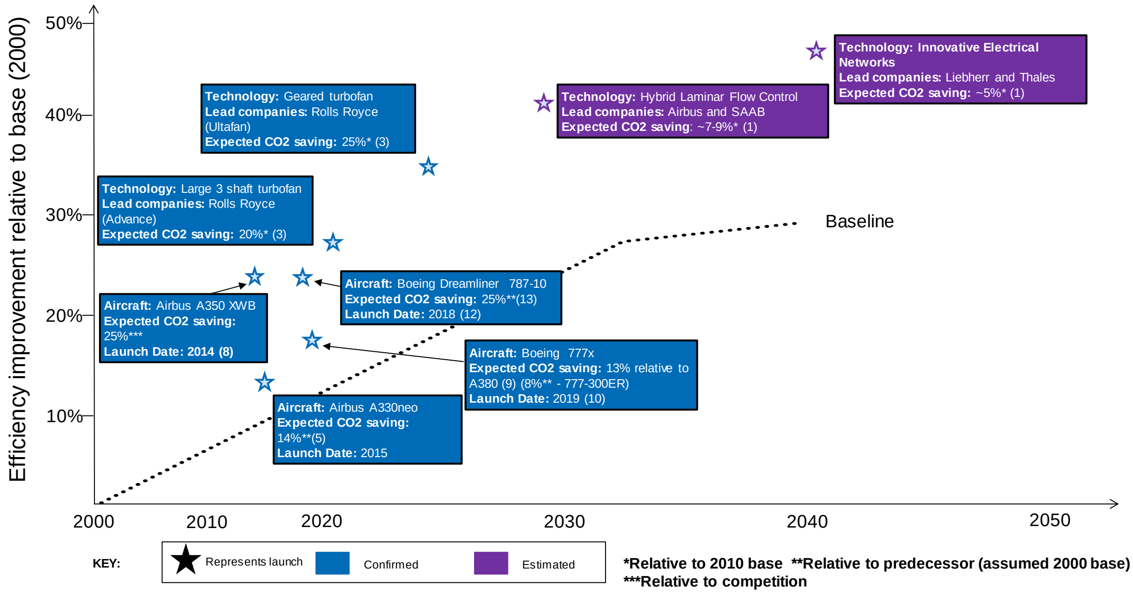
Figure 4-1 Baseline technology improvements and published information on aircraft research and development projects – single-aisle aircraft



Data sources:

(1) *Clean Sky 2 programme (2015), http://ec.europa.eu/research/participants/data/ref/h2020/other/guide-appl/jti/h2020-guide-techprog-cleansky-ju_en.pdf, accessed 19/04/2017*
(2) *Airbus (N.b), http://www.airbusgroup.com/int/en/news-media/corporate-magazine/Forum-89/Clean-Sky.html, accessed 19/04/2017*
(3) *Rolls Royce (N.b), https://www.rolls-royce.com/products-and-services/civil-aerospace/future-products.aspx, accessed 20/04/2017*
(4) *IDTechEx (2016), https://www.slideshare.net/IDTechEx/idtechex-research-manned-electric-aircraft, accessed 20/04/2017*
(5) *Airbus (2013), Sustainable Aviation -> Aviation Environmental Roadmap, accessed 20/04/2017*
(6) *Aviation voice (2016), https://aviationvoice.com/airbus-a320-neo-vs-boeing-737-max-201602121522/*

Figure 4-2 Baseline technology improvements and published information on aircraft research and development projects – twin-aisle aircraft



Data sources:

(1) Clean Sky 2 programme (2015), http://ec.europa.eu/research/participants/data/ref/h2020/other/guide-appl/jti/h2020-guide-techprog-cleansky-ju_en.pdf, accessed 19/04/2017
(2) Airbus (N.b), http://www.airbusgroup.com/int/en/news-media/corporate-magazine/Forum-89/Clean-Sky.html, accessed 19/04/2017
(3) Rolls Royce (N.b), https://www.rolls-royce.com/products-and-services/civil-aerospace/future-products.aspx, accessed 20/04/2017
(4) IDTechEx (2016), https://www.slideshare.net/IDTechEx/idtechex-research-manned-electric-aircraft, accessed 20/04/2017
(5) Airbus (2013), Sustainable Aviation -> Aviation Environmental Roadmap, accessed 20/04/2017
(6) Flightglobal (2016), https://www.flightglobal.com/news/articles/boeing-advances-777x-service-entry-sources-423032/, accessed 20/04/2017
(7) Boeing (N.b), http://www.boeing.com/commercial/787/, accessed 19/04/2017
(8) Airbus (N.b), //http://www.a350xwb.com/delivery/, accessed 19/04/2017
(9) https://leehamnews.com/2014/02/03/updating-the-a380-the-prospect-of-a-neo-version-and-whats-involved/
(10) https://www.flightglobal.com/news/articles/boeing-advances-777x-service-entry-sources-423032/

When considering Figure 4-1 and Figure 4-2, it should be noted that the references on which the expectations for future technologies are based generally do not present the improvements relative to the year-2000 aircraft, as shown here. Instead, they usually refer to improvements relative to “existing aircraft types” or “the competition”. Therefore, best efforts have been made to align the claimed improvements in a consistent manner; however, there is uncertainty as to whether the values shown reflect the actual (unpublished) expectations of the companies concerned.

From the review of these figures, it was determined that there is scope for research and development programmes to contribute to improvements in efficiency beyond those in the baseline. However, there is considerable uncertainty over the efficiency levels that would be achieved in the new aircraft types and there are risks that the known research programmes may not fully deliver their expected benefits in the proposed timeframes. Therefore, no recommendations were made to change the fuel efficiency values for the aircraft types in the baseline analysis. Nonetheless, the results shown in Figure 4-1 and Figure 4-2 suggest that further improvements of between 5% and 10% may be feasible under a scenario where research programmes are able to fully deliver against expectations.

The mechanism for implementing this measure in the DfT aviation CO_2 model was through improvements to the fuel efficiency of the future aircraft types included in the model. For example, the existing baseline included:

- aircraft types with an EIS date of (approximately) 2030 with fuel efficiency improvements of 24.5% compared to year 2000 aircraft types; and
- aircraft types with EIS dates of 2040 with efficiency improvements of 31.5%.

Based on the expert judgement of the study team, it was considered that increasing the improvements for the 2040 aircraft by a further 5% could be realistic for a medium policy ambition, with 2.5% and 7.5% increases for the low and high ambitions. Lower improvement values were used for the post-2020 and post-2030 aircraft types as there is significantly less time for the extra R&D funding to lead to actual product developments in that timeframe. These lower values of improvement were derived using a constant improvement rate from 2020 to reach the relevant improvement assumed for the 2040 aircraft types.

Table 4-1: Fuel efficiency improvements over the 2040 baseline aircraft types under the three levels of policy ambition

Policy Ambition Scenario	Increase in aircraft efficiency relative to baseline (2040 aircraft types)
Low	+2.5%
Central	+5%
High	+7.5%

4.1.2 Costs

This policy measure involves R&D expenditure above baseline levels, in particular increased funding for aerospace R&D under Innovate UK or similar programmes. The approach for estimating the costs related to the measure was based on an analysis of the current levels of R&D funding, assumed to be consistent with delivering the technology required to achieve the fuel efficiency improvements implemented in the baseline. The analysis considered current research funding under national programmes in the UK, France and Germany (the main countries with aircraft end engine manufacturing industries and research programmes supporting those industries), and the EU funding under the Horizon 2020 programme (principally through the Clean Sky 2 programme). This provides the annual funding levels shown in Table 4-2.

Table 4-2 Annual funding of aerospace R&D programmes in Europe

Funding source	Annual funding
UK	£ 1.7 billion[16]
France	£ 3.0 billion[17]
Germany	£ 3.5 billion[18]
EU	£ 0.3 billion[19]
Total	**£ 8.5 billion**

Although the aim of the study is to consider UK-based policy measures, the aerospace industry is international in nature and the fuel efficiency improvements assumed in the baseline result from efforts throughout the European aerospace industry. Therefore, the additional funding required to achieve further efficiency improvements (beyond those in the baseline) could be across Europe or confined to the UK (provided that the UK research community is able to deliver the additional improvements when sufficient funding is made available). The exploitation of the technology improvements would then be through UK industry (such as Rolls-Royce, Airbus UK and Bombardier UK) or European industry.

The total funding required to deliver the fuel efficiency improvements in the baseline case were established by assuming a constant £8.5 billion annual funding of R&D programmes. Figure 4-3 shows the cumulative efficiency gain against cumulative R&D funding.

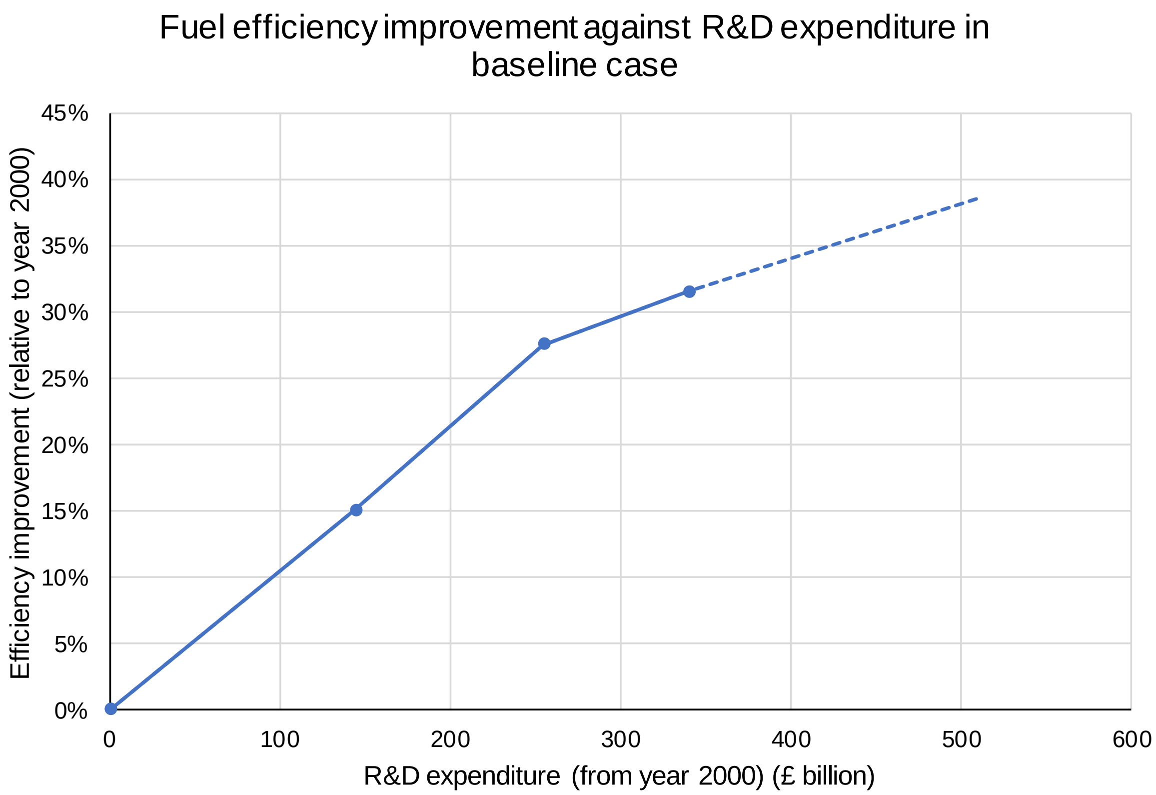
[16] https://www.ons.gov.uk/economy/governmentpublicsectorandtaxes/researchanddevelopmentexpenditure/bulletins/ukgrossdomesticexpenditureonresearchanddevelopment/2015

[17] http://en.businessfrance.fr/Media/Default/BlogPost/10_PTS_CLES_INDUSTRIES_DE_POINTE_AERONAUTIQUE__EN_PROCOM_DAPE_2017-04-11.pdf

[18] https://www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Mobility/aerospace.html?view=renderPdf

[19] http://www.ati.org.uk/international/european-funding/

Figure 4-3 Cumulative fuel efficiency improvement with cumulative R&D expenditure to 2060



The dotted line in Figure 4-3 shows the extrapolation beyond the efficiency improvement assumed to be achieved in 2040 (that which delivers the efficiency of the G3x aircraft types in the baseline) to show the additional (total) funding required to deliver the additional efficiency improvements specified for the policy measure. The additional R&D funding (compared to the baseline) has been divided by the number of years between 2020 and 2040 to derive the additional annual expenditure required for the three policy cases, as shown in Table 4-3.

Table 4-3 Additional annual expenditure required on R&D programmes to deliver relevant aircraft fuel efficiency improvements

Policy ambition	Additional annual R&D expenditure
Low	£ 3.04 billion
Mid	£ 6.07 billion
High	£ 9.11 billion

4.1.3 Uncertainties

The assumptions and analyses of the impacts of this policy measure, like the others described in this report, carry some considerable uncertainties, related both to the likely impact of the policy and the costs of implementation.

The reductions in fuel and carbon costs presented for each policy measure have been calculated using the changes in CO_2 emissions and the BEIS projections of oil and carbon prices. Therefore, there are no additional uncertainties in those calculations, beyond those associated with the impact of the measure on emissions. We have attempted to capture the uncertainty relating to the BEIS projections through estimating the impacts under the range of oil and carbon price projections.

The analysis of this policy measure assumes that the UK is able to contribute to further advances in aircraft fuel-efficiency technology through the availability of further funding for R&D. The UK has a very good industrial and research base for performing this research. However, as the UK does not produce complete commercial aircraft, there is some uncertainty about the ability to ensure that the technology developed will be incorporated in the future aircraft types (although, as there is always a strong demand for more fuel-efficient aircraft, demonstrated improvements in technology are quite likely to be pulled through into new products).

For the purposes of this study, it has been assumed that the additional emphasis on R&D into aircraft fuel-efficiency could yield a further improvement of 2.5% to 7.5% reduction in fuel consumption in aircraft types in 2040 (depending on the policy ambition). The recent (and ongoing) introduction of new engine types on the Airbus A320 and Boeing 737 series aircraft has yielded about a 15% reduction in fuel consumption, so the high policy ambition represents approximately half of this level of improvement (above the baseline levels of improvement by 2040). Although this is not necessarily unrealistic, there are always risks of under-delivery or late-delivery of technology from research programmes, so there is an inherent uncertainty regarding the levels of improvement that would actually be achieved.

The costs of this measure have been calculated from the expected improvements in fuel efficiency in the baseline and the estimated current actual expenditure on R&D in Europe. Although this estimate is based on a review of published information on major aviation R&D projects, it is possible that not all existing R&D expenditure has been captured. Also, the analysis has assumed that all R&D contributes to improvements in fuel efficiency. Whilst considerable research is focused on other environmental and performance aspects (such as noise, NOx emissions and aircraft range), the results may be important for enabling improvements in fuel efficiency. For example, NOx emissions tend to increase with increasing engine pressure ratio, which is a key technology for enabling improved fuel efficiency. Therefore, improved NOx-control technology is important for enabling improved fuel efficiency while maintaining or reducing NOx emissions. It is, therefore, very difficult to identify the portion of aviation R&D expenditure that does not contribute to improved fuel efficiency.

4.2 Early fleet replacement with more fuel-efficient aircraft

This policy measure consists of incentives to airlines to renew their aircraft fleet more frequently, thus accelerating the penetration of the latest aircraft types into the operating fleet.

Feasibility and capacity to be applied unilaterally by the UK

Airlines take account of a number of factors when deciding to renew their aircraft, including

- the age of their existing aircraft;
- the availability of improved aircraft types (particularly those with lower operating costs through reduced fuel burn);
- the availability of finance;
- changing requirements through the evolution of their route network.

Influencing fleet replacement decisions to encourage an earlier replacement may be feasible through either operating restrictions (such as “Green” slots or emissions-based landing charges at airports) or incentives (such as UK Government departments working with the airlines to negotiate loans from financial institutions such as the Green Investment Group Ltd, provided they are used to acquire aircraft to be used on UK routes and that replace less fuel-efficient aircraft of a certain age or more).

The aircraft protocol of the Cape Town Convention[20] (formally the “Protocol to the Convention on International Interests in Mobile Equipment on matters specific to aircraft equipment”) was ratified by the UK in 2015. The convention is intended to protect the interests of creditors (e.g. financiers or lessors) in aircraft in the event of an airline’s insolvency[21]. The protocol should simplify the process of making loans available to airlines to acquire new aircraft and reduce the costs of those loans, hence, making it easier to provide incentives to airlines to replace their fleets earlier.

Policy levers that could be used to incentivise/regulate the application of the measure

Possible levers for this measure would include linking access to UK airports to the CO_2 performance of the aircraft type. This would need to be widespread in implementation (i.e. across all major UK airports) or the airlines would simply switch their most fuel efficient aircraft to certain airports and redeploy their less good aircraft to others. This policy lever would apply to the low policy ambition case. For the mid and high policy ambition cases, a greater level of incentive would be required. The

[20] http://www.unidroit.org/instruments/security-interests/cape-town-convention
[21] https://www.dentons.com/en/insights/alerts/2015/november/25/aircraft-finance-briefing

mid policy ambition could include increased support for negotiating access to finance, while the high policy ambition case could involve the UK Government providing loan guarantees to assist airlines in negotiating more favourable terms, provided that the aircraft being replaced are younger than under the mid policy ambition case.

Who is responsible for implementing the measure/lever?

Ultimately, the acquisition of new aircraft is the responsibility of the airlines (or the leasing companies, with the airlines then having responsibility to negotiate the lease of the latest types). The responsibility for implementing the green slots lever would apply jointly to the relevant UK Government Departments (for developing the policy) and the airports (for implementing and monitoring the requirements). Under the mid and high policy ambition cases, Government departments would have the responsibility to provide support to airlines when negotiating finance for the acquisition of new aircraft to achieve the aims of the measure.

What different policy level abatement scenarios would look like?

The application of the incentives for fleet renewal under the three different policy ambitions would lead to an earlier retirement of aircraft from UK operations (than under the baseline scenario). It is important to note that the term “retirement” in this case does not necessarily imply the ultimate retirement of the aircraft from service. When removing the aircraft from operations to, from and within the UK, the airline may choose to deploy it on other routes (assuming that the restrictions imposed by the UK are not copied by other countries) or they may sell it to airlines operating routes in other regions (for example, Africa or South America).

Some initial, simplified, calculations of the impact of different retirement ages on CO_2 emissions were performed to assist the determination of potential options for the effect of the policy measure. These calculations used average CO_2 emissions per flight for the different aircraft types, obtained from the baseline analysis, together with the variations in the percentage of flights performed by each aircraft type from the FMM, including the changes in those percentages as the retirement age was varied. The results of these calculations indicated a high sensitivity of emissions to the changes in retirement age and, following discussions with DfT, it was decided to apply reductions in retirement age of one, two and three years (relative to the baseline values) to represent the effect of the low, mid and high policy ambitions for this measure.

The DfT aviation CO_2 modelling system, which was used to assess the impacts of the policy measures on emissions, uses a set of fixed aircraft retirement ages, derived from airframe data from the UK Civil Aviation Authority (CAA), as reported in the DfT 2011 UK Aviation Forecasts[22]. For the majority of aircraft types, these are set to either 22 years (for scheduled and no-frills carrier (or “low-cost carrier”) operations) or 25 years (for charter operations). These retirement ages are approximations to average retirement ages derived from previous assessments; therefore, the adjustments of one, two and three years under this measure are also indicative of an average effect. Before implementing this measure in practice, it would be necessary to conduct a more comprehensive review of airline fleet renewal plans and the likely effects of incentives to accelerate those plans.

Main costs/benefit impact areas

The principal costs arising from this measure are the additional costs of acquiring new aircraft, as the reduced retirement age leads to a greater number of aircraft being retired overall. The benefits would be felt through the reduced fuel burn, emissions and maintenance costs due to a younger, more efficient (and more reliable), fleet.

The costs calculated in this analysis cover the full additional costs resulting from the early replacement of the aircraft fleet that serves the UK, However, the emissions benefits that are captured relate only to the flights departing the UK; they do not include the reductions in emissions that would occur on the flights to the UK, nor the reduction that could occur if the replacement aircraft are also used on non-UK flights. Therefore, the global benefits in reduced CO_2 emissions could be significantly greater than those that are presented in the results of this policy measure.

Barriers to take up and the cost of overcoming them

A potential barrier to implementing this measure could be a reluctance of some airports to implement restrictions or CO_2 emissions-based landing charges, due to concerns about airlines deciding to move

[22] https://www.gov.uk/government/publications/uk-aviation-forecasts-2011

to other airports, including non-UK airports in the case of non-UK airlines. The greatest impact of the measure would occur when implemented at the busier airports with more long-haul flights, so efforts to encourage airports to participate in the scheme should be focused on those airports.

There are already international measures in place or under development that encourage airlines to operate fuel-efficient aircraft, such as the EU ETS and the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Therefore, implementing a further scheme, specific to the UK, that encourages the use of more fuel-efficient aircraft (or penalises the use of older, less fuel-efficient types) could raise concerns over duplicative measures.

For the mid and high ambition cases, there could also be challenges in ensuring that the financial institutions make sufficient funds available for the loans to airlines. Some negotiations between the Government and the financial institutions may be necessary to ensure that they are willing to support the scheme.

The timeframe over which the measure would be expected to have an effect

This policy measure improves the fuel efficiency of the fleet from the time that it is implemented, as it increases the rate at which the latest, and most fuel efficient, aircraft types enter the fleet. Like the other policy measures that affect the aircraft being acquired by airlines, the initial impact on the average fuel efficiency will be small, as the new aircraft still enter the fleet gradually, but the impact becomes greater over time. The continued impact of the measure in the long term would depend on further new aircraft types becoming available so that those being acquired remain more fuel efficient than those being retired. The policy measure would still contribute to emissions reductions after the policy has finished, and the retirement age has reverted to the baseline value, as the fleet would remain more fuel efficient than in the baseline case.

Potential for carbon leakage

An important aspect of this policy lever is that retirement from the UK fleet does not necessarily mean that aircraft are totally removed from service. In many cases, aircraft that are retired from service in Europe are sold to airlines operating in other regions. This could be seen as shifting the CO_2 burden (due to operating the older aircraft types) onto another region or, alternatively, as improving the other region's CO_2 performance due to the replacement of even older aircraft (e.g. a 20-year-old A320 might replace a 50-year-old Boeing 737). This potential improvement in global emissions has not been quantified in the modelling of this policy lever (which considers emissions from 'UK aviation' only) but is an important caveat to this analysis.

It is also possible that some airlines, rather than disposing of their older aircraft types, might choose to redeploy their existing fleet so as to use their newer aircraft on UK routes and their older (less fuel-efficient) aircraft on non-UK routes. This would allow them to meet the requirements of the policy measure on UK flights, but would lead to increased emissions on other routes (and could, potentially, lead to an overall increase in global emissions if those aircraft were not of the optimum size or capability for those non-UK routes).

The potential for this measure to be regarded as duplicating the aims of the EU ETS or CORSIA, referred to above, and the consequent increase in airline costs, could lead to the movement of some international traffic to other European hub airports, leading to some carbon leakage as a result. If the increased costs of aircraft replacement were to be fed through to increased ticket prices (particularly for long-haul flights), some passengers might choose to fly via another European hub (from which long haul flights might be cheaper). This could also lead to some carbon leakage through the increased demand for flights from those airports.

4.2.1 Implementation in the DfT aviation model

This policy measure was implemented in the DfT aviation CO_2 model through changes to the default retirement age for aircraft. The value in the baseline is 22 years for most types in the Scheduled and NFC categories (25 years in the Charter categories). Investigations were made regarding the potential effect of different reductions in this parameter. The FMM was used to investigate the effect of different retirement ages on estimated fuel burn in 2050. From this, the changes in retirement age shown in Table 4-4 were chosen.

Table 4-4: Change in retirement age for each operator category

Policy Ambition Scenario	Scheduled	Charter	NFC
Low (-1 year)	21 years	24 years	21 years
Central (-2 years)	20 years	23 years	20 years
High (-3 years)	19 years	22 years	19 years

4.2.2 Costs

The main costs of early fleet renewal are related to the changes in aircraft acquisition costs as a result of the different numbers of deliveries of different types of aircraft (compared to the baseline). The number of aircraft delivered of each type have been calculated from the outputs of the DfT modelling (using data from the Fleet Mix Model and the CO_2 outputs). The FMM output is given in air transport movements (ATMs), and was converted to number of aircraft using utilisation rates from CAA[23]. Each ATM refers to a return journey (two trips), so the utilisation rate, which refers to number of trips a day, was halved before being applied to the number of ATMs. The prices of the aircraft types have been derived from public sources for aircraft list prices, information on the difference between list price and actual prices paid and projects of prices for the future aircraft types.

The list prices of in-production aircraft (and some near-term future aircraft), were obtained from manufacturer websites for Airbus[24], Boeing[25] and Bombardier[26]. Price data for products of other manufacturers were obtained from other sources (including Wikipedia). The results of this review of aircraft list prices is shown in Annex 4.

It is widely recognised that the actual prices paid by airlines are considerably lower than manufacturers' list prices. Data were identified from different sources, such as Airinsight[27] and "Challenges"[28] that give estimates of the discounts that airlines receive on aircraft purchases. These aircraft price discounts vary from 28% to 63%; the full lists are presented in Annex 5.

The specific percentage discounts for each aircraft type were applied to the list prices of the existing in-production and near future aircraft types. For aircraft types where no discount had been identified, that for the nearest equivalent types was used.

For the future aircraft types included in the modelling, the price was calculated by assuming that it would reflect the efficiency improvement over the in-production types in the seat class. The approach adopted was to identify the price and fuel efficiency parameters[29] for other aircraft in the same seat class and to extrapolate the variation to the fuel efficiency parameter for the future type. This gave the prices for the future types as shown in Table 4-5**Error! Reference source not found.**.

Table 4-5 Calculated prices for future aircraft types

Aircraft code	Description	Discounted price ($ million)
G16	New G1 Post 2026 CL6	211.4
G21	New G2 Post 2030 CL1	26.6
G22	New G2 Post 2030 CL2	49.7
G23	New G2 Post 2030 CL3	64.7
G24	New G2 Post 2030 CL4	168.6

23 https://www.caa.co.uk/uploadedFiles/CAA/Content/Standard_Content/Data_and_analysis/Datasets/Airline_data/2016/Annual/Table_1_11_1_Aircraft_Type_and_Utilisation_All_Airlines_2016.pdf
24 http://www.airbus.com/content/dam/corporate-topics/publications/backgrounders/Airbus_commercial_aircraft_price_list_Jan17.pdf
25 http://www.boeing.com/company/about-bca/
26 http://press.commercialaircraft.bombardier.com/en/media/list-prices---commercial-aircraft---bombardier.html
27 https://www.airinsight.com/aircraft-pricing-list-vs-market/
28 https://www.challenges.fr/salon-du-bourget/le-vrai-prix-des-avions-d-airbus-et-de-boeing_10040
29 For this purpose, the fuel efficiency parameter was calculated as fuel burn / distance / number of seats. The fuel burn was obtained from the EMEP/EEA aviation emissions calculator for three different flight distances and the values of fuel burn / distance were averaged when calculating the parameter.

Aircraft code	Description	Discounted price ($ million)
G25	New G2 Post 2030 CL5	230.7
G26	New G2 Post 2030 CL6	240.5
G31	New G3 Post 2040 CL1	29.4
G32	New G3 Post 2040 CL2	54.8
G33	New G3 Post 2040 CL3	71.4
G34	New G3 Post 2040 CL4	173.4
G35	New G3 Post 2040 CL5	237.3
G36	New G3 Post 2040 CL6	247.4

The annual spend by airlines is partly offset by the resale of retired aircraft. The total value of retired aircraft was calculated using the retirement data from the FMM model and a depreciation of 5.2% per year. This depreciation rate was calculated by averaging the depreciation rates used by a number of airlines, as published by the International Air Transport Association (IATA)[30]. The retirement age used was 22 years for scheduled and NFC carriers, and 25 years for chartered carriers.

The total cost per year to airlines from aircraft replacement was calculated as the cost of replacement aircraft minus the payback from resale of retired aircraft. The increased fleet turnover that results from the policy measure, leads to an increased number of aircraft being purchased, giving higher purchase costs than in the baseline. These higher purchase costs were partially offset by the increased sales of retired aircraft. As well as more aircraft being sold (because of the increased fleet turnover), the aircraft being sold are also younger and, hence, have a higher value (because of the reduced depreciation).

4.2.3 Uncertainties

This policy measure assumes that there would be incentives available that would cause airlines to renew their fleets earlier than in the baseline case (leading to reduced average ages at which the aircraft are removed from the UK fleet). It is not certain what form that incentive would take, nor whether the availability of the incentive would be sufficient to cause airlines to renew their fleet earlier, though the reductions in retirement ages that have been analysed in this study do not represent large percentage reductions.

The costs of this measure have been calculated using aircraft list price data and estimates of discounts that airlines receive from manufacturers, based on other published studies. The discounts offered by manufacturers are known to be considerable, but the actual values are commercially sensitive, so there is a degree of uncertainty around the aircraft prices assumed in this study and the costs calculated for this policy measure.

4.3 Improvements to the ICAO CO_2 emissions standard

This policy measure involves improving the international CO_2 standard to encourage the production of more fuel efficient aircraft types.

Feasibility and capacity to be applied unilaterally by the UK

The International Civil Aviation Organisation (ICAO) CO_2 standard agreed in 2016 is the first standard of this nature. The standard that has been agreed will apply to aircraft types with application dates for type certification from 2020[31,32] and to all newly manufactured aircraft from 2028. Following the example of other ICAO standards (noise, NOx, etc.), it is expected that the CO_2 standard will be reviewed and revised in future CAEP cycles. The development and analysis of ICAO standards requires the involvement of representatives of ICAO Member States. The development of options for

30 https://www.iata.org/publications/Documents/Airline-Disclosure-Guide-aircraft-acquisition.pdf
31 https://www.icao.int/Newsroom/Pages/ICAO-Council-adopts-new-CO2-emissions-standard-for-aircraft.aspx
32 The implementation date for new aircraft types with a maximum take-off mass of less than 60,000kg is 2023

the existing CO_2 standard, the analysis of the potential impacts and the final agreement involved inputs from a wide range of stakeholders (Member States and other organisations) over a period of more than six years. The UK took a major role in the development of this standard and continues to contribute strongly to CAEP activities.

The achievement of this policy measure, as a future tightening of the CO_2 standard with a greater impact than would be the case otherwise, would require considerable levels of cooperation and negotiation between the UK and other ICAO Member States, particularly those with significant aerospace manufacturing industries (primarily the EU and the USA, but also other states such as Brazil, Canada, Russia, China and Japan). As the UK (like other Member States) has a single voice within CAEP, it is not possible to force through a change in standards without obtaining the consensus among Members followed by approval in the ICAO Council. Nonetheless, it was felt that the assessment of the possible contribution of an improved ICAO CO_2 emissions standard to the abatement of UK aviation emissions merited consideration in this study.

Policy levers that could be used to incentivise/regulate the application of the measure

The primary policy lever to achieve a significant tightening of the ICAO CO_2 standard is a strong involvement in the CAEP process, with negotiation with the other Member States to prioritise the achievement of the tighter CO_2 standard. Negotiations would also be required with international industry bodies, such as the International Air Transport Association (IATA) and the International Coordinating Council of Aerospace Industries Associations (ICCAIA) among others. As noted above, given the nature of the ICAO standard setting process, there would still be significant uncertainty regarding the ability of the UK to achieve a particular outcome when considering an improved standard.

Who is responsible for implementing the measure/lever?

The ICAO CO_2 standards are agreed at international level among CAEP members. The UK Government (principally DfT) would be responsible for working with and encouraging CAEP members to develop and implement more stringent standards.

What would different policy-level abatement scenarios look like?

The definition of the different policy-level abatement scenarios assumes that they would involve progressively more stringent standards. As the stringency increases, the pool of compliant aircraft will decrease, leaving only the most fuel efficient aircraft.

The analysis of the baseline scenarios concluded that the “New Types” element of the current CO_2 standard (to be implemented from 2020) would not affect any of the future new aircraft types in the model, nor would the “In-Production” element (to be implemented from 2028) require any of the aircraft types in the model to be taken out of production at that date. The impact of the increased stringency of a future standard, under this policy measure, could be seen through required improvements to the future aircraft types or the removal of aircraft types (both current in-production types and the 2030-generation future types included in the model) from production in a future year.

The low ambition policy measure is assumed to only affect aircraft types that are in production in 2040 (12 years, equivalent to four CAEP cycles, after the currently agree standard is implemented for in-production types). For this low ambition case, it is assumed that the additional impact would be small and it would remove only the least fuel efficient aircraft types from each seat class.

For the mid and high ambition cases, it has been assumed that the standard would be “technology-forcing”, rather than “technology-following”, which has not traditionally been the case for ICAO standards. As such, it would cause future aircraft types to be more fuel efficient than in the baseline. It has been assumed that the new “New Types” standard would be implemented in 2032 (12 years after the initial implementation date for the current CO_2 standard). This would apply to aircraft types for which the initial application for type certification occurred after that date. As the application date for type certification occurs several years before the entry into service of a new aircraft type, the impact of this new regulation would be seen on aircraft types entering service from 2040 onwards. The increased stringency of the standard under the mid and high policy ambition cases would also result in more aircraft types being taking out of production in 2040.

In each case, the impact of the policy measure is seen through the aircraft types available to enter service, and their fuel efficiencies, after 2040.

Main costs/benefit impact areas

The direct costs to achieve the increased stringency of a future aircraft CO_2 standard, those of UK involvement in the CAEP process, are very low in comparison to the other costs included in this study. However, the outcome is heavily dependent on the success of negotiations with other CAEP Member States and industry, to agree an increased prioritisation of CO_2 emissions reductions.

The tightening of the regulation would lead to increased investment costs for airlines as less efficient aircraft, which might be less expensive to acquire, would no longer be produced. Under the mid and high policy ambition cases, the future aircraft types that enter service after 2040 will be improved (compared to the baseline); this will incur costs for the manufacturers to develop and incorporate the more advanced technology, which will then be recovered from the airlines through increased acquisition costs. The agreement on the new CO_2 standard would be obtained in 2028 under this policy measure, which would be expected to provide the manufacturers sufficient time to develop the improved aircraft types in time for their introduction in 2040.

The aircraft types that are assumed to be removed from production in 2040 under this policy measure would have been in production for a number of years, with newer aircraft types already in production (or expected in the near future). As a result, there would be no additional costs to manufacturers (beyond those of developing and introducing the new types, as described above).

The benefits of the policy measure would be seen through the increased average fuel efficiency of the aircraft in each seat class after 2040. Under the low policy ambition, this will occur through the removal of the least efficient aircraft types in production. Under the mid and high policy ambition cases, more of the less efficient aircraft types will be removed from production and the most efficient aircraft types, those types that enter service after 2040, will be improved relative to the baseline. As the measure only affects aircraft that are manufactured after 2040, the impact on total emissions to 2050 is expected to be relatively small.

Barriers to take up and the cost of overcoming them

The principal barrier to the achievement of this policy measure is likely to be international resistance to agreeing a significantly more stringent standard (than would be expected under a baseline level of effort within CAEP). The increased costs of a more stringent standard would be likely to lead to concerns from aircraft manufacturers and airlines, so additional efforts would be required to obtain agreement from all stakeholders (particularly the other CAEP Member States, as they would be responsible for agreeing the new standard).

The timeframe over which the measure would be expected to have an effect

There is currently no clear view on when CAEP will revisit the CO_2 standard. The current (CAEP/11) cycle will address the development of a new non-volatile particulate matter (nvPM) standard for aircraft engines. Once completed, there will be four different 'classes' of CAEP environmental standards (CO_2, NOx, nvPM, noise). Traditionally, CAEP has only worked towards a recommendation for a single standard in a cycle. For this study, it has been assumed that CAEP would revisit the CO_2 standard every four cycles (12 years, assuming that CAEP continues to work to a three-year cycle). This would lead to a new standard with implementation dates of 2032 for new types and 2040 for in-production types. Given the normal delay between the application date for a type certification and the aircraft type entering service, the new "New Types" standard would be applicable to the new aircraft types in the DfT aviation CO_2 model that enter service after 2040.

Potential for carbon leakage

The ICAO CO_2 standard would be applied internationally, and therefore unlikely to result in any carbon leakage. There is a small possibility that the increased prices of the new aircraft types introduced after 2040 could lead to some airlines delaying the purchase of new aircraft, but the effect of this is unlikely to be significant.

Conversely, because of the international nature of the CO_2 standard, the improved fuel efficiency of aircraft types being acquired after 2040 would be realised globally, not just on aircraft to be operated on UK routes. Therefore, there would be considerably greater benefits globally through the improved fleet fuel efficiency.

4.3.1 Implementation in the DfT aviation model

The implementation of this policy measure in the DfT aviation model was through changes in the aircraft types available in the supply pool after 2040 and adjustments to the fuel efficiencies of the post-2040 aircraft types (for the mid and high policy ambitions). As the CO_2 metric values of actual aircraft types have not yet been published, it is not currently possible to identify which types would, in reality, be affected by any given change to the standard definition. Therefore, the worst performing aircraft for each seat class were identified through the EMEP/EEA 2016 fuel burn data. An average fuel burn across three different stage lengths was identified for each aircraft in each seat class, and then compared to the maximum take-off mass (MTOM) to identify the aircraft with the worst fuel burn per nautical mile per kg of weight. The different stage lengths used for this calculation, which depended on the seat class, are shown in Table 4-6.

Table 4-6 Stage length used for calculation of fuel efficiency parameter (all stage lengths in nautical miles)

Seat Class	Stage Length 1	Stage Length 2	Stage Length 3
1	200	250	500
2	500	750	1,000
3	750	1,000	1,500
4	1,500	2,500	3,500
5	1,500	2,500	3,500
6	1,500	2,500	3,500

The different policy ambition scenarios assumed restrictions on the aircraft available in 2040, with the low ambition scenario removing the worst aircraft type in each seat class, the central ambition scenario removing all but the best two aircraft, and the high ambition scenario removing all but the best aircraft type in each seat class. For some seat classes with limited aircraft choice the central and high policy ambition scenario have the same impact.

Table 4-7: Best and worst aircraft in each seat class in 2040

Low ambition: remove “worst” aircraft in each seat class

Policy Ambition Scenario	Aircraft to remove by seat class					
	1	2	3	4	5	6
Low	ATR42	CS1	39M	788	-	-

Mid and high ambition: retain only the best aircraft in each seat class

Policy Ambition Scenario	Aircraft to retain by seat class					
	1	2	3	4	5	6
Mid (retain (at most) two best aircraft)	G21	19N, G22	20N, G23	G24, 359	G25	G16, G26
High (retain only best aircraft)	G21	G22	G23	G24	G25	G26

Under the mid and high ambition cases, the fuel efficiencies of the post-2040 aircraft types were also improved in the DfT aviation CO_2 model. For the mid ambition case, the efficiency improvements were set equal to those achieved under the low ambition of the increased R&D policy measure. Similarly, under the high ambition case, the efficiency improvements were set equal to those achieved under the mid ambition of the increased R&D policy measure.

4.3.2 Costs

The direct costs of this measure to the UK Government were considered to be negligible, as it will involve only a greater encouragement to other CAEP Members to strive for a significant increase in the stringency of the CO_2 standard. Therefore, these costs have not been included in the calculations.

The costs to airlines are a result of the changes in aircraft acquisition costs, due to the different numbers of deliveries of different aircraft types relative to the baseline case (and the higher prices assumed for the more fuel-efficient aircraft types). These costs have been calculated as described in Section 4.2.

4.3.3 Uncertainties

The principal uncertainty on this policy measure relates to the ability of the UK, as just one CAEP Member State, to influence CAEP analyses and objectives sufficiently to obtain a significant tightening of the CO_2 standard. There is also significant uncertainty of the timing of a follow-on CO_2 standard, as CAEP has not determined any timeline for reviewing any environmental standards after the current development of a new nvPM standard.

As a result, this policy measure was included in the study to illustrate the savings that could be achieved through a tighter CO_2 standard, rather than as an expected outcome of UK policy.

The costs of implementing this measure use a similar approach to the early fleet replacement policy measure and, therefore, include the same uncertainty around future aircraft prices.

4.4 Reduced aircraft cabin weight

The development of this measure considered a range of operational measures that could be applied by airlines, including improvements to flight efficiency through optimising flight speed and altitude. However, it was recognised that it is already in the financial interest of airlines to optimise flight speeds and altitude, subject to Air Traffic Control (ATC) constraints. The introduction of efficiency improvements through the US NextGen and European Single European Sky projects is already yielding benefits in reduced fuel burn. Improvements in the ability of airlines to fly ‘cruise-climb’ flight profiles, rather than ‘step-climb’ may allow further optimisation of fuel burn. Such an approach would entail little cost, so these measures are likely to have limited or even negative costs to airlines, but any emissions savings will be small. There is no evidence of airlines taking action to fly at altitudes below optimum. Therefore, there are no policy measures that can be taken to encourage them to fly at more efficient altitudes.

Steps to reduce aircraft speeds would be likely to reduce aircraft utilisation with associated increased operating costs. These are unlikely to yield significant reductions in fuel burn unless future aircraft types are optimised for lower cruise speeds.

Therefore, the focus of this policy measure is on encouraging and supporting airlines to take steps to improve the efficiency of their aircraft through reducing operational weight, without compromising safety (which might be the case if, for example, airlines reduced the quantity of fuel loaded, removing some of the safety margin for diversions and holding.

The reduction of aircraft empty weight (e.g. lighter seats, cabin overhead bins, in-flight entertainment systems, etc.) can lead to reduced fuel burn and emissions. However, the maximum take-off mass of the aircraft would be unchanged, so it is possible that the airlines would increase the belly hold cargo carried, particularly on long haul flights, thus offsetting the gain from reducing the cabin weight. The costs to airlines are likely to be significant; therefore, the improvements are most likely to be implemented as part of wider refurbishment of the aircraft.

There are examples of significant weight savings from lighter seats, with the Economist[33] suggesting that a standard economy seat weighs 12kg and could be reduced to about 4kg. Additional information on the availability of such seats has been published by the aviation industry[34,35,36]. A saving of 8kg per economy seat could yield significant fuel savings, however it is also possible that this reduced weight would be used to add additional seats to the aircraft, increasing revenue for the airline but not reducing fuel consumption. Weight savings from advanced in-flight entertainment systems have also been shown (for example, by Thales[37]), however the magnitude of the weight saved is lower than that from lightweight seats. Furthermore, the costs of replacing these systems are much higher than seats, and therefore less likely to be cost-effective.

Feasibility and capacity to be applied unilaterally by the UK

[33] https://www.economist.com/news/technology-quarterly/21651920-how-technology-changing-passenger-cabin-whatever-class-you-fly-flying
[34] http://expliseat.com/
[35] http://www.peugeotdesignlab.com/en/projects/transportation/expliseat-titanium-seat-neo
[36] http://www.atraircraft.com/newsroom/atr-expands-its-seat-offer-with-expliseat-1389-en.html
[37] https://www.thalesgroup.com/en/flight-entertainment

The ability to reduce aircraft weight through the fitment of lighter cabin furnishings, such as seats, is evidently feasible, as there are products available on the market. However, it requires significant expense by the airline, particularly when implemented as a mid-life update, so a more rapid take-up is likely if some support is made available. For unilateral action by the UK to have the desired effect, the support would need to be available to all airlines, not just those registered in the UK.

Policy levers that could be used to incentivise/regulate the application of the measure

The main policy lever for this measure would be the provision of support to airlines to encourage them to use the lightest available cabin fittings, particularly seats, when refurbishing their aircraft. Similarly to other measures, this support might be provided in the form of support for negotiating loans (or loan guarantees) to assist the airlines in justifying the additional costs of refurbishment.

Who is responsible for implementing the measure/lever?

UK Government Departments would be responsible for working with airlines and financial institutions to ensure that the necessary level of funding is available to airlines to incorporate lightweight seats into their aircraft when refurbishing them and to encourage them to take up the opportunity offered. The DfT would be likely to be the focus to the encouragement and support to airlines to implement the measure, with support from BEIS. Appropriate sources of the investment for installing the lightweight seats could include the Green Investment Group[38].

What would different policy-level abatement scenarios look like?

The low, mid and high policy ambition scenarios have been assumed to be characterised by different levels of take-up of the support for introducing lightweight cabin furnishings. For the purposes of this analysis, it has been assumed that the baseline case includes no take-up of the lightweight furnishings. It has also been assumed that lightweight furnishings would save 8kg per seat, with a 25% take-up under the low policy ambition, 50% under the mid policy ambition and 100% under the high policy ambition. These improvements are assumed to be applied to the aircraft when they have their interiors refurbished at their mid-life point (11 years of age for aircraft in the scheduled and NFC categories and 13 years for aircraft in the chartered category).

Main costs/benefit impact areas

The main costs of implementing this policy measure would be the additional costs of the lightweight seats (exemplifying the reductions in cabin interior weight). These costs would fall on the airlines. The benefits of the lightweight seats would be seen through the reduced aircraft weight and, hence, the reduced fuel consumption and emissions. Further details of the approach adopted for calculating this reduction in fuel consumption are given in Section 4.4.1 below.

Barriers to take up and the cost of overcoming them

The primary barrier to a widespread adoption of lightweight cabin furnishings is likely to be the additional costs of introducing them. Their ability to access finance to assist with these costs will be important in overcoming this barrier.

The lightweight seats are assumed to be installed during a normal aircraft interior refurbishment (assumed to occur half-way to the aircraft's retirement age). Therefore, there would be no additional costs or delay in the process, other than the additional costs of the seats themselves.

The timeframe over which the measure would be expected to have an effect

Lightweight seats are already on the market, so the measure could be implemented in the near future. The rate at which aircraft are retrofitted with these seats would be dependent on the timing of cabin interior refurbishments.

Beyond 2020, the analysis assumes that newly manufactured aircraft will also be fitted with lightweight cabin interiors under this policy measure. Therefore, the reductions in aircraft weight are applied to aircraft delivered prior to 2020 when they are refurbished at their mid-life point and to new aircraft delivered after 2020.

Potential for carbon leakage

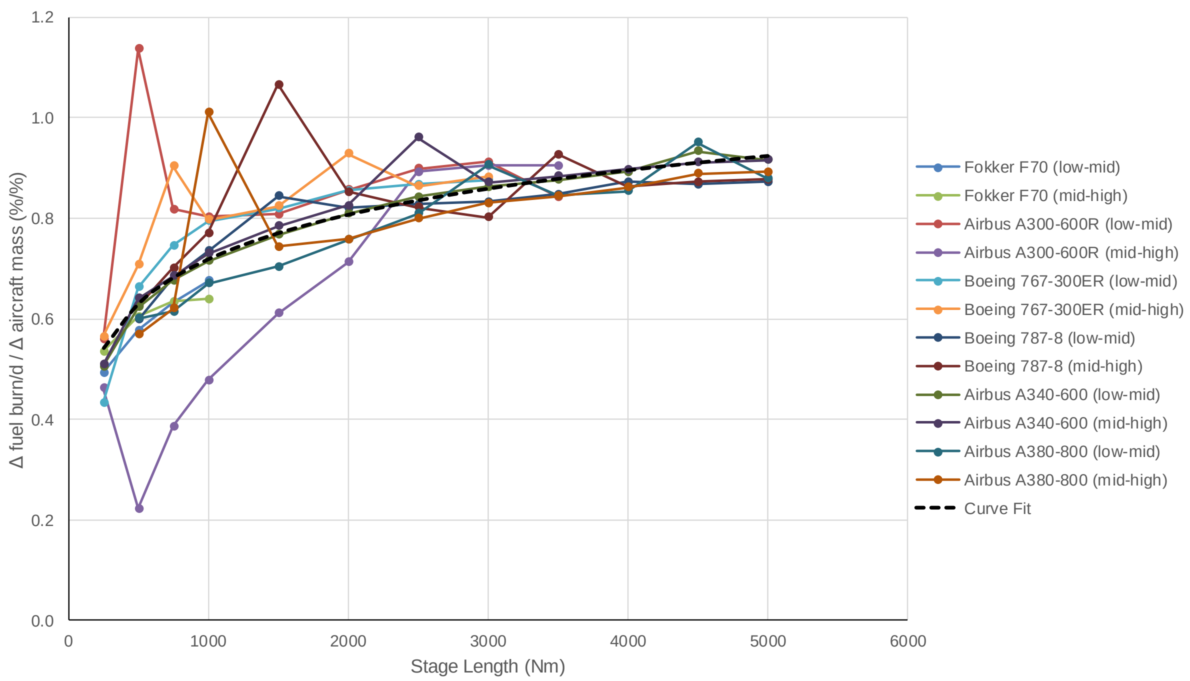
[38] The UK Government sold the Green Investment Bank to the Macquarie Group in August 2017, forming the Green Investment Group Limited. They retain a commitment to investing in green infrastructure projects. http://greeninvestmentgroup.com/

There is limited likely scope for carbon leakage under this policy measure. The availability of support for refurbishment (using lightweight fittings) for aircraft flying from the UK could lead airlines to refurbish aircraft on UK routes earlier than those operating on other routes. However, the delays in refurbishing those aircraft operating non-UK routes are unlikely to lead to any increase in fuel consumption or emissions from them.

4.4.1 Implementation in the DfT aviation model

Using the PIANO X[39] modelling tool, fuel burn and aircraft mass values were calculated for a variety of aircraft. By dividing the change in fuel burn per nautical mile by the change in aircraft mass and plotting this number over a range of stage lengths, a logarithmic curve was produced, shown in Figure 4-4. Although there is some scatter evident in the results, probably due to the limited precision to which the calculated values are output from the PIANO-X tool, the fitted curve appears to give a reasonable approximation to most of the aircraft types modelled. This curve shows how a change in aircraft weight impacts fuel burn, and hence aircraft efficiency. By estimating the reduction in cabin weight as a percentage of total aircraft weight, this curve can be used to calculate the resulting change in fuel burn, and hence the fuel efficiency improvement from the reduced weight.

Figure 4-4: Variation in fuel burn due to change in aircraft mass for different stage lengths



The DfT aviation CO_2 model does not allow the input of aircraft efficiency factors as a function of flight distance; therefore, it was decided to use a factor based on an average or typical flight distance. For example, using an average flight length of 2000 Nm, a reduction in empty aircraft weight of 1% would result in a reduction in fuel burn of 0.8% (based on the curve shown in Figure 4-4). Each seat class was assigned an average stage length, derived from the ranges of the aircraft types employed in that seat class, as shown in Table 4-8.

Table 4-8 Average stage lengths derived for each seat class

Seat class	Average stage length (Nm)
1	500
2	1,000
3	2,000
4	5,000
5	6,000
6	7,000

[39] http://www.lissys.demon.co.uk/PianoX.html

These average stage lengths were then used to derive the percentage change in fuel burn per percentage change in aircraft mass from the curve shown in Figure 4-4.

The potential weight saving was estimated for each aircraft type, based on an 8 kg reduction per seat, to give a percentage change in aircraft mass. This value, multiplied by the percentage change in fuel burn per percentage change in mass was applied to each aircraft halfway to its retirement age (i.e. at 11 years for the Scheduled and NFC categories), through adjustments to the aircraft efficiency parameters input to the DfT aviation CO_2 model.

To calculate the uptake for each year, the age distribution from the FMM was used to calculate the number of aircraft that would be either retrofitted or added into service each year as a percentage of the active fleet, from 2020 to 2033. This percentage was used to represent the progress towards the maximum potential weight savings for the fleet when all aircraft have lightweight seats, achieved in 2031 for Scheduled and NFC flights, and 2033 for Chartered flights.

The three levels of policy ambition were represented through different percentage take-ups of the lightweight seats during cabin refurbishments. The values assumed for these percentage take-ups are shown in Table 4-9.

Table 4-9: Percentage take-up of lightweight seats during refurbishments by policy ambition scenario

Policy Ambition Scenario	Percentage of refurbishments using the lightweight seats
Low	25%
Central	50%
High	100%

4.4.2 Costs

The costs to airlines of implementing this measure are related to replacing existing seats with lightweight alternatives. An estimate for the costs of current seating was based on an example of an airline purchasing 220 seats for $300,000 in 2006 (£264,305 in 2016) (The Economist, 2015). The same source suggests that lightweight titanium seats were used to replace the existing seats, costing three times as much.

Based on these values, the price of a conventional seat was estimated at £1,200, with a lightweight seat costing £3,600 under the high policy ambition scenario. The total costs of the measure were then calculated using the same percentage take-ups under the different policy ambitions as described for the impact on fuel consumption.

The number of replacement aircraft and retrofitted aircraft for each year (derived from the FMM data and the assumed percentage take-up) was multiplied by the number of seats in each of those aircraft. This number was then multiplied by the difference between the baseline seat price and the policy seat price to arrive at an annual cost for each aircraft type, and hence a total annual cost for this measure.

4.4.3 Uncertainties

Aircraft cabin furnishings consist of more than just seats and R&D activities have sought to create light weight versions of several aspects. The analysis of this policy measure has focused on a single element, the seat, as some information is available regarding seats that are available for installation that show a significant weight reduction. There is, however, some uncertainty about the assumption that such weight savings can be extended to other classes. Seats in first class and business class are significantly heavier than those in economy class, so the 8kg reduction represents a much lower percentage reduction in weight, but there is no information available on such weight reductions for these seats. Similarly, aircraft seats for long-haul flights also normally include in-flight entertainment systems; while there is some indication of lighter systems being developed (wireless systems, for example), there is little information on the weight savings that might be achieved.

The analysis of this measure assumed that all aircraft would be refurbished 11 years after being delivered. The actual timing of an airline choosing to refurbish an aircraft depends on many factors, including the future plans for its use.

Therefore, there is some uncertainty regarding the weight savings that would be achieved on the full range of aircraft as a result of this policy measure.

Limited information is available regarding the costs of alternative aircraft furnishings. The analyses of the costs for implementing this policy measure have relied on a single quote by an airline executive and assumptions about the values to which they referred. Therefore, there are significant uncertainties around the costs of an individual lightweight seat assumed in this analysis.

4.5 Regulation of aircraft types operating from UK airports

The concept of this policy measure is to regulate the aircraft types that can operate from UK airports, based on their environmental performance. It has similarities to the concept of "Green Slots", that was included in the proposals for the expansion of Heathrow Airport prior to 2010. However, it differs significantly in that green slots were only to be applied to the additional slots that would be made available through the expansion of the airport (to include a third runway), while the proposed new measure is intended to apply to all departures from UK airports. Furthermore, the environmental restrictions associated with the earlier green slots concept were related to NOx emissions and noise close to the airport, whereas the focus here is on emissions of CO_2 during the full flight, through only allowing the most fuel efficient aircraft to operate. An alternative to this formal restriction may be the use of differentiated landing charges to encourage airlines to use the most fuel efficient aircraft. This is something that has been used at Heathrow, which applies NOx emissions-based landing charges. Until now it has not been possible to differentiate landing charges on the basis of CO_2 emissions due to the lack of standardised emissions rates. However, the recently-agreed CAEP CO_2 emissions standard will generate a database of CO_2 metric values for in-production and new aircraft types, which would allow differentiation based on CO_2 emissions.

Feasibility and capacity to be applied unilaterally by the UK

As noted above, the landing charges at some airports, including Heathrow, already include a component related to environmental impacts. The idea of green slots was also included in previous proposals for a third runway at Heathrow (for the proposals considered prior to 2010). Therefore, the availability of regulatory data for the CO_2 emissions of aircraft should allow restrictions based on CO_2 emissions to be feasible. However, extending the restrictions to all departures from all UK airports, rather than specific slots at specific airports, could require significant expenditure by airlines (to ensure that they have sufficient compliant aircraft available), unless they can meet the UK requirements by moving aircraft from non-UK routes to routes from the UK. These issues might lead to international challenges to the implementation of the measure, particularly for a higher level of ambition.

As the measure is based on the ability of aircraft to operate from UK airports, it is a policy that can be implemented by the UK unilaterally, subject to any international challenges related to its implementation.

Policy levers that could be used to incentivise/regulate the application of the measure

The options for policy levers for implementing this measure would include setting landing charges to include a component related to the CO_2 emissions performance of the aircraft or a regulatory requirement that aircraft operating from airports must meet the emission requirement. For the landing charges approach to be effective, it would be important that the emissions-based charge was significant if the aircraft did not meet the target emissions limit, as landing charges currently form only a small part of an airlines operating costs.

Who is responsible for implementing the measure/lever?

Airports in the UK are private businesses. Therefore, there would need to be negotiations between Government Departments and the airports to implement the regulation of aircraft types, whether through landing charges or regulatory requirements.

What would different policy-level abatement scenarios look like?

The different levels of policy ambition have been considered to limit the aircraft types that can operate from UK airports, based on their certificated CO_2 emissions performance. The limits on these emissions parameters could be set as a fixed value or, for a greater effectiveness, specified to reduce steadily over time, giving a greater margin to the ICAO aircraft CO_2 standard. For this study, it was assumed that the limits on emissions would reduce over time, further restricting the aircraft types that can operate from UK airports; further details of these assumptions are given in Section 4.5.1.

Main costs/benefit impact areas

The different limits on the CO_2 emissions of aircraft operating from UK airports would influence the aircraft fleet and hence the total emissions. The costs to airlines would be related to the need to remove some aircraft types from operating from UK airports and the need to acquire sufficient compliant aircraft to meet demand.

Barriers to take up and the cost of overcoming them

The costs to airlines caused by the implementation of this policy measure could be significant, if they need to make significant changes to their aircraft fleet in order to continue operating to and from the UK. This could potentially give rise to legal challenges related to restriction of trade. The means to overcome this barrier could potentially include the provision of support to airlines when negotiating finance to assist them to refresh their fleet.

As noted under the early fleet replacement measure, there are already international measures in place or under development that encourage airlines to operate fuel-efficient aircraft, such as the EU ETS and the ICAO CORSIA scheme. Therefore, the implementation of a further scheme, specific to the UK, that regulates the aircraft types able to be used on flights with the aim of reducing CO_2 emissions could raise concerns about duplicative measures.

The timeframe over which the measure would be expected to have an effect

This policy measure applies directly to the aircraft types operating from UK airports. Therefore, it could begin to have an impact on emissions soon after it was implemented (depending on the exact level of emissions parameter chosen for the start and how soon the progressive reduction in emissions limits affects an aircraft type). Assuming that, as modelled here, the measure is targeted at allowing only the best-performing aircraft to operate from UK airports by 2050, it would continue to have an impact to that time (and beyond, assuming that further new aircraft types, with improved fuel efficiencies, become available from about 2050).

Potential for carbon leakage

The measure relates to restrictions imposed on the types of aircraft that can operate from the UK. In the event that an airline has compliant aircraft in its fleet, but does not use them on flights from the UK, there is the potential for them to move the more fuel efficient types from the non-UK routes to UK routes (and vice-versa) leading to some increases in emissions on the non-UK routes.

As the regulation under this policy measure would be related to the compliance of the aircraft with the ICAO CO_2 standard (or the margin to that standard) and the standard allows heavier aircraft (greater Maximum Take-Off Weight (MTOW)) to have higher emissions, there is a possibility that some airlines would choose to use larger (but compliant) aircraft on UK routes than are required to meet demand. These larger aircraft would operate at low load factors (because of the limited demand) and potentially increase emissions. However, the increased emissions would be accompanied by increased fuel costs, so it would be unlikely that such a situation would remain for long.

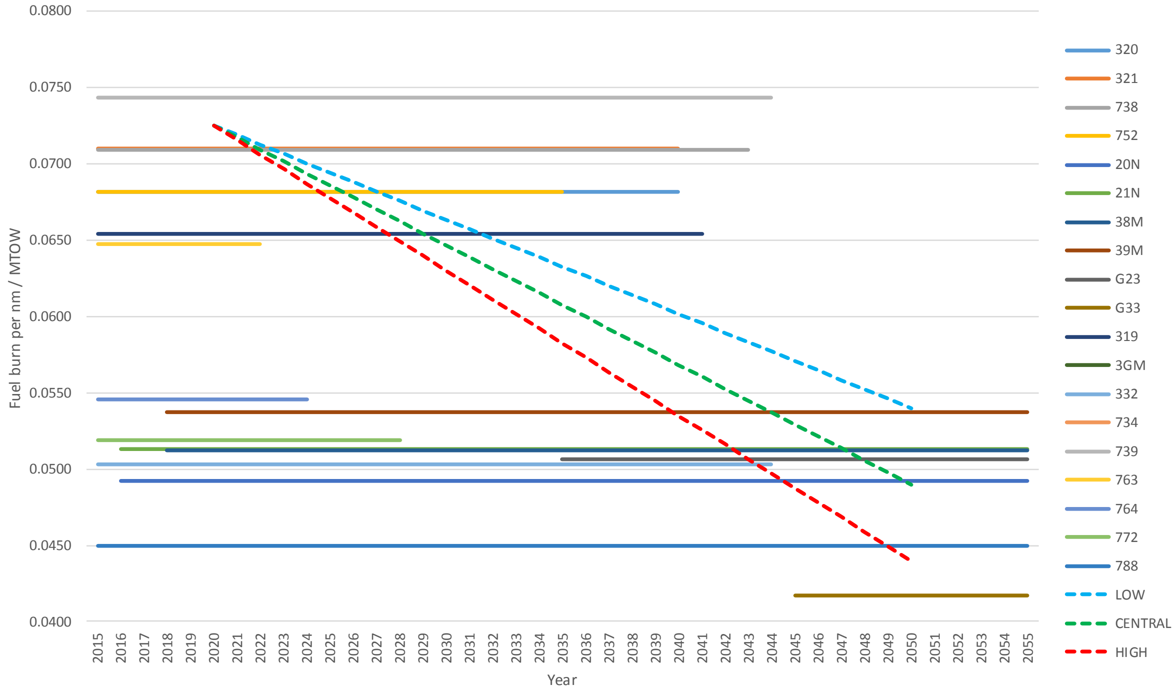
In a similar manner to the policy measure on early fleet replacement, it is possible that this measure could be seen as duplicating the efforts of the EU ETS and CORSIA, with the potential for carbon leakage if airlines choose to move hub operations to other European airports.

4.5.1 Implementation in the DfT aviation model

The implementation of this measure in the DfT aviation CO_2 model was based on setting limits on the fuel efficiency of aircraft that would be allowed to operate from UK airports in future years, with the limits becoming progressively tighter over time. For each seat class, the fuel burn data for the different aircraft types were analysed to assess which types could be considered ‘better’ and hence more likely to be acceptable under the policy. For the central policy ambition, the measure would result in all older aircraft being removed from service by 2050, with the exception of post-2030 and post-2040 models. For the low ambition scenario, only the worst performing aircraft were removed, while for the high ambition scenario all but the post-2040 aircraft are removed by 2050. The approach to implementing the measure in the modelling involved adjusting the ‘Phase Out’ dates in the FMM to remove the aircraft types from service (rather than changing the in-production dates, which would only affect new deliveries of the aircraft type).

Figure 4-5 shows three possible policy ambition levels across all the aircraft in seat class 3. The point at which the policy line intersects an aircraft line indicates the proposed phase out year under the policy ambition scenario. The higher policy ambition level forces inefficient aircraft out of service sooner, reducing emissions.

Figure 4-5: Seat Class 3 aircraft by fuel burn per distance over MTOM against years of aircraft use



From this graph, the changes to aircraft phase out dates shown in Table 4-10 were made in the Fleet Mix Model.

Table 4-10: Aircraft phase out year by policy ambition scenario

Aircraft	Low	Central	High
320	2028	2026	2025
321	2023	2022	2022
738	2023	2023	2022
752	2027	2026	2025
20N	-	2050	2045
21N	-	2048	2043
38M	-	2048	2043
39M	-	2044	2040
G23	-	2048	2044
G33	-	-	-
319	2032	2030	2028
332	-	-	2044

734	P/O	P/O	P/O
739	2020	2020	2020
763	P/O	P/O	P/O
764	P/O	P/O	P/O
772	P/O	P/O	P/O
788	-	-	2049

Note: P/O refers to aircraft that are already phased out in the baseline due to age.

The approach to modelling future aircraft types in the DfT aviation CO_2 model, which includes single "generic" future types in each seat class for two future generations (the "G2" and "G3" aircraft that enter service after 2030 and 2040 respectively), caused some problems with the modelling results for this measure. In later years (of the analysis period), the number of aircraft types operating in each seat class is small in the baseline (in some cases, only the G2 and G3 types), so removing the G2 type from service has a sudden and significant effect on the emissions. This problem was exacerbated for seat class 6 (the largest seat class in the analysis), which has only one aircraft type (in the baseline) currently in service (the Airbus A380), which is replaced in production (in the model) by future generation aircraft types from 2026, 2036 and 2046. Seat class 6 is the only seat class that includes a new generation type in the 2020s (the G1 generation type) as the other seat classes include known near-term future types such as the Airbus A320neo family and the Boeing 777x family.

According to the DfT demand and CO_2 forecast model, the Airbus A380 aircraft accounts for a significant fraction of future CO_2 emissions; over 24% in 2026, for example. Based on the analysis described above, the A380 would be phased out in 2020. However, the replacement aircraft type (referred to as the G16 in the DfT aviation model) is assumed to not enter service until 2026. Therefore, the phase-out of the A380 was delayed until 2026 in the analysis. The analysis of this policy measure then showed a very large reduction in emissions (and fuel costs) due to this transition, which was considered to be unrealistic. Therefore, the modelling of the impact of the measure on this aircraft type was adjusted to give a more gradual transition between the A380 and its replacement. The percentage of the supply pool in seat class 6 allocated to the A380 was reduced linearly to zero over a period of eight years under the low policy ambition (six and four years under the mid and high policy ambitions), starting in 2026, with the G16 aircraft type being allocated the remainder. The phase-out years for the A380 were set at 2040, 2036 and 2032 under the low, mid and high policy ambitions, to allow time for the last delivered aircraft of the type to be used on UK flights after delivery[40]. Although this approach deviates from the approach used for modelling the impact of the measure on emissions and costs for the other seat classes, it was considered to give more realistic results, given that the large and sudden impacts arose from the specific approach used to model future aircraft types.

4.5.2 Costs

The approach to modelling the costs of this measure assumed that there are no costs to manufacturers as they develop products to meet a global demand, and any increases or reductions in sales of certain aircraft types in the UK will not significantly affect their total orders.

The costs to airlines will be related to the changes in aircraft acquisition costs as a result of the different numbers of deliveries of different aircraft types. These costs have been calculated in the same manner as for the early fleet replacement policy measure (Section 4.2).

4.5.3 Uncertainties

The analysis of this measure included the calculation of a fuel efficiency metric parameter for each aircraft type in the modelling framework. This was necessary as the formal ICAO CO_2 metric values, on which such a measure would need to be based, are not yet publicly available. Whilst there is some

[40] It should be noted that the phase-out of the use of specific aircraft types is assumed to be a UK-only measure. Airlines would be able to move those aircraft types from UK flights to other routes after the phase-out date, if there is sufficient demand. The policy measure does not assume that Airbus would be required to cease production of the A380 at any given point, but it assumes that airlines would no longer purchase the type for use on UK routes at that point.

uncertainty regarding whether the "correct" aircraft types are identified as the measure is tightened over time, and hence whether the abatement is calculated accurately, the actual implementation of this measure would include the identification of the limits for the metric values (of aircraft allowed to operate from UK airports) to achieve the same effect.

The uncertainty in the calculations of the costs of implementing this measure are similar to those for the early fleet replacement policy measure, as they depend on the calculation of the costs to airlines of acquiring compliant aircraft. There is also an uncertainty regarding whether airlines would need to acquire new aircraft (and incur these costs) or whether they would be able to switch compliant aircraft from non-UK routes (leading to carbon leakage). It is widely considered that the UK has a relatively young and fuel-efficient fleet, so this option is unlikely to be available to many airlines; therefore, this additional uncertainty is likely to be small.

4.6 More efficient ground movements

Normally, aircraft use their main engines to taxi from the gate or stand to the runway for take-off, and after landing. However, options are now available to reduce fuel burn and emissions during this phase, the most prominent of which include:

- Reduced engine taxiing ('single-engine taxi' for a twin-engined aircraft);
- Advanced tug systems;
- On-board electric drive systems.

Reduced engine taxiing, whereby only one (in the case of twin-engine aircraft) or two (in the case of four-engine aircraft) engines are used for propulsion during taxiing, is currently used by approximately 25% of all aircraft on departure at Heathrow airport (based on unpublished airline survey information). The frequency of its use at other airports in the UK is not known, but it is likely to be used less at smaller airports where the taxi time is less. Reduced engine taxiing can occur for the full taxi time, except for approximately three minutes on each journey for engine warm up prior to take-off and cool down after landing. The use of reduced engine taxiing is anecdotally even more common on arrival (the practice was first used on arrivals as there were concerns about the increased workload for the cockpit crew on departures; these concerns have now been largely removed, as evidenced by the level of use during departures), but no publicly available data is currently available on rates of use. Therefore, this analysis assumed that reduced engine taxiing occurs at the same rate on arrival as on departures.

Reduced engine taxiing is already in common use, but the other options listed above are still under development. Ricardo Energy & Environment led the technical aspects of the project 'Deriving benefits from alternative aircraft-taxi systems' (ACRP 02-50) for the US Transportation Research Board (TRB)[41]. That study identified cost and performance data for different advanced taxiing technologies, which were used, together with additional analysis, to assess the potential reductions in emissions from such systems and the investment costs for airlines and airports. The analysis also considered the extent to which Government intervention (such as investment support or airport regulations) can contribute to the use of these technologies.

Aircraft are currently pushed back from the terminal gate for departure (prior to engine start) using push-back tugs that couple to the aircraft nose wheel system ('nose gear'). They are also towed, unladen, between gates (or stands) and maintenance hangars. The use of similar tugs to tow the aircraft (laden) from the gate to the runway has been considered. However, the nose gear on an aircraft is not designed for prolonged towing and there have been concerns about the impact on the fatigue life of the nose gear. Concerns have also been expressed about the control of the aircraft during taxiing being passed to the tug driver, and the implications for safety. Therefore, technologies are under development to enable the aircraft to be towed, under the control of the pilot, without impacting the fatigue life of the nose gear. One such technology, that has been trialled and is under consideration for use in some airports, is the TaxiBot system (under development by IAI[42]). This has been certified for use with the Airbus A320 and Boeing 737 families; a larger version for use with wide-body aircraft is also under development.

[41] http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3696
[42] http://www.taxibot-international.com/

An alternative to the use of an advanced tug is to use an on-board electric drive system (powering the aircraft through its wheels). In principle, such technologies could drive the aircraft through either the main or nose wheel; however the one system that is known to be under development, WheelTug[43], drives through the nose wheel. The company states that it currently has an order book for 1,000 systems over 22 airlines, but is awaiting certification by the FAA. Products are expected to be in service late in 2018.

For this study, the two technologies described above have been used as examples of advanced systems that enable taxiing to be performed without using the aircraft main engines. It is recognised that other technologies may be developed in the future to fulfil the same requirement. The promoters of on-board drive technologies have suggested that they will also bring other benefits, such as reduced waiting time for pushback. However, it has not been possible to quantify such benefits, so they have not been included in this study.

Feasibility and capacity to be applied unilaterally by the UK

Reduced-engine taxiing is already used quite routinely at some airports in the UK, both for taxiing out (from the gate or stand to the runway on departure) and for taxiing in (on arrival). Encouraging airlines and pilots to use the practice more frequently and more widely (i.e. at all UK airports where taxiing times are long enough for the practice to be beneficial) should be feasible. During taxiing, the aircraft is under the control of the pilot, who bears responsibility for the safety of the aircraft and passengers. Therefore, it may not be possible to mandate the practice (especially as there may be times when it is more difficult to use, such as during inclement weather or, for certain aircraft types, there may be a preferred engine to shut down and the majority of turns to be made may be in the “wrong” direction). The measure would, therefore, involve additional training and guidance to pilots and airlines. As it is a measure that affects operations at airports and does not require significant investment, it could be applied unilaterally by the UK.

For higher levels of abatement, the use of the new taxiing technologies would be required. These are currently under development and have been certificated for use with some aircraft types. It is unlikely to be feasible to mandate the use of a particular technology for taxiing (as they are commercial products and alternative solutions may appear in the future); however, imposing restrictions on the percentage of taxiing that can be performed using the aircraft main engines, while ensuring that the advanced technologies are suitable for use at the airport, may be an acceptable manner of encouraging their use.

Policy levers that could be used to incentivise/regulate the application of the measure

The technologies described are already under development (and used in practice, in the case of reduced engine taxiing) and are expected to appear even in the absence of policy action. Therefore, the key effects of the policy measure are to accelerate the uptake of these new practices and technologies.

For the low policy ambition scenario, Government support for training and guidance is assumed to lead to a more widespread use of reduced-engine taxiing; it is assumed that such an approach will lead to a maximum use of the practice by 2030. To achieve this, the DfT, working with the CAA, could develop guidance on the use of reduced-engine taxiing and engage with all UK airports to identify any local barriers to the use of the practice and means of overcoming them.

For the central and high policy ambition, the accelerated adoption of alternative taxiing technologies (probably expressed as a limit on the amount of taxiing performed using aircraft main engines, as described above) would be mandated by Government. Such a mandate would ensure that the necessary level of adoption, significantly increased over that assumed for the baseline, would be achieved.

It is unlikely to be feasible to enforce a ban on the use of aircraft main engines for taxiing activities, given that the responsibility for the safety of the aircraft during taxiing lies with the pilot (and as the main engines need to be warmed up for around three minutes before take-off and, similarly, need about three minutes operating at idle before being switched off). Therefore, the regulation would probably need to set a maximum percentage of total taxiing time during which the main engines are operated, either on each flight or, more probably, an annual average at an airline level.

Who is responsible for implementing the measure/lever?

[43] http://www.wheeltug.com/

The implementation of this policy measure will require action by Government Departments, airports and airlines. The implementation of the mid and high levels of policy ambition may also require the involvement of the certification authorities, to ensure that the advanced technologies are able to be used at all suitable UK airports.

What would different policy-level abatement scenarios look like?

Under the low ambition scenario, it has been assumed that the policy measure will lead to an increased use of “reduced engine” taxiing, giving a significant reduction in the emissions that occur during taxiing at airports. The practice is already used to a certain extent at some airports, so the policy measure will increase the frequency of use at those airports and also result in its use at others.

The mid and high ambition scenarios will result in the use of advanced technologies being used for taxiing. These will allow taxiing to be performed without the use of main engines at all, except for the required periods for engine start and warm up on departure and engine cool down on arrival. The advanced technologies do not eliminate all emissions; the advanced tug approach produces emissions of its own (with the magnitude depending on the degree of hybridisation of the tug), while the on-board systems will require the aircraft auxiliary power units (APUs) to operate at high power levels for extended periods. The use of APUs is limited at many airports during the time that the aircraft are parked at the gate; however, they are commonly used during taxiing. The additional power demand will raise the emissions (particularly NOx) from the APUs during taxiing manoeuvres, but it is expected that an overall benefit will be obtained in comparison with reduced-engine taxiing.

Main costs/benefit impact areas

Apart from additional training and guidance for reduced-engine taxiing, the main costs for this measure arise from the acquisition of the advanced taxiing technologies under the mid and high policy ambition scenarios. The information for the cost and emissions reductions of these technologies was obtained from the ACRP 02-50 study referred to above and other studies referred to by that report.

Barriers to take up and the cost of overcoming them

For the widespread use of advanced taxiing technologies to occur, they would need to be developed and certificated for a wide range of aircraft types. The products described above have been developed as commercial projects, but there may need to be some support provided to ensure that they, or other, similar technologies, are available for use for all aircraft types.

The acquisition of the advanced technologies will cause airlines and airports (and/or suppliers of ground support services) to incur significant expense. Some support may be needed to assist the access of sufficient units to meet the demand.

The timeframe over which the measure would be expected to have an effect

It is expected that reduced-engine taxiing will become more widely used over time even without any policy intervention; therefore the impact of a policy to encourage its use would diminish after about 2030. Although alternative taxiing technologies are currently under development, and are likely to start entering service in the near future, policy intervention will be required to achieve widespread use more quickly. Therefore, it is likely that the policy would continue to help reduce emissions for the foreseeable future.

Potential for carbon leakage

The implementation of the policy to encourage reductions in emissions from taxiing would be expected to affect only operations at UK airports, with a small impact on the fuel efficiency of those aircraft fitted with on-board taxiing systems. Therefore, there is little likelihood of direct carbon leakage from the measure presented here. If fully-electric advanced tugs were subsequently developed, they would need to use electricity generated elsewhere (in power stations, for example). However, the efficiency of the power station would be higher than the existing diesel-engined tug (particularly if the electricity was generated renewably), so there would still be a net reduction in carbon emissions.

If this measure were to be implemented, it would be expected to apply to aircraft arriving at UK airports, as well as those departing from them. The reduction in emissions from aircraft taxiing in after landing are not captured in the quantitative analysis (as it only covers flights departing from the UK).

4.6.1 Implementation in the DfT aviation model

Based on the information presented above, it has been assumed for the analysis of this policy measure that 25% of all aircraft use reduced-engine taxiing for the full duration of taxi-in and out. The prevalence of this option at smaller airports is unknown. While the value is likely to be lower at smaller airports as the taxi time is shorter, aircraft with the ability to use reduced-engine taxiing are likely to use it in the future regardless of the taxi time as there is little to no cost in doing so. This value is expected to increase over time, even in the absence of policy intervention, given the obvious cost savings associated with this measure. There are external factors that will limit the full adoption of reduced engine taxiing, such as weather conditions, aircraft specification and taxi routes. Therefore, it has been assumed that the adoption of the practice would reach 95% by 2050 in the absence of further policy intervention.

The current DfT aviation CO_2 model baseline does not include the current use of reduced-engine taxiing, nor any assumptions about its increased adoption in the future. Therefore, the emissions reductions and costs related to this policy measure have been calculated relative to the “no policy intervention” assumptions described above.

The ACRP 02-50 study estimates that advanced tug systems could reduce total on-airport fuel use by 2 to 6%, although savings on individual aircraft could be significantly higher[44]. The use of the advanced tug does not increase the aircraft weight, so does not affect the fuel burn during the rest of the flight. However, it is unlikely that such tugs would be used on arrivals, due to the taxi time being shorter (than on departures) and the necessity of stopping the aircraft after it has turned off the runway to attach the tug. This limits the overall effectiveness of the technology.

The ACRP 02-50 study estimated that on-board drive systems would reduce total on-airport fuel use by 2 to 4%, although savings for individual aircraft can be much higher. For example, we have estimated that significant fuel burn savings in the landing and take-off (LTO) cycle are achievable, at about 21% for individual aircraft.

A key benefit of an advanced tug system, compared to using existing push-back tractors for taxiing, is the reduced fatigue load on the aircraft nose gear. A previous trial by Virgin Airlines of using conventional tugs to tow aircraft to the runway was abandoned because of maintenance problems caused by the continuous jerks to the landing gear[45]. The on-board electric system currently under development is also fitted to the nose gear. Larger (wide-body) aircraft have many more wheels and landing gear struts than narrow-body aircraft, but still only two nose wheels on a single strut. Therefore, for the purposes of this study, it has been assumed that advanced tugs will be more suitable for use with wide-body aircraft and on-board systems will be confined to narrow-body aircraft.

As on-board taxiing systems are close to achieving certification and are expected to enter service in the near future, it has been assumed that all post-2030 narrow-body aircraft will have a similar system fitted as standard.

The use of on-board taxiing systems may also reduce fuel burn while taxiing from the runway to the gate on arrival. In principle, this could reduce the fuel that needs to be carried for the flight and hence give a small reduction in the aircraft take-off weight (and a small reduction in the fuel burn during the flight). However, it is unclear whether this could be realised in practice, as the aircraft may still need to carry enough fuel to complete the flight (plus mandatory reserves) even if there is a problem with the taxiing system and it needs to taxi using its main engines. Similarly, the on-board system adds to the aircraft empty weight (a value of about 136 kg has been suggested for the WheelTug system); a quick estimate of the effect of this additional weight, using the same approach as for the reduced aircraft cabin weight policy measure, indicates that it could add 0.1% to 0.2% to the fuel burn on a short or medium-haul flight. This would offset any gains from any reduction in fuel carried for the flight due to the use of the on-board system for taxiing on arrival. Therefore, the impact of these potential changes in aircraft weight has not been included in the current study.

In order to apply more efficient ground movement to the DfT aviation CO_2 model, the savings from alternative taxiing have been calculated as a change in aircraft efficiency.

ICAO standard values for fuel burn during taxi out and taxi in amount for approximately 40% of LTO fuel burn. The LTO values are based on the ICAO standard values, which assume 26 minutes of taxi time per movement. Of this, 3 minutes are needed for engine warm up and 5.5 minutes to cool down,

[44] http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3696
[45] https://www.theengineer.co.uk/issues/7-december-2009/reducing-runway-emissions/

leaving 20.5 minutes (about 80%) of taxi time to which these measures can be applied. Reduced engine taxiing would reduce fuel burn by 50% (half the number of engines active) during the remaining 20.5 minutes, resulting in a 16% reduction of LTO fuel burn. Similarly, the values from the ACRP 02-50 report can be applied to the 40% of LTO fuel burn, resulting in reductions in fuel burn of 21% and 22% during the LTO phase respectively.

The LTO fuel burn as a percentage of total fuel burn varies depending on the stage length. Baseline movements data have been used to estimate the average stage length for an aircraft. Using this value, an average LTO percentage of total fuel burn was calculated for each aircraft, which can then be multiplied with the LTO fuel burn reduction values shown in Table 4-11 to give a change in total aircraft efficiency, when 95% adoption is reached.

Table 4-11: LTO fuel burn reductions from alternative taxiing technologies at 95% adoption

Technology	LTO fuel burn reduction
Reduced engine taxiing	15%
Alternative taxiing technologies	20%

The mid policy ambition assumes a gradual increase in adoption of alternative taxiing technologies by relevant aircraft, reaching 95% by 2050. For the high policy ambition scenario, the date by which 95% adoption is achieved was set to 2040.

The fuel burn reduction achieved from the alternative taxiing technologies is relative to the baseline case (aircraft using all main engines to taxi) and is not in addition to that from reduced engine taxiing. The alternative technologies replace reduced engine taxiing, increasing the reduction in fuel burn and emissions achieved from 15% to 20%. Therefore, the low policy ambition scenario achieves a 15% reduction by 2030, which remains constant to 2050, the central policy ambition scenario achieves a 20% reduction by 2050 (exceeding 15% by 2030) and the high policy ambition scenario achieves 20% by 2040.

Table 4-12: LTO fuel burn reduction from reduced engine taxiing (RET), and alternative taxiing technologies (ATT) by policy ambition, assuming 95% maximum adoption

Policy Ambition Scenario	Technology application
Baseline	RET – 15% by 2050
Low	RET – 15% by 2030
Central	ATT – 20% by 2050
High	ATT – 20% by 2040

4.6.2 Costs

The costs of alternative taxiing technologies relate to the cost of the technology itself, paid for by the airlines or airport. The use of reduced engine taxiing is assumed to have no cost, as no further technology would be required. Advanced tugs are estimated to cost £2.25 million ($3 million in 2014) for wide-body aircraft, while on-board taxiing technologies are estimated to cost £0.20 million ($0.26 million in 2014) for narrow-body aircraft (Vaishnav, 2014).

The costs for advanced tugs will be covered by airlines or airports who purchase and operate the tugs. Airlines who have a significant presence at a specific airport are likely to purchase their own tugs for use at that location, while in other places the airports own the tugs which are used by all airlines using the airport. The number of systems required was identified by looking at the total number of wide-body aircraft in use for a given year, and estimating the number of tugs required per aircraft. The estimation for the number of tugs per aircraft was derived from the number of tugs and wide-body aircraft owned by BA at Heathrow (based on unpublished Heathrow airport data), with one tug per four aircraft. The assumption was made that advanced tugs will be used for approximately twice as long as current tugs, as they will tow the aircraft for the full duration of the taxiing time, other than three minutes of engine warm up. Therefore, the costing assumes one tug for every two aircraft.

The number of wide-body aircraft in service was identified from the FMM data using the same calculations described in Section 4.2.2. The number of tugs purchased each year was identified from the adoption rate used in calculating the impact of the policy option.

The costs for on-board taxiing technologies will be covered by airlines retrofitting such devices on existing aircraft, and manufacturers who will install them on new aircraft deliveries. The number of narrow-body aircraft per year was identified from the FMM data using the same calculations described in Section 4.2.2. The number of on-board devices purchased each year was identified from the adoption rate used in calculating the impact of the policy option until full fleet penetration (95%) was reached in 2038. Beyond this point, the number of devices purchased was equal to the number of new aircraft that enter service that year.

4.6.3 Uncertainties

This policy measure assumes, for the mid and high policy ambition cases, that mechanisms are available to incentivise or mandate the use of the advanced taxiing technologies at a wide range of UK airports. As airports are commercial entities (as are the organisations that provide ground support services at them), it is not certain that incentivisation would be successful in all cases. Further assessment of the feasibility achieving a wide take-up of these technologies would need to be undertaken before committing to this policy.

The abatement and cost calculations for this measure were based on results published from a separate study. Those results were based on inputs from a number of stakeholders and the report was peer-reviewed before publication, so the values used are considered to be reliable.

4.7 Increased use of biofuels

This policy measure seeks to increase the use of biofuels within aviation. Aviation fuel is highly regulated, with stringent specifications defined by ASTM International (ASTM D1655-17[46] and by the UK Ministry of Defence (Def Stan 91-91[47]. Biofuels for aviation must meet the same specification, thus creating “drop-in” fuels that can be used with existing aircraft (gas turbine) engines without modification. Aviation biofuels must also be certified to ASTM D7566[48], the specification for aviation turbine fuel containing “synthesized hydrocarbons”. The savings in lifecycle CO_2 emissions of aviation biofuels relative to jet fuel vary depending on the source of the biofuels, ranging from 20% to 95%[49]. These values assume that the emissions from fuel burn are offset by the absorption of CO_2 by the biofuel feedstock, so that emissions from biofuels arise entirely from production and transportation. The E4Tech report[50] suggests that hydrogenated renewable jet (HRJ) fuel from many conventional feedstocks such as rapeseed oil and palm oil offer significantly lower CO_2 savings than biomass to liquid (BTL) fuels from energy crops and forestry residues. This is partly due to indirect land use changes, whereby the use of crops for biofuels results in conversion of land elsewhere to crop production, potentially releasing significant emissions depending on the source. This effect is considered to be larger for HRJ, while energy crops for BTL could be grown on abandoned or unused agricultural land as well as recovered from forestry residue, with minimal indirect land use impacts. Previous studies by the Committee on Climate Change (CCC)[51] and the International Energy Agency (IEA)[52] have assumed a 50% saving from biofuels as a conservative estimate given the uncertainty in what feedstocks will be used.

The issue of land use is a key factor in understanding the future use of biofuels. The CCC report indicates that the global population is predicted to require a 70% increase in food production by 2050; as a result, agricultural land demand is expected to increase. This demand will be partly met through increased agricultural productivity from advances in technology and better utilisation of marginal or idle land. However some of this effect is expected to be mitigated by reduced productivity of agricultural land in some places, specifically Sub-Saharan Africa and South East Asia.

Overall, the competition for land use between biofuels and food provides a great deal of uncertainty around the eventual levels of biofuels penetration over the coming decades. For this reason, E4Tech

[46] https://www.astm.org/Standards/D1655.htm)
[47] http://www.jigonline.com/wp-content/uploads/2012/05/Bulletin-51-AFQRJOS-Issue-26-May-2012.pdf
[48] https://www.astm.org/Standards/D7566.htm
[49] http://www.e4tech.com/wp-content/uploads/2015/06/SustainableAviationFuelsReport.pdf
[50] E4Tech. Sustainable Aviation Fuels – Potential for the UK aviation industry. E4Tech, 2014. (available at http://www.e4tech.com/reports/sustainable-aviation-fuels-potential-for-the-uk-aviation-industry/)
[51] https://www.theccc.org.uk/archive/aws2/Aviation%20Report%2009/21667B%20CCC%20Chapter%205.pdf
[52] http://www.iea.org/publications/freepublications/publication/technology-roadmap-biofuels-for-transport.html

envisages BTL fuel to have a greater potential for biofuels production, as the process could rely on forestry residues and biomass waste rather than land use changes, thereby providing greater emissions savings compared to less advanced HRJ biofuels. In a report in 2009[53], they estimated that 100% of global jet demand in 2050 could be achieved by using 35% of global residue and waste resources. Furthermore, feedstock could also come from woody energy crops, which E4Tech estimate could be grown on abandoned agricultural land and grassland, and only 15% of the global energy crop resource could supply 100% of global jet demand in 2050. Between energy crops and residue and waste resources, there is expected to be sufficient feedstocks to meet the demand for biofuels. Jet fuel derived from algal oils is another potential source of biofuel; however, this method still has a number of commercial and technological challenges to overcome before algal oil will contribute to biofuel demand. However, HRJ from algae is estimated to have the greatest potential for emissions reductions, with E4Tech estimating realistic savings of 98%.

The availability of these resources for aviation biofuel production is also dependent on the economic capacity of the industry to invest in biofuel production as well as the scale of market pull from the aviation sector. Whilst in the short-term, production capacity can be based on operational and planned production plants, future production will depend on the commercial availability of advanced feedstocks, with aviation in competition with other fuel users. Biofuels can be imported from regional and global markets, such as the EU, as it is unlikely that the UK will have the capacity to manufacture biofuel in these quantities on their own, nor sufficient feedstock to produce the biofuel required.

Biofuels will only achieve a widespread adoption when their price is on a par with that of conventional kerosene. Furthermore, the cost of producing bio-kerosene relative to biodiesel will determine the demand in either the aviation or road transport sector respectively. Currently bio-kerosene is at a premium and is unlikely to attract investment by airlines; this is expected to continue until at least 2030 without government intervention. Indeed, a study by Utrecht University[54] (2017) estimated that only 13,000 tonnes of aviation biofuel will be produced in the EU by 2030 without government intervention, while the E4Tech (2014) study suggests production of 100,000 tonnes in the UK by 2030. Comparatively, the CCC's "likely" scenario suggests 2% biofuels penetration in the aviation sector by 2030, which is estimated to be about 275,000 tonnes of fuel. Given the range of these values, it is considered optimistic to assume a 10% baseline penetration of biofuels by 2050. Nevertheless, recent initiatives to increase the use of biofuels in aviation (for example through the UK's Future Fuels for Freight and Flight Competition (F4C)) may support this level of penetration in the future. Based on this, the existing baseline value of 5% penetration by 2050 appears appropriate to use as the baseline for this policy measure.

Feasibility and capacity to be applied unilaterally by the UK

It is clear that there is considerable scope to increase the quantity of biofuels used by the aviation sector. Several studies have indicated a wide range of estimates of the future penetration. The lack of consensus suggests uncertainty regarding feedstock availability and the costs of making biofuels competitive with conventional fuel. Therefore, policy to encourage investment in new feedstock sources and new production facilities is likely to achieve significant growth.

Of note is that aviation jet fuel and automotive diesel fuel are quite similar in chemistry. The anticipated rapid increase in sales of electric and hybrid cars, combined with the negative impacts of the VW "Dieselgate" controversy, are already leading to a reduction in demand for diesel vehicles and hence diesel fuel. This has the potential to free up resources that may have been targeted at advanced biodiesel (current production is dominated by fatty acid methyl ester (FAME), which is not a drop-in fuel for aviation) towards aviation applications.

Policy measures aimed at increasing the use of biofuels in aviation are likely to be able to be implemented unilaterally by the UK, particularly for policies that encourage a greater use of biofuel without mandating a minimum content. Some collaboration with other European countries, at least at an industrial level, may be needed to ensure that sufficient supplies are available to UK airports in the future, given the potential demand from airports elsewhere in Europe. There may also be a need for efforts to address any remaining concerns of destination countries regarding the safety of biofuels.

Policy levers that could be used to incentivise/regulate the application of the measure

[53] https://www.theccc.org.uk/archive/aws2/Aviation%20Report%2009/E4tech%20%282009%29,%20Review%20of%20the%20potential%20for%20biofuels%20in%20aviation.pdf

[54] https://www.uu.nl/sites/default/files/renewable_jet_fuel_in_the_european_union_-_scenarios_and_preconditions_for_renewable_jet_fuel_deployment_towards_2030.pdf

There is already an incentive to the aviation industry to increase the use of biofuels; for example, the inclusion of aviation in the EU Emissions Trading System (ETS) and the zero-rating of biofuels. The existence of these incentives is reflected through the application of carbon prices to all CO_2 emissions and the 5% penetration of biofuels by 2050 in the baseline assumptions for this analysis. Several policy levers have been identified to increase biofuel penetration further. The E4Tech report highlighted the potential of allowing aviation biofuel producers to claim certificates under the renewable transport fuels obligation (RTFO). Following consultation with stakeholders, the Government has now announced plans for the inclusion of sustainable aviation fuel in the RTFO scheme[55].

Business and consumer offsetting could provide additional mechanisms to cover these costs, whereby businesses and consumers pay an additional fee to offset their emissions. This money could be used to cover the additional costs of biofuels, and therefore realise the emission savings from this switch. KLM currently runs such a programme whereby businesses can cover the difference in fuel price to switch to biofuels and hence reduce their emissions. The UK Government could promote further use of this mechanism to encourage airlines to use biofuels.

Scaling up production to deliver economically competitive aviation biofuel will be critical; the E4Tech report referred to above suggests that UK sustainable aviation fuel production could be increased from 100,000 tonnes under BAU up to 640,000 tonnes in a high scenario by 2030. Current policy levers such as the Future Fuels for Freight and Flight Competition are considered to form part of the baseline biofuels penetration. Additional support to fuel companies to construct production plants could have a significant effect in leading to increased biofuel availability. E4Tech estimates the capital investment costs of achieving the production capacity above to be between £50 and £130 million per year (2020-2030). Scaling up production could therefore be aided by the use of loan guarantees, which has been found to be effective for biofuel plants in other countries, such as the US.

However, the recent report by the International Renewable Energy Agency, IRENA[56], notes that the certification process for aviation biofuels is costly (millions of dollars) and can take several years to complete. The capital investment for bringing an aviation biofuel to market needs to cover the certification process as well as the construction of the plant.

A further policy lever considered for the high ambition scenario is the potential to mandate a minimum proportion of biofuels in the fuel dispensed at UK airports. This would achieve a target level of use of biofuel in UK aviation; however, it would only be feasible if the suppliers are able to supply the required quantity of biofuel.

Another possibility to scale up production of biofuels is through direct investment by the UK Government. The US provides an example of such a scheme in the form of the Great Green Fleet Initiative, a US Government initiative to procure alternative fuels for the Navy[57]. As part of this project, funding was awarded for the production of biofuel refineries. Such schemes can help achieve economies of scale by ensuring bulk purchasing of the product on completion. However, the UK has a considerably smaller fleet, and therefore this measure is considered unlikely to be realistic.

The policy levers presented above are listed in order of ambition level, and therefore correspond to the different ambition levels for implementation in the modelling. It is assumed that the low policy ambition level would apply the policy levers of RTFO certificates or credits, and promotion of consumer and business offsetting of the additional biofuels cost. The central policy ambition would include loan guarantees to assist in the scaling up of production. Finally, the high policy ambition level would involve applying a mandated minimum portion of biofuel in the fuel available at UK airports.

Who is responsible for implementing the measure/lever?

UK Government departments would be responsible for implementing this policy measure, with additional efforts potentially being required to ensure that aviation is included in the RTFO and providing support for the scaling up of production facilities. For the high policy ambition case, involving a mandatory minimum biofuel content in aviation fuel, the Civil Aviation Authority (CAA) may also have a role in monitoring and enforcing the regulation at airports.

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[55] DfT *The Renewable Transport Fuel Obligations Order: Government response to the consultation on amendments*, September 2017. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/644843/renewable-transport-fuel-obligations-order-government-response-to-consultations-on-amendments.pdf

[56] IRENA. Biofuels for Aviation – Technology Brief, IRENA, 2017 (available at https://www.irena.org/DocumentDownloads/Publications/IRENA_Biofuels_for_Aviation_2017.pdf)

[57] http://greenfleet.dodlive.mil/energy/great-green-fleet/

What would different policy-level abatement scenarios look like?

The different policy ambitions relate to the achievement of different levels of biofuel penetration in aviation fuel in the future. For this study, these have been set at 7.5%, 10% and 20% by 2050 for the low, mid and high policy ambition, respectively. The assumed achievement under the high policy ambition scenario (20% penetration by 2050) represents a significant increase over the baseline assumption of 5% penetration. However, it is significantly lower than some more optimistic studies (such as that by Sustainable Aviation) have suggested.

The fuel consumption in 2050 under the central fuel price baseline assumption is approximately 11.75 million tonnes, so the baseline assumption of 5% biofuel penetration by that date represents a biofuel requirement of 587,000 tonnes. Similarly, the 20% penetration under the high policy ambition assumptions represents a requirement of 2.35 million tonnes of aviation biofuels. The DfT report on biofuels supplied in the UK under the RTFO between April 2016 and April 2017[58] shows that 423 million litres (approximately 355,000 tonnes) of biofuels were supplied in that period, with 165 million litres (approximately 138,600 tonnes) considered to be sustainable. These values include imports as well as UK production and are of similar magnitudes to the aviation biofuel requirement in 2050 under this policy measure, providing confidence that the supply requirements could be met in that timeframe.

Although the E4Tech (2014) report indicated a range of savings in CO_2 emissions from the use of biofuels, the analysis of this policy measure has retained the 50% value used in the baseline. Therefore, the CO_2 abatement due to biofuels would reach 3.75%, 5% and 10% by 2050, giving increases of 1.25%, 2.5% and 7.5% compared to the baseline.

Main costs/benefit impact areas

There are a number of costs that may be incurred to increase the penetration of biofuels in aviation. These include the costs of setting up demonstration processing plants, scaling up to full production capability and the costs of feedstocks. All of these would feed through to a higher price of biofuels (compared to conventional aviation fuel). For this study, the costs have been calculated using the "minimum fuel selling price" projections for the "n^{th}" plant (i.e. once the initial technology development costs have been amortised) from the Utrecht University report, which includes the recovery of the investment costs. To avoid double counting, the investment costs have not been included in the cost calculations.

When analysing this measure, it has been assumed that the biofuel content of aviation fuel will not be subject to carbon pricing. Therefore, the reduction in the carbon costs contributes to offsetting the increase in fuel purchase costs due to the inclusion of biofuel content.

Barriers to take up and the cost of overcoming them

The use of blends of biofuels and conventional fuel (kerosene) is already accepted in aviation, provided that any blend meets the existing standard specification (the biofuels used in the aviation sector must be "drop-in" fuels). There are, therefore, no technical barriers to using such fuels in aircraft.

The main barriers to the wider use of biofuels in aviation are sourcing feedstocks that can be classified as "sustainable", which requires that they do not interfere with the normal food chain, and the investment in demonstration and production facilities, together with the certification process. The additional certification and production costs associated with these will lead to biofuels having a significantly higher price than conventional fuels. The Utrecht University report suggests additional investment and production costs in Europe of about €5 billion per year by 2030 under a "Delayed Action" scenario, corresponding to a penetration of approximately 7%.

The timeframe over which the measure would be expected to have an effect

Whilst an increased penetration of biofuels could begin soon after a policy measure was put in place (for example, as a result of credits being available under the RTFO), the ramp-up to higher levels of penetration is likely to take a number of years, due to the level of investment required in new production facilities and the time required for certification of new fuels. Therefore, most of the impact of the policy measure is likely to be seem later in the period to 2050.

[58] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/567173/rtfo-year-9-report-1.pdf

The penetration level of biofuels would be expected to continue to grow to 2050 and beyond. At some point, it is likely that biofuels will become economically competitive with conventional kerosene, particularly if all conventional kerosene use is subject to carbon pricing and biofuels are not. However, given the significant uncertainties regarding future biofuel costs, it is not clear how long it will be before this occurs. Until then, the continued increase in biofuel penetration would continue to require policy action, either in the form of financial support or a mandated minimum level.

Potential for carbon leakage

Although much of passenger transport is anticipated to move away from liquid fuels, particularly towards electrification, this is less likely for heavy goods vehicles (HGVs). Therefore, there may be some competition between the aviation and HGV sectors for biofuel supplies, potentially leading to a reduced availability for biodiesel for HGVs if there is increased policy support for aviation biofuels. Although this would not represent a true form carbon leakage, if defined as an increase in another countries carbon emissions, it does represent a reduced capacity for carbon abatement in another sector as the result of the policy measure. There may also be strong competition for biofuel feedstocks, not only from other transport sectors in the UK, but also from the aviation sector in other countries and the chemical and energy generation sectors. Again, a strong demand for these feedstocks for UK aviation may lead to reduced availability for biofuel production in other countries.

4.7.1 Implementation in the DfT aviation model

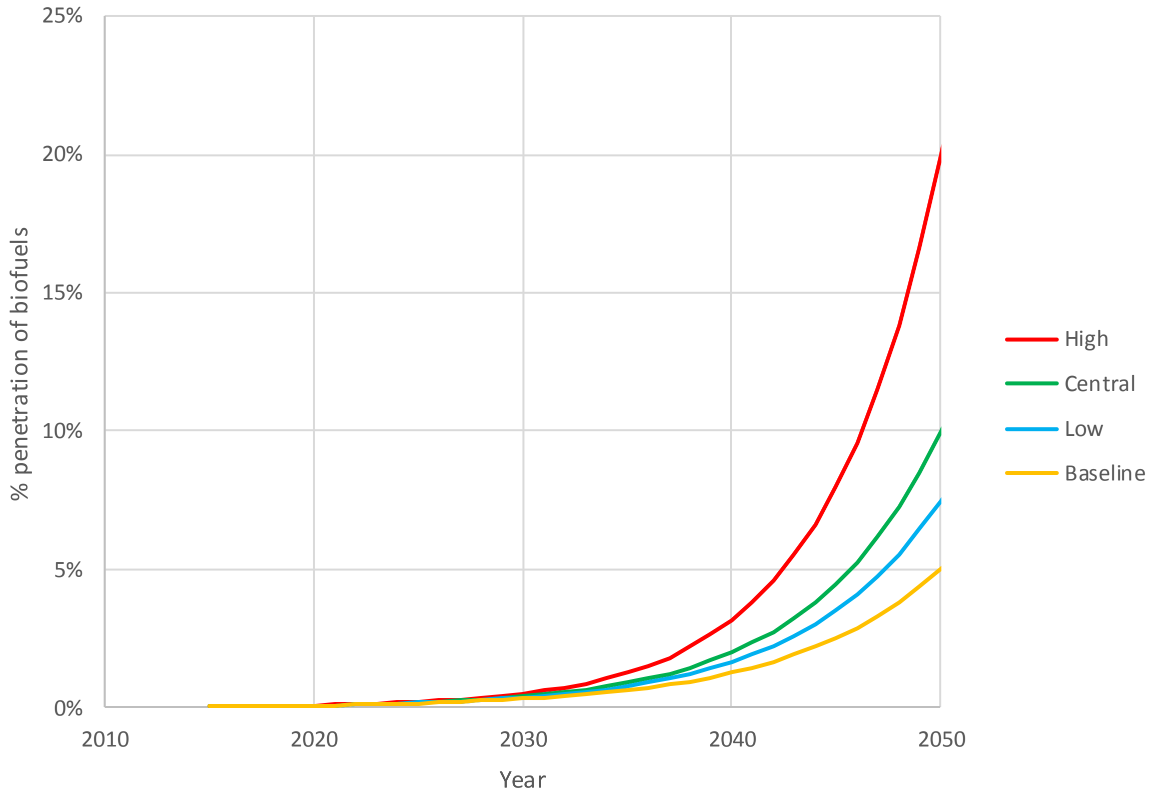
The existing DfT aviation CO_2 model includes an assumption of a 5% penetration of biofuels in aviation fuel demand by 2050. This assumption has been reviewed as part of this study. A 10% penetration by 2050 was considered a likely scenario in the CCC report, whereby they assumed land constraints and limited progress in developing commercially viable biofuels production using residue and waste or algae. The studies by E4Tech and Utrecht University suggested a baseline situation lower than this. Following discussions with DfT, it was decided to retain the existing baseline assumption for this study.

Total aviation fuel demand in 2050 has been forecast at approximately 15 million tonnes by DfT[59], so a 10% penetration would require 1.5 million tonnes of biofuel. This is generally consistent with other published values, such as the 3.3 million tonnes E4Tech estimated to be required for 25% penetration. The policy measure will result in higher penetration of biofuels due to government investment. The central policy ambition scenario assumes an increase to 10% penetration by 2050, with the low and high ambition scenarios increasing to 7.5% and 20% respectively.

The high ambition case is consistent with the more optimistic scenarios that have been published by the CCC (a 20% penetration by 2050 under the ‘optimistic’ scenario) and the IEA (a 25% penetration by 2050 under the IEA BLUE Map scenario. The CCC have also published a ‘speculative’ scenario with a 30% penetration; however, this target was considered to be too optimistic given the land use and technological issues mentioned above.

[59] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223839/aviation-forecasts.pdf

Figure 4-6: Penetration of biofuels by 2050 for baseline and policy ambition scenarios



A key assumption in the current baseline is that biofuels have CO_2 savings of 50%. As mentioned above, the range of savings from different feedstocks varies significantly. Advanced biofuel technologies, especially biomass-to-liquid (BTL) and algae-based fuels, could have significantly greater savings than conventional biofuels, reaching up to 95% CO_2 savings. The E4Tech (2014) report states that Sustainable Aviation members are committed to sustainable aviation fuels, with a target of reducing CO_2 emissions by at least 60% compared to fossil kerosene. Furthermore, such a value is in line with the expectations established in the EU Renewable Energy Directive, which requires 50% currently, rising to 60% on the 1st January 2018. However, discussions with DfT determined a strong preference for retaining the existing assumption of a 50% CO_2 saving, as they felt that the strength of evidence was insufficient to warrant departing from the current assumption at this time. Therefore, the 50% value was used in the analyses performed.

Table 4-13: Changes to biofuel penetration by policy ambition

Policy Ambition Scenario	Biofuel penetration
Low	7.5% penetration
Central	10% penetration
High	20% penetration

4.7.2 Costs

The costs from biofuels have been calculated as the additional spend on fuel by airlines. The price of A-1 jet fuel was obtained from the projections by BEIS to 2050 and beyond. The price of aviation biofuel was identified from a review of available literature. The Utrecht University report provided predictions of biofuel costs for a range of feedstocks, as well as calculating a renewable jet fuel premium (RJFP), which gives the price of biofuel above that of A-1 jet fuel. The values obtained from the report were converted to £ per tonne of biofuel and used with all three fuel price scenarios, as shown in Table 4-14.

Table 4-14 Biofuel premium over kerosene (derived from Utrecht University report, 2017) and effective biofuel price

Year	Biofuel premium (£/tonne)	Effective biofuel price		
		Low fuel price scenario	Central fuel price scenario	High fuel price scenario
2015	503	728	789	894
2020	503	728	901	1067
2025	413	737	917	1151
2030	768	1182	1370	1671

However, the IRENA report also indicated that biofuel prices are very dependent on the feedstock and production process, so there is significant uncertainty around these price assumptions. The price of biofuels was estimated between 2020 and 2030 using these references; outside this period, the premium was set equal to that in 2020 (for years up to 2020) and that in 2030 (for years beyond 2030).

4.7.3 Uncertainties

The CO_2 abatement calculations for this policy measure directly used the assumed biofuel penetration assumed for each policy ambition. Therefore, there is no uncertainty in those results (beyond that inherent in the baseline calculations).

It has been assumed that the costs of implementing this policy measure, such as the investment required to scale up production facilities and to ensure that land is available for growing feedstocks, would feed through to the price of the biofuels. The selection of the "minimum selling price" from a previous study on the cost of aviation biofuels should ensure that this is taken into account. Therefore, the uncertainty in the cost calculation for this policy measure relates to the accuracy of the projection of the price of biofuels.

5 CO_2 abatement results

The following tables and figures show the CO_2 abatement for flights departing from the UK estimated to be achieved by the policy measures against the baseline. The results from all three fuel price scenarios are presented, although there is only a small amount of variation in abatement between the three, as the baseline also changes under the fuel price scenario. The abatement values presented were calculated for each policy measure in isolation, by subtracting the total CO_2 emissions calculated for the policy case from those calculated for the baseline. They have not been discounted (though CO_2 abatement values may sometimes be discounted to reflect the additional benefits of early abatement).

The descriptions of the policy measures presented in Section 4 focused on the period up to 2050, with an assumption that all policy action would complete by that date. However, when calculating the cumulative costs and benefits it is important to recognise that the impacts of the policies could continue after that date. For example, the new aircraft types with improved fuel efficiencies (under the increased R&D policy measure) would continue to be produced and operated, giving benefits in emissions, well after 2050. Therefore, the total abatement and costs presented in the following sections have been calculated as cumulative values to 2065. For the central fuel price scenario, Table 5-1 also presents the abatement in the year 2050.

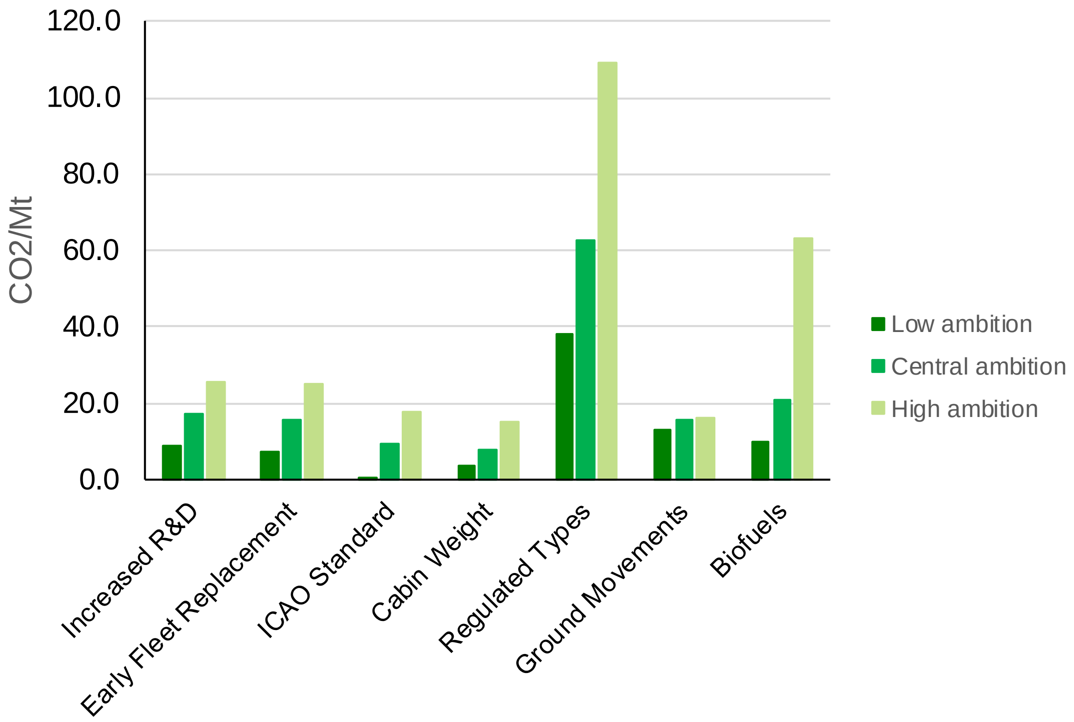
Table 5-1 CO_2 abatement for each policy measure under the central fuel price scenario in 2050 (all values in thousand tonnes of CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	389	33	8	98	1081	306	446
Mid	763	161	407	197	1720	385	893
High	1146	339	791	394	2876	401	2678

Table 5-2 Total CO_2 abatement for each policy measure under the central fuel price scenario to 2065 (all values in million tonnes of CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	8.7	7.3	0.2	3.8	37.9	13.1	10.1
Mid	17.1	15.7	9.1	7.6	62.8	15.3	21.0
High	25.7	24.8	17.7	15.1	109.0	16.4	63.1

Figure 5-1: Total CO_2 abatement to 2065 for each policy measure under central fuel price scenario



The CO_2 abatement achieved by the regulated types measure is estimated to exceed that of the other measures by a considerable margin, with 22.2 to 68.7 million tonnes of CO_2 being abated. This is primarily due to the assumptions made in the modelling of this policy measure, with the A380 aircraft type being replaced by the G16 type in 2026, as described in Section 4.5.1. Although the modelling approach was adjusted to make the effect more gradual and with a lower overall reduction, it still results in the calculation of very high abatement values. The early fleet replacement measure is estimated to have the next most significant abatement across all three ambition levels, although the high ambition biofuels measure comes close to matching it. The ICAO standard measure is estimated to deliver the least abatement, with the low policy ambition level being an order of magnitude lower than other policy measures. This estimated low level of abatement is due to the assumptions used to implement the measure in the modelling. These include the removal of certain aircraft types from production in 2040 (which has a limited effect due to the small number of aircraft types modelled as being in production at that point) and the technological improvements assumed for those aircraft types which enter production following the implementation of the new standard. The impact of this policy measure would be increased if the policy was assumed to impose even higher fuel efficiency standards on aircraft.

Table 5-3 Total CO_2 abatement for each policy measure under low fuel price scenario to 2065 (all values in million tonnes of CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	9.4	7.2	0.2	4.0	39.1	14.0	10.9
Mid	18.4	15.7	9.8	8.1	66.3	16.5	22.8

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
High	27.6	24.8	19.1	16.2	115.5	17.6	68.3

Figure 5-2: Total CO_2 abatement to 2065 for each policy measure under the low fuel price scenario

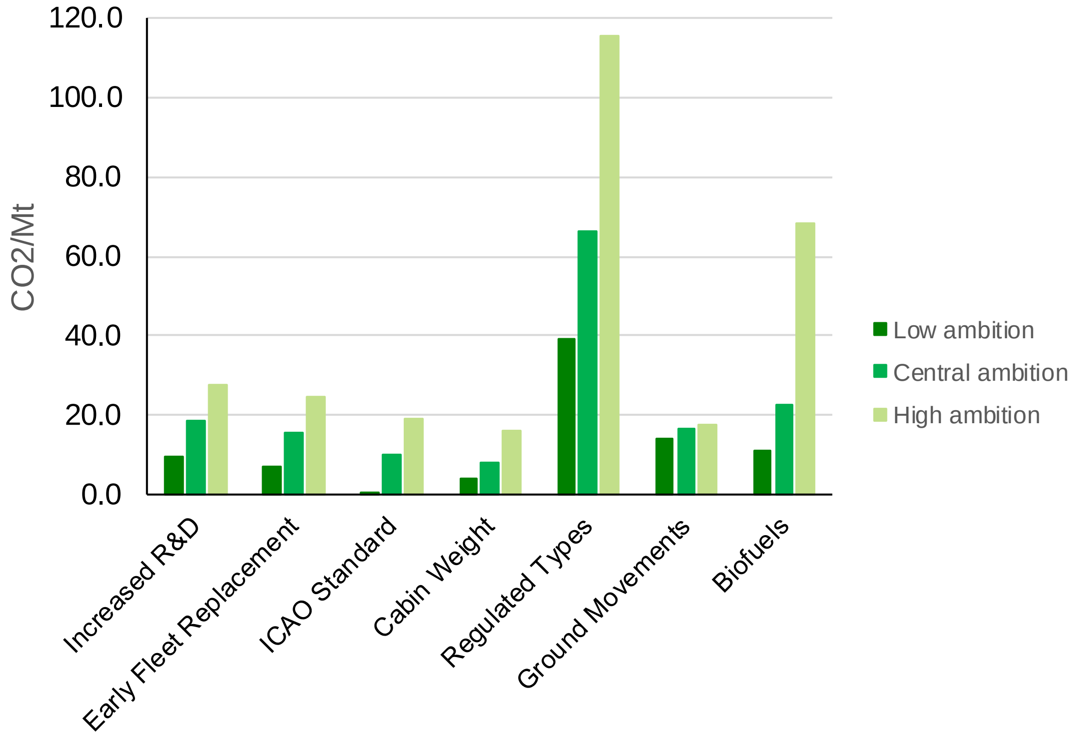
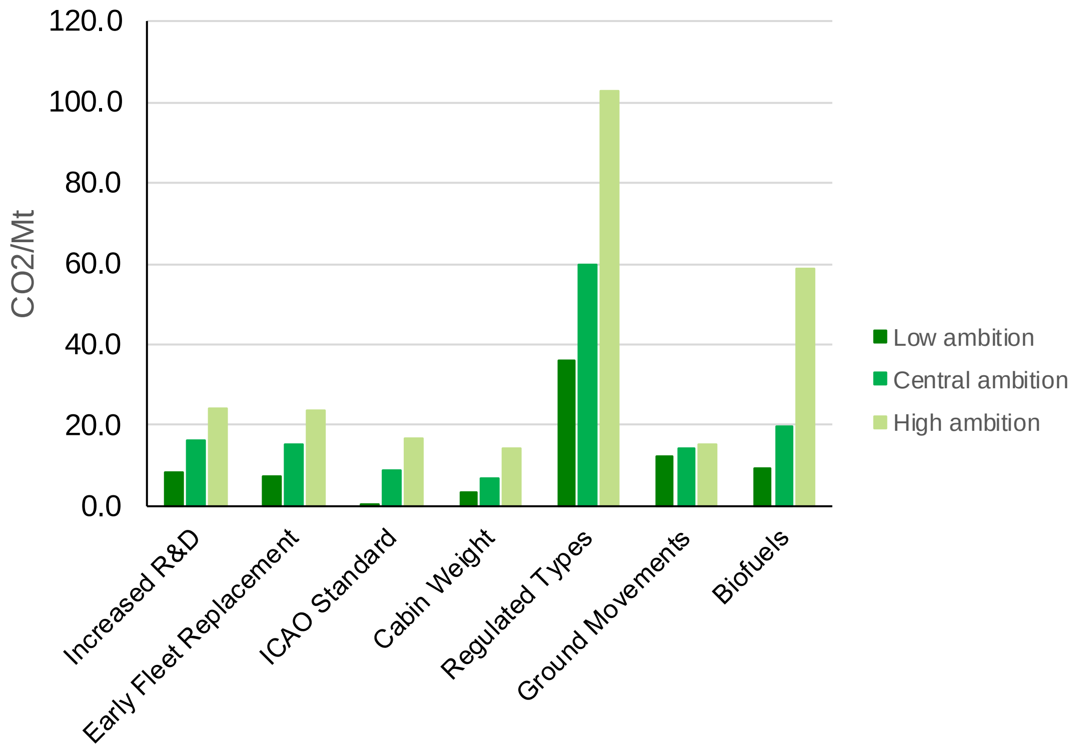


Table 5-4 Total CO_2 abatement for each policy measure under high fuel price scenario to 2065 (all values in million tonnes of CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	8.3	7.1	0.1	3.5	36.3	12.2	9.5
Mid	16.2	15.2	8.6	7.1	59.6	14.3	19.7
High	24.3	23.8	16.7	14.1	102.9	15.3	59.0

Figure 5-3: Total CO_2 abatement to 2065 for each policy measure under the high fuel price scenario



6 Policy measure costs

This section presents the total costs for implementing each policy measure under low, mid and high levels of policy ambition. The costs have been split into implementation, fuel and carbon price costs, and are presented for the low, central and high fuel price scenarios. The implementation costs include elements such as increased spend on R&D, increased aircraft acquisition costs (due to changes in fleet renewal patterns), etc. The effects of the policy measures on fuel and carbon price costs are usually negative as most policy measures result in reduced fuel consumption (the increased biofuels policy measure does not lead to any change in fuel consumption, but the life-cycle emissions are reduced and the fuel costs increase as a result of the partial replacement of the fossil fuel). Most of the costs occur over a period of time from 2017 through to 2050 (and beyond for some policy measures), so the costs have been calculated for each year to 2065 and then discounted back to 2017. The discount rates used are 3.5% up to 2047 and 3.0% from 2047.

The costs elements presented here (excluding the change in carbon costs) are used to derive the cost effectiveness results presented in Section 7.

6.1 Implementation costs

6.1.1 Central fuel price scenario

The implementation costs under the central fuel price scenario are presented in Table 6-1. The increased R&D measure has the highest implementation costs (£37,598m to £112,795m) due to the magnitude of spending required to increase aircraft efficiency. The regulated types measure is also very costly (£13,872m to £86.768m) due to the large number of aircraft replacements required (the increased value of the aircraft being sold as they are removed from UK operations is also included in this calculation). Comparatively, the implementation costs of the improved CO_2 standard measure is very small (£21m to £33m) as there are limited impacts on the fleet mix and they only occur after 2040 where costs are heavily discounted.

The low policy ambition for the more efficient ground movements measure is assumed to have zero cost, as its implementation only requires additional guidance and encouragement to airlines and airports to implement reduced-engine taxiing more widely. There would be some costs associated with this work but they are assumed to be negligible. The implementation costs for the increased biofuels measure are zero under all levels of policy ambition as it is assumed that the investments in new plants would be recovered through the price premium on biofuels, so these costs are set to zero to avoid double counting.

Table 6-1 Total implementation costs to 2065 (discounted), central fuel price scenario (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	37,598	7,245	21	373	13,872	0	0
Mid	75,196	14,363	-24	746	26,116	1,432	0
High	112,795	18,808	33	1,492	86,768	1,522	0

6.1.2 Low fuel price scenario

The implementation costs under the low fuel price scenario, shown in Table 6-2, are slightly higher for most policy measures than the central fuel price scenario. This is due to a lower fuel price resulting in greater demand, and hence more aircraft replacements which affects several policy measures. The implementation costs for the increased R&D policy measure are independent of the fuel price assumptions, as they relate to the costs of developing the technology to deliver the required improvements in fuel efficiency.

Table 6-2 Total implementation costs to 2065 (discounted), low fuel price scenario (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	37,598	7,624	23	396	14,470	0	0
Mid	75,196	14,972	-26	792	27,482	1,534	0
High	112,795	19,577	35	1,584	92,662	1,617	0

6.1.3 High fuel price scenario

The implementation costs under the high fuel price scenario, shown in Table 6-3, are slightly lower for most policy measures than the central fuel price scenario. This is due to the lower demand (as a result of the high fuel price) leading to fewer replacement aircraft being required, which affects several measures.

Table 6-3 Total implementation costs to 2065 (discounted), high fuel price scenario (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	37,598	6,910	20	378	13,147	0	0
Mid	75,196	13,827	-22	755	24,383	1,354	0
High	112,795	18,377	31	1,511	81,067	1,427	0

6.2 Fuel and carbon price costs

This section presents the changes in fuel costs and carbon costs resulting from the policy measures. In line with BEIS guidance[60], the calculations of the cost-effectiveness values presented in Section 7

[60] Department for Business, Energy and Industrial Strategy Valuation of Energy Use and Greenhouse Gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government, 2017. Available at:

include only the implementation costs and the changes in fuel costs and do not include the changes in carbon costs. The changes in carbon costs are, therefore, presented in this section for completeness.

6.2.1 Central fuel price scenario

The total difference in fuel costs between the policy measures and the baseline is presented in Table 6-4. The regulated types measure has a significantly higher difference in fuel costs (-£3.953m to -£10,803m) than other policy measures due to the severe impact on in service aircraft. The increased biofuels measure has a positive difference in fuel costs (£1,338m to £8,494m), as biofuel is more expensive than conventional fuel. The improved CO_2 standard measure has a very small difference in fuel costs as the impact is relatively small and the fuel savings occur only after 2040 when the costs are heavily discounted.

Table 6-4 Total difference in fuel costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-716	-818	-13	-379	-3,953	-1,378	1,338
Mid	-1,404	-1,730	-749	-758	-6,218	-1,580	2,822
High	-2,110	-2,704	-1,454	-1,515	-10,803	-1,700	8,494

The difference in carbon price costs between the policy measures and the baseline are presented in Table 6-5. The difference in carbon price costs are similar (in absolute and relative magnitude) to the difference in fuel costs across all policy measures. However, the increased biofuels measure is very different as the carbon price only applies to conventional fuel (biofuel is assumed to have no carbon price) and hence there is a reduction in carbon price costs of -£1,546m to -£9,621m.

Table 6-5 Total difference in carbon price costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-638	-443	-12	-246	-2,413	-778	-1,546
Mid	-1,252	-967	-668	-492	-4,131	-937	-3,198
High	-1,880	-1,534	-1,296	-985	-7,223	-995	-9,621

6.2.2 Low fuel price scenario

The difference in fuel costs under the low fuel price scenario, shown in Table 6-6, are slightly lower than under the central fuel price scenario for all policy measures, except for increased biofuels where the positive difference is increased.

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https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/615374/1._Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2016.pdf

Table 6-6 Total difference in fuel costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-540	-565	-10	-282	-2,810	-1,004	1,553
Mid	-1,060	-1,201	-565	-563	-4,532	-1,156	3,275
High	-1,592	-1,880	-1,098	-1,126	-7,921	-1,243	9,849

The difference in carbon price costs are slightly lower under the low fuel price scenario, shown in Table 6-7, than under the low fuel price scenario as the carbon price also decreases.

Table 6-7 Total difference in carbon price costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-324	-217	-6	-127	-1,194	-402	-789
Mid	-637	-474	-340	-255	-2,110	-483	-1,635
High	-956	-751	-660	-509	-3,699	-514	-4,920

6.2.3 High fuel price scenario

The difference in fuel costs under the high fuel price scenario, shown in Table 6-8, are slightly greater than under the central fuel price scenario for all policy measures, except for increased biofuels where the positive difference is reduced.

Table 6-8 Total difference in fuel costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-1,003	-1,188	-16	-525	-5,610	-1,898	1,100
Mid	-1,966	-2,491	-1,047	-1,050	-8,784	-2,175	2,321
High	-2,953	-3,867	-2,030	-2,100	-15,165	-2,340	6,998

The difference in carbon price costs are slightly higher under the high fuel price scenario, shown in Table 6-9, than under the central fuel price scenario as the carbon price also increases.

Table 6-9 Total difference in carbon price costs to 2065 (discounted) for each policy measure against baseline (all values in £ millions)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	-923	-650	-15	-349	-3,509	-1,099	-2,212
Mid	-1,810	-1,404	-964	-698	-5,944	-1,322	-4,574
High	-2,718	-2,212	-1,870	-1,397	-10,334	-1,404	-13,764

7 Cost-effectiveness results

The cost effectiveness for each policy measure is calculated by dividing the total costs by the CO_2 abatement achieved on flights departing the UK. Policy measures with a high numerical values (i.e. where costs per tonne of CO_2 abated are large) are less effective than those with a low or negative values (negative values relate to a cost saving per tonne of CO_2 abated).

For some policy measures, the implementation of the measure would be expected to contribute to reductions in CO_2 emissions from flights to the UK from overseas and from non-UK flights, neither of which are included in this study. For example, the increased R&D and improved CO_2 standard measures both lead to more fuel efficient aircraft being manufactured and available for use on these flights. Similarly, the early fleet replacement and reduced cabin weight measures would reduce emissions on flights to the UK from overseas; they could also contribute to reducing emissions on non-UK flights if the airline decided to improve its total fleet as a result, although they would not be required to do so. If these additional reductions in emissions were included in a study of this nature, the cost-effectiveness of some of these measures (particularly the increased R&D and improved CO_2 standard) could be improved significantly.

Section 5 presented the estimated CO_2 abatement results, while Section 6 presented the calculated effects of the policy measures on costs, including the implementation costs, the change in fuel costs and the change in carbon costs. In line with BEIS guidance[61], the cost-effectiveness values presented in this section include the implementation and fuel cost changes, but not the changes in carbon costs.

Table 7-1 presents the estimated cost effectiveness values for each policy measure that are estimated to be achieved under the central fuel price scenario. The increased R&D measure is the least cost effective option (i.e. it has the highest cost-effectiveness value) by at least one order of magnitude when compared to the other options. This is primarily related to the policy measure involving the UK funding research at very high levels (representing an increase over the normal total level of funding across Europe), but only recognising the benefit on flights departing the UK. As a result of the improved fuel efficiency of new aircraft, there would also be benefits in reduced emissions from other flights (both flights from overseas to the UK and non-UK flights). The mid and high policy ambition variants of the improved CO_2 standard measure have negative cost effectiveness values, due to the improvements in efficiency of new aircraft types from the technologies introduced to meet the standard. The more efficient ground movements measure is very cost effective under all policy ambition levels (negative cost effectiveness indicators for all three levels) but is most cost effective (i.e. gives the greatest cost savings) under the low policy ambition (in which CO_2 abatement is achieved through reduced engine taxiing which has no implementation cost).

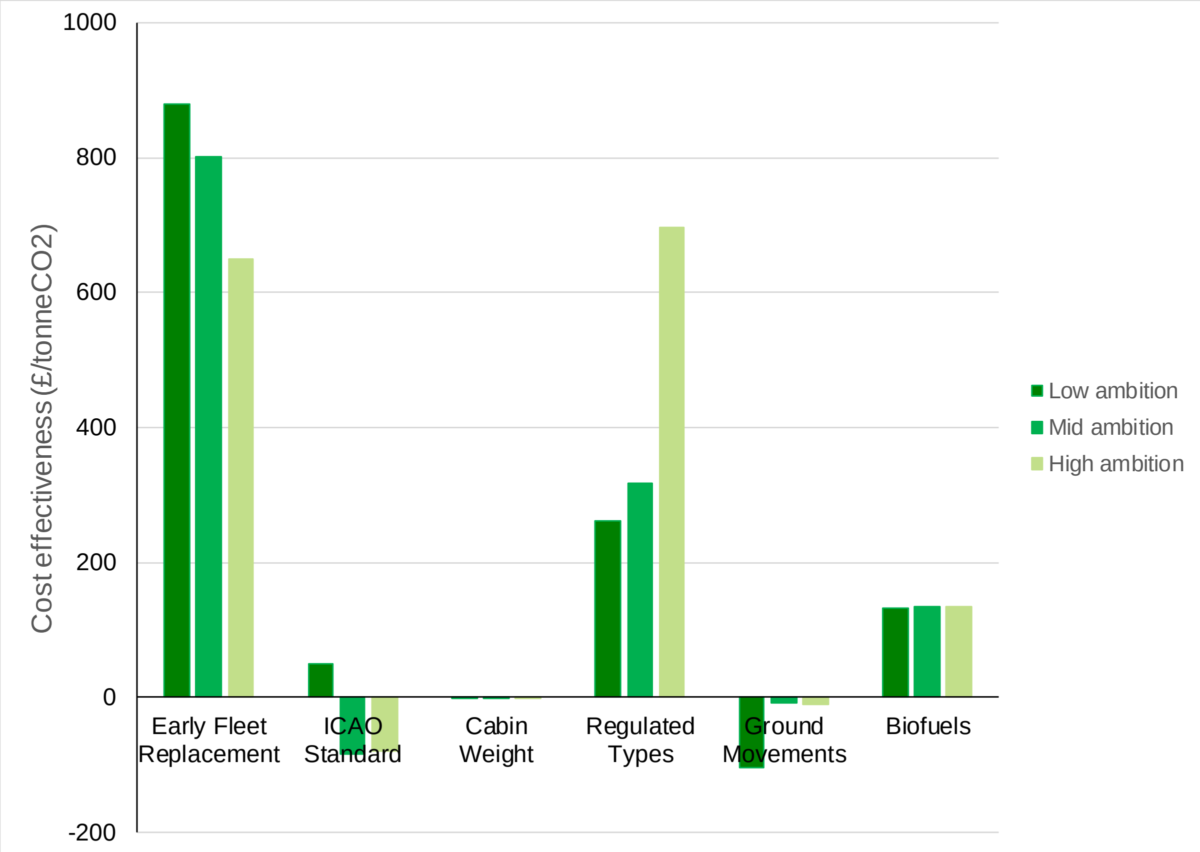
Table 7-1 Cost effectiveness, central fuel price scenario (all values in £/tonne CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	4232	880	50	-2	262	-105	132
Mid	4317	802	-85	-2	317	-10	134
High	4311	649	-80	-2	697	-11	135

Figure 7-1 shows the cost effectiveness of all measures except increased R&D (which is removed due to the difference in magnitude of the results).

[61] Department for Business, Energy and Industrial Strategy Valuation of Energy Use and Greenhouse Gas: Supplementary guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government, 2017. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/615374/1._Valuation_of_energy_use_and_greenhouse_gas_emissions_for_appraisal_2016.pdf

Figure 7-1: Cost effectiveness, central fuel price scenario (increased R&D is not presented due to the significant difference in magnitude; all values in £/tonne CO_2)



The policy measure relating to the ICAO standard has a very low cost effectiveness for low ambition but a high cost effectiveness for the mid and high policy ambition levels. This is a result of the technology-forcing nature of the standard at the mid and high policy ambition levels, which results in greater reductions without increasing costs.

The cabin weight measure has the same cost effectiveness at all policy ambition levels, as the amount of CO_2 abatement achieved is directly proportional to the uptake of lightweight seats. All three policy ambition levels have a (small) negative cost effectiveness value, suggesting that light-weighting is a cost effective option for reducing emissions. Based on such a result, it might be expected that the technology would be adopted widely, even in the absence of policy action. However, it should be noted that these cost-effectiveness values have been calculated using discount rates that are appropriate for policy appraisal. For commercial organisations, such as airlines, analyses for investment decisions are more likely to use higher discount rates, which would lead to positive cost-effectiveness values being calculated. Similarly, the increased biofuels policy measure gives cost-effectiveness values that vary only slightly with policy ambition. However the biofuels measure has a positive cost effectiveness value and is therefore less cost effective than lightweighting.

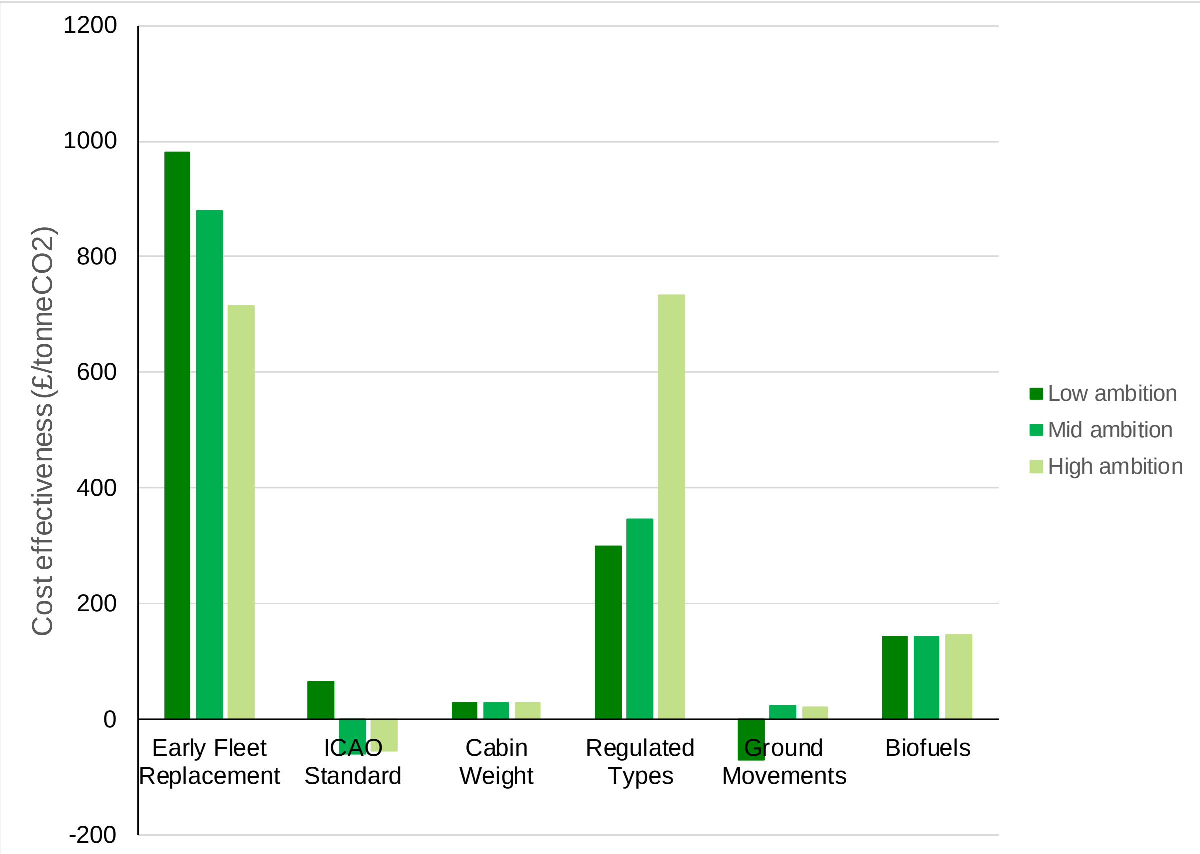
The regulated types measure has a large cost effectiveness value at all levels of ambition, due to the significant changes in aircraft replacement required. The measure becomes even less cost effective as the ambition increases which requires more significant aircraft replacement at greater cost.

The cost-effectiveness under the low fuel price scenario is presented in Table 7-2 and Figure 7-2. All policy measures are slightly less cost effective under the low fuel price scenario (most by 40 to 80 £/t CO_2), except for increased R&D which is more cost effective (by at least £800 £/t CO_2). Most policy measures see an increase in costs as demand (which increases as fuel price decreases) increases, which increases the number of replacement aircraft needed (which represents a large part of the costs). Furthermore, the low fuel price means that the value of the fuel and carbon price savings are reduced. However, increased R&D is not affected from an increase in replacement aircraft and therefore the costs remain constant but the CO_2 abatement achieved increases.

Table 7-2: Cost effectiveness, low fuel price scenario (all values in £/tonne CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	3956	980	65	28	298	-71	142
Mid	4029	879	-60	28	346	23	144
High	4025	714	-56	28	734	21	144

Figure 7-2: Cost effectiveness, low fuel price scenario (increased R&D is not presented due to the significant difference in magnitude; all values in £/tonne CO_2)

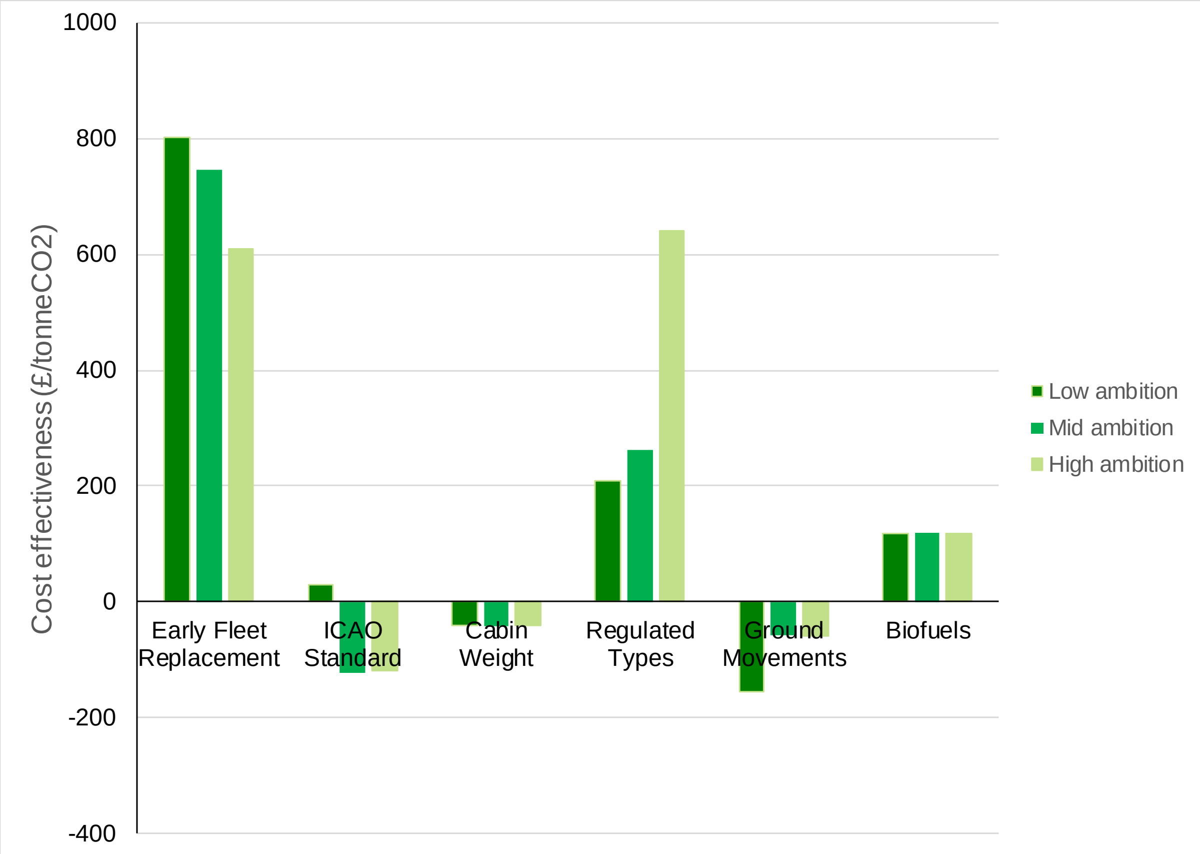


The cost effectiveness under the high fuel price scenario is presented in Table 7-3 and Figure 7-3. The reverse effect is seen compared to the change between central and low fuel price scenarios, with most policy measures becoming more cost effective. The increased fuel price results in a greater cost saving from the CO_2 abatement, while demand decreases which reduces the implementation costs. The increased biofuels measure reaches a negative cost effectiveness value, as high fuel and carbon prices make biofuels (which do not have a carbon price) cheaper than conventional fuel.

Table 7-3: Cost effectiveness, high fuel price scenario (all values in £/tonne CO_2)

Policy ambition	Increased R&D	Early Fleet Replacement	Improved CO_2 Standard	Reduced Cabin Weight	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Low	4432	802	29	-42	208	-156	116
Mid	4525	745	-124	-42	262	-58	118
High	4519	610	-120	-42	640	-60	119

Figure 7-3: Cost effectiveness, high fuel price scenario (increased R&D is not presented due to the significant difference in magnitude; all values in £/tonne CO_2)



8 Policy measure interactions

This section presents some indications of the extent of interactions between policy measures that might need to be taken into account when generating the MAC curves.

The analyses of the abatement due to the different policy measures reported above has assumed that they have each been applied in isolation. For the construction of the MAC curves, it is necessary to consider the abatement that would occur when a policy measure is applied in combination with one or more other measures. In some cases, the policy measures may be considered as independent, meaning that the application of one policy measure does not affect the abatement from another. It should be noted that, when calculating abatement from multiple policy measures in this way, the abatements (in millions of tonnes) are not summed, but the percentages of the baseline emissions that remains after abatements are multiplied together to give a percentage that remains after multiple measure are applied[62].

When analysing policy measures to create MAC curves, it is possible to identify pairs of measures that are mutually exclusive. In such cases, it is not possible to create MAC curves that contain both policies within such pairs. In the current study, it is considered that there are no such pairs of mutually exclusive measures.
Table 8-1 presents pairs of policy measures and the expectation of the extent of any interaction between them. In the majority of cases, the measures are regarded as being independent and no factor would need to be applied. For the other combinations, DfT has performed some calculations including the application of multiple policy measures to identify the magnitude of factors that should be applied.

[62] Thus, if policy measures with abatements of 10% and 20% are applied together, the emissions that remain when both are applied are 90% * 80% of the baseline, giving 72% of the baseline remaining with both measures in place and an abatement of 28%. This is less than the abatement that would be obtained if the two individual abatements were added (to give 30% abatement).

Table 8-1 Anticipated interactions between pairs of policy measures

	Increased R&D	Early Fleet Replacement	Reduced Cabin Weight	Improved CO_2 Standard	Regulated Types	More Efficient Ground Movements	Increased Biofuels
Increased R&D		Interaction	Independent	Interaction (small effect)	Interaction (small effect)	Independent	Independent
Early Fleet Replacement	Interaction		Independent	Interaction	Interaction (small effect)	Independent	Independent
Reduced Cabin Weight	Independent	Independent		Independent	Independent	Independent	Independent
Improved CO_2 Standard	Interaction (small effect)	Independent	Independent		Interaction (may zero effect of CO_2 Standard)	Independent	Independent
Regulated Types	Independent	Interaction	Interaction	Interaction (small effect)		Independent	Independent
More Efficient Ground Movements	Independent	Independent	Independent	Independent	Independent		Independent
Increased Biofuels	Independent	Independent	Independent	Independent	Independent	Independent	

9 Conclusions

A study has been performed by Ricardo Energy & Environment, together with our partners SYSTRA Ltd., Gaia Capital Ltd., Michael Mann, Bethan Owen and Prof. David Lee, to assess policies that could be used to reduce carbon in UK aviation and to provide the cost and abatement data needed for DfT to produce updated marginal abatement cost (MAC) curves for the UK aviation sector.

The aim of the study was not to recommend future Government policy, but to assess a range of measures that could be implemented in the future depending on the aims, objectives and priorities of the Government at the time. Although the report considers polices that are considered technically feasible, based on discussions with DfT and other Government Departments, and a high level description of each is provided, detailed consideration has not been given to the precise mechanisms by which they would be implemented.

The assessment of the abatement produced by the policy measures used the DfT aviation modelling framework. The assumptions included in the baseline calculations (those representing the case in which there is no further policy action) were reviewed and recommendations were made for updates to be made to the calculation. These were implemented by the DfT and the updated model was used for the baseline and policy measure calculations using the model.

Three baseline calculations were used in the study, based on low, central and high forecasts of oil and carbon prices, as published by BEIS.

A number of policy measures were considered for this study. They were assessed for their feasibility and those that were considered feasible were taken forward to the quantitative analysis. In each case, three levels of policy ambition (low, mid and high) were assessed. The policy measures analysed in this manner were:

- Increased R&D in more efficient engines and aircraft
- Early fleet replacement with more fuel-efficient aircraft
- Improvements to the ICAO CO_2 emissions standard
- Reduced aircraft cabin weight
- Regulation of aircraft types operating from UK airports
- More efficient ground movements
- Increased use of biofuels

The potential impact of these policy measures on the CO_2 emissions from flights departing from the UK was identified and supplied to DfT for inclusion in the aviation modelling framework. The model then calculated the emissions in future years so that the abatement could be derived.

The approach to implementing the impact of the different policy measures included changes to the assumed fuel efficiency of future aircraft types, changes in the assumed retirement ages, changes to the years in which aircraft types were phased out of UK operations and changes to the CO_2 factors applied to the fuel consumption.

The calculation of the costs of the measures included implementation costs (such as the cost of the increased R&D or the increase in aircraft acquisition costs), the change in fuel costs and the change in the costs of carbon. In most cases, the policy measure led to a reduction in fuel consumption, giving negative changes in fuel and carbon costs.

The CO_2 abatement, implementation costs and fuel costs were used to calculate cost effectiveness values for each policy measure. Following guidance published by BEIS, the reduction in the costs of carbon was not included in the calculation of cost-effectiveness. The cost effectiveness values were based on total (discounted) values between 2017 and 2065.

The increased R&D measure was found to have a poor cost-effectiveness. This is primarily due to the UK bearing all the costs of the measure, but only identifying a small part of the benefits (as the more efficient aircraft types would be sold and used globally).

The early fleet replacement and regulation of aircraft types policy measures also gave high cost-effectiveness values, due to the high costs incurred by airlines in acquiring additional aircraft. The abatement under the policy measure for the regulation of aircraft types was the highest of all the measures considered, but the airline costs were also very high.

The policy measure related to the increased use of biofuels was found to have a good cost effectiveness if the reduction in the costs of carbon was included in the calculation, but was less good when it was not (in line with BEIS guidance). This was because the biofuels were assumed to be more expensive than fossil-fuel-based kerosene, but they were also assumed to be exempt from carbon pricing.

The policy measure related to an improved ICAO CO_2 standard was found to have a good cost-effectiveness, but there is considerable uncertainty regarding the ability of the UK to unilaterally cause such an improved standard to be agreed.

The policy measures on reduced cabin weight and more efficient ground movements were also found to have good cost-effectiveness as the overall costs are low (or even negative due to the savings in fuel cost) and the abatement of CO_2 emissions is similar to most of the other measures.

As well as having different values of cost-effectiveness, as calculated using the assumptions employed in this study, it is clear that there are differing levels of uncertainty around the implementation and results of the policy measures. The implementation of the increased R&D policy measure would depend on the research community and aerospace industry responding to the policy and increased funding, giving an uncertainty around the ability to implement the aims of the policy. Equally, research is an uncertain process and it is not certain that an increase in research efforts, in line with the increased funding described in this report, would deliver the improvements in fuel efficiency assumed in this study.

There is also significant uncertainty around the ability of the UK to achieve a significant improvement in the international CO_2 standard by unilateral (or even collaborative) action within ICAO.

The policy measures that would be implemented through action by airlines, such as the early fleet retirement or the reduced aircraft cabin weight measures, could bring challenges in implementation, especially as many of the airlines that would be affected are not registered in the UK.

Other policy measures, such as the more efficient ground movements or increased biofuels measures, are more likely to deliver the expected results in reduced fuel consumption and/or reduced net CO_2 emissions when implemented. They are also likely to be easier to implement through unilateral policy action by the UK, as they depend less on international collaboration.

The cost and abatement results from the analyses have been supplied to DfT for incorporation into the update MAC curves under development. These updated MAC curves will be reported separately by DfT.

A.1 Annex 1 – Analysis of baseline assumptions

The following table presents the full review of the baseline assumptions from the DfT aviation CO_2 modelling system. This review was based on the calculations for the 2016 aviation forecasts. Many of the recommendations (including that parameters should be confirmed as using the latest values) were implemented in the calculations performed for the 2017 aviation forecasts.

Table 9-1 Assumptions identified from DfT baseline model and recommendations for changes (where appropriate)

Model	Assumption	Reference	Value (where available)	Recommendation
Passenger Demand Model	Carbon allowance prices	Section 3.14-3.15 in 2013 Aviation forecast (2012 DECC Forecast) Model parameters tab	• Model values updated Mar31 2016 - £20.3/tCO_2e in 2012, £250 in 2030, increasing to £719 by 2050	DfT has confirmed that these values have been updated using the latest data. It was noted that these values were derived to be the cost per tonne of *carbon*, rather than per tonne of *carbon dioxide* (CO_2). As a result, they are significantly higher than published prices, which are usually per tonne of CO_2.
Passenger Demand Model	Exchange rates	Section 3.12 in 2013 aviation forecast	1.6$ to the £ in 2017/18	DfT has confirmed that this value is updated using the latest data.
Passenger Demand Model	Air passenger Duty rates	Section 3.17 in 2013 Aviation forecast Parameters tab in model	See table 3.3 2013 Aviation Forecast	DfT has confirmed that these values have been updated using the latest data.
Passenger Demand Model	Oil prices	Section 2.33 in 2011 Aviation forecast Section 7.9 in 2013 Aviation forecast	2013 Forecast = $123 per barrel in 2030 (in 2008 prices)	DfT has confirmed that these values have been updated using the latest data.
National air passenger model	Airport capacities	Section 3.50-3.51 in 2013 aviation forecast	Key specific changes; • Birmingham runway extension adds 9% capacity and allows new destinations to be reached • Luton adds 35% to its runway capacity and 70% to its terminal capacity • Manchester independently operates its 2 runways and increases passenger capacity from 30m to 56m	DfT has confirmed that these values have been updated using the latest data.

Model	Assumption	Reference	Value (where available)	Recommendation
Fleet mix model/CO_2 Forecast model	New aircraft types	Sections 3.38-3.45 in 2013 Aviation Forecast Aircraft efficiency tab in model		• The model has been updated to include recommendations from the QinetiQ "Future Aircraft Fuel Efficiencies" study[63] • FMM has been updated with recently announced new aircraft types • No updates required for future aircraft types
Fleet mix model/CO_2 Forecast model	Fuel efficiency of new aircraft	Section 3.34 2011 Aviation forecast Box 3.3 2013 Aviation forecast Aircraft efficiency tab in model	See box 3.3 in 2013 aviation report	The modelling of the fuel efficiency of future aircraft types is unchanged from the values used during the 2011 study. Assessments of the assumptions in the model against published targets for future technology developments have shown that the existing assumptions are slightly conservative (i.e. represent lower improvements in efficiency than identified for the results of technology development projects (such as the Rolls-Royce 'UltraFan'). However, it is considered that they remain valid as they take account of the potential under-delivery of the research projects.
CO_2 Forecast model	Fuel efficiency modelling of aircraft types		Defined through coefficients for curve fits – specified in CO_2 Forecast model spreadsheet	It is recommended that the fuel burn modelling is updated to use fuel burn data from the most recent EMEP/EEA calculator (2016). See below for more details,
Fleet mix model/CO_2 Forecast model	Retrofit fuel efficiency improvement	Section 3.57 in 2013 Aviation forecast Aircraft efficiency tab in model	No efficiency gains	Although some in-service aircraft have been retrofitted (mainly with winglets) and more advanced options are likely to be fitted in the future (e.g. Sharklets on A320-series, split-scimitar on B737 family), it is unlikely that they will significantly affect the baseline fuel burn. It is recommended that the current assumption of no efficiency change in the baseline due to retrofits is retained. The policy measure related to retrofitting will need to consider just the additional retrofits that may be introduced as the result of interventions.
Fleet mix model/CO_2 Forecast model	Aircraft retirement ages	Table 3.12 2013 aviation report	22 years for Scheduled and No-Frills Carrier (NFC) categories; 25 years	The analysis of the base year air traffic movements (ATMs) presented in the review of the Fleet Mix Model (FMM) indicates that

[63] G.Horton Future Aircraft Fuel Efficiencies – Final Report, QinetiQ/10/00473, March 2010, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/4515/future-aircraft-fuel-efficiency.pdf

Model	Assumption	Reference	Value (where available)	Recommendation
			for Charter category. Some different values for individual aircraft types where more information is available.	some changes to the retirement age assumptions could be appropriate. Possible updates to the 'retirement age' were derived (based on the age for which 5% of ATMs were performed by aircraft older than this age): Scheduled: 26 years Charter: 21 years NFC: 17 years However, discussions with DfT established that the data from the FMM used for this analysis were not based on actual observations, but used a combination of some information on average ages (and standard deviations) together with assumptions. Therefore, it is recognised that the data used do not form a robust basis for recommendations for changes to the retirement ages (which have been found to have a significant effect on the results of the model). As a result, it is recommended that the existing retirement ages should continue to be used for this analysis, but that a more comprehensive investigation should be undertaken into aircraft ages, and the ages at which aircraft are removed from UK operations (and, potentially, sold to be used elsewhere in the world).
CO_2 forecast model	Load factors	Section 3.21 in 2013 aviation report Model spreadsheet LF Tab	See model spreadsheet LF tab, LF ceilings set at 80% for internal domestic flights, 80% for short haul flights, and 90% for long haul flights	IATA reports that European carriers achieved load factors of 82.8% on international flights in 2016[64]. Similar data are not available for domestic flights in Europe, but the overall value (domestic and international combined) for Europe is 82.4%, suggesting that the load factor for domestic flights is slightly lower than that for international flights. This would indicate that the current limits in the baseline remain realistic.
CO_2 forecast model	Route distances	Section C.31 in 2011 aviation report Sections 3.61-3.63 in 2013 aviation report Distances tab in model	See distances tab	The great circle distances in the tab do not require updating.

[64] http://www.iata.org/pressroom/pr/Pages/2017-02-02-01.aspx and http://www.iata.org/whatwedo/Documents/economics/passenger-analysis-dec-2016.pdf

Model	Assumption	Reference	Value (where available)	Recommendation
CO_2 forecast model	Airline (carrier) operational efficiency gains	Section 3.35 in 2011 aviation forecast Table 3.12 in 2013 aviation forecast Operational efficiency tab in model (Carrier efficiency)	No efficiency gains in Central baseline +0.25% change in efficiency p/a for low demand growth -0.25% change in efficiency p/a for high demand growth	The basis of the current efficiency changes in the DfT model is not fully clear. However, the magnitude of the efficiency improvements to 2050 (about 9%) is reasonable.
CO_2 forecast model	Air traffic management system efficiency gains	Section C.31 in 2011 aviation report Sections 3.61-3.63 in 2013 aviation report Operational efficiency tab and Great Circle Adj tab in model.	No efficiency gains	Air traffic management efficiency gains are unlikely to have changed
CO_2 forecast model	Great Circle Adjust	Section 3.22 in 2011 aviation forecast Section 2.55 in 2013 aviation forecast Great Circle Adj tab in model	8%	The great circle distance adjustment is used to increase flight distances (over the value for the most direct route) to represent the effects of the need to comply with ATC instructions, deviations due to weather, etc.). Evidence from a study by Ricardo (for the European Commission, DG MOVE) indicates that average extra distance flown (above the Great Circle Distance) is between 4.5% and 5% for flights in Europe[65]. Another study (Reynolds, 2009) indicated that the extra distance flown on North Atlantic routes was 5%, while the extra distance on typical Europe – SE Asia routes was 7%. Combining the results of these studies, we recommend that the "Great Circle Adjust" parameter is set to 5% for flights to/from Europe (including UK domestic) and 6% for flights to/from long-haul destinations.
CO_2 forecast model	Biofuel penetration rate (fuel factor)	Section 2.33 in 2011 aviation forecast Table 3.12 in 2013 forecast CO_2 Fuel Factor tab in model	1% biofuel use in 2030 rising to 5% by 2050, equating to 0.5% and 2.5% reduction in CO_2 emissions, respectively.	Sustainable Aviation (2012) projects sustainable biofuels penetration of 25-40% by 2050, whilst E4Tech (2014) states that biofuels may achieve 80-95% reduction in GHG emissions. At the same time, planned biofuel production capacity in the UK will not be developed. Based on the large differences in projected future biofuel use and emission saving potential between

[65] https://ec.europa.eu/transport/sites/transport/files/2017-03-06-study-on-options-to-improve-atm-service-continuity-in-the-event-of-strikes.pdf

Model	Assumption	Reference	Value (where available)	Recommendation
				the existing DfT assumptions and the E4Tech report, we recommend that the current assumptions on penetration of biofuels (5% by 2050) and life cycle CO_2 emission savings (50%) should be reviewed for future analyses. For the current study, we recommend that the existing assumptions are retained because of the uncertainty around the availability of the advanced biofuels needed to meet the E4Tech projections.
CO_2 forecast model	ICAO CO_2 standard	The current baseline does not take account of the ICAO CO_2 standard		The ICAO CO_2 standard has two elements – a New Types standard from 2020 and an In-Production standard from 2028. The New Types standard could only impact the future aircraft types included in the model; all such types are set to represent realistic improvements in technology over current types, so no changes are considered to be required. The In-Production standard could potentially affect existing in-production types in the model after 2028. The aircraft types available in the supply pool in 2028 have been reviewed; no significant outliers (i.e. aircraft types with CO_2 levels significantly above the average for the seat class) were identified. Therefore, no changes to the supply pool are recommended as a result of the ICAO CO_2 standard.

A.2 Annex 2 – Maps to EMEP/EEA aircraft types

As part of the review of the fuel burn modelling in the DfT aviation CO_2 model, data were provided mapping each aircraft type in the Fleet Mix Model to an aircraft type in the EMEP/EEA aviation emissions calculator, including, where appropriate, adjustment factors. Table 9-2 presents the list of aircraft types and the maps to EMEP/EEA types.

Table 9-2 Aircraft types from the existing baseline and recommended EMEP/EEA aircraft types for fuel burn modelling

FMM Code	Name	EMEP/EEA aircraft type
APH	AEROSPATIALE AS332 SUPER PUMA C1E	**DHC6**
NDH	AEROSPATIALE AS365 DAUPHIN N3	**DHC6**
AGH	AGUSTA A139	**DHC6**

FMM Code	Name	EMEP/EEA aircraft type
319	AIRBUS A319	**A319**
19N	AIRBUS A319NEO	**A319 -15.0%***
320	AIRBUS A320-100/200	**A320**
20N	AIRBUS A320NEO	**A320 -15.0%***
321	AIRBUS A321	**A321**
21N	AIRBUS A321NEO	**A321 -15.0%***
332	AIRBUS A330-200	**A332**
333	AIRBUS A330-300	**A333**
338	AIRBUS A330-800NEO	**A332 -10.0%**
339	AIRBUS A330-900NEO	**A333 -10.0%**
343	AIRBUS A340-300	**A343**
346	AIRBUS A340-600	**A346**
351	AIRBUS A350-1000	**A350 +10.0%**
359	AIRBUS A350-900	**A350**
380	AIRBUS A380-800	**A380**
AT4	ATR42-300	**ATR42**
AT5	ATR42-500/600	**ATR42**
AT7	ATR72 200/500/600	**ATR72**
AR1	AVROLINER RJ100/115	**BAE143**
AR8	AVROLINER RJ85/QT	**BAE142**
S61	AW189	**DHC6**
J32	BAE JETSTREAM 31/32	**BAE31**
J41	BAE JETSTREAM 41	**BAE41**
3GM	BOEING 737 MAX 7	**B737 -15.0%***

FMM Code	Name	EMEP/EEA aircraft type
38M	BOEING 737 MAX 8	**B738 -15.0%***
39M	BOEING 737 MAX 9	**B739 -15.0%***
733	BOEING 737-300	**B733**
734	BOEING 737-400	**B734**
736	BOEING 737-600	**B736**
73G	BOEING 737-700	**B737**
738	BOEING 737-800	**B738**
739	BOEING 737-900	**B739**
744	BOEING 747-400	**B744**
748	BOEING 747-8	**B748**
752	BOEING 757-200	**B752**
753	BOEING 757-300	**B753**
763	BOEING 767-300	**B763**
764	BOEING 767-400ER	**B764**
772	BOEING 777-200	**B772**
77W	BOEING 777-300ER	**B77W**
78X	BOEING 777-8X	**B77W -13.0%**
79X	BOEING 777-9X	**B77W -13.0%**
78J	BOEING 787-10 DREAMLINER	**B789**
788	BOEING 787-800 DREAMLINER	**B788**
789	BOEING 787-900 DREAMLINER	**B789**
CS1	BOMBARDIER CS100	**A319 -15.0%***
CS3	BOMBARDIER CS300	**A319 -15.0%***
CR2	BOMBARDIER REGIONAL JET CRJ900	**CL600RJ**

FMM Code	Name	EMEP/EEA aircraft type
DH4	DE HAVILLAND DASH 8 Q400	**DHC8**
DHT	DE HAVILLAND DH6 TWIN OTTER	**DHC6**
D28	DORNIER 228-100/200/NG	**L410**
D38	DORNIER 328	**BAE41**
FRJ	DORNIER 328 JET	**E135**
E70	EMB ERJ170 (170-100)	**E170**
E75	EMB ERJ175 (170-200)	**E175**
175	EMBRAER E175-E2	**E175 -15.0%***
190	EMBRAER E190-E2	**E190 -15.0%***
195	EMBRAER E195-E2	**E195 -15.0%***
E90	EMBRAER ERJ190	**E190**
E95	EMBRAER ERJ195	**E195**
ER3	EMBRAER RJ135	**E135**
ER4	EMBRAER RJ145	**E145**
EC3	EUROCOPTER EC155 B1 (H155)	**DHC6**
100	FOKKER 100	**F100**
F50	FOKKER 50	**F50**
F70	FOKKER 70	**F70**
L4T	LET 410	**L410**
M82	McDonnell Douglas MD82	**MD82**
BNI	PILATUS BN-2A ISLANDER	**BN2**
BNT	PILATUS BN-2A TRISLANDER MK3	**SF340**
S20	Saab 2000	**S2000**
SF3	SAAB FAIRCHILD 340	SF340

FMM Code	Name	EMEP/EEA aircraft type
SFB	Saab Fairchild 340	**SF340**
S76	SIKORSKY S76 SPIRIT	**DHC6**
S92	SIKORSKY S92	**DHC6**
U95	SUKHOI SUPERJET 100-95	**E175**
G16	New G1 Post 2026 CL6	**A380 -17.5%***
G21	New G2 Post 2030 CL1	**ATR42 -24.5%***
G22	New G2 Post 2030 CL2	**B734 -24.5%***
G23	New G2 Post 2030 CL3	**B734 -24.5%***
G24	New G2 Post 2030 CL4	**B772 -27.5%***
G25	New G2 Post 2030 CL5	**A343B772 -27.5%***
G26	New G2 Post 2030 CL6	**A380 -27.5%***
G31	New G3 Post 2040 CL1	**ATR42 -31.5%***
G32	New G3 Post 2040 CL2	**B734 -31.5%***
G33	New G3 Post 2040 CL3	**B734 -31.5%***
G34	New G3 Post 2040 CL4	**B772 -29.5%***
G35	New G3 Post 2040 CL5	**A343B772 -29.5%***
G36	New G3 Post 2040 CL6	**A380 -29.5%***

** Proxy aircraft identified using the same approach as agreed for 2011 MAC Curves study.*

A.3 Annex 3 – Additional policy measures

In addition to the policy measures described in the main report, the study also considered further measures. After consideration, it was decided not to include them further. This section provides descriptions of these additional policy measures.

A.3.1 Retrofitting

What is the measure?

The retrofitting policy measure was related to policies aimed at encouraging the retrofitting of new, fuel efficient technologies to the existing fleet of aircraft. However, the scope of such a policy would be very broad, making it difficult to evaluate the effects of a policy. It was considered that, where technology improvements are cost effective and provide fuel efficiency improvements, airlines would adopt them in the absence of policy.

There is evidence that retrofitting is an approach employed by airlines (for example, a number of Airbus A320 and Boeing 737 family aircraft have been retrofitted with the latest winglet designs). However, the number of aircraft eligible for the upgrades is limited (particularly if the measure is restricted to UK-registered aircraft).

The primary focus of this measure was on relatively near-term updates to current in-service aircraft. For a 'stronger' policy lever, it was considered that the measure could be extended to assume that other aircraft types (possibly including future types) may have retrofits available in the future as the result of technology developments. Based on information reported to date, the fuel efficiency improvements available through retrofits are likely to be less than 5%.

What policy levers were considered?

The lever would be likely to be either support to airlines to assist them in accessing the finance for the upgrades, or the implementation of either green slots (i.e. slots restricted to aircraft meeting specified environmental standards) or environmental-performance-based landing charges (giving a discount to aircraft retrofitted with later technologies)

Why was this measure removed from consideration?

This policy measure is no longer included in the review, following discussions with DfT. It was determined that the effectiveness would be difficult to evaluate (and would be likely to be small) and it would be difficult to identify a policy lever through which retrofits could be supported (particularly as many airlines that operate flights to/from the UK are registered overseas).

A.3.2 Advances in communication technology and demand management

What is the measure?

The 2011 MAC curves study included a policy option related to the promotion of videoconferencing as a means to reduce demand for business travel. The use of videoconferencing has increased considerably as broadband speeds have increased and on-line presentation technology (e.g. Skype) has improved. In assessing this measure, consideration was given to whether there is evidence videoconferencing leads to a change in demand for business travel.

What policy levers were considered?

A range of policy levers were investigated including competitions to improve video conferencing and government campaigns to encourage its use for businesses.

Why was this measure removed from consideration?

Many businesses are already adopting Skype or similar techniques for internal communications between different sites. It is difficult to quantify the reduction in the number of flights that has resulted, although some businesses have reported savings through published environmental credentials.

An analysis of trends in business and leisure travel from UK airports showed that business travel is becoming a smaller proportion of the air travel market. It was determined that it would be difficult to show that encouraging more use of communication technology would result in fewer aircraft movements and therefore a saving in carbon emissions. A review of the literature suggested that there was no significant new evidence on the relationship between videoconferencing and the demand for flights, since the publication of the 2011 Study commissioned by DfT

After discussion with DfT, it was decided that this potential area would be removed from further consideration.

A.3.3 Changes to Air Traffic Management Systems

What is the measure?

Two main elements were considered under this policy measure:

- The improvement of Air Traffic Management to provide a more direct and efficient flight profile for the en-route portion of an aircraft movement;
- Improvements to the approach and departure routes to and from UK airports to make air movements more efficient (for example, the removal of stacks for airports by slowing aircraft

down en-route and giving aircraft their optimal climb and descent profiles rather than step climbs and descents).

It was identified that NATS (the UK air navigation service provider) is already planning and leading some of the major changes in ATM as part of the EUROCONTROL SESAR programme, such as:

- Free routing;
- The use of integrated management systems to give more time to adjust an aircraft's arrival time to meet their landing slot without stacking;
- 3Di profiling of aircraft to allow them to fly their optimal climb and descent profiles;
- Making military airspace in the UK available to civil aviation when it is not in use.

ICAO are also rolling out a similar programme of improvements around the world. This is called Block 0 of ICAO's Aviation System Block Upgrade (ASBU) programme, which is taking place between 2013 and 2018. The Block 0 measures are wide ranging and expected to result in savings in fuel burn of approximately 150kg to 250kg per flight by 2018.

The area that is most difficult to improve is the lower airspace and, in particular, areas such as the London Terminal Manoeuvring Area, where there are a lot of airports in close proximity.

The DfT has recently consulted on the UK Airspace Change Framework. The proposals seek to improve the process for making changes to airspace, including departure and arrival routes. Airports are also encouraged to fine airlines for noise infringements.

Heathrow Airport is keen to improve climb and descent profiles as part of their credentials for expansion. They have carried out various trials which may provide both noise and emission benefits. They have also carried out demonstration projects with improved communication systems as part of the SESAR programme which results in improved emissions through improved flight efficiency.

What policy levers were considered?

Given the programmes already in place there seemed little that intervention from the Government or other parties would achieve at this time. Given the radical changes that NATS, EUROCONTROL and ICAO are rolling out, airlines (because of the fuel savings) would be keen to adopt these changes.

Why was this measure removed from consideration?

The changes and motivation of NATS for bringing in these changes to UK Airspace does not require any further intervention. Safety implications of changing air traffic management also suggest that these changes should not be pushed through earlier

A.3.4 Consumer offsetting

What is the measure?

Voluntary schemes for passengers to offset flight emissions have existed for several years. Whilst they do not reduce emissions from flights, they offset a portion of them through sponsoring projects that reduce emissions elsewhere.

In parallel with these schemes, from 2021, ICAO will introduce the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), requiring airlines to offset their international aviation emissions above 2020 levels. Whilst states' participation will initially be voluntary, the UK has committed to implementing the scheme from the start. ICAO estimates for an "optimistic" scenario show that, by 2040, total international aviation emissions will be approximately 1,400 Mt CO_2e, which would require 590Mt of CO_2e to be offset, accounting for 42% of total emissions. A less optimistic scenario has approximately 1,800 Mt CO_2 total emissions, which would require 819 Mt of offsetting to achieve similar results. To analyse the potential reductions in emissions from implementing this measure, it was intended to use the data presented by ICAO to estimate a percentage reduction in emissions from offsetting over time, which would be applied to the baseline emissions. This would identify the quantity of emissions which were still 'available' to be offset through consumer offsetting.

UK aviation was responsible for 34Mt of CO_2e in 2013, although this value has been decreasing slightly since 2005; 95% of UK emissions is associated with international flights, and will therefore be included in CORSIA from 2021

What policy levers were considered?

In light of the estimated impact of CORSIA, consumer offsetting could in theory be applied to the remaining 60% (approximately) of total emissions by 2040. However, a brief review of the current uptake of consumer offsetting programmes indicated that achieving such a value may be optimistic. British Airways reported 114,900 passengers taking part in the offsetting programme in 2010, which accounted for only 0.3% of its total passengers, and a similar percentage of total emissions. In comparison, KLM reported 220,000 tonnes of CO_2e saved through consumer offsetting between 2008 and 2015, compared to a total 12.1m tonnes of emissions in 2015, again saving approximately 0.3% per year on both these measures. Lufthansa has had less success with its scheme, with only 16,000 tonnes offset of 27 million tonnes of emissions in 2014, saving only 0.06%. It was considered that this very limited penetration of offsetting in the baseline should be extrapolated into the future at moderately improved rates, thereby leaving a significant technical potential remaining to be achieved by the various relevant UK Government policy levers.

For private aviation consumers, the policy lever for the low ambition level of this measure would be through supporting awareness campaigns to raise the profile of offsetting and encourage passengers to offset their emissions, while the mid policy level would involve providing a clearer opportunity to purchase offsets at the point of sale of the tickets (e.g. through an opt-out rule, or introducing a new optional ‘emissions surcharge’).

Offsetting for business travel could be further encouraged by Government, with the high policy ambition potentially involving mandatory offsetting. Therefore, the uptake by business users was expected to be significantly higher than for private consumers.

Why was this measure removed from consideration?

The potential effectiveness of this measure was considered in light of the expectation that the UK will be part of CORSIA after 2020. As a result, airlines will have already offset part of their emissions on international flights (that part representing growth over 2020 levels), leaving only a small portion available for voluntary offsetting by customers. In addition, it was noted that the assumptions for the baseline demand and CO_2 forecasts already assume that all emissions are subject to carbon pricing (either through the purchase of allowances under the EU ETS or offsetting). Therefore, for the purposes of this study, any further offsetting as a result of policy intervention was considered to represent double counting.

A.3.5 Passenger carbon tax

The concept was for an additional tax, similar to the air passenger duty (APD), based on a passenger’s carbon footprint. However, discussions with DfT early in the study clarified that policy measures related to taxes should not be included in this study (being a Treasury responsibility).

A.4 Annex 4 – Aircraft list price assumptions

Following a review of available sources of aircraft list prices, the following list prices were assumed for this study.

Table 9-3 List prices for in-production and near future aircraft types

Aircraft type	List price ($ million)
AIRBUS A319	89.6
AIRBUS A319NEO	99.5
AIRBUS A320-100/200	98.0
AIRBUS A320NEO	108.4
AIRBUS A321	114.9
AIRBUS A321NEO	127.0

Aircraft type	List price ($ million)
AIRBUS A330-200	231.5
AIRBUS A330-300	256.4
AIRBUS A330-800NEO	254.8
AIRBUS A330-900NEO	290.6
AIRBUS A350-1000	359.3
AIRBUS A350-800	275.1
AIRBUS A350-900	311.2
AIRBUS A380-800	436.9
ATR42-500/600	21.6
ATR72 200/500/600	26.0
BOEING 737 MAX 7	90.2
BOEING 737 MAX 8	110.0
BOEING 737 MAX 9	116.6
BOEING 737-700	80.6
BOEING 737-800	89.1
BOEING 737-900	96.1
BOEING 747-8	351.4
BOEING 777-300ER	339.6
BOEING 777-8X	371.0
BOEING 777-9X	400.0
BOEING 787-10 DREAMLINER	306.1
BOEING 787-8 DREAMLINER	206.8
BOEING 787-9 DREAMLINER	249.5
BOMBARDIER CS100	79.5
BOMBARDIER CS300	89.5
BOMBARDIER REGIONAL JET CRJ900	46.5

Aircraft type	List price ($ million)
DE HAVILLAND DASH 8 Q400	32.2
DE HAVILLAND DH6 TWIN OTTER	6.5
DORNIER 228-100/200/NG	7.0
EMB ERJ170 (170-100)	26.5
EMB ERJ175 (170-200)	28.0
EMBRAER E175-E2	45.0
EMBRAER E190-E2	52.7
EMBRAER E195-E2	49.8
EMBRAER ERJ190	46.2
EMBRAER ERJ195	47.0
EMBRAER RJ135	16.5
EMBRAER RJ145	21.0
LET 410	0.5
SUKHOI SUPERJET 100-95	26.5

A.5 Annex 5 – Aircraft price discounts

For the calculation of aircraft prices, a review was made of sources of information on discounts offered by manufacturers to airlines acquiring their aircraft. The percentage discounts were applied to the aircraft list price assumptions for the calculation of new aircraft prices for this study. The percentage discounts identified from two sources, Airinsight[66] and "Challenges"[67], are shown in Table 9-4 and Table 9-5.

Table 9-4 Aircraft price discounts from Airinsight

Aircraft type	Discount
A330-200	62.6%
A319	58.4%
A330-300	57.3%
737-700	56.2%
A320neo	54.8%
A320	54.7%

[66] https://www.airinsight.com/aircraft-pricing-list-vs-market
[67] https://www.challenges.fr/salon-du-bourget/le-vrai-prix-des-avions-d-airbus-et-de-boeing_10040

Aircraft type	Discount
777-300ER	54.4%
A321	52.5%
737-900ER	52.8%
737-800	51.6%
A350-900	51.3%
CRJ1000	48.0%
787-8	47.9%
787-9	46.0%
CRJ900	45.6%
A380	45.3%
E-175	34.8%
E-195	34.0%
E-190	33.5%
SS100-95	27.9%

Table 9-5 Aircraft price discounts from Challenges

Aircraft type	Discount
747-8	59%
A320-200	58%
A330-300	58%
737-800	53%
777-300ER	52%
A380	52%
A320neo	51%
737 Max8	49%
787-8	48%
A350-900	47%

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