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CO_2 ROAD-MAP

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FOREWORD BY SUSTAINABLE AVIATION'S ADVISORY BOARD

The climate policy landscape has seen dramatic changes in 2016. The Paris Agreement was ratified and entered into force on 4th November, and the International Civil Aviation Organization (ICAO) agreed an international deal to tackle growth in carbon emissions beyond 2020 using market-based measures. Closer to home, we have the public voting to leave the European Union and the Government supporting the Airports Commission's recommendation for an additional runway at Heathrow. Since 1990 we have also seen UK aviation emissions rise both in absolute terms and as a percentage of UK emissions as other sectors decarbonise. Aviation now accounts for over 7% of UK CO_2 emissions. Given these seismic shifts, the 2016 CO_2 Road-Map produced by Sustainable Aviation (SA) could not be timelier.

The CO_2 Road-Map is the flagship report of SA. This report updates its 2012 Road-Map which set out a suggested pathway for UK aviation out to 2050. Despite an expected 150% rise in air traffic between 2010 and 2050, the 2012 Road-Map showed a scenario for how a combination of changes to operations, to the fleet and the introduction of alternative fuels could lead to limited emission increase. The Road-Map also suggested market-based measures could be used to halve net emissions by 2050.

In this new Road-Map the proposed future pathway and the contribution from the different wedges are largely unchanged. However, the Road-Map does an excellent job of examining each of these wedges and their impact on UK aviation emissions. This new evaluation accounts for increased runway capacity. It also considers increased knowledge on sustainable fuels and future fleets.

The SA Advisory Board welcomes this new Road-Map and we acknowledge the efforts that all parts of the industry have made to decarbonise both immediately and going forward. We think the Road-Map sets a good level of ambition that is broadly in line with the UK Committee on Climate Change recommendations. It also goes about half way towards the long-term climate goals of balancing sources and sinks of carbon in the second half of this century articulated in the Paris agreement, when market based measures are accounted for.

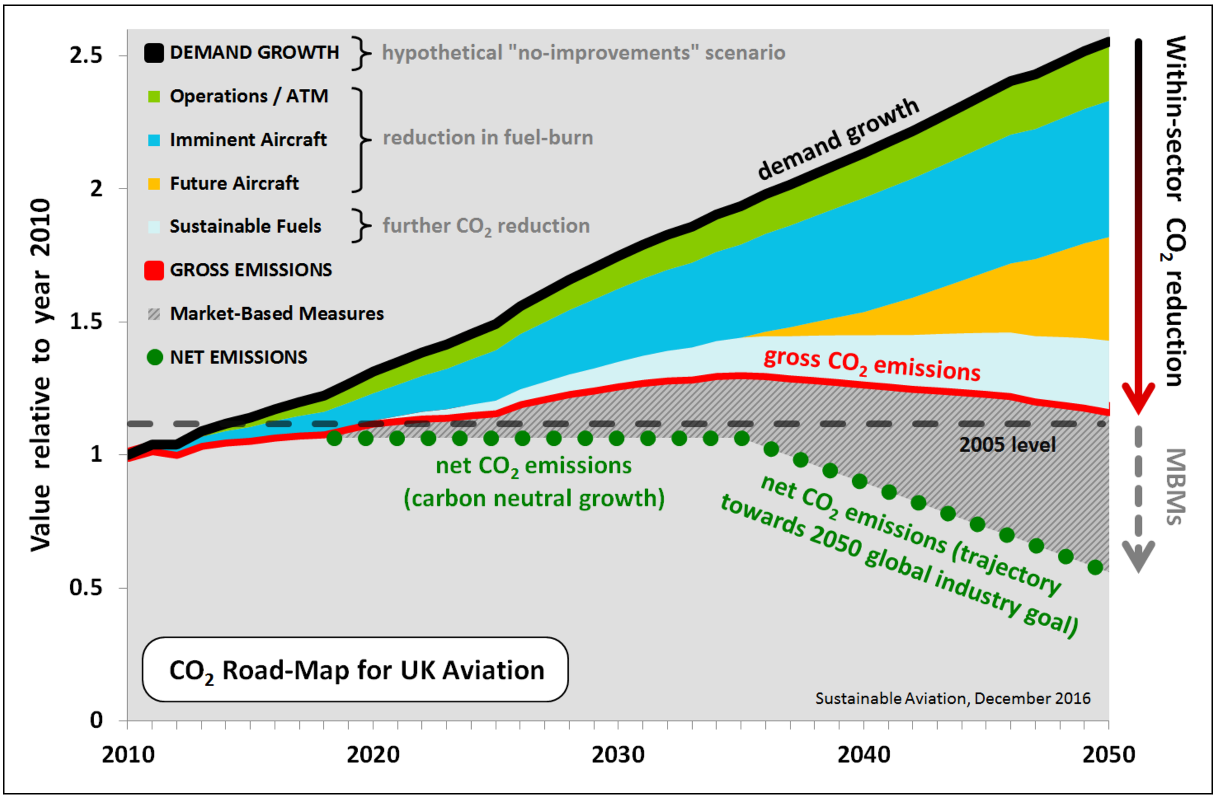
Going forward we would encourage SA to identify the key practical interventions that would support the UK aviation industry both to implement this level of ambition and to grow the level of ambition across the industry. Lastly, as stated in the report, CO_2 should not be considered in isolation, as other aviation emissions which also have a warming effect need to be accounted for. We look forward to a continued close working relationship with this important UK industry.

The SA Advisory Board

The Sustainable Aviation Advisory Board works with Sustainable Aviation to provide independent advice and feedback. It provides rigorous challenge to the SA Council in order to enable it to reach its cleaner, quieter, smarter goals effectively and efficiently.

EXECUTIVE SUMMARY

This CO_2 Road-Map, like its predecessor published in 2012, demonstrates the potential for the UK to accommodate significant aviation growth to 2050 without a substantial increase in CO_2 emissions, through a better than doubling of carbon efficiency.



UK aviation can accommodate significant growth to 2050 without a substantial increase in CO_2 emissions. We also illustrate the potential reduction of net CO_2 emissions through internationally agreed market-based measures.

Key findings

- Through the adoption of newer, more efficient aircraft, sustainable fuels and better air traffic management and operational procedures, the aviation industry in the UK will be able to accommodate significant growth through to 2050, including the effect of additional runway capacity in the South East of England, without a substantial increase in CO_2 emissions.

- By 2050, UK aviation's CO_2 emissions are expected to be broadly in line with levels recommended by the Committee on Climate Change. Further improvements in the industry's carbon intensity can be expected post-2050.

- The historic agreement for a global market based measure (MBM) at this year's ICAO Assembly will support the global aviation industry's drive for carbon neutral growth from 2020. It is also a major step towards the global industry's longer term goal of halving its net CO_2 emissions by 2050 versus 2005 levels. The industry's focus is now, with Government support, to ensure the successful implementation of this global measure from 2020. Our Road-Map shows the level of contribution required from MBMs, additional to the within-sector improvements listed above, if UK aviation is also to halve its net CO_2 emissions relative to 2005 levels whilst accommodating a more than doubling of demand over the same period.

Improvements to our Road-Map since 2012

- Our demand-growth assumptions now take account of additional runway capacity in the South-East of England, using forecasts from the Airports Commission.
- Recent international agreements concerning new-aircraft fuel-efficiency and market based measures for aviation have been taken into account.
- Our assessment of the potential for fleet fuel-efficiency improvements has been refined, taking more accurate account of the existing fleet and including recently-announced new aircraft types.
- Significant advances in sustainable aviation fuels have been taken into account.
- We have refined our analysis of near-term air traffic management efficiency improvements related to the target set by NATS, the UK's air navigation service provider.

Where Government can help

Recognising aviation's benefits to the economy, to employment and to connectivity, the UK Government has provided resource and assistance to enable a vibrant aviation and aerospace manufacturing industry in the UK. This report demonstrates how that support is yielding significant dividends.

However, delivery of the full range of improvement initiatives set out in this document will require not only continued focus from the industry itself but also appropriate levels of ongoing support from Government - on both Research and Development (R&D) and policy - in the following specific areas:

- **Airspace Reform**: The Government should continue to support airspace modernisation in the UK, and maintain momentum towards improved air traffic management (ATM) collaboration across Europe.
- **Supporting Research and Development (R&D)**: Just as the fuel-efficiency of new engines and aircraft today is the result of past investment in R&D, so the improved fuel-efficiency and commercial competitiveness of future engines and aircraft will hinge on R&D investment made today and in the future. In the coming years, the Government must ensure that access by UK aerospace industry to ongoing funding for high-value collaborative R&D remains in place.
- **Sustainable Fuel Strategy**: We welcome the UK Government's recent consultation on the inclusion of Sustainable Aviation Fuels (SAF) in future policy for renewable transport fuels. We urge the Government to introduce binding legislation and to provide clear long-term policy as soon as possible to enable the UK to realise the opportunities for UK sustainable fuels production. The UK should develop a new vision and strategy for SAF, to ensure the development of UK expertise and innovation, to enable the UK to benefit from global opportunities in these emerging technologies and to deliver on the jobs and growth identified in our 2014 Sustainable Fuels Road-Map.
- **Market Based Measures (MBMs)**: We welcome the role played by the UK Government in negotiations towards ICAO's Global MBMs agreement, which supports as far as 2035 the global aviation industry's carbon neutral growth ambition. Government should now focus on implementation details including avoiding duplication of coverage with regional schemes. Government should also start the process towards the global mechanism for 2035 onwards, which will be essential in supporting the global aviation industry's commitment to reduce net aviation CO_2 emissions by 50% by 2050, relative to 2005 levels, while increasing capacity in support of economic growth.

Aviation in the UK

- UK aviation, comprising domestic and international flights departing from UK airports, accounted for some 7.4% of UK CO_2 emissions in 2014.
- The UK aviation sector has a turnover of over £60 billion, contributes over £52 billion to our GDP[1] and almost £9 billion in taxes, and directly or indirectly supports almost one million UK jobs.
- Our aerospace manufacturing sector generates annual exports of £26 billion and has a global market opportunity of £3.5 trillion over the next twenty years.

As this document shows, the UK aviation industry is working hard to enhance its economic benefits while managing its carbon footprint through a better than doubling of carbon efficiency between 2010 and 2050.

Sustainable Aviation members' progress

- **Airspace Management** – by introducing more efficient aircraft routes and a range of other measures, NATS has made strong progress towards a target of reducing CO_2 from aircraft under their control by 10% by 2020 relative to 2006 levels. Improvements made so far are saving more than a million tonnes of CO_2 per year.
- **Airlines & Airports**
    - Airline members are investing billions of pounds in significant upgrades to their fleets, adopting the latest, most fuel-efficient aircraft. Since 2005, UK airlines have brought in 470 new aircraft. Alongside reductions in emissions, these aircraft offer further benefits such as lower noise levels. Between 2005 and 2015, Sustainable Aviation's member airlines have improved their fuel efficiency by almost 12%, equivalent to a saving of 20 million tonnes of CO_2.
    - Airline and airport members are identifying and adopting a wide range of improved operational practices such as reducing the use of aircraft APUs, and taxiing on a reduced number of engines. This complements broader on-airport work to reduce carbon emissions from energy use in buildings and by vehicles. Between 2010 and 2012, the combined carbon footprint of the UK's 18 biggest airports – representing 95% of passengers using UK airports – reduced by 3%, whilst passenger numbers increased by 5%.
- **Manufacturers** - Aerospace manufacturers, having created the latest generation of efficient aircraft, are already investing heavily in the cutting edge technology that will ensure the next generation of aircraft and engines will be able to reduce CO_2 emissions further.
- **Fuels** – Aerospace manufacturers, airlines and fuel companies have worked collaboratively to approve new fuels that can be manufactured from sustainable sources. Additionally, SA members are actively involved in developing new supply chains.
- **Market based measures** - Between 2012 and 2015, 6 million tonnes of CO_2 emissions reductions were made by UK airlines through the EU Emissions Trading System (ETS).

[1] including direct, indirect and induced economic benefits

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1 Introduction and Context

1.1 What Is the CO_2 Road-Map?

Put simply, this document (like its predecessor [SA, 2012]) sets out Sustainable Aviation's latest view of the likely trajectory of UK aviation's carbon dioxide (CO_2) emissions to 2050. It takes into account expected growth in UK aviation activity in the coming decades and explores the likely impact of a number of CO_2 mitigation measures. It is based on the latest information available to us at the time of writing.

The Road-Map's purpose is to inform debate, to highlight the efforts being taken by the aviation industry to reduce its carbon intensity, to assess the likely effectiveness of those efforts in the specific context of UK aviation, and to identify areas where Government can help.

This document does not represent a target set by Sustainable Aviation for the industry to deliver, and should not be viewed as a promise or commitment. It does not warrant that UK aviation emissions will follow a particular path.

However, neither is this document an aspirational statement. Wherever possible we have based our position on quantitative analysis of hard data. In some areas we have needed to exercise informed judgement, and in the text we make clear where this is the case.

As with our previous CO_2 Road-Maps, we interpret "UK aviation" to mean "flights which depart from UK airports". This is consistent with the accounting convention used by the UK to assess emissions from UK aviation. Our use of this interpretation is motivated by the need for consistency with published figures and does not imply support for or agreement with the corresponding accounting practice.

Besides carbon dioxide, emissions from aviation also include oxides of nitrogen (NO_x), water vapour, particulates, carbon monoxide, unburned hydrocarbons, soot and oxides of sulphur (SO_x). The climate impact of many of these is discussed in a separate paper [SA, 2014a]. This Road-Map focuses purely on CO_2.

1.2 Sustainable Aviation

Launched in 2005, Sustainable Aviation (SA) brings together the main players from UK airlines, airports, aerospace manufacturers and air navigation service providers to set out a collective long term strategy to ensure a sustainable future for UK aviation.

We are focused on finding collaborative ways of becoming cleaner, quieter and smarter to enable the more sustainable development of our industry and the economy. We continue to promote the principles of our strategy, both within the UK and internationally.

SA has set a range of goals and commitments covering climate change, local air quality and noise to deliver a sustainable future for our industry[2]. We regularly report on our progress towards these objectives, monitoring and tracking the practical cooperative work being undertaken by SA's signatories. Our Progress Reports can be found at www.sustainableaviation.co.uk.

1.3 UK Aviation's Social and Economic Value

[SA, 2016][3] sets out the importance to the UK of aviation and its various sub-sectors, both from an economic standpoint and a social standpoint. The UK aviation sector has a turnover of over £60

[2] SA's goals can be found at http://www.sustainableaviation.co.uk/our-goals/

[3] See references at the end of this document

billion, contributes over £52 billion[4] to our GDP, and directly or indirectly supports almost one million UK jobs. Our aerospace manufacturing sector generates annual exports of £26 billion and has a global market opportunity of £3.5 trillion over the next twenty years.

As this document shows, the aviation industry is working hard to enable these benefits to continue into the future while substantially reducing CO_2 emissions per unit of delivered benefit.

1.4 Aviation and the Environment

The aviation industry takes extremely seriously its responsibility to reduce its environmental impact, as its track record illustrates. Over the last half-century, fuel-burn per passenger-kilometre has been reduced by some 70 percent against a backdrop of progressively tightening regulations for noise and NO_x emissions. The industry remains resolute in its drive to reduce its emissions intensity even further, as demonstrated not only by the commitments of aircraft operators to refreshing their fleets with newer, more efficient aircraft, but also by significant research and development investment within the aerospace design and manufacturing sector to ensure that future generations of engines and aircraft are even more efficient.

However, aviation's social and economic contribution to society is such that underlying demand for air travel continues to rise, placing upward pressure on emissions. Several years ago, the global aviation industry agreed an overall strategy for managing its CO_2 emissions [IATA, 2009].

Our UK-specific Road-Map brings together analysis from the various sectors of the UK industry, together with a demand-growth projection based on forecasts from the UK's Airports Commission, to set out Sustainable Aviation's view of the likely trajectory of CO_2 emissions from UK aviation over the period to 2050.

1.5 UK Aviation in the National and International Context

CO_2 emissions from global aviation account for some 2% of all human-attributable CO_2 emissions[5]. Furthermore, CO_2 emissions from UK aviation[6] currently correspond to around one twentieth of CO_2 emissions from aviation worldwide[7]. Whilst forecast growth in UK aviation activity to 2050 will average up to 2.4% per annum[8], global aviation activity growth rates are expected to be considerably higher due to the rapid development of emerging markets in Asia and elsewhere[9,10]. As a result, the proportion of global aviation's CO_2 emissions attributable to the UK is likely to diminish substantially over time. The most compelling opportunity for the UK to exert an influence over CO_2 emissions from aviation is therefore not by heavily constraining demand for UK aviation, but rather through 1) investment in advanced technologies[11] which can be deployed globally, earning export revenues for the UK while contributing to a more environmentally efficient industry world-wide, and 2) continuing to engage at the international level to ensure that decarbonisation happens in the most cost effective way possible, through the use of market-based measures.

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4 including direct, indirect and induced economic benefits

5 Source: http://www.atag.org/facts-and-figures.html, viewed 3rd Oct 2016

6 Our interpretation of this phrase is set out in **section 1.1**

7 Source: SA analysis of data from [CAA], [NAEI], and http://www.atag.org/facts-and-figures.html, viewed 3rd Oct 2016

8 Demand growth is discussed in detail in **section 2**

9 See page 7 of http://www.airbus.com/company/market/global-market-forecast-2016-2035/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=109228

10 See page 5 of http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/cmo_print_2016_final_v6.pdf

11 This would include not only engine and aircraft technologies, but also technologies related to sustainable aviation fuels and to air-traffic management.

Since CO_2 is a well-mixed greenhouse gas, the distribution of CO_2 emissions between sectors of activity or geographical locations does not influence the climate system's response to those emissions. Accordingly, the pursuit of the most cost-effective mitigation opportunities, irrespective of sector or geography, should be incentivised. We welcome the agreement of a global market-based measures scheme to address CO_2 emissions from international aviation, which will enable reductions in UK aviation's net CO_2 emissions over and above the substantial reductions made within the aviation industry itself.

Looking closer to home, CO_2 emissions from UK aviation accounted in 2014 for some 7.4% of the UK's total CO_2 emissions[12]. This figure has risen - from slightly under 3% in 1990[13] - as aviation activity has continued to grow strongly while over the same period the UK as a whole (comprising all sectors of activity including international aviation and international shipping) has reduced its total CO_2 emissions by around a quarter. Aviation's proportion of UK emissions is likely to continue to rise into the future as other sectors of economic activity - particularly electrical power generation and sectors amenable to increased electrification such as light duty road-transport and domestic space heating – reduce their carbon intensity very substantially over the coming decades. The UK's Committee on Climate Change recognises that cost-effective opportunities for deep decarbonisation vary between different sectors of activity, and that some sectors - particularly aviation, agriculture and parts of industry - are not expected to reach zero emissions by 2050 [CCC, 2016a].

Nonetheless, UK aviation CO_2 emissions per terminal passenger reduced by 20% between 2000 and 2014[14], and our CO_2 Road-Map shows how the carbon-intensity of UK aviation can be reduced very substantially between 2010 and 2050 through a combination of measures. Additional reductions in UK aviation's carbon intensity post 2050 are likely but lie largely beyond the scope of this document.

1.6 Motivation for an Updated Road-Map

Since our CO_2 Road-Map was last updated in 2012, the following significant developments have taken place:

- The Airports Commission has published demand growth scenarios encompassing a range of economic futures and various options for additional runway capacity in the South East of the UK [AC, 2015].
- Several new aircraft types have been announced, and will enter service in the next few years. These include the Airbus A330neo, the Boeing 777X, the Boeing 787-10 and the Airbus A321LR.
- The marketplace success of the Airbus A320neo family and Boeing 737 MAX family, and the resulting very large order-books, means that their production runs will likely be longer than we previously supposed. As a result, our view of the timescale within which their respective successor aircraft types will enter service has changed materially.
- A further three classes of alternative fuel for aviation have been certified for commercial use, and together with a significant expansion in the range of suppliers offering these fuels this has expanded the options available to aircraft operators wishing to employ them. This area continues to develop rapidly, both technically and commercially.
- The UN's International Civil Aviation Organization (ICAO) has agreed an international fuel-efficiency standard for new aircraft, to enter force from 2020.
- ICAO has also agreed a global market-based measures scheme applicable to international aviation, which will enable aviation to fund cost-effective emissions reduction activities in other

12 Data source: [NAEI], UK total includes CO_2 emissions from bunker fuels (aviation and marine)

13 Data source: [NAEI], UK total includes CO_2 emissions from bunker fuels (aviation and marine)

14 Source: SA analysis of data from [NAEI] and [CAA]

sectors through the purchase of offsets. We note that a high proportion of UK aviation CO_2 emissions is due to international routes, and so this development has considerable relevance to the UK.

- In December 2015, over 190 of the world's nations reached an agreement, known as the Paris Agreement, which aims to limit rises in global average temperature (relative to pre-industrial levels) to well below 2 degrees C, with an aspiration to limit the rise to 1.5 degrees C. The Paris Agreement goes beyond the basis upon which the UK's current climate policy is founded. In [CCC, 2016a], the Committee on Climate Change (CCC) explores the implications of the Paris Agreement for UK climate policy, recommending that "*the Government does not alter the level of existing carbon budgets or the 2050 target now*" and that "*The priority for now should be robust near-term action to close the gap to existing targets and open up options to reach net zero emissions*". [CCC, 2016a] also re-iterates the CCC's "central" scenario to 2050, representing CCC's "*best assessment of the technologies and behaviours required to meet targets cost-effectively while meeting the other criteria in the Climate Change Act*", in which UK aviation emissions in 2050 are "*around 2005 levels*".
- Following the outcome of a referendum held in mid-2016, the UK is now on a path towards leaving the European Union. [CCC, 2016b] considers the implications of this development for UK climate policy, concluding that "*The UK's 2050 target for reducing greenhouse gas emissions and the legislated carbon budgets (including the fifth carbon budget set in July 2016) remain appropriate as part of a UK contribution to global efforts to tackle climate change*". Nonetheless, there will no doubt be implications for UK travel patterns and the strength of the UK economy, with a resulting impact upon levels of UK aviation activity. [IATA, 2016] provides a preliminary analysis of the topic, discussing relevant factors and suggesting that "*the number of UK air passengers could be 3-5% lower by 2020*". Subsequent analysis by IATA[15] suggests that UK passenger traffic, as measured by number of passengers, could by 2035 be 6% smaller in a "hard" Brexit case than in a "soft" Brexit case. Our view is that the consequences of the 2016 referendum result will play out over a number of years, and that future updates of our Road-Map will be better placed than this one to assess any resulting impact upon levels of demand for UK aviation. In this edition of our Road-Map, we do not take explicit account of any effects related to the 2016 referendum result.

1.7 Methodology

As with our previous Road-Maps, we first consider the likely growth in demand for UK aviation, using it to derive a hypothetical "no-improvements" CO_2 emissions scenario. We then consider the potential for mitigation due to improvements in air-traffic management and operational practices, more efficient engines and aircraft, and the increasing use of sustainable aviation fuels. We also consider the further contribution from market-based measures which will be required to supplement the expected reductions from the sources described immediately above if UK aviation is to reduce its net CO_2 emissions in 2050 to half of their 2005 levels.

1.8 Options for Reducing CO_2

Section 3.3 of our 2012 CO_2 Road-Map [SA, 2012] set out a number of broad approaches for reducing CO_2 from aviation. One item that was missing from that list, and whose prospects have strengthened considerably since 2012, is the partial or complete electrification of aircraft propulsion for certain sectors of the market. This is a topic that is explored more deeply in **section 4.10.2 below**.

[15] http://www.iata.org/publications/Pages/brexit-impact-uk.aspx

1.9 The Role of Government

This document explores the substantial efforts being made across all parts of the aviation industry to improve fuel-efficiency and reduce CO_2-intensity, and sets out SA's view of how those efforts will impact CO_2 emissions from UK aviation relative to a hypothetical no-improvements scenario. However, bringing to fruition the projections set out in our CO_2 Road-Map will not only require the continued commitment and focus of the aviation industry itself, but will also rely on engagement from Government.

- Government should continue to support airspace modernisation in the UK, and maintain momentum towards improved Air Traffic Management (ATM) collaboration across Europe.
- We acknowledge the significant levels of government support to the UK aerospace industry provided through initiatives such as the Aerospace Growth Partnership (AGP). In the coming years Government must ensure that access by UK aerospace industry to ongoing funding for high-value collaborative R&D remains in place.
- SA believes that there is great potential for the development of new supply chains for Sustainable Aviation Fuels (SAF) in the UK. The SA Fuels Road-Map [SA, 2014] identified the potential for 5-12 UK production facilities producing a range of sustainable fuels and chemicals in the period to 2030. Government has recently indicated that there will be a role for SAF in future transport policy. A lack of policy certainty has damaged investor confidence and deterred investment in new UK infrastructure. We urge the Government to introduce binding legislation and to provide clear long-term policy as soon as possible to enable the UK to realise the opportunities for UK sustainable fuels production.
- We welcome the role played by the UK Government in negotiations towards the ICAO global MBMs agreement, which supports as far as 2035 the global aviation industry's carbon neutral growth ambition. Government should now focus on implementation details including avoiding duplication of coverage with regional schemes. Government should also start the process towards the global mechanism for 2035 onwards, which will be essential in supporting the global aviation industry's commitment to reduce net aviation CO_2 emissions by 50% by 2050, relative to 2005 levels, while increasing capacity in support of economic growth.

In reaching our view of the extent to which mitigation options identified in this document will reduce CO_2 emissions from UK aviation, we have assumed that suitable levels of Government engagement will be achieved with respect to each of the above areas.

1.10 Document Structure

The remainder of this document is structured as follows:

- **Section 2** sets out our hypothetical "no-improvements" scenario detailing the notional growth in CO_2 emissions from UK aviation that would take place assuming no improvements in fleet fuel efficiency, no improvements in operational practices, and no adoption of sustainable aviation fuels.
- In **sections 3 to 5** we set out our assumptions and analysis concerning the potential for aviation to improve its carbon intensity through a variety of within-sector measures.
- **Section 6** discusses opportunities to reduce aviation's net emissions further through market-based measures which enable aviation to fund mitigation actions in other sectors in cases where they can be implemented more cost effectively than within the aviation industry itself.
- Finally, **section 7** summarises the assumptions and presents the Road-Map itself along with a discussion of its key messages.

2 Hypothetical "No-Improvements" Scenario

SUMMARY

This hypothetical scenario uses as its starting point the Airports Commission's "Global Growth" economic scenario, assuming new runway capacity in South East England and assuming a "carbon-traded" framework.

Given these assumptions and choices, in the absence of any improvements in fleet fuel efficiency or in operational practices, and assuming no use of sustainable aviation fuels, CO_2 emissions from UK aviation would rise by 155% between 2010 and 2050, implying an average annual growth rate of 2.37%. This is a slightly higher average growth rate than that used in our 2012 Road-Map, representing a balance between a number of factors as described in this chapter.

Subsequent chapters of this document use this hypothetical "no-improvements" scenario as a reference against which the potential impact of CO_2 mitigation measures can be assessed.

2.1 Introduction

In this section we identify the hypothetical trajectory that UK aviation's CO_2 emissions could be expected to follow in the absence of any action to improve the industry's carbon intensity. Our hypothetical "no-improvements" scenario therefore assumes a constant level of technology, operational procedures and sustainable aviation fuel penetration, in which more aviation activity is delivered at the same load factors using an increasing number of the same types of aircraft without changing over time the manner in which they are operated or the type of fuel used. This hypothetical "no-improvements" trajectory for UK aviation CO_2 therefore follows forecast growth in aviation activity[16], and serves as a reference against which the potential impact of our anticipated improvement activities can be assessed.

Clearly, this hypothetical scenario does not correspond to a "business as usual" scenario, since "business as usual" involves the rigorous pursuit of cost-reduction opportunities of which improving fuel efficiency - and hence carbon intensity - is a major part.

2.2 Defining "Growth in Aviation Activity"

Growth in aviation activity can be expressed in many different ways, not all of them representative of the corresponding growth in CO_2 emissions that would take place in a hypothetical "no-improvements" scenario. For example, growth could be expressed in terms of numbers of passengers, or number of air transport movements. However, neither of those metrics captures the distance travelled by each passenger or aircraft, and therefore they do not capture fundamental shifts in the market, for example shifts in the balance between long-haul and short-haul flights. A more appropriate unit is the Revenue Passenger Kilometre (RPK) which captures both the number of passengers carried and the distance of travel. Growth in freight activity can be similarly represented using Freight Tonne Kilometres (FTKs), capturing both the number of tonnes uplifted and the distance travelled.

Overall air-freight activity comprises two elements – firstly freight carried in the lower hold of passenger aircraft (known as "bellyfreight" or "bellyhold") and secondly freight carried on dedicated freighter flights. Fuel-efficiency figures for passenger aircraft typically take account of the carriage of bellyfreight, which often forms a significant element of the business models of aircraft operators. Clearly, significant changes in the amount of bellyfreight carried can affect fuel-burn of a flight and hence the apparent fuel efficiency per passenger kilometre on that flight. Based on evidence

[16] A term which we define below

presented below, we make the assumption that bellyfreight tonnage is growing no more quickly than passenger numbers.

A full picture of changing levels of aviation activity can thus be conveyed by considering growth in RPKs on passenger flights and, separately, growth in FTKs on dedicated freighter flights.

2.3 Data Sources, Key Assumptions, and Calculations

This section provides a summary of our choice of data sources, key assumptions, and calculation methods. Full details can be found in **APPENDIX B**.

Our demand growth forecasts for passenger flights are based on those published by the Airports Commission [AC, 2015]. Starting with the family of demand growth forecast trajectories corresponding to the Airports Commission's "Global Growth" economic scenario in a "carbon-traded" framework[17], we have taken the three RPK forecasts corresponding to the three additional-runway-capacity options and averaged them[18] to produce a single trajectory corresponding to our assumed growth in passenger flights.

We have then shown that it is reasonable to assume that growth in FTKs on freighter flights will grow no more quickly than RPKs on passenger flights. This has enabled us to estimate an "upper bound" demand growth trajectory for freighter flights. Combining the two gives us our hypothetical "no-improvements" demand growth trajectory. Full details can be found in **APPENDIX B**.

2.4 The Hypothetical "No-Improvements" Scenario

Table 1 summarises our hypothetical "no-improvements" scenario and the method used to combine growth in passenger RPKs and freighter FTKs.

Hypothetical "No-Improvements" CO_2 trajectory for UK aviation, relative to 2010							
Year	Pax RPKs		Freighter FTKs		Combined		
	Growth factor	Weighting	Growth factor	Weighting	Growth Factor	% Growth 2016 Road-Map	% Growth 2012 Road-Map
2010	1		1		1	0	0
2020	1.32		1.1		1.31	31	35
2030	1.75	0.976	1.46	0.024	1.75	75	72
2040	2.14		1.79		2.13	113	113
2050	2.56		2.14		2.55	155	150
Average growth rate						2.37 % p.a.	2.32 %p.a.

Table 1 – Key figures relating to the hypothetical "no-improvements" emissions trajectory used in this CO_2 Road-Map. Scope: UK aviation. Source: SA analysis of data from [AC, 2015], [AC, 2015a], [DfT, 2013] and [CAA] as described in the main text.

Comparing the last two columns of the table, we can see that the demand-growth trajectory is only slightly higher than that which we employed in our 2012 Road-Map [SA, 2012]. This outcome is co-incidental and is the result of a balance between a number of factors:

17 Reasons for these choices are given in **APPENDIX B**.

18 Sustainable Aviation does not have a position on the relative attractiveness of the three additional runway capacity options

- For our 2016 Road-Map we have used recent aviation demand-growth forecasts which take account of the strong economic downturn experienced in recent years, and its long-term negative impact on demand for aviation.
- Our assumptions for growth in freighter activity are no longer based on what with hindsight was an overly ambitious growth forecast. Nonetheless we expect that our new assumptions still overestimate slightly the likely out-turn for freighter FTKs.
- CO_2 emissions from freighters in our baseline year of 2010 are now believed to be 0.8 $MtCO_2$ [DfT, 2013] rather than the 1.1 $MtCO_2$ [DfT, 2011] which we used in our 2012 Road-Map. As a result, not only is the rate of growth in freighter FTKs less strong in our 2016 Road-Map than in our 2012 Road-Map, but it is starting from a lower baseline position.
- Increased runway capacity enabling greater aviation activity through reduction in capacity constraints.

Carbon pricing, with a resulting upward pressure on ticket prices and corresponding downward pressure on demand for aviation, is employed both in the [AC, 2015] forecasts upon which our 2016 Road-Map is based, and also in the [DfT, 2011] forecasts upon which our 2012 Road-map was based. The assumed price of carbon in 2050 is respectively £196 (in 2008 pounds, figure 4.1 of [AC, 2015]) and £200 (in 2009 pounds, box 2.4 of [DfT, 2011]).

In a hypothetical "no-improvements" scenario such as that illustrated in **Figure 1**, CO_2 emissions from UK aviation would rise by 155% during the period from 2010 to 2050, implying an average annual growth rate of 2.37%. In subsequent sections of this document we examine opportunities for mitigating this growth-driven upward pressure on CO_2 emissions from UK aviation.

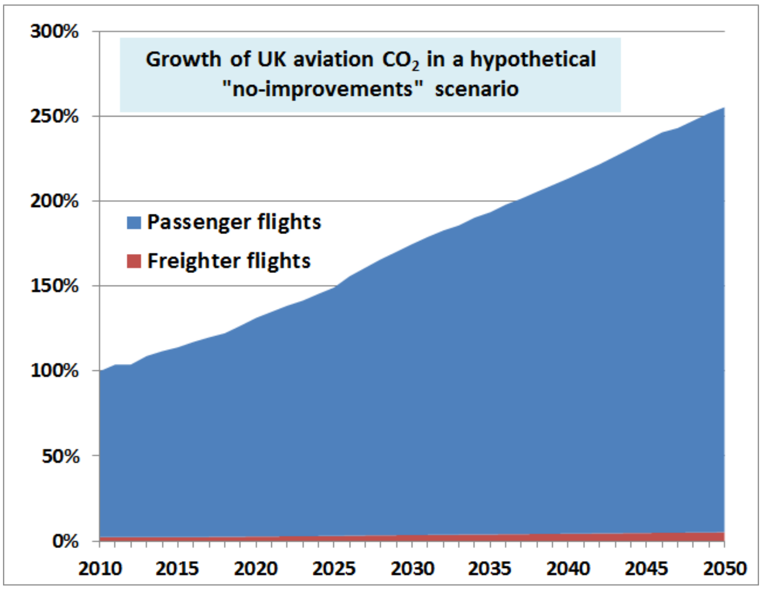


Figure 1 – UK aviation CO_2 emissions, relative to 2010, in a hypothetical "no-improvements" scenario in which technology levels, operational practices, and sustainable aviation fuel penetration levels remain unchanged from 2010. Scope: UK aviation. Source: SA analysis of data from [AC, 2015], [AC, 2015a], [DfT, 2013] and [CAA] as described in the main text.

3 Improvements in Air Traffic Management and Operations

SUMMARY

Improvements in air traffic management and operational practices are likely to improve the carbon intensity of UK aviation by around 8.7% by 2050 relative to 2010, with the potential for additional savings which we do not at this stage include in our assumptions. This result is very similar to the 2012 Road-Map, although we have substantially improved the calculation methodology in one area within this category.

To enable these improvements, Government must continue to support airspace modernisation in the UK, and maintain momentum towards improved Air Traffic Management (ATM) collaboration across Europe.

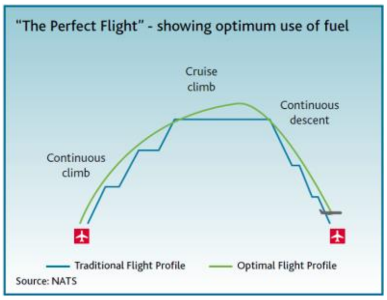
3.1 Introduction

As with our 2012 Road-Map [SA, 2012], this section sets out our view of likely improvements in UK aviation's carbon intensity arising from more efficient air traffic management (ATM), more efficient aircraft operations, and the substitution of some aircraft auxiliary power unit (APU) usage with more efficient and/or lower-carbon airport-based alternatives. A useful discussion of the range of opportunities for fuel-efficiency improvement through improved ATM and operational practices can be found in [ATAG, 2016]. Here we focus on assessing the scale of the available improvements, specific to UK aviation.

3.2 Air Traffic Management (ATM)

3.2.1 Introduction

Section 4.2 of our 2012 CO_2 Road-Map provides an overview of this topic and the broad areas in which efficiency improvements may be obtained, as well as listing some of the initiatives underway at that time. A more in-depth discussion of improvement opportunities has since been published by NATS[19]. In this 2016 Road-Map, we again consider ATM-related CO_2 mitigation opportunities in three categories – 1) near term in NATS controlled airspace, 2) near term in non-NATS airspace, and 3) longer term. We also list some recent developments and achievements that have taken place since 2012.



3.2.2 Near-Term ATM-related CO_2 Mitigation Opportunities – on ground and in NATS airspace

In 2008, NATS committed to a target of reducing CO_2 emissions from aircraft under NATS control by 10% per flight by 2020 relative to a 2006 baseline. However, the scope of "*aircraft under NATS control*" is rather different from the scope of "*UK aviation*". In **APPENDIX C**, we present our updated and expanded analysis of how the NATS target translates into a reduction of **2.8%** in CO_2 from UK aviation by 2020, relative to 2010.

Although the above discussion refers to a stated target for 2020, much progress has already been made towards the achievement of that target. [NATS, 2016] describes recent achievements and ongoing work to improve ATM efficiency, of which some highlights are as follows:

19 http://www.nats.aero/wp-content/uploads/2013/05/11001_NATS_Swatch-book_Online_Linked_240413_HS.pdf

- A 4.3% reduction in CO_2 emissions (relative to the 2006 baseline) has been achieved so far, equivalent to reducing CO_2 emissions from aircraft under NATS control by some 1.1 $MtCO_2$ per year relative to 2006 emissions.
- XMAN (Cross Border Arrival Management) allows airborne holding time to be reduced by instructing aircraft to reduce slightly their cruise speed at a distance of up to 350 nautical miles from their destination airport, thus timing their arrival more precisely. Previous arrangements for London-inbound flights meant that such speed reduction could be instructed only 80 nautical miles from the destination. In the coming years, XMAN will be deployed more widely across Europe, enabling the benefits to apply to UK-outbound flights (within scope of our Road-Map) as well as to UK-inbound flights (out of scope).
- As part of the Borealis alliance, the implementation of Free Route Airspace, firstly in parts of Scottish airspace and then more widely across UK airspace, will allow aircraft greater scope to follow fuel-optimal routings (including taking account of weather conditions) rather than following pre-defined routes. The iTEC system[20], which entered operational service in 2016, will support the introduction of Free Route Airspace above 28,000 feet.
- The number of continuous descent operations continues to increase, with work underway to optimise the altitude at which continuous descent commences, increasing the efficiency improvement[21].

3.2.3 Near-Term ATM-related CO_2 Mitigation Opportunities – Non-NATS airspace

We anticipate that other ANSPs will also deliver improvements in ATM efficiency within the 2010-2020 timeframe[22,23], and that these will yield CO_2 reductions during the en-route and arrival phases of outbound international flights once they leave NATS airspace. We conservatively estimate that the benefit to these flights corresponds to two tenths of the 10% efficiency improvement targeted by projects such as the Single European Sky (SES)[24]. In 2006, CO_2 emissions outside NATS airspace attributable to flights which departed from UK airports amounted to 28.1 $MtCO_2$[25]. Saving 2% of these emissions would yield a reduction of 0.56 $MtCO_2$ relative to 2006 emissions, corresponding to 1.5% of total UK aviation CO_2 emissions in 2006. Again, due to the anticipated delivery timescale of these savings, we assume that this 1.5% also applies to the Road-Map's 2010 baseline. To take account of possible uncertainties, in our Road-Map we assume **1.0%** as the likely contribution from this source.

3.2.4 Longer-Term ATM-related CO_2 Mitigation Opportunities

In this category, we have no additional information relative to that available in 2012. As a result we again assume a **2.5%** efficiency improvement from longer-term (2020-2050) ATM improvements including restructuring of airspace boundaries and improved separation minima allowing more optimum flight profiles.

As with our 2012 Road-Map, it has not been possible in this longer-term ATM category to produce a calculation-based estimate, and we rely on judgement to underpin our assumption in this category.

20 http://www.nats.aero/news/next-generation-air-traffic-technology-goes-live-at-nats-prestwick/, viewed 14th July 2016

21 Although CDO will yield genuine reductions in aviation CO_2 emissions, only the savings relating to domestic arrivals are within scope of our Road-Map, while those relating to international arrivals are not.

22 See for example http://www.navcanada.ca/EN/about-us/Documents/CIFER_English_Final_Medium_Res.pdf, which describes ATM improvements implemented and planned by NAV CANADA which are expected to save some 15 million tonnes of CO_2e (cumulative) between 2010 and 2020. A proportion of this saving is attributable to flights from Europe to North America.

23 http://www.sesarju.eu/sites/default/files/documents/reports/SESAR_Demo_Brochure_2012_2014.pdf

24 http://www.sesarju.eu/benefits/environment/how-sesar-contributing-environmental-flight-performance, viewed 14th July 2016

25 38.1 $MtCO_2$ total [NAEI, 2011], minus the 10.0 $MtCO_2$ taking place in NATS airspace, leaves 28.1$MtCO_2$ outside NATS airspace.

However, we anticipate that greater clarity will emerge over time, and we shall revise our assumptions in this category as and when substantially better information becomes available.

3.2.5 Supporting Products, Technologies and Research Programmes

In addition to the examples of improvement initiatives listed in **section 3.2.2 above**, other technologies, products and research programmes offering opportunities for efficiency improvement in ATM and/or aircraft operations over a variety of timescales include the following:

- NATS is investing significantly to transform operations[26] in support of the Single European Sky project, helping to reduce inefficiency between different areas of NATS airspace.

- The TRANSIT research programme, announced during 2016, will develop opportunities to optimise aircraft taxi routings around airports, reducing "*aeroplane taxi times, operating costs and environmental impact at airports around the world*"[27].

- NASA's Traffic Aware Planner application searches for "*route and/or altitude changes that could save fuel or flight time and displays those solutions directly to the flight crew*" [28].

- Boeing's Wind Updates service "*delivers timely, accurate weather information to the FMC while in flight to enhance flight efficiency and on-time performance*"[29].

- Boeing's Direct Routes service "*identifies and communicates emergent in-flight opportunities to reduce one minute or more of flight time*"[30].

- NASA's Terminal Sequencing and Spacing tool "*will allow pilots to better use flight deck automation to fly fuel-efficient, optimized profile descents*"[31].

- Required Navigation Performance (RNP) and the Global Navigation Satellite Landing System (GLS) use navigation satellites for precision guidance of aircraft. Although most commercial aircraft today are equipped with RNP and GLS capability, further opportunities exist to deploy that capability to full effect and thus further efficiency improvement opportunities exist. Advantages of full RNP/GLS deployment include reductions in track miles flown, and an increase in airport capacity (with possible reductions in airborne holding) enabled by concurrent approach and landing operations on parallel runways.

- The TOPFLIGHT collaborative project - involving NATS, Airbus ProSky, Boeing and British Airways - tested sustainable gate-to-gate transatlantic flight optimisation, demonstrating a potential reduction in CO_2 emissions of up to 2% for each transatlantic flight, without detriment to other airspace users [SA, 2015].

- Rolls-Royce VisiumFUEL enables operators "*to quickly understand their current fuel usage and implement immediate fuel saving initiatives…..Whether it is a pilot making confident fuel-related decisions without compromising safety, or control centre staff improving the routing of*

[26] http://www.nats.aero/news/next-generation-air-traffic-technology-goes-live-at-nats-prestwick/, viewed 21st Sept 2016

[27] https://alumni.cranfield.ac.uk/Public/News_Item.aspx?Id=1467&Ref=en0816, viewed 16th Aug 2016

[28] http://www.nasa.gov/press-release/nasa-developed-technology-aims-to-save-commercial-airlines-fuel-time, viewed 14th July 2016

[29] http://www.boeing.com/resources/boeingdotcom/commercial/services/assets/brochure/fs-windupdates.pdf, viewed 30th August 2016

[30] http://www.boeing.com/resources/boeingdotcom/commercial/services/assets/brochure/directroutes.pdf, viewed 20th August 2016

[31] http://www.nasa.gov/press-release/nasa-developed-air-traffic-management-tool-flies-into-use, viewed 14th July 2016

aircraft to minimise unnecessary fuel consumption, VisiumFUEL provides the insight they require”[32].

- Airbus NAVBLUE[33] offers a range of digital flight operations solutions which contribute to reducing fuel consumption and noise. ELISE by NAVBLUE uses full 3D interference simulation software to predict and analyse disturbances caused by objects such as buildings and aircraft on Instrument Landing System (ILS) signals. ELISE helps airport services to increase capacity, reduce holdings and increase safety. This ultimately increases the efficiency of Air Traffic Management, reducing costs and emissions. Airspace by NAVBLUE allows airports to implement Performance Based Navigation (PBN), reducing fuel-burn and hence CO_2 emissions by making shorter and more direct routes possible and reducing airport and airspace congestion whilst improving access to airports in poor visibility. NAVBLUE’s N–Flight Planning software suite is a flight plan optimisation solution that helps create the safest and most cost-effective and energy–effective routes.

- NASA’s Flight Deck Interval Management system[34] (FIM) offers the potential for more precise management of the time interval between successive aircraft as they arrive at airports, enabling increased runway throughput and reductions in aircraft fuel-burn. Demonstration flight tests are planned for 2017. FIM uses NASA’s ASTAR software which was demonstrated in 2014 on Boeing’s ecoDemonstrator 787 aircraft (see **section 4.10.1**)

3.2.6 Summary

The above discussion is summarised in **Table 2**.

ANSP	Timescale	Phase of Flight	Assumed Saving (% of UK aviation CO_2)	
			2016 Road-Map	2012 Road-Map
NATS	Pre 2020	All	**2.8**	3.0
Other	Pre 2020	En-Route, Descent	**1.0**	1.0
NATS & Other	Post 2020	All	**2.5**	2.5
TOTAL			**6.3**	6.5

Table 2 – assumed scope for reductions in CO_2 emissions from flights which depart from UK airports, arising from anticipated improvements in ATM efficiency.

3.3 APU Substitution

This topic relates to reducing the use of aircraft auxiliary power units (APUs) while aircraft are on stand, instead providing aircraft with electrical power and air-conditioning services from airport infrastructure. Our analysis of the potential for APU substitution to reduce CO_2 emissions from UK aviation (relative to a 2010 baseline) is set out in section 4.3 of our 2012 CO_2 Road-Map. Having reviewed the topic again, our view is that the figure of **0.3%** assumed in our 2012 Road-Map remains valid, subject to the availability of competitively-priced FEGP[35]/PCA[36] at UK airports.

[32] http://www.controlsdata.com/civil-aero/fuel-management, viewed 31st August 2016

[33] https://navblue.aero/en/products-and-services/overview, viewed 29th Sept 2016

[34] https://www.nasa.gov/aero/nasa-aircraft-arrival-technology-gets-big-test-in-2017, viewed 03 Nov 2016

[35] FEGP = fixed electrical ground power

[36] PCA = pre-conditioned air

3.4 Aircraft Operations

In section 4.4 of our 2012 CO_2 Road-Map, we considered opportunities to reduce UK aviation CO_2 through higher passenger load-factors, better optimisation of fuel-loading, and miscellaneous measures such as maintenance of door seals and dents, regular cleaning of engines and airframes, and reducing the carriage of potable water.

Our 2016 review of this area revealed good progress in all three areas. For example, [SA, 2015] gives an overview of the efforts being made across the industry and progress made so far by SA members.

Our view is that the assumption used in our 2012 Road-Map of a **2.1%** fuel-efficiency improvement (relative to a year 2010 baseline) remains valid. However, in our 2016 Road-Map we assume that this improvement is delivered over a ten-year period to 2020.

One area of potential improvement that has not been formally included into our assessment is that of electric taxiing, either through the use of electric motors mounted in the aircraft itself and powered by the aircraft's APU[37], or through the use of a dedicated electrically-propelled tractor[38]. The prospects for electric taxiing's deployment at scale are not yet clear. However, we acknowledge the possibility that it may enable a material reduction in global aviation emissions in future years and will monitor its deployment.

3.5 Potential Mitigation Impact – ATM and Operations

Table 3 summarises the key figures presented in this chapter. In our 2016 Road-Map, as with our 2012 Road-Map, we assume a potential efficiency improvement opportunity from ATM and operations of just under 9%.

Category	**Assumed % CO_2 Saving**
ATM	6.3
APU substitution	0.3
Aircraft Operations	2.1
TOTAL	**8.7**

Table 3 – potential reductions in CO_2 emissions from UK aviation, due to anticipated improvements in ATM efficiency and operational practices.

37 See for example http://www.wheeltug.com/

38 See for example http://www.taxibot-international.com/

4 Improvements in Aircraft and Engine Efficiency

SUMMARY

1. **Introduction of the "imminent" generation of aircraft types will improve the fleet-average fuel efficiency of UK aviation by some 22% by 2050 relative to the year 2010 baseline fleet, with the bulk of this improvement delivered by around 2040.**

2. **Introduction of the subsequent "future" generation of aircraft types from 2035 onwards has the potential to further improve fleet average fuel efficiency within UK aviation by some 21% by 2050, taking account of likely fleet penetration by that date.**

3. **This yields a combined potential improvement in fleet-average fuel efficiency (2010-2050) of some 39%[39].**

4. **Post 2050, improvements in fleet-average fuel efficiency will continue due to the ongoing penetration into the fleet of "future" aircraft types. However, those improvements lie beyond the time-horizon of our Road-Map and therefore do not feature in our analysis.**

We acknowledge the significant levels of government support to the UK aerospace industry provided through initiatives such as the Aerospace Growth Partnership (AGP). In the coming years Government must ensure that access by UK aerospace industry to ongoing funding for high-value collaborative R&D, essential for delivering highly-efficient future aircraft and propulsion systems, remains in place.

CHANGES SINCE OUR 2012 CO_2 ROAD-MAP

"Imminent" Aircraft

1. In the narrow-body segment, the extent to which the Airbus A320neo family and the Boeing 737 MAX will improve upon the fuel efficiency of their respective predecessors is now significantly greater than was understood in 2012. An additional member of the Airbus A320neo family, the A321LR, has been launched.

2. In the wide-body segment, three new aircraft types have been launched: the Airbus A330neo[40], Boeing 777X[41] and Boeing 787-10[42].

3. We have taken advantage of additional data sources to establish a more accurate picture of the baseline (year 2010) fleet, rather than assuming that the baseline fleet

[39] 0.78 (representing a 22% improvement from "imminent" aircraft types relative to the baseline fleet) multiplied by 0.786 (representing a further 21.4% improvement from "future" aircraft types,) yields 0.613 i.e. a combined improvement of 38.7%.

[40] http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/airbus-launches-the-a330neo/, viewed 26 Apr 2016

[41] http://boeing.mediaroom.com/2013-11-17-Boeing-Launches-777X-with-Record-Breaking-Orders-and-Commitments, viewed 26 Apr 2016

[42] http://boeing.mediaroom.com/2013-06-18-Boeing-Launches-787-10-Dreamliner, viewed 26 Apr 2016

was composed solely of the latest aircraft types available in that year. This enables a more complete assessment of the fuel-saving opportunity presented by replacing the baseline fleet with "imminent" aircraft types.

4. We have increased the granularity of our fleet replacement model for the "baseline" to "imminent" transition, now considering ten aircraft categories rather than three. This allows us to capture more correctly the timing of various improvements to fleet fuel efficiency.

"Future" Aircraft

5. The considerable marketplace success of the Airbus A320neo and the Boeing 737 MAX families means that their respective production runs will likely be significantly longer than we anticipated in our 2012 Road-Map. As a result we now believe that their replacements will be some 10 years later than we previously assumed.

6. Our fleet replacement model for the "imminent" to "future" transition now considers four aircraft categories rather than three. This allows us to distinguish between different parts of the "wide-body" aircraft category whose replacement timescales and characteristics may be different.

Outcome

7. As a result of the above changes, fleet efficiency improvements related to the introduction of "imminent" aircraft types will be larger than we anticipated in our 2012 Road-Map, while the subsequent transition from "imminent" to "future" aircraft will have a lower impact by 2050 due to its later starting point. At 2050 the overall improvement in fleet fuel efficiency relative to the 2010 baseline is very similar to our 2012 assessment.

4.1 Introduction and Framework

This chapter sets out our view of the potential for improvements in aircraft and engine fuel efficiency to reduce UK aviation's carbon intensity by 2050. We detail our assumptions concerning the fuel efficiency of "imminent" and "future" aircraft relative to their respective predecessors, their likely entry into service dates, and their resulting impact on fleet-average fuel efficiency. We also provide an update concerning technology options being explored by the aerospace manufacturers, which collectively underpin our fuel-efficiency assumptions for "future" aircraft. Throughout this chapter, we define "the fleet" as aircraft used to conduct flights falling within the scope of "UK aviation".

As with our 2012 CO_2 Road-Map [SA, 2012], we start with a "baseline" ("generation 0" or "G0") fleet in the year 2010 and then consider in turn two distinct generations of aircraft ("imminent" or "G1" and "future" or "G2") which, as they displace older aircraft from the fleet, cause a reduction in CO_2 emissions for a given level of aviation activity.

However, relative to our 2012 CO_2 Road-Map, our fleet model now has more granularity. When modelling the replacement of the 2010 "baseline" fleet with "imminent" aircraft types, we use a fleet model based wherever possible on individual aircraft families, resorting to aircraft size categories only where necessary due for example to a lack of clarity concerning likely market share of competing aircraft, or a lack of information concerning the comparative efficiency of particular aircraft pairs. When modelling the transition from "imminent" aircraft to "future" aircraft, rather than the three size categories employed in our 2012 Road-Map, we now consider four size-categories of aircraft: "narrow-body" (NB), "small-to-medium twin aisle" (SMTA), "large twin-aisle" (LTA) and "very-large" (VL). This enables a more realistic representation of the likely entry-into-service dates and fuel-efficiency characteristics, relative to their respective predecessors, of various aircraft types lying in very different parts of what was previously a single "wide-body" category.

4.2 Issues to Consider

4.2.1 Fuel Price

Historically, the cost of fuel has accounted for a substantial proportion of the total cost of ownership of commercial aircraft. For example, even with crude oil prices currently at relatively low levels, the International Air Transport Association (IATA) estimates that in 2015 the global aviation sector spent $181 billion on fuel, representing 27% of operating expenses (the lowest percentage since 2005)[43].

Aircraft and engine manufacturers have therefore experienced strong demand from customers for more fuel-efficient aircraft, and have responded to this with successive generations of aircraft offering improved fuel-efficiency over their predecessors. Competition between manufacturers drives very significant investment in research and development activities, often over very long timescales.

In recent times (since 2013), the price of fuel has fallen significantly (see **Figure 2**). However, evidence suggests that airlines are still viewing fuel price with a long-term lens, taking advantage of the current respite associated with low crude-oil prices to position themselves more strongly for the future and the possibility of higher fuel prices to come.

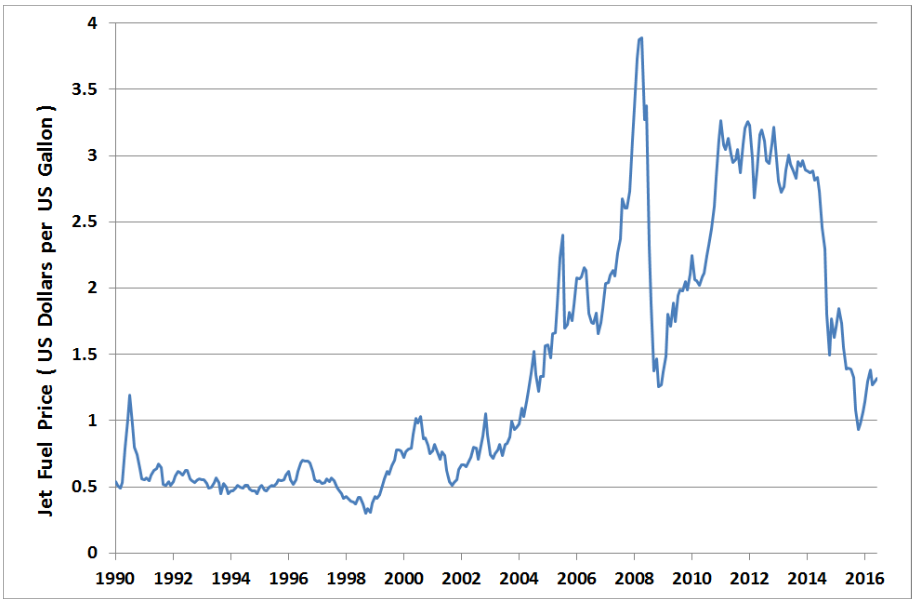


Figure 2 – spot price of US Gulf-Coast Kerosene-type jet fuel (FOB). Data source: US Energy Information Administration.

In the unlikely event that crude oil prices remain low indefinitely, the introduction of a price for carbon, perhaps through a global market-based measures scheme such as that agreed by ICAO in 2016, will act to increase the effective price of jet fuel, albeit to an extent that is unknowable at present[44].

[Avolon, 2015] considers the possibility that sustained low fuel prices might encourage the return to service of stored aircraft. Such aircraft would likely be substantially less fuel efficient than aircraft of the following generation, whose introduction into the fleet they might delay. Nonetheless, the report

43 Assuming oil at $55 per barrel. Source: http://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-fuel.pdf

44 It should also be noted that an element of carbon pricing is inherent to the demand growth forecasts upon which we have based our hypothetical no-improvements scenario, as described in **chapter 2**.

concludes that the number of aircraft identified "*as potentially returning to operation is extremely small in the context of the global fleet*". The same report also considers the possibility of deferred retirements arising from sustained low fuel prices, concluding that "*the aggregate displacement of younger aircraft in the operating fleet, net of additional demand growth, is not expected to exceed a manageable 5% to 10% of new deliveries*".

In the very unlikely event that fuel price stays low and is not supplemented with a material carbon price, the effects upon our Road-Map would likely be limited to the following:

- Efficiency characteristics and EIS of "imminent" aircraft types: **not affected**
    - The efficiency characteristics of almost all of the "imminent" aircraft types considered in our analysis are already defined, and many of them have already entered service or will do so in the next couple of years.
- Timescale for fleet transition from baseline to "imminent" aircraft types: **lengthened slightly**
    - Although in a persistently-low fuel-price scenario, aircraft operators may choose to use older aircraft for slightly longer prior to spending on newer, more efficient aircraft[45], nonetheless aircraft have finite in-service lives and eventually will need to be replaced. Consequently, a delay in the uptake of "imminent" aircraft might be expected but it is reasonable to assume that by 2050 the number of baseline aircraft still flying will be very small, even in a persistently-low fuel-price scenario.
- Efficiency characteristics and EIS of "future" aircraft types: **dependent upon future fuel-efficiency standards**
    - A persistently low fuel price could alter the economics of new aircraft such that non-fuel-related characteristics dominate the design drivers for future aircraft types, which as a result could, based on purely commercial drivers, be less fuel-efficient than in a higher fuel-price scenario. However, future fuel-efficiency standards - such as developments of that agreed in 2016 by ICAO - may mitigate such effects.
- Timescale for fleet transition from "imminent" to "future" aircraft types: **delayed or lengthened materially**
    - In a persistently-low fuel-price scenario, retirements are likely to be deferred as older aircraft remain competitive for longer. Unlike the baseline-to-"imminent" fleet transition, the impact on the 2050 fleet fuel-efficiency in our Road-Map model due to delays in the commencement of the "imminent" to "future" fleet transition could be material, since any delay or lengthening of that fleet transition can impact the degree to which the fleet transition is completed by 2050.

In our 2016 CO_2 Road-Map, we make the assumption that in the long-term, fuel-prices, perhaps supplemented by carbon prices, will not remain at their currently low levels, and that aircraft replacement schedules or future aircraft characteristics will not be impacted materially. Should fuel prices remain low for many years, and should a carbon price fail to materialise, future updates of our Road-Map will take that into account.

4.2.2 New Entrants

The extent to which aircraft from emerging competitors such as UAC[46] and COMAC[47] will influence UK aviation fuel-burn in the future is unclear at present. As a result, this 2016 CO_2 Road-Map does not explicitly model the impact on fleet fuel efficiency of aircraft from those manufacturers.

45 At the time of writing, there is little evidence of a significant upward trend in aircraft average retirement ages, despite the recent period of low fuel prices.

46 United Aircraft Corporation

47 Commercial Aircraft Corporation of China

It can be argued that our approach introduces no material error to the Road-Map, since for new entrants to take a material share of the market will require products of similar fuel-efficiency to those offered by established market participants. Furthermore, all manufacturers' aircraft will be subject to the same fuel-efficiency standard (see **section 4.2.3**).

Greater clarity on this issue will no doubt emerge over time, and future updates of the Road-Map (e.g. in 5 or 10 years from now) may be able to take explicit account of products from these emerging manufacturers.

4.2.3 ICAO Fuel-Efficiency Standard

The International Civil Aviation Organization (ICAO) has recently agreed a fuel-efficiency standard[48] for aircraft. The standard will apply to the certification and production of new aircraft types from 2020, modified existing types from 2023, and unmodified existing aircraft types from 2028.

The aim of this certification standard is to reduce CO_2 emissions from aviation by encouraging the integration of fuel efficient technologies into aircraft designs and developments, ensuring older aircraft are replaced by newer, more efficient designs.

The CO_2 Standard is a certification standard, not an operational standard, and as such does not impact current aircraft in use or (until 2028) in production but will impact the next generation of aircraft designs represented by the "future" aircraft wedge of the CO_2Road-Map.

Future updates of our CO_2 Road-Map will take into account the prevailing standard at the time of their preparation.

4.2.4 Freighters

In **chapter 2** and **APPENDIX B** we explain that freight-only flights account for only a small single-digit percentage of UK aviation CO_2 emissions and that we expect their materiality to remain constant or perhaps even decline relative to that of passenger flights.

In the current chapter, we are concerned with the efficiency with which demand for aviation is met. So our next step regarding freight-only flights is to reach an assessment of the how the efficiency of the freighter fleet may evolve over time.

Besides variations in the size of freighter aircraft, a key distinction is whether the aircraft was built from new as a freighter, or converted from a passenger aircraft. Clearly a converted passenger aircraft is likely to be of a previous generation (and hence arguably less fuel-efficient) relative to a new-build freighter. Nonetheless, it is likely to be substantially more efficient than an even earlier generation passenger-to-freight conversion which it may displace from the fleet, thus resulting in an improvement to fleet fuel-efficiency.

In the absence of available UK-specific data concerning the likely usage balance within UK aviation between passenger-conversions and new-build freighters, we make the simplifying assumption that the efficiency of the freighter fleet will improve at a similar rate to that of the passenger fleet. The error this may introduce to the overall analysis is small, due to the low materiality of freight-only flights.

4.2.5 Technology Targets

Significant technology research programmes are required in order to deliver future aircraft with substantially improved fuel efficiency. Such research programmes are typically coordinated and

48 http://www.icao.int/Newsroom/Pages/New-ICAO-Aircraft-CO2-Standard-One-Step-Closer-To-Final-Adoption.aspx

funded at the national or international level due to their scale. Associated technology acquisition goals have been adopted in the US and Europe as follows:

- In Europe, the goals of FlightPath 2050 include "*In 2050 technologies and procedures available allow a 75% reduction in CO2 emissions per passenger kilometre.... relative to the capabilities of typical new aircraft in 2000*"[49]. The ACARE[50] organisation has established a strategic research and innovation agenda as a route towards those targets.
- In the US, NASA's goals for subsonic air transport includes technology acquisition, to technology readiness level (TRL) 4-6, for reductions in aircraft fuel or energy consumption as follows[51],[52]:
    - N+2 goal: by 2020 aircraft energy consumption reduction of 50% relative to 777-200.
    - N+3 goal aircraft energy consumption reduction of 60% by 2025 relative to 737-800

In **section 4.7 below** we have used these goals to derive "calibration" points against which to "sense-check" our proposed central-case assumptions for "future" aircraft fuel efficiency. However, in order to allow a like-for-like comparison, we assume that there will be a lead time of several years between achievement of the above technology-development goals and the earliest possible entry into service (EIS) of a commercial aircraft product embodying the developed technologies and achieving in-service fuel-efficiency levels consistent with the goal. With regard to the FlightPath2050 targets, we assume a lead-time of 5 years between achievement of the technology goals (usually interpreted to mean attainment of TRL6) and EIS of the corresponding aircraft, while for the NASA N+2 and N+3 targets we assume a lead-time of 8 years between achievement of TRL4-6 and EIS.

4.3 Baseline Fleet Composition

4.3.1 Distribution of 2010 UK Aviation Activity by Aircraft Type

Figure 3 shows the distribution between aircraft types of CO_2 produced by flights departing from UK airports, i.e. within UK aviation, for 2010 and 2014. This takes account not only of the number of seats installed on an aircraft, but also the distance covered by each flight and the efficiency of each aircraft type for the specific mission performed. The changes between 2010 and 2014 are related to replacement of B747-400s with A380s and other, twin-engined, aircraft, and a slight migration away from B757s towards single-aisle aircraft and/or small twin-aisle aircraft. In other respects, the distribution between families / categories shows little change between these two snapshots. There may of course be changes within families or categories, as discussed in **section 7.3.1**.

In many cases, we can identify a clear and credible "like-for-like" replacement path for aircraft types. For example, we assume that in-service examples of the existing 737 family will be replaced largely by 737 MAX aircraft, and that A320ceo aircraft will be replaced largely by A320neo aircraft. Although there will inevitably be some counter examples, the error it will introduce is relatively small.

Where there is not a clear "like-for-like" replacement path for individual aircraft types, we have grouped them into aircraft size categories, specifically SMTA[53] and LTA[54]. Categories have also been applied for regional jets and for turboprops which are both of fairly low materiality in terms of their respective shares of UK aviation CO_2 emissions.

This approach represents an improvement upon our 2012 CO_2 Road-Map in several respects:

49 http://www.acare4europe.org/sria/flightpath-2050-goals/protecting-environment-and-energy-supply-0, viewed 21st Sept 2016

50 ACARE = Advisory Council for Aviation Research and innovation in Europe

51 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150002081.pdf, viewed 21st Sept 2016

52 https://www.nas.nasa.gov/assets/pdf/ams/2015/AMS_20150521_DelRosario.pdf, viewed 21st Sept 2016

53 SMTA: "small to medium twin aisle", category includes A300, A310, A330, A340-200/300, B767, A330neo, B787

54 LTA: "large twin-aisle" category includes A340-500/600, B777, A350 XWB, B777X

- We more correctly take account of the fact that in our baseline year of 2010, replacement of some B747-400s by A380s had already commenced, reducing slightly the remaining fuel-efficiency improvement opportunity.

- We take account of the migration of some activity from large 4-engined aircraft to medium or large 2-engined aircraft

- We model regional jets and turboprops explicitly, rather than including them within a generic "narrow-body" category.

- We take explicit account of the materiality of the many different aircraft types within what was previously a single "narrow-body" size category.

- We can also explore more deeply the composition of the baseline fleet, and quantify some of the additional improvement opportunity arising from replacement with "imminent" aircraft of legacy aircraft whose fuel-efficiency is less good than the majority of the baseline fleet.

- Although wide-body aircraft are still categorised, the use of two categories (SMTA / LTA) rather than one (WB) allows us to more effectively capture distinctions between different parts of that segment.

- Our more detailed categorisation of aircraft allows us to model more accurately the phasing of the introduction of newer aircraft types.

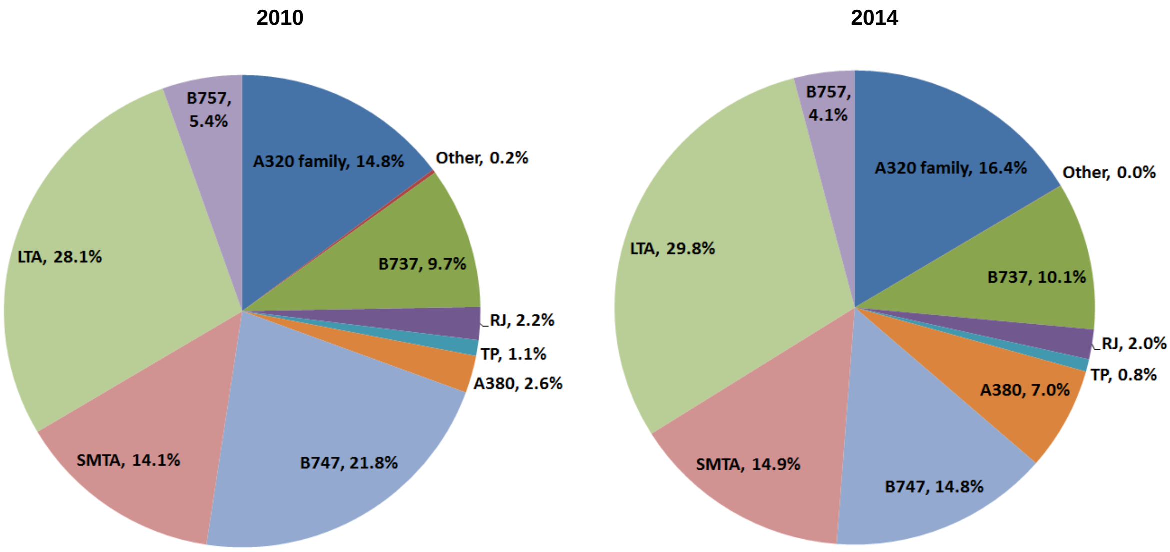


Figure 3 – distribution of CO_2 emissions between aircraft types or categories. LEFT: 2010. RIGHT: 2014. Scope: UK aviation. SOURCE: SA analysis of data from OAG.

4.4 "Imminent" Aircraft – Efficiency Characteristics and EIS[55] Dates

APPENDIX D gives details of the fuel-efficiency characteristics of "imminent" aircraft relative to previous generation aircraft, as well as their entry into service dates. **Table 4** provides a summary**.**

Aircraft	Entry into service[56]	Manufacturers' claimed fuel efficiency improvement vs previous generation aircraft[57]	
		2016 Road-Map	2012 Road-Map (for comparison)
Bombardier C Series	2016	20	20
Embraer E2	2018	16 – 24	N/A
Airbus A320neo family	2015	19 – 23	15
Boeing 737 MAX	2017	14 – 20	10 -12
Airbus A321LR	2019	30	N/A
Airbus A330neo	2017	14	N/A
Boeing 787 Dreamliner	2011	20 – 25	20
Airbus A350 XWB	2015	25	25
Boeing 777X	2019	20	N/A
Airbus A380[58]	2007	40	17

Table 4 – fuel-efficiency improvements offered by "imminent" generation aircraft relative to the aircraft they replace. Note that replacement of significantly older members of the baseline fleet (rather than the latest available aircraft in 2010) will enable additional efficiency improvements.

APPENDIX D also explains our assumptions concerning the length of time taken for new aircraft to displace corresponding older aircraft from the fleet. A summary can be found in **Table 5**.

4.5 "Imminent" Aircraft – Impact on Fleet Fuel Efficiency

This section sets out the opportunities for the "imminent" aircraft types discussed above to influence fleet fuel efficiency in their respective categories, taking account - where possible - of the composition of the baseline fleet in the year 2010. In particular we take account of the materiality of different aircraft types and the additional improvement opportunities relating to the presence within the baseline fleet of "legacy" aircraft which are of an older generation than the immediate predecessors of "imminent" aircraft types. Where such account cannot be taken for a particular category, we conservatively assume, for the category being considered, that the 2010 baseline fleet was composed entirely of the latest aircraft available in that year.

[55] EIS = Entry Into Service – the date at which the first instance of a new aircraft type enters commercial service

[56] Source: aircraft manufacturers

[57] See **APPENDIX D** for references

[58] The Airbus marketing position regarding fuel efficiency of the A380 relative to that of the 747-400 has been updated since 2012. The revised position is calculated on a "like-for-like" basis, taking account of the available floor area of the passenger cabins in the two aircraft types, and assuming similar proportions of the various possible classes of seating.

Note that aircraft representing the “imminent” generation of technology are already entering service and/or are currently offered for sale to the market. As such the fuel-efficiency characteristics of these aircraft are well-defined and lead us to have a high degree of confidence in their impact, over time, upon fleet efficiency.

It should also be noted that the entry into service dates of “imminent” types, coupled with our assumptions concerning fleet refresh periods (see **Table 4** and **APPENDIX D** respectively) mean that there is an extremely high likelihood that displacement of the baseline fleet by “imminent” types will be complete by 2050, and a high likelihood of completion by 2040.

APPENDIX E gives the detailed analysis leading to the summary provided in **Table 5**.

<table>
<tr><th rowspan="2">Category</th><th colspan="2">Replacement</th><th rowspan="2">Materiality: CO_2 Share (2010)[59]</th><th colspan="2">Within-Category Improvement</th><th colspan="2">Overall Improvement</th><th rowspan="2">Comment</th></tr>
<tr><th>Start[60]</th><th>Period (years)[61]</th><th>%[62]</th><th>Factor</th><th>Factor</th><th>%</th></tr>
<tr><td>RJ</td><td>2016</td><td>25</td><td>0.0225</td><td>20</td><td>0.8</td><td rowspan="10">0.780</td><td rowspan="10">22.0</td><td rowspan="10">Overall improvement factor is the sum of the within-category improvement factors, weighted according to the materiality of each category.

Overall fleet efficiency improvement associated with replacing baseline-fleet with “imminent” aircraft is 22.0%</td></tr>
<tr><td>TP</td><td>N/A</td><td>N/A</td><td>0.0108</td><td>0</td><td>1</td></tr>
<tr><td>A320 family</td><td>2015</td><td>25</td><td>0.1478</td><td>20.7</td><td>0.793</td></tr>
<tr><td>B737 family</td><td>2010[63]</td><td>32</td><td>0.0970</td><td>19.9</td><td>0.801</td></tr>
<tr><td>B757</td><td>2019</td><td>10</td><td>0.0542</td><td>30</td><td>0.7</td></tr>
<tr><td>SMTA</td><td>2011</td><td>25</td><td>0.1407</td><td>17.3</td><td>0.827</td></tr>
<tr><td>LTA</td><td>2010[64]</td><td>30</td><td>0.2811</td><td>25</td><td>0.75</td></tr>
<tr><td>B747-400</td><td>2010[65]</td><td>15</td><td>0.2180</td><td>25</td><td>0.75</td></tr>
<tr><td>A380</td><td>N/A</td><td>N/A</td><td>0.0256</td><td>0</td><td>1</td></tr>
<tr><td>Other</td><td>N/A</td><td>N/A</td><td>0.0024</td><td>0</td><td>1</td></tr>
<tr><td colspan="3">TOTAL</td><td>1.0000</td><td colspan="5"></td></tr>
</table>

Table 5 – values used in our model of the fleet transition from the baseline (year 2010) fleet to one composed entirely of “imminent” aircraft types.

59 Source: As **Figure 3** (LEFT)

60 In many cases the “start” year is simply the EIS date (source: **Table 4)** of the earliest “imminent” aircraft type applying to that category. Exceptions are noted in separate footnotes below.

61 Source: **APPENDIX D**

62 Source: **APPENDIX E**

63 Some migration from 737 classics towards 737 Next Generation aircraft is evident during the years 2010-2015. As with the LTA category, we model fuel-efficiency improvements in this category, due to a migration from the baseline fleet - via intermediate types - to a fleet composed entirely of “imminent” types, as commencing before the first EIS of a corresponding “imminent” type. The duration of the fleet transition is extended accordingly.

64 A migration from the 777-200 and 777-200ER aircraft towards the more fuel-efficient 777-300ER aircraft (as discussed in **APPENDIX E**) is evident between 2010 and 2015, as is a migration away from the A340 (source: operational data from Heathrow, Gatwick and Manchester airports plus data from OAG). Hence we model the fuel-efficiency improvement in the LTA category, associated with a migration from the baseline fleet - via intermediate types - to a fleet composed entirely of “imminent” types, as commencing in 2010 rather than upon the first EIS of an “imminent” type. The duration of the transition is correspondingly longer as a result.

65 Although the A380 entered service in 2007, replacement of 747-400 aircraft from our baseline year-2010 fleet commenced (by definition) in year 2010. A380s already in service on UK routes by that time are accounted for in the next line of the table.

4.6 "Future" Aircraft – Approach Taken

Unlike the transition from the baseline (year-2010) fleet to a fleet of "imminent" aircraft whose fuel-efficiency characteristics and entry-into-service dates are already known in some detail, when we look at the transition from "imminent" to "future" aircraft types the situation is much less clear-cut and some judgement is required to arrive at a sensible set of assumptions.

As explained in **section 4.1**, we consider four categories of "future" aircraft, covering narrow-body (NB), small-to-medium twin-aisle (SMTA), large twin-aisle (LTA) and very-large (VL) aircraft. We believe that this strikes an appropriate balance between complexity and simplicity, allowing us to capture the different timescales in which different categories of aircraft may reach the market, but without requiring an unduly complex model for which many parameter values would need to be determined. In particular we have subsumed turboprop and regional-jet aircraft into the NB category for the purposes of simplicity, given the relatively low materiality of those aircraft within UK aviation's overall CO_2 footprint.

4.6.1 Definition of Aircraft Categories

Firstly we must identify how the 10 aircraft categories we used to model the "baseline" to "imminent" fleet transition relate to the four aircraft categories we are using to model the "imminent" to "future" fleet transition. This turns out to be very simple and is set out in **Table 6**.

baseline to "imminent"[66]	"imminent" to "future"
B747-400, A380	VL
LTA	LTA
SMTA	SMTA
757, A320, B737, TP, RJ, Other	NB

Table 6 – relationships between 1) the 10 aircraft categories used in modelling the baseline to "imminent" fleet transition, and 2) the 4 aircraft categories used in modelling the "imminent" to "future" fleet transition

4.6.2 Materiality of Categories

We must establish the relative materiality of the four aircraft categories in order to take account of the relative significance of fuel-efficiency improvements in different parts of the market. We do this by looking at the fuel-burn distribution in 2015 (the latest full year for which data are available) and assuming that this distribution will remain approximately constant. Significant hazards to this assumption's validity, and their likely materiality, are as follows:

- Constrained availability of airport landing-and-take-off slots may move demand towards larger aircraft. Conversely, opportunities to offer increased frequency of service may move airlines towards smaller aircraft. We assume for the purposes of our Road-Map that the relative fuel-efficiencies of "future" aircraft in neighbouring size categories such as LTA and VL are broadly equivalent and that modest migration of demand from one category to an adjacent category will not introduce significant changes into the overall fuel-efficiency of the fleet once the transition from "imminent" to "future" aircraft is complete. There may however be small but material impacts on fleet-average efficiency during the transition period if the EIS dates of "future" aircraft in neighbouring categories differ substantially. This aspect has relevance

[66] The "other" category shown in **Table 5** (which shows 2010 data) is of such low materiality that we could add it to any of the four categories without affecting the outcome. Its materiality in 2015 is significantly lower still.

because the transition from "imminent" to "future" aircraft types will still be underway in 2050, based on the EIS dates we have chosen (see **APPENDIX F**);

- Battery electric aircraft may (in time) alter the landscape substantially, moving demand towards smaller aircraft for which electric propulsion will become feasible earlier than for larger long-range aircraft, and perhaps incentivising travel in a number of short-range segments rather than one non-stop flight. In such a scenario, one might see the relative materiality of LTA or VL aircraft decline as they remain dominant only on long over-ocean routes. Such a scenario could lead to a substantial reduction in the carbon-intensity of UK aviation, in which case our Road-Map might be viewed as unduly pessimistic regarding CO_2 emissions from UK aviation.

We do not take explicit account of the potential for migration of demand between aircraft categories, nor of the potential for significant decarbonisation from purely battery-electric flight. However, as subsequent sections describe, we do take account of potential improvements in fuel-efficiency due to the adoption of hybrid gas-turbine/electric propulsion systems.

Table 7 shows the materiality assumption values used in our Road-Map model.

Aircraft Category	Materiality (based on year-2015 fuel-burn)
NB	33.6 %
SMTA	16.4 %
LTA	28.0 %
VL	22.0 %

Table 7 – materiality of aircraft categories assumed in our "imminent" to "future" fleet transition. Scope: UK aviation. Source: SA analysis of data from OAG.

4.6.3 Defining Within-Category Assumptions

Our approach to defining within-category assumptions consists of several steps, carried out for each of the four aircraft categories. The application of this approach will be discussed in detail below; here we simply describe the method:

1. We define a prototypical reference aircraft against which the efficiency of other aircraft will be compared. By definition the fuel-burn per passenger-kilometre of the reference aircraft is set at 100%. In most cases the reference aircraft corresponds to a typical new aircraft available in the year 2000, and is therefore compatible with the definition of the ACARE FlightPath 2050 goals[67], a fact which we make use of in later steps. It is worth noting that the fuel-efficiency of the reference aircraft does not correspond to the fleet-average fuel-efficiency in our baseline year of 2010, since the latter arises from the use of a combination of aircraft types of widely varying vintages (some post 2000, some around 2000, some very much pre-2000).
2. We define a representative "imminent" aircraft, whose entry-into-service (EIS) date and fuel-efficiency relative to the corresponding "reference" aircraft are determined with reference to the actual aircraft types involved in the category.
3. We identify the boundaries of the possible space of "future" aircraft characteristics, comprising their EIS dates and the fuel-efficiency improvement they offer relative to equivalent "imminent" aircraft. Specifically, we establish a "best" case and a "worst" case fuel-efficiency improvement relative to the corresponding representative "imminent" aircraft, as well as "earlier" and "later"

[67] See **section 4.2.5**

EIS dates spanning a region within which we consider the first availability of "future" aircraft to be likely. The space bounded by the four corners ("best-earlier", "best-later", "worst-later", "worst-earlier") defines a region outside which we consider the characteristics of "future" aircraft are very unlikely to sit.

   a. The "worst" case fuel-efficiency improvement (relative to the representative "imminent" aircraft) is that which we believe a new "future" aircraft must meet to be considered a commercially viable proposition.

   b. To identify the "best-case" fuel-efficiency improvement, we make use of the FlightPath 2050 technology targets (see **section 4.2.5**). These call for technology and procedures enabling a 75% reduction in CO_2 per passenger kilometre, relative to a typical new aircraft from year 2000, to be available by 2050. We take the view that this would enable an aircraft embodying such technologies to enter service from 2055 (5 years being a typical time lag from TRL6[68] to EIS[69]). We further assume that 10% of the 75% target improvement is delivered by improved operational practices and air-traffic management[70], leaving aircraft fuel efficiency to deliver a 72.2% improvement[71]. We then construct a trajectory (characterised by a constant annual rate of fuel-efficiency improvement) from the reference aircraft to the 2055 EIS fuel-efficiency target for a FlightPath2050-compliant aircraft. Using our "earlier" and "later" EIS dates, we can then read from that trajectory corresponding fuel-efficiencies relative to the reference aircraft. These can if necessary be restated relative to the representative "imminent" aircraft.

4. We define an EIS date for our "future" aircraft. In most cases, it is simply the midpoint between the "earlier" and "later" dates defined in the above step. We also make a judgement concerning how many years after EIS it will take for the "future" aircraft to displace corresponding "imminent" aircraft from the fleet to an extent such that any remaining "imminent" aircraft are no longer material for UK aviation CO_2.

5. To establish a "central" case for the fuel-efficiency of the "future" aircraft relative to the corresponding representative "imminent" aircraft, we apply a similar methodology to that used in our 2012-Road-Map, namely to assume an underlying rate of fuel-efficiency improvement over time, supplemented by a step-change to represent the deployment of one or more technologies or design configurations which offer a significant improvement in performance (and which are discussed in **section 4.10 below**). The assumed fuel-efficiency of the "future" aircraft relative to the corresponding representative "imminent" aircraft thus depends upon the size of the step-change, the annual rate of underlying improvement, and the number of years between EIS of the two aircraft types.

6. We can then "sense-check" the proposed characteristics of the "future" aircraft with reference to 1) previous rates of progress in fuel efficiency (e.g. between the "reference" aircraft and the representative "imminent" aircraft), 2) our bounding-box (being certain that it lies well within the box), and 3) other external calibration points, in order to place it in some form of context.

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68 TRL = technology readiness level. TRL6 = fully functional prototype demonstrated in a representative environment. See for example https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

69 EIS = entry into service

70 Note that our Road-Map assumption of 8.7% CO_2 reduction from improved ATM and operations is lower than the 10% assumed here. If we were to assume 8.7% rather than 10% in the present calculation, the resulting aircraft fuel-efficiency improvement required to reach the FlightPath2050 goal would be correspondingly larger.

71 A 10% improvement in fuel-efficiency from improved ATM and operations corresponds to reducing fuel-burn per passenger-kilometre by a factor of 0.9. Similarly, a 72.22% efficiency improvement from aircraft corresponds to a factor of 0.2777. The combined effect is 0.2777*0.9 = 0.25 i.e. a 75% reduction in fuel-burn per passenger kilometre, consistent with the FlightPath 2050 target.

4.6.4 Combining Categories

Finally, we can use the above information to determine the impact upon fleet fuel-efficiency due to the transition from “imminent” aircraft types to “future” aircraft types, taking account of the incompleteness of that transition by 2050.

4.7 “Future” Aircraft – Assumptions by Category

APPENDIX F sets out the derivation of the assumptions we have employed in our Road-Map model for the fuel-efficiency and entry-into-service dates of “future” aircraft. A summary is given in **Table 8**.

Category	EIS	Central case: Fuel-efficiency % improvement vs…		Central case: Fuel-burn per ASK vs “reference” aircraft
		…representative “imminent” aircraft	…“reference” aircraft	
NB	2035	28.9	44.2	55.8%
SMTA	2035	34.6	45.9	54.1%
LTA	2035	32.8	49.6	50.4%
VL	2040	40.3	55.2	44.8%

Table 8 – characteristics of “future” aircraft (central case) used in the Road-Map model.

4.8 “Future Aircraft” - Sense-Check and Context

APPENDIX G explores the relationship between our central case assumptions and technology development goals set by NASA (N+2, N+3) and by ACARE (FlightPath2050). We conclude that while our central case represents an increase in the average annual rate of new aircraft fuel efficiency improvements relative to that observed in the past two or three decades, nonetheless it is substantially less ambitious than the rate of improvement required to reach the NASA N+2/N+3 goals or the FlightPath2050 goal. As such our assumptions lie well within the level of ambition being targeted by the industry.

Furthermore, [ICCT, 2016] takes the view that “*the fuel consumption of new aircraft can be reduced by approximately 25% in 2024 and 40% in 2034 compared with today’s aircraft by deploying emerging cost-effective technologies. The latter value….may be conservative because of the modeling assumptions used and the exclusion of non-conventional airframes like blended wing body or strut-based wings.*”

Our assumptions (set out in **Table 8**) for new aircraft fuel-efficiency in 2035-2040, relative to our “reference” aircraft, involve higher percentage savings than those suggested by [ICCT, 2016], but we do not exclude non-conventional airframe configurations.

It is worth considering what factors may allow the rate of efficiency improvement to be accelerated relative to that observed in recent decades. Firstly, customer demand for more efficient products continues to strengthen, driven by the cost of fuel and potentially by additional carbon costs. Secondly, analysis, simulation and design tools continue to improve, giving the industry greater capability with which to address that customer demand. Thirdly, a number of technologies representing opportunities for a step-change improvement in fuel efficiency have been demonstrated and are progressing well through their development phases. Finally, a number of aircraft concepts have been proposed which are claimed to have the potential to achieve fuel-efficiency levels at or close to the NASA N+3 and FlightPath 2050 goals, which are substantially more ambitious than our assumed levels of efficiency for “future” aircraft.

Section 4.10 explores the upcoming technologies which may contribute towards enabling our assumed levels of fuel-efficiency to become reality.

4.9 "Future" Aircraft – Impact on Fleet Fuel Efficiency

In this section we take the central-case fuel-efficiency improvement assumptions set out in the previous section for each aircraft category and combine them, taking account of the category-specific materiality set out in **section 4.6.2**, to give a view of their combined impact on fleet fuel efficiency, both at 2050 (when the transition will be incomplete) and later when the fleet transition is complete. There will be substantial improvement in fleet fuel efficiency after 2050 as the "imminent"-to-"future" transition continues, enabling aviation to play its part in the UK's efforts to decarbonise further beyond 2050. Although outside the scope of our Road-Map, subsequent generations of aircraft (beyond our "future" generation) can be expected to offer even greater reductions in carbon-intensity.

Category	Replacement[72]		Materiality[73]	Within-Category Improvement		Within-category CO_2, relative to pre-transition					
						Transition Complete (after 2050)			2050 (Transition only partially complete)		
	Start	Period (years)		%[74]	Factor	P[75]	CO_2		P	CO_2	
							Imminent	Future		Imminent	Future
NB	2035	25	0.336	28.9	0.711	1.0	0	0.239	0.6	0.134	0.143
SMTA	2035	20	0.164	34.6	0.654	1.0	0	0.107	0.75	0.041	0.080
LTA	2035	20	0.280	32.8	0.672	1.0	0	0.188	0.75	0.070	0.141
VL	2040	20	0.220	40.3	0.597	1.0	0	0.131	0.5	0.110	0.066
				Improvement factor			0.666			**0.786**	
				Improvement %			33.4 %			**21.4 %**	

Table 9 – impact on fleet efficiency of "future" aircraft (central case) replacing "imminent" aircraft, shown for 2050 (fleet transition incomplete) and a later date when fleet transition is complete. Scope: UK aviation.

4.10 "Future" Aircraft Efficiency – Enabling Technologies

Section 5.2 of our 2012 CO_2 Road-Map explores in detail the opportunities for improving the efficiency of future aircraft types. In the present document we explore some recent developments along the route to improved efficiency. This section is intended to supplement, rather than replace, the corresponding section of our 2012 Road-Map. Illustrating the scale of the technology development effort within the aerospace industry, [ATAG, 2016] reports that "a*ircraft and engine manufacturers spend an estimated $15 billion each year on research and development*".

[NAP, 2016] discusses the NASA N+3 goals in which the "*the energy reduction goal is 60-70 percent better than the reference 1990s design aircraft for similar missions*". It goes on to say that "*Several organizations and teams have published designs that they claim have the potential to meet these goals given sufficient investment. All require innovation in aircraft design..., in propulsion, and in*

[72] Source: **APPENDIX F**

[73] Based on 2015 fuel-burn and hence CO_2. Source: **Table 7**

[74] Central case. Source: **Table 8**

[75] P = proportion of aviation activity within the size category that is delivered by "future" aircraft", with the remainder (1-P) being delivered by "imminent" aircraft. P is a measure of the extent to which fleet transition is complete, and depends upon the EIS date, the duration of the fleet transition period, and the point in time at which P is evaluated. Post-transition, P is by definition 1.0. At 2050, P<1.0.

aircraft–propulsion integration". We explore each of those three subject areas below, along with developments in manufacturing technology which act as enablers for bringing future concepts to reality in a cost-effective and commercially-viable manner.

4.10.1 Aircraft Technologies and Configurations

One method of improving aircraft fuel-efficiency is to increase the aspect ratio of the wing. However, with a conventional cantilever wing arrangement there are limits to how far this approach can be pursued. One potential solution is to use a "truss-braced wing" (TBW) in which the wing is supported part-way along its length by a strut which carries part of the load to the fuselage, allowing the wing to be made longer and thinner. Wind-tunnel testing by Boeing and NASA has shown the supported wing arrangement can reduce fuel use "*by 5 to 10 percent over advanced conventional wings*"[76]. The TBW arrangement requires that the wing is mounted to the top of the fuselage, rather than to the bottom of the fuselage as is common in many modern commercial aircraft. The top-mounted wing is more suited to the accommodation of very high bypass ratio engines (characterised by a large diameter relative to lower bypass ratio equivalents of equivalent thrust), offering further advantages related to increased propulsion system efficiency.

In 2016, Boeing and NASA conducted wind-tunnel tests[77] of a scale model Blended Wing Body (BWB) aircraft – a configuration that could offer substantially improved fuel-efficiency relative to a conventional "tube-and-wings" aircraft configuration.

Boeing's ecoDemonstrator Program[78] serves as a catalyst for engineering innovation and learning, using flying test beds to accelerate new technologies. By the end of 2015, the ecoDemonstrator Program had tested more than 50 technologies using three airplanes:

- **ecoDemonstrator 737** flight tests began in 2012, testing 15 technologies including variable area fan nozzle and flight trajectory optimisation, and validating "*additional aerodynamic performance of natural laminar flow technology on the new 737 MAX Advanced Technology Winglet*"[79].
- **ecoDemonstrator 787** flight tests began in 2014. More than 25 technologies were tested, many of them targeting improved fuel efficiency, such as a ceramic matrix composite (CMC) engine nozzle; aerodynamic and flight control improvements; wireless sensors; and "*software applications and connectivity technologies that can improve flight planning, fuel-load optimization, in-flight routing and landing*"[80]. NASA also tested its Airborne Spacing for Terminal Arrival Routes (ASTAR), a technology which "*is intended to increase landing frequency and reduce holding patterns, saving fuel, emissions and time*"[81].
- **ecoDemonstrator 757** took place in 2015, in collaboration with TUI Group and NASA. The 757's left wing tested "*technologies to reduce environmental effects on natural laminar flow as a way to improve aerodynamic efficiency, including a Krueger shield to protect the leading edge from insects*"[82]. "*On the 757's right wing, NASA tested "bug-phobic" coatings that can reduce drag from insect residue*"[83]. "*On the vertical tail, NASA and Boeing tested active flow control to improve airflow over the rudder and maximize its aerodynamic efficiency*"[84], which may enable smaller vertical tail designs in the future. Also tested was "*solar and thermal*

[76] http://www.nasa.gov/feature/nasa-aeronautics-budget-proposes-return-of-x-planes, viewed 21st Sept 2016
[77] http://www.boeing.com/features/2016/09/blended-wing-body-09-16.page, viewed 21st Sept 2016
[78] http://www.boeing.com/resources/boeingdotcom/principles/environment/pdf/Backgrounder_ecoDemonstrator.PDF, viewed 31st August 2016
[79] ibid
[80] ibid
[81] ibid
[82] ibid
[83] ibid
[84] ibid

"energy harvesting" to power electronic dimmable windows, as a way to reduce wiring, weight, fuel use and carbon emissions"[85], as well as 3D printed components made from excess carbon fibre from 787 production, reducing airplane weight and factory waste.

- A further ecoDemonstrator program is planned for 2016, using an Embraer E170 prototype airplane.

During 2014-15, NASA conducted flight tests to demonstrate "*Adaptive Compliant Trailing Edge (ACTE) flight control surfaces that offer significant improvements over conventional flaps used on existing aircraft*"[86]. The technology may enable reduced wing structural weight and aerodynamic improvements, leading to reduced fuel-use.

NASA's New Aviation Horizons[87] document sets out a 10-year plan, starting in 2017, to flight test "*new technologies, systems and novel aircraft and engine configurations*", including propulsion-airframe integration, hybrid wing-body, and truss-braced wing,

Fuel cells produce electricity in a cleaner, more efficient way than combustion engines, and their use can be envisaged to power an airliner's cabin and systems, replacing the gas-turbine-based auxiliary power unit (APU). Furthermore, the exhaust of a hydrogen-powered fuel-cell is primarily water which can be used for the aircraft's water and waste system (in place of water carried all the way from the departure airport), saving weight and therefore reducing fuel consumption and emissions. Fuel cells could also displace APU usage from other functions such as main engine start and air conditioning, paving the way towards emissions-free ground operations. In 2008, Airbus and its partners DLR and Michelin performed flight evaluations of a fuel cell emergency power system on a test bed A320[88]. The fuel cells for commercial aviation are at an early stage of research and technology.

In Europe, the Smart Fixed Wing Aircraft (SFWA) integrated technology demonstrator will develop and validate technologies with the aim of reducing aircraft drag by 10% through the use of laminar flow employing both passive and active flow control[89]. The BLADE project[90], led by Airbus and involving an additional 16 partners, is a flight test demonstrator programme - due to begin in 2017 using an Airbus A340-300 flight test aircraft - which aims to show that wings smooth enough to sustain drag-reducing natural laminar flow (NLF) can be manufactured and maintained economically.

There may be further advantages for fuel efficiency associated with designing aircraft to travel slightly slower (as discussed in section 5.2.5 of our 2012 Road-Map). However, requirements for continued compatibility with existing airport landing and take-off slots may limit the deployment of such aircraft.

4.10.2 Propulsion Technology

Section 5.3 of our 2012 CO_2 Road-Map gives an overview of the technology options and research programmes which could contribute towards improved engine fuel efficiency. In this section we cover some additional items not reported in that earlier document, and report on recent developments.

85 ibid

86 http://www.nasa.gov/press-release/nasa-successfully-tests-shape-changing-wing-for-next-generation-aviation, viewed 21st Sept 2016

87 http://www.aeronautics.nasa.gov/pdf/NASA-Aero-10-Yr-Plan-508.pdf, viewed 11th Oct 2016

88 http://www.airbus.com/newsevents/news-events-single/detail/fuell-cell-development-for-emission-free-power/, viewed 21st Sept 2016

89 http://www.cleansky.eu/content/page/sfwa-smart-fixed-wing-aircraft, viewed 11

90 http://www.cleansky.eu/content/interview/blade-makes-significant-progress-tow viewed 11th Oct 2016

Figure 4 – progress in fuel efficiency within the Trent engine family.
Image – Rolls-Royce.

In 2014, Rolls-Royce shared details of its next generation engine designs[91]. "*The first design, Advance, will offer at least 20 per cent better fuel burn and CO_2 emissions than the first generation of Trent engine and could be ready from the end of this decade. The second, UltraFan™, a geared design with a variable pitch fan system, is based on technology that could be ready for service from 2025 and will offer at least 25 per cent improvement in fuel burn and emissions against the same baseline*". The engine designs feature composite carbon/titanium (CTi) fan blade technology which delivers lighter fan blades while retaining aerodynamic performance. Combined with a composite engine casing, it forms a system that reduces weight by up to 1,500lb per aircraft, the equivalent of carrying seven more passengers at no cost. The engine designs also feature higher pressure ratios than existing engines. Research programmes such as LEMCOTEC[92,93] have researched engine core technologies, including those supporting higher pressure ratios, to enable a 20-30% reduction in CO_2 emissions vs year 2000, while projects such as ENOVAL[94] are exploring enablers for higher engine efficiency through ultra-high bypass ratios.

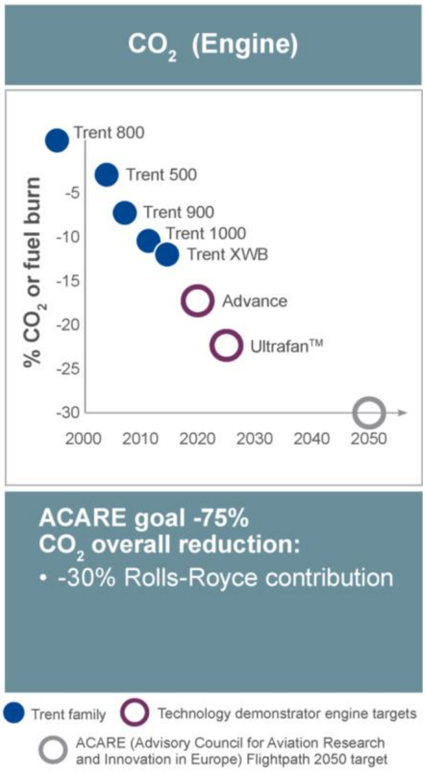

Image – Rolls-Royce

Looking further ahead, the ULTIMATE[95] project, running 2015-2018 and bringing together European universities, research centres and aero-equipment industry partners, will explore a range of more radical engine core technologies[96] with the aim of identifying the most promising concepts for more detailed study in the future. The ambition is to reduce key sources of efficiency loss enabling a greater than 18% reduction in fuel burn[97] relative to a year 2050 reference configuration. Although this clearly lies beyond the time horizon of our Road-Map, it illustrates that there is potential for further substantial efficiency improvements to be achieved in generations of aircraft following on from those we have considered above.

The prospect of hybrid-electric propulsion for aircraft has moved forward considerably since our 2012 Road-Map was published:

- In 2013, Rolls-Royce and EADS (now Airbus) presented E-Thrust[98], a new concept for future airliners, featuring a serial hybrid propulsion system comprising a single large gas-turbine, an advanced energy storage system, and six electrically driven fans. "*During climb the distributed fans draw power from the energy storage system, but during descent, they act like wind turbines to generate electrical energy which re-charges the batteries…..A major benefit of the distributed propulsion system is that it can be integrated into the airframe's structure to maximise aerodynamic efficiency and optimise the airflow around it. This reduces the aircraft's weight, drag and the amount of noise it makes.*"[99]

[91] http://www.rolls-royce.com/media/press-releases/yr-2014/260214-next-generation.aspx, viewed 31st August 2016
[92] http://www.rolls-royce.com/about/our-technology/research/research-programmes/lemcotec.aspx, viewed 31st August 2016
[93] http://www.lemcotec.eu/page/achievements.php, viewed 31st August 2016
[94] http://www.enoval.eu/, viewed 29th Sept 2016
[95] http://www.ultimate.aero/, viewed 29th Sept 2016
[96] See for example http://publications.lib.chalmers.se/records/fulltext/237482/local_237482.pdf
[97] http://www.ultimate.aero/page/en/ultimate-technologies.php, viewed 29th Sept 2016
[98] http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/technology-tutorial/E-Thrust.html, viewed 31st August 2016
[99] http://www.rolls-royce.com/media/press-releases/yr-2013/18062013-works-with-eads.aspx, viewed 31st August 2016

- Boeing's SUGAR[100] Volt concept aircraft has a hybrid electric propulsion system which allows for "*typical short-range flights to use mostly electric power while keeping a supply of jet fuel on board for longer-range flights*"[101].

- Among the technical challenges to be explored within NASA's Advanced Air Transport Technology (AATT) project[102] are hybrid propulsion systems and compact high-OPR[103] gas generators.

- [NAP, 2016] considers "propulsion and energy system technologies that could reduce CO_2 emissions from global civil aviation" and identifies four highest-priority research areas, including "*Improvements in gas turbine engines*" and "*Development of turboelectric propulsion systems*".

While pure battery-electric propulsion for large commercial airliners is unlikely to see service for many decades, nonetheless significant progress in this area is being made:

- In 2015, the Airbus E-Fan technology demonstrator programme completed a manned crossing of the English Channel using an all-electric aircraft. The E-Fan 2.0 is planned "*to be the world's first all-electric plane certified to international airworthiness standards...scheduled to take its maiden flight in late 2017*"[104]. The E-Fan Plus "*incorporates an internal combustion engine as a range extender in addition to the aircraft's on-board lithium-ion batteries.*"[105]

- NASA's Sceptor experimental aircraft is modified from a standard small aircraft to allow experimentation with electric propulsion and direct performance comparisons between the modified (electric-powered) aircraft with the standard, unmodified aircraft[106].

- NASA's X-57 electric research plane (known as "Maxwell") is intended to explore the benefits of "*distributing electric power across a number of motors integrated with an aircraft*" with the hope of demonstrating "*a five-time reduction in the energy required for a private plane to cruise at 175 mph*"[107].

4.10.3 Integration of Propulsion System and Airframe

Consideration of how the engine and airframe are integrated will become increasingly important in the coming years as the industry drives for reduced drag and noise and increased efficiency. In the US, [NAP, 2016] identifies "*advances in aircraft–propulsion integration*" as being one of four highest-priority research areas for reducing global civil aviation CO_2. In the UK the Aerospace Integration Research Centre (AIRC)[108], being built at Cranfield University with co-investment partners Airbus and Rolls-Royce, is due to open at the end of 2016 and will focus on technology development and testing up to high technology readiness levels.

Integration of engine and airframe is essential to enable key efficiency improvements such as boundary layer ingestion (BLI), in which the engine is sited close to the aircraft structure and is able to ingest air that the aircraft has already slowed down (through for example skin friction), thus reducing

[100] SUGAR = Subsonic Ultra Green Aircraft Research

[101] http://www.boeing.com/aboutus/environment/environment_report_14/2.3_future_flight.html, viewed 31st August 2016

[102] http://www.aeronautics.nasa.gov/aavp/aatt/index.html, viewed 21st Sept 2016

[103] OPR = overall pressure ratio – an indicator of the thermal efficiency of a gas turbine engine.

[104] http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/Programme.html, viewed 31st August 2016

[105] http://www.airbusgroup.com/int/en/corporate-social-responsibility/airbus-e-fan-the-future-of-electric-aircraft/Programme.html, viewed 31st August 2016

[106] http://www.nasa.gov/centers/armstrong/features/sceptor.html, viewed 21st Sept 2016

[107] http://www.nasa.gov/image-feature/nasas-x-57-electric-research-plane, viewed 21st Sept 2016

[108] https://www.cranfield.ac.uk/centres/aerospace-integration-research-centre, viewed 14th Sept 2016

the disadvantageous inlet momentum of air entering the engine. Successful implementation of BLI may offer fuel-efficiency improvements of several per cent.

Examples of technical projects and/or aircraft concepts aimed at enabling or taking advantage of BLI include:

- Bauhaus Luftfahrt's "*Propulsive Fuselage*" concept, which uses a propulsive fan encircling the aft section of the aircraft fuselage and driven by a co-located gas turbine engine, was shown in initial analyses to offer some 10% improvement in range relative to an equivalent twin-engined aircraft, even after the weight of the third engine is taken into account[109]. The collaborative project "DisPURSAL"[110] explored this and other arrangements aimed at making use of boundary layer ingestion.

- NASA's Advanced Air Transport Technology (AATT)[111] project includes in its scope the exploration and development of technologies for distortion-tolerant fans, a crucial enabler for many BLI arrangements in which the engine experiences spatially non-uniform inlet flow characteristics.

- NASA's Starc-ABL[112] concept uses an electrically-driven aft-fuselage mounted BLI fan, powered by electrical generators attached to conventional underwing gas turbine engines.

- The D8 "Double Bubble"[113] concept uses two rear-mounted engines which ingest boundary layer air from the top of the aircraft's fuselage.

- The use of distributed electrical propulsion, whether hybrid or pure-electric, acts as an enabler for boundary layer ingestion, by making possible the positioning and sizing of propulsive fans so as to maximise the possibilities for ingestion of slow-moving boundary layer air.

4.10.4 Manufacturing Capability

Advanced manufacturing technologies not only open up new design opportunities leading potentially to improved product performance, but they also form a critical element of lowering unit cost, making aerospace products more affordable and enhancing the viability of aircraft or engine concepts which, without suitable manufacturing technologies, might not see the light of day as commercial products.

A key manufacturing technology receiving much research attention at present is additive layer manufacturing (ALM), sometimes referred to as 3D printing. ALM offers the prospect of manufacturing components of entirely new shapes which were previously not possible to make, opening up the design space and presenting opportunities for weight reduction which is one of the key enablers for improved aircraft fuel-efficiency. Components in which material properties vary from one area of the component to another can also be envisaged using ALM.

For example, Airbus has used ALM, working with a new material entitled Scalmalloy® specially designed for use with 3D printing, to manufacture a prototype cabin partition with a structure "*created with custom algorithms that generated a design that mimics cellular structure and bone growth*"[114]. This enables the required strength of the component but saves 45% of the component's weight.

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[109] http://www.bauhaus-luftfahrt.net/research/system-und-flugzeugtechnologien/propulsive-fuselage, viewed 31st August 2016

[110] http://www.dispursal.eu/doc/20140515_BHL_ILA_2014_DisPURSAL.pdf, viewed 31st August 2016

[111] http://www.aeronautics.nasa.gov/aavp/aatt/index.html, viewed 14th Sept 2016

[112] https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007561.pdf, viewed 14th Sept 2016

[113] http://www.aurora.aero/D8/, viewed 14th Sept 2016

[114] http://www.airbusgroup.com/int/en/story-overview/Pioneering-bionic-3D-printing.html, viewed 29th Sept 2016

Composite materials based on carbon fibre or glass fibre have seen increasing use in aircraft in recent decades. Aircraft such as the Boeing 787 or the Airbus A350 XWB feature a high percentage of such materials. For future aircraft, NASA is developing a method of "*sewing together layers and rods of composite material*" which could allow entirely new aircraft shapes to be built[115].

4.10.5 Discussion

This section has set out some examples of the technologies and design configurations being explored for potential use in future aircraft types. The scope for improving aircraft fuel-efficiency through deploying various combinations of these technologies and design configurations is substantial.

The UK has a strong aerospace manufacturing sector, underpinned by high levels of technological capability built on decades of research. The UK Government must ensure that access to funding for high-value collaborative R&D programs is maintained in the coming years, to ensure continued competitiveness in the global market.

[115] http://www.nasa.gov/aero/prseus-composite-survives-torturous-testing, viewed 21st Sept 2016

5 Sustainable Aviation Fuels

SUMMARY

We retain the view, expressed in our 2012 Road-Map, that by 2050 sustainable aviation fuels (SAF) will offer between 15% and 24% reduction in CO_2 emissions from UK aviation. This assumption is based on a 25-40% penetration of SAF into the global aviation fuel market, coupled with a 60% life-cycle CO_2 saving per litre of fossil-based aviation fuel displaced. For the purposes of our CO_2 Road-Map, we assume as our central case an 18% reduction in CO_2 emissions from UK aviation through the use of SAF.

We are encouraged by the recent Government consultation on the inclusion of aviation in the Renewable Transport Fuel Obligation in the period to 2030. We urge the Government to introduce binding legislation and to provide clear long-term policy as soon as possible. We are concerned that some promising sustainable fuels technologies are not recognised in the proposals. This could mean that opportunities to build sustainable fuels production into existing UK manufacturing facilities would be missed.

Unlocking the full potential for UK production and deployment of sustainable aviation fuels requires Government to develop a UK vision and strategy for their deployment, for the creation of UK expertise and technologies; implementing financial support mechanisms for both commercial-scale and demonstration facilities and ensuring that aviation fuels are prioritised in future research and development. With policy support, SAF production in the UK could provide gross added value to the UK economy of £265m by 2030. UK manufacture of SAF would reduce the UK's dependency on jet fuel imports which now make up more than 70% of UK volumes.

5.1 Introduction

Traditionally, fossil fuel has dominated aviation and other forms of motorised transport, as well as electrical power generation. While the use of Sustainable Aviation Fuels (SAF) does not necessarily reduce so-called "tail-pipe" emissions of CO_2, it does offer the prospect of significantly reducing the associated CO_2 emissions over the fuel's full life-cycle. For example, production of biofuels involves absorption of CO_2 from ambient air to produce the feedstock from which the fuel is derived. A number of technologies are under development that are able to convert waste gases, liquids and solid materials into transport fuels and these also yield life-cycle CO_2 reductions. Compared with fossil-based aviation fuels, sustainable aviation fuels typically reduce life-cycle CO_2 emissions between 60-95%[116], as well as reducing emissions of particulates.

Unlike light-duty ground transport or power generation, aviation is likely to remain dependent on liquid hydrocarbon fuels for many decades and therefore the development of sustainable aviation fuels to meet this need should be a priority of government policy. [NAP, 2016] lists "*advances in sustainable alternative jet fuels*" as being one of four high-priority approaches to the reduction of CO_2 emissions from commercial aviation.

Since our 2012 CO_2 Road-Map [SA, 2012], SA has completed a Sustainable Fuels Road-Map [SA, 2014b] comprising a detailed study of the potential for SAF to contribute to the mitigation of UK aviation CO_2 emissions (see **Figure 5**). Scenario analysis estimated that in 2030 there may be 90-160 operational sustainable fuel plants globally, producing aviation fuels in combination with other fuels and products. Global revenue for these sustainable fuel plants was estimated to be £8-17 billion in 2030. The study concluded that the estimate used in the 2012 CO_2 Road-Map was appropriate, provided that policy support is given to assist aviation to decarbonise alongside other sectors.

116 Source: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277436/feedstock-sustainability.pdf

To be acceptable for use in aviation, any candidate SAF must be technically suitable for use in existing fuel-systems and engines (in other words it must be a "drop-in" replacement for fossil-based aviation fuel), it must meet strict criteria concerning sustainability, and it must have the longer term potential to be produced in a large-scale commercial environment and to compete on price with conventional fossil-based aviation fuel. These issues are explored in more detail below.

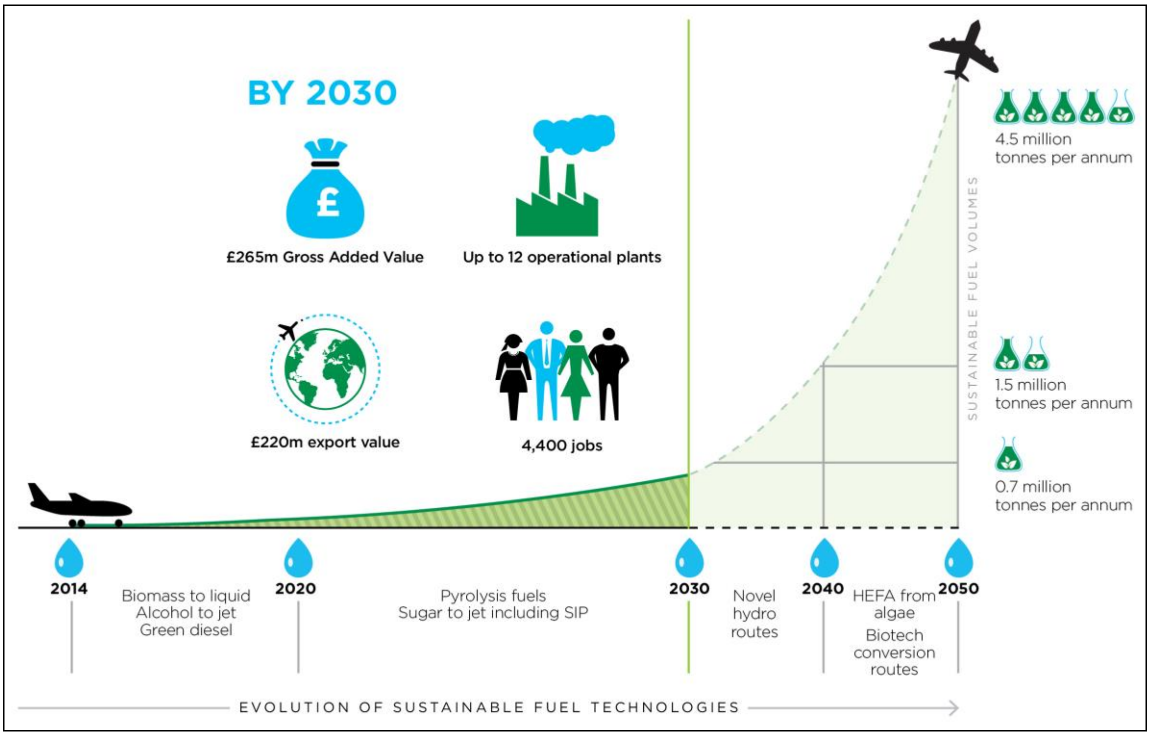

Figure 5 – "high" scenario for UK potential of sustainable fuels. Source: [SA, 2014b]

5.2 Progress Since 2012

5.2.1 Certification of new fuels

Equipment manufacturers, bioenergy/oil companies and the US government have continued to invest in testing to ensure that the pace of technological progress in certifying new aviation fuel production methods has not slowed. The ASTM international fuel specification ASTM D1655 covers the approval of all new production pathways. The latest aviation fuel production pathway to be approved is Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK). Created from isobutanol, an alcohol that can be manufactured from feed stocks such as sugar, corn or waste woody biomass, this brings the number of approved production pathways for synthetic aviation fuels to five, including: ATJ-SPK, Synthesized Iso-paraffins (SIP), Hydro-processed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK), Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) and Fischer-Tropsch Synthetic Kerosene with Aromatics (FT-SKA). All can use a variety of renewable or waste-derived feedstocks. In addition to these certified technology pathways, a further six production options are being assessed within the ASTM D4054 approval process. Although the US government has reduced funding for some research and testing of new types of SAF, a number of measures are being taken to streamline future fuel certification, so we do not anticipate that this will lead to any measureable decrease in the adoption by aircraft operators of SAF.

ASTM D1655 and the UK's Ministry of Defence standard DEF STAN 91-091 are the petroleum industry and global reference standards for aviation fuel. DEF STAN 91-091 has a mechanism to implement the ASTM fuel approval for use in the UK, Europe and around the world. The development of this standard is necessary to keep pace with technological improvements, and ongoing support from the UK MOD is essential to ensure that the UK does not lag behind other countries.

5.2.2 Progress towards commercialisation

Since 2012, there has been considerable progress in the use of SAF by commercial airlines, with over 3,000 flights having taken place. Oslo and Los Angeles airports both have a regular supply of SAF which is purchased by a number of carriers. In the USA a number of new technologies have received support from the US government to construct initial demonstration plants.

However, barriers to wider-scale adoption of these fuels still exist. SAF is currently more expensive than fossil-based aviation fuel and few governments provide incentives for their production or use. Both the USA and the Nordic region do provide support for the development of SAF technologies and also provide a level playing field for SAF to qualify for incentives, alongside sustainable road-transport fuels. This has greatly assisted the creation of SAF supply chains in those regions. However, the ongoing low oil price and the uncertainty in long-term policy support for renewable technologies both contribute to a lack of investor confidence in the sector and this has prevented more innovative technologies reaching commercial scale.

The assumptions in our Sustainable Fuels Road-Map [SA, 2014b] are based on a policy framework that provides equivalence for aviation and road transport fuels in future incentive mechanisms. As ICAO's recently-agreed Global Market-Based Measures (GMBM) scheme[117] will recognise the use of SAF in meeting the climate obligations of the airlines, there will hopefully be more opportunities for airlines to fuel their aircraft with SAF at key hubs around the world. ICAO is working to identify policy support mechanisms that could be used to provide greater investment in SAF. We acknowledge the work done so far by the UK government to address this issue and we welcome the recently-launched consultation on proposals to incorporate SAF into the longer-term policy framework for UK transport fuels.

5.2.3 Emerging new technologies

To some extent, even technology pathways that have been approved for some years can still be considered as emerging technologies. This is especially true of the waste-to-fuels routes where, although the individual technology components exist today in commercial plants, there is still no large-scale integrated plant in operation globally. There is a need for ongoing support from the research and development community to assist in overcoming remaining technical challenges associated with manufacturing processes. Within the UK's research councils, a number of programmes address future energy challenges and we encourage a greater focus on aviation, where presently limited options for low carbon solutions exist.

In the medium term, fuels derived from waste CO_2 and algal biomass may provide greater opportunities but, in our view, hydro-treated waste oils, cellulosic conversion routes (mainly using wastes) and conversion of carbon monoxide will provide the main volumes in the aviation sector over the next 10 years.

In the long-term, short-haul aircraft may move to electrical propulsion systems (see discussion in **section 4.10.2**). However, long-haul aircraft will continue to operate on liquid hydrocarbons for many decades, and within UK aviation those aircraft account for the biggest fuel volumes, so demand for SAF is expected to extend well beyond 2050. In the longer-term, disruptive technologies may provide much greater volumes of fuels. There are a number of technologies using biotechnology and renewable energy (e.g. solar) that have shown some promise at lab scale. Many of these are capable of reprocessing CO_2 from industrial processing and some have been demonstrated using CO_2

[117] Discussed in more detail in **Chapter 6**

extracted from ambient air[118]. Our Sustainable Fuels Road-Map [SA, 2014b] did not build any of these still nascent technologies into its future projections.

5.3 Sustainability

In our Sustainable Fuels Road-Map [SA, 2014b], when assessing the potential for SAF to displace fossil-based aviation fuel, we defined the following sustainability principles which the feedstock/fuel must meet. SAF should:

- not displace or compete with food crops or cause deforestation;
- minimise impact on biodiversity;
- produce substantially lower life cycle emissions than fossil fuels;
- be sustainable with respect to land, water and energy use;
- deliver positive socioeconomic impacts.

SA members support the Roundtable on Sustainable Biomaterials standard[119] as the most robust standard for assessing the sustainable development of fuel production.

In the period since our 2012 CO_2 Road-Map, concerns over the sustainability of road transport fuels have remained. SA has supported the UK Government's Transport Energy Taskforce that assessed the introduction of greater volumes of advanced fuels in the UK's transport energy mix. The main advantage of advanced fuels is the ability to process low value wastes and residues, hence avoiding the land use concerns associated with crop based fuels. SA is supportive of policy mechanisms that ensure that the Indirect Land Use Change (ILUC) of these fuels is addressed and mitigated.

Some technologies are based on the biological capture of carbon monoxide rich waste gases from industries such as steel making, using fermentation to make ethanol. This can be converted to "drop–in" jet fuel with a 65% GHG reduction[120] compared to fossil alternatives. By recycling waste carbon for a secondary purpose, this technology presents an opportunity to keep more fossil resources in the ground and to help contribute to meeting climate change commitments. It is important to ensure that emerging regulation recognises carbon emission reductions generated by recycling carbon rather than solely focusing on fuels produced directly from plant biomass. We have significant concerns that innovative aviation fuel technologies that meet sustainability criteria and result in overall carbon reductions will not be exploited in the UK due to regulations being centered on using only plant feedstocks to produce fuel. This means that opportunities for building sustainable fuel technology into existing UK manufacturing facilities will be missed unless we act now.

The UK Government and aviation industry have a role to ensure that global aviation policy frameworks address the issue of sustainability and that sustainable fuels are incorporated into global climate change policy for aviation. However, most importantly there is the need to ensure that approaches to sustainability are harmonised or as a minimum there is a mechanism for mutual recognition of sustainability standards. This factor could present a significant barrier to the uptake of SAF within the future global market based measure.

118 See for example https://www.chemistryworld.com/research/solar-jet-fuel-made-out-of-thin-air/7325.article

119 http://rsb.org/sustainability/

120 Source: http://www.lanzatech.com/low-carbon-fuel-project-achieves-breakthrough/, viewed 02 Dec 2016

5.4 Potential for Sustainable Aviation Fuels – Risks and Opportunities

5.4.1 Economics of SAF

At this time, technological pathways using low value wastes and residues are not at commercial scale and incentive mechanisms do not exist for the deployment of SAF. Therefore, uptake levels for commercial flights remain low. Sustainable production of sufficient amounts of feedstock at lower cost is key to the deployment of SAF at a commercial scale. Realising a substantial contribution towards the accomplishment of the aviation industry's climate goals from sustainable aviation fuels requires significant investment and governmental support. A number of airlines have started to invest in SAF production to address this market failure, but further policy support will be essential to make meaningful volumes available.

The economics of SAF production are presently unfavourable. With limited policy support frameworks in place, the shift to commercial production remains challenging in the near term. Although prices of fossil-based aviation fuel are expected to increase over the longer term, ongoing market volatility presents significant challenges for the price-competitiveness of SAF. Uncertainty for investors in renewables incentives and a lack of longer term policy support also deters investment in large scale production.

However, the introduction of SAF into ICAO's GMBM will hopefully prompt more governments to provide policy support for the production of these fuels. In future, the application of carbon pricing in global economies, combined with increasing costs of carbon, will help to bridge the price gap between fossil-based aviation fuel and SAF, by enabling greater numbers of projects to move from demonstration to commercial scale. This will lead to lower production costs due to economies of scale, technology learning, and the ability to use lower quality feedstocks.

5.4.2 Scale up and Deployment – UK Opportunities

In the analysis undertaken for our Sustainable Fuels Road-Map [SA, 2014b], it was estimated that by 2030 there may be 90-160 operational sustainable fuel plants globally, producing aviation fuels in combination with other fuels and products. Global revenue for these sustainable fuel plants was estimated to be £8-17 billion in 2030. SA believes that the UK should capitalise on its leadership in global aerospace and aviation and take the opportunities presented by the emerging sustainable fuel market to reduce emissions, create jobs and bolster investments in science and technology. Sustainable fuels will be essential in meeting the climate challenges for aviation in the period to 2050, as part of a portfolio approach alongside substantial improvements in fuel efficiency, air traffic management and operational procedures. As road transport shifts away from liquid hydrocarbon fuels, the UK has an opportunity to build on its strengths in refining technologies, waste handling and processing and in bioscience to build a new sector, providing not only high value aviation fuels, but also other high value fuels and chemicals.

In order to unlock the potential for UK production and deployment, the UK should:

- Develop a UK vision and strategy for the deployment of SAF and the creation of UK expertise and technology;
- Ensure that innovative new technologies are recognised in future incentive mechanisms;
- Ensure that financial support mechanisms are in place to address problems in accessing finance for commercial and demonstration facilities;
- Ensure that future policies include aviation fuels in incentive frameworks;
- Ensure that aviation is addressed in future research and development priorities, from fundamental research through to support structures that will lead to the creation of commercial volumes of fuel.

5.5 Assessment of Potential Mitigation Impact

Our assessment is unchanged from our 2012 CO_2 Road-Map, namely that by 2050 SAF could offer between 15 and 24% reduction in CO_2 emissions attributable to UK aviation by 2050. This assumption is based on a 25-40% penetration of SAF into the global aviation fuel market, coupled with a 60% life-cycle CO_2 saving per litre of fossil-based aviation fuel displaced.

For the purposes of our CO_2 Road-Map, from within the range of 15-24% set out above, we take as our central estimate an 18% reduction in CO_2 emissions from UK aviation through the use of SAF.

6 Market-Based Measures

SUMMARY – substantial progress has been made since 2012 on the development of a global market-based measure. In October 2016, governments agreed to a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), the first ever global sectoral agreement to introduce carbon pricing, based on the goal of capping net CO_2 emissions at 2020 levels. CORSIA is the next necessary step to enable aviation to contribute to overall carbon reductions beyond those achievable within the industry itself. We welcome the role played by the UK in negotiations towards the agreement. There is now an opportunity to have a fresh look at environmental regulation in Europe and to review existing measures such as the EU ETS. The global aviation industry has set out a goal for aviation to reduce its net emissions in 2050 to 50% of levels in 2005 through market-based measures. In our CO_2 Road-Map we illustrate the required extent of net emissions reduction through market based measures to allow UK aviation to achieve the same goal.

6.1 Context

Other sections of this Road-Map have described the significant improvements expected in the carbon intensity of aviation over the next few decades. Notwithstanding these improvements, there is now widespread acceptance that to fully address CO_2 emissions from aviation, and to meet challenging reduction targets, carbon pricing, achieved through a carbon trading policy framework, is essential.

Since CO_2 is a well-mixed greenhouse gas, the distribution of CO_2 emissions between different locations or sectors of activity does not influence the climate system's response to those emissions. Accordingly, the pursuit of the most cost-effective mitigation opportunities, irrespective of sector or geography, should be incentivised.

The international character of aviation means that attribution of CO_2 emissions to the UK and attempting to manage them in a national silo approach would lead to competitive distortions without reducing global net emissions. For this reason we have consistently opposed inclusion of international aviation in the UK carbon budget or introduction of related national targets or measures.

In 2005 when Sustainable Aviation was established, we pledged to support practical inclusion of aviation in the EU Emissions Trading System and we called for aviation to be incorporated into a global climate policy framework. Members of Sustainable Aviation are proud to have played a leading role in the successful inclusion of aviation in the EU ETS from 2012 and the 2016 CORSIA global market-based measure agreement for international aviation.

Sustainable Aviation will continue to support practical and efficient implementation of CORSIA and future development of the global system in line with our long term targets.

6.1.1 Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

CORSIA is an important development in the context of the UK CO_2 Road-Map since emissions from intercontinental flights as well as intra-European flights will be included in a climate policy measure for the first time. The scheme has a far broader coverage of emissions than the EU ETS and therefore marks a substantial step forward towards achieving net emissions targets for global aviation.

CORSIA was agreed at the ICAO General Assembly in October 2016 following extensive global stakeholder engagement, analysis and discussion.

The scheme aims to address any annual increase in total CO_2 emissions from international civil aviation above the 2020 levels. In any year from 2021 when international aviation CO_2 emissions covered by the scheme exceed the baseline, this difference represents the sector's offsetting requirements for that year.

The scheme is implemented in phases, starting with participation of States on a voluntary basis from 2021 to 2026, followed by participation of all major aviation States - except the exempted States - from 2027.

CORSIA is a route-based scheme whereby all operators on a route will be covered by the scheme if both States connecting the route are participating in the scheme. This is one element that protects against policy-induced competitive distortion.

Offset requirements are determined in proportion to each operator’s total emissions in the years until 2030, from which point an element of each operator’s individual growth is included in the determination.

Operators will be required to obtain emission reduction units, typically through carbon markets, from projects outside the aviation industry that provide cost-effective emissions reductions and meet a set of eligibility criteria.

6.1.2 EU Emissions Trading System

The EU ETS provided an important first step towards a global system by establishing the first international system for carbon trading in aviation. The EU ETS has achieved net emissions reductions for intra-European flights in the period since 2012 and has served as a key reference for non-European governments in developing their own national ETS approaches for aviation, as well as for the design of the CORSIA.

Following the ICAO agreement, there is now an opportunity to have a fresh look at environmental regulation in Europe and to review existing measures such as the EU ETS for aviation to ensure the continued competitiveness of UK and European airlines and avoid double regulation with separate, overlapping measures and a duplication of administrative obligations.

6.2 Implementation of MBMs

SA members will continue to work with IATA, ICAO and other bodies to define aspects of the CORSIA scheme to ensure successful implementation, and to define the criteria for offsets.

6.3 Representation of MBMs in our CO_2 Road-Map

6.3.1 Sources of Uncertainty

Although there has recently been agreement at the international level concerning a global MBMs scheme for international aviation, there are still many source of uncertainty that make it difficult to calculate a representative trajectory for net CO_2 emissions from UK aviation. Sources of uncertainty include:

- The outcome of the 2016 referendum on the UK’s membership of the Europen Union, and the uncertainty it creates regarding whether all UK-departing international flights will continue to fall within scope of the EU ETS.
- The future coverage of the EU ETS following agreement of the CORSIA scheme at ICAO.
- While the overall aim of incorporating aviation into the EU ETS - namely to cap aviation’s within-scope CO_2 emissions to a fixed percentage of a baseline level – is fairly straightforward

to understand, it is not so simple to calculate the net emissions attributable to an individual nation.

6.3.2 Our approach

In our 2016 Road-Map, due to the sources of uncertainty referred to above, we have chosen to present an indicative trajectory of net CO_2 emissions from UK aviation, rather than attempting to provide a forward-looking calculation of the actual impact of the EU ETS and CORSIA upon UK aviation's net CO_2 emissions. This indicative trajectory covers the period to 2035 (when the CORSIA scheme reaches its end) and simply illustrates a capping of net emissions at 95% of 2005 levels, consistent with the overall aim of the EU ETS as it applies to aviation.

Although we have been unable to provide a detailed calculation of the likely trajectory of net CO_2 emissions from UK aviation to 2035, we believe that over that period actual net emissions will likely lie below the level we have broadly indicated on our Road-Map chart, in other words that the cumulative reduction in net CO_2 emissions from UK aviation will likely be greater than we have shown.

In the period after 2035, for which there is currently no agreed MBMs scheme or emissions trading scheme in place, we simply show one possible path from 2035 to 2050 consistent with allowing UK aviation to meet the same goal as has been adopted by the global aviation industry, in other words to reduce net emissions to half of 2005 levels by 2050. Achieving this will require support from governments as we discuss in the next section.

We have not considered the impact upon demand for UK aviation associated with any significant changes to the carbon price associated with aviation's participation in market-based measures. However, we note that the Airport's Commissions "carbon-traded" demand growth forecasts that we employed to construct our hypothetical no-improvements scenario (see **chapter 2**) incorporate the effect upon demand of carbon pricing. We are unable to predict the extent to which actual carbon prices to 2050 may differ from those assumed by the Airport's Commission,

6.4 "Asks" for Government

We welcome the role played by the UK Government in negotiations towards the ICAO global MBMs agreement, which supports as far as 2035 the global aviation industry's carbon neutral growth ambition. Government should now focus on implementation details including avoiding duplication of coverage with regional schemes. Government should also start the process towards the global mechanism for 2035 onwards, which will be essential in supporting the global aviation industry's commitment to reduce net aviation CO_2 emissions by 50% by 2050, relative to 2005 levels, while increasing capacity in support of economic growth.

7 The Sustainable Aviation CO_2 Road-Map

SUMMARY – based on our assumptions and analysis, we conclude that UK aviation is able to accommodate significant growth to 2050 without a substantial increase in CO_2 emissions. Further reductions in net CO_2 emissions are achievable through internationally agreed market-based measures, and our Road-Map illustrates the potential reduction of net CO_2 emissions to 50% of 2005 levels by 2050.

7.1 Introduction

This CO_2 Road-Map has drawn on expertise from all corners of the UK aviation industry, including airlines, airports, aerospace manufacturers and air navigation service providers. Starting from UK-specific aviation demand growth forecasts which not only assume a high level of economic growth (with correspondingly high aviation demand growth) but also take account of additional runway capacity in the South East of England, we have then considered the likely impact on UK aviation's CO_2 emissions of a portfolio of mitigation measures. This document has set out in a transparent manner the assumptions underpinning our Road-Map, the method of working used to transform our assumptions into the results of our analysis, and the distinction between those areas in which quantitative data-driven analysis has been possible and those areas where informed judgement has been necessary.

7.2 The 2016 CO_2 Road-Map

7.2.1 Summary of Assumptions

To arrive at our assumed demand-growth curve, we have selected the highest-economic-growth option from among the Airport's Commission's scenarios. We have also captured any additional demand arising from new runway capacity in South-East England (should such capacity be introduced) by taking the average of the Airports Commission's three additional-runway-capacity options within the highest-economic growth scenario. As a result, there is good reason to believe that demand out-turn could be lower than we have assumed, which in turn would cause UK aviation CO_2 emissions to be correspondingly lower. Our hypothetical "no-improvements" scenario assumes demand growth by 155% (i.e. a factor of 2.55) between 2010 and 2050, including both passenger flights and freight-only flights.

Our assumptions for CO_2 reduction that can be achieved through improved air-traffic management and operational practices are very similar to our 2012 Road-Map, at a little under 9%. Further savings may be possible (as discussed in our 2012 Road-Map document [SA, 2012]) but we do not yet take account of those in our assumptions.

Our assessment of the potential for "imminent" aircraft to reduce UK aviation CO_2 emissions (relative to continued use of the "baseline" fleet) is now substantially larger than in our 2012 Road-Map, at 22%. This not only takes account of revised "imminent" aircraft characteristics but also reflects a much more detailed view of the fleet composition in the baseline year of 2010.

Based on the most recent evidence, we now consider it likely that "future" aircraft types will become available on average a little later than we assumed in our 2012 Road-Map, particularly in the "narrow-body" aircraft category. Although "future" aircraft may offer very substantial fuel-efficiency improvements relative to their "imminent" counterparts, their availability timescale means that their contribution to fleet efficiency improvements will likely carry on well past 2050. At the 2050 point, our assessment suggests they contribute an approximately 21% reduction in UK aviation CO_2 relative to a fleet composed entirely of "imminent" aircraft types.

We see no reason to change our assumption concerning the potential for sustainable aviation fuels to reduce UK aviation CO_2 by 2050, which remains at 18%. Since our 2012 CO_2 Road-Map, we have conducted a detailed analysis which was published as our Fuels Road-Map and confirms our position.

The Market-Based Measures (MBMs) landscape has changed considerably since 2012. ICAO has agreed a scheme for international aviation which would run until 2035 and is intended to enable carbon-neutral growth from 2020. In our Road-Map graphic, we illustrate one trajectory that net CO_2 emissions from UK aviation could subsequently follow to achieve a 50% reduction by 2050, relative to 2005 levels, matching the stated ambition of the global aviation industry.

7.2.2 Road-Map Graphic

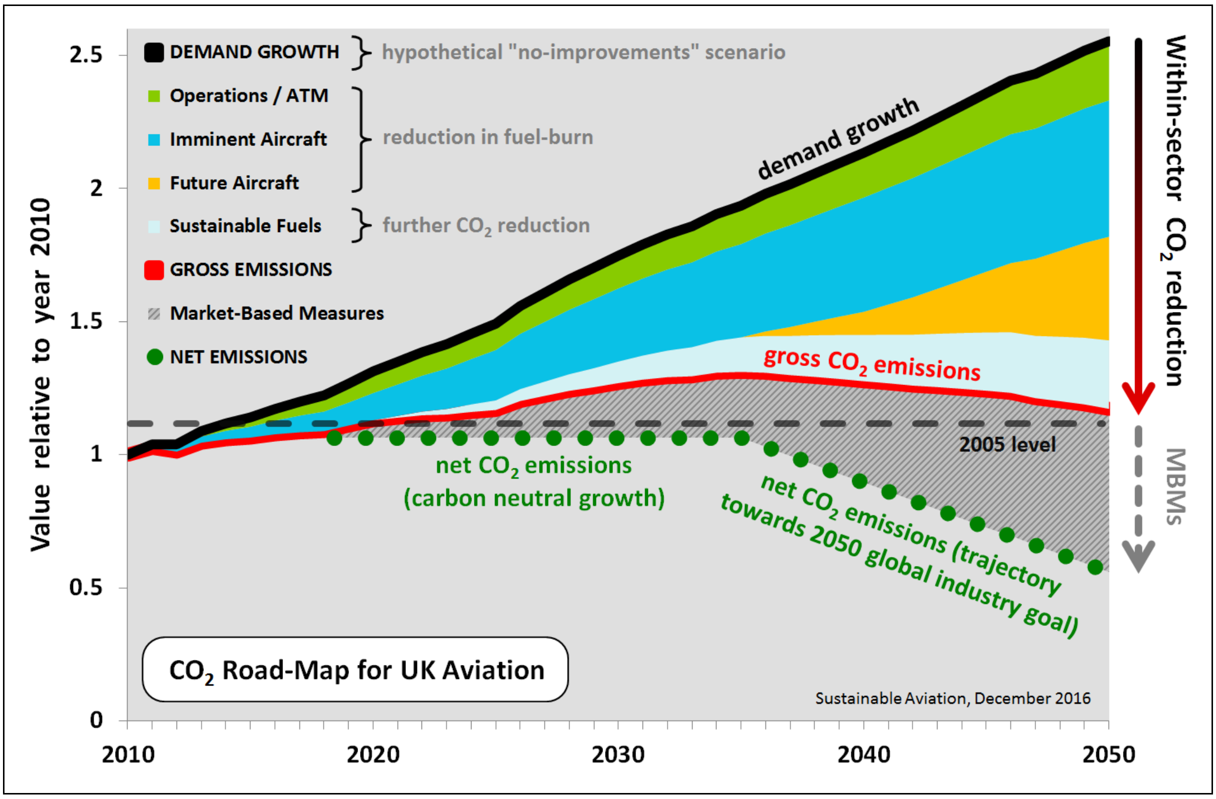

Figure 6 – Sustainable Aviation CO_2 Road-Map, showing that UK aviation can accommodate significant growth to 2050, including that associated with additional runway capacity in the South East of England, without a substantial increase in CO_2 emissions. We also illustrate the potential reduction of net CO_2 emissions to 50% of 2005 levels through internationally agreed market-based measures.

7.3 Discussion

7.3.1 Modelled CO_2 Emissions vs Reported Out-Turn CO_2 Emissions

Figure 7 shows the CO_2 emissions calculated by our Road-Map model for the years 2010-14, and compares them to out-turn data from the UK's National Atmospheric Emissions Inventory [NAEI] for the same period. It can be seen that the out-turn is slightly lower than our model's results.

The most likely explanation for this is that our fleet refresh model treats the displacement of older aircraft from the fleet by newer types as a linear process occurring gradually over the full duration of the assumed fleet refresh period (see **Table 5** and **APPENDIX D** for details of the fleet refresh model and assumed refresh periods for each aircraft size category). However, in practice, fleet refresh within individual aircraft size categories can progress in bursts of activity as individual airlines receive batches of new aircraft and retire older aircraft. As a result our model will fail to capture short-term structure in the fleet refresh process.

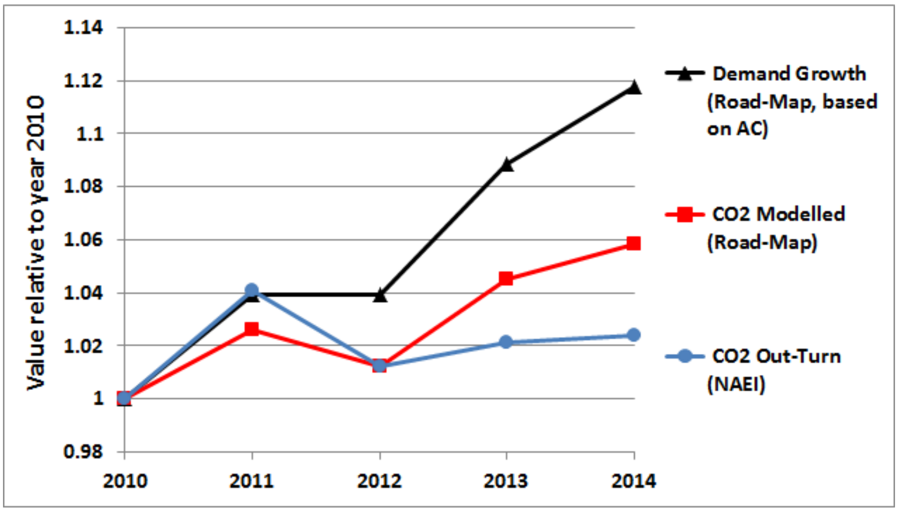

Figure 7 – comparison of reported emissions of CO_2 from UK aviation (source: [NAEI]**) against modelled CO_2 emissions (**source: CO_2 Road-Map**)**

Supporting evidence for this diagnosis can be found in **Figure 8** which shows the change in the number of available seat kilometres (ASKs) in recent years for Boeing 767 and 787 aircraft. A swift transition away from the 767 and towards the 787 can be seen. Since the 787 offers a substantial fuel-efficiency advantage relative to the 767, this transition is material to the average efficiency of the overall fleet. Our Road-Map model, which incorporates the 767/787 alongside the A330/A330neo aircraft into a single "small-medium twin-aisle" category, does not capture this fine detail and so will underestimate the rate of improvement in fleet-average fuel efficiency in the early years in this case. We are confident that the long-term conclusions of our Road-Map are unaffected by this.

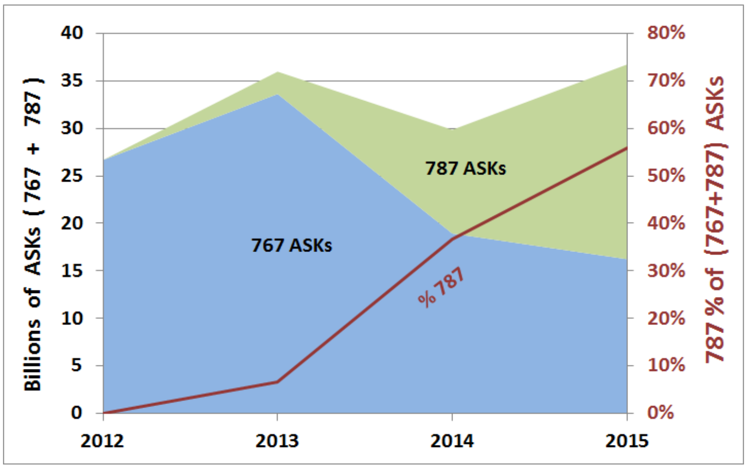

Figure 8 – illustration of the swift reduction in Boeing 767 activity from 2013 onwards, with corresponding swift increase in Boeing 787 activity. Data source: OAG. Scope: flights which depart from UK airports.

Another possible contributing factor (albeit of much lower materiality) is the reduction of belly-freight tonnage carried relative to passenger tonnage carried. **Figure 11** shows that between 2010 and 2014, UK-departing belly-freight tonnage remained broadly unchanged, while freight-only tonnage fell slightly. On the other hand, **Figure 7** shows overall demand (predominantly passenger traffic with a small component of freight-only flights) rising strongly over the same period. The resulting reduction in the ratio of belly-freight tonnage relative to passenger tonnage can reduce very slightly the fuel burned to deliver passengers to their destinations, all other things being constant. Our Road-Map model does not take account of changes in belly-freight carriage and so does not capture this small effect.

7.3.2 Average Rates of Improvement

Taken together, our mitigation assumptions (summarised in **Table 10**) combine to yield an average rate of improvement, in UK aviation's fuel efficiency between 2010 and 2050, of 1.44% per annum, of which an average of 1.22% per annum arises from the deployment of more fuel-efficient aircraft. When the assumed impact of sustainable aviation fuels is taken into account, the average annual rate of improvement in carbon intensity is 1.93%. These numbers are very similar to those in our 2012 Road-Map.

<table>
<tr><th>Mitigation Source</th><th colspan="4">Impact on Fleet-Average CO_2 Intensity
(average rate of improvement, % p.a. 2010-2050)</th></tr>
<tr><td>ATM / Operations</td><td>0.23</td><td rowspan="2">1.44</td><td rowspan="3">1.93</td><td rowspan="4">3.72</td></tr>
<tr><td>Engines / Aircraft</td><td>1.22</td></tr>
<tr><td>Sustainable Aviation Fuels</td><td colspan="2">0.49</td></tr>
<tr><td>MBMs</td><td colspan="3">1.83</td></tr>
</table>

Table 10 – rates of improvement in fleet-average CO_2 per unit of delivered benefit, averaged over the period 2010-2050

The rate of improvement in fleet-average aircraft fuel efficiency (1.22% p.a.) is of course lower than the assumed rate of fuel-efficiency improvement between new "imminent" aircraft and new "future" aircraft. (1.3% p.a. plus step-changes) set out in **APPENDIX F**. Reasons for this are:

- The figure of 1.22% p.a. captures the full 40 year period 2010-2050 which also includes the transition from the baseline fleet to a fleet of "imminent" aircraft.
- Given the assumptions we have used for entry into service dates and fleet transition periods, replacement of "imminent" aircraft types with "future" aircraft types is only partially complete by 2050. The full effect upon fleet efficiency of "future" aircraft is therefore not captured by our Road-Map which looks ahead only as far as 2050.

7.3.3 UK Aviation CO_2 Emissions and National CO_2 Budgets

The UK has a legislated commitment to reduce GHG emissions by at least 80% relative to 1990 levels by 2050. In that context, the Committee on Climate Change (CCC) advises Government on setting and meeting carbon budgets.

The CCC recognises that cost-effective opportunities for deep decarbonisation vary between different sectors of activity, and that some sectors - particularly aviation, agriculture and parts of industry - are not expected to reach zero emissions by 2050 [CCC, 2016a]. The CCC has advised that to meet the 2050 target for the UK as a whole in a cost effective manner, aviation CO_2 emissions in 2050 should be "*around 2005 levels*" [CCC, 2016a].

This implies that aviation's CO_2 emissions in 2050 will constitute around a quarter of the UK's GHG budget in 2050. We emphasise that although in our Road-Map UK aviation emissions in 2050 are shown as being a little over the 2005 level, this is in the context of our assumptions for demand growth being based upon the highest-growth scenario (entitled "Global Growth") from among the economic scenarios considered by the Airports Commission (see **chapter 2**). If we were instead to base our demand growth assumptions on the Airports Commission's "Assessment of Need" or "Global Fragmentation" economic scenarios (but still assuming additional runway capacity) then our Road-Map chart would show 2050 CO_2 emissions from UK aviation as being materially below 2005 levels.

Post 2050, it is reasonable to expect that the UK will need to make additional reductions in its GHG emissions, particularly in the light of the December 2015 Paris Agreement (see **section 1.6**). As discussed in **section 4.9**, the transition from “imminent” aircraft to “future” aircraft will be incomplete by 2050, meaning that substantial further improvements to fleet fuel efficiency can be expected in the years immediately following 2050 due to factors considered in this document. Yet further improvements post-2050 - through a further generation of aircraft and still further displacement of fossil-based aviation fuels by sustainable aviation fuels - can be contemplated, but lie beyond the time horizon of this document.

7.4 Conclusions

This document has set out Sustainable Aviation’s view of future CO_2 emissions from UK aviation, taking account of anticipated growth in demand for aviation based upon forecasts from [AC, 2015], combined with our assessment of the likely impact of substantial efforts being made across all parts of the aviation industry to improve fuel-efficiency and reduce CO_2-intensity.

We conclude that UK aviation is able to accommodate significant growth to 2050 without a substantial increase in CO_2 emissions. We also illustrate the potential impact of ICAO’s GMBM scheme, and the further reduction of net emissions post 2035.

The technologies and know-how which will enable UK aviation to limit increases in its own CO_2 emissions can also be deployed worldwide, earning export revenues for the UK and supporting efficiency improvements in the much larger global aviation market.

Government has a substantial role to play in enabling these environmental and economic benefits for the UK, by supplementing and supporting determined and consistent action within the aviation industry.

- Government should continue to support airspace modernisation in the UK, and maintain momentum towards improved Air Traffic Management (ATM) collaboration across Europe.
- We acknowledge the significant levels of government support to the UK aerospace industry provided through initiatives such as the Aerospace Growth Partnership (AGP). In the coming years Government must ensure that access by UK aerospace industry to ongoing funding for high-value collaborative R&D remains in place.
- We urge the UK Government to progress the consultation on future fuels policy and on the inclusion of Sustainable Aviation Fuels (SAF) in the Renewable Fuels Transport Obligation to encourage investment in this emerging sector. This should ensure the development of UK expertise and technologies and establish the UK as a centre of excellence for SAF production and innovation.
- We welcome the role played by the UK Government in negotiations towards the ICAO global MBMs agreement, which supports as far as 2035 the global aviation industry’s carbon neutral growth ambition. Government should now focus on implementation details including avoiding duplication of coverage with regional schemes. Government should also start the process towards the global mechanism for 2035 onwards, which will be essential in supporting the global aviation industry’s commitment to reduce net aviation CO_2 emissions by 50% by 2050, relative to 2005 levels, while increasing capacity in support of economic growth.

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APPENDIX A – Comparing the 2012 and 2016 CO_2 Road-Maps

This appendix summarises material from the main text comparing this 2016 CO_2 Road-Map with its predecessor [SA, 2012], explaining any differences and the reasons for them. **Table 11** presents the key figures and assumptions.

Hypothetical "No-improvements" Scenario

The average rate of growth in aviation activity from 2010-2050 in our hypothetical "no-improvements" scenario is slightly higher in our 2016 Road-Map, due to a balance between several factors. In our 2016 Road-Map, we use demand growth forecasts based on an assumption of additional runway capacity in South East England. Alongside increased runway capacity, those forecasts also take account of the reduction in aviation demand associated with the economic downturn experienced in recent years in the UK. We also use a less optimistic forecast for growth in freighter activity, which moderates overall demand growth slightly.

ATM and Operations

Our improved analysis of potential CO_2 savings within UK airspace attributable to ATM improvements planned for implementation by NATS up to 2020 has produced slightly lower results than our 2012 review. No new evidence has emerged regarding ATM improvements outside UK airspace or in the period 2020-2050, hence we have retained the assumptions we used in 2012 for those categories. The assumptions used in our 2012 Road-Map concerning the potential savings from improved operational practices remain valid, and good progress has been observed towards implementing many of the identified improvements. As a result the combined assumptions used in our Road-Map model for ATM and operations are only slightly changed from those used in 2012.

Engine and Aircraft Technology

Our view of the potential for "imminent" aircraft to improve fleet-average fuel-efficiency relative to a year 2010 baseline has changed materially. We have taken more complete account of the composition of the baseline fleet, rather than assuming that it comprised exclusively the "best-available" aircraft at the time in each size-category. We have increased the granularity of our model which enables us to capture more effectively the different timescales within which different aircraft in different parts of the market will become available, and the different rates at which various older aircraft are likely to be phased out. We also take account of several new aircraft types which have been announced since our 2012 Road-Map.

When considering the subsequent replacement of "imminent" aircraft types by "future" aircraft types, we have retained the same overall methodology as used in our 2012 Road-Map, but we now assume a later entry into service of some "future" aircraft types, meaning that the fleet transition to "future" aircraft is now shown as being less complete by 2050 than in our 2012 Road-Map.

Overall, our view of the likely CO_2 mitigation offered by more efficient engines and aircraft by 2050 relative to the 2010 baseline is very similar in our 2016 Road-Map to that in our 2012 Road-Map. However the balance has shifted materially towards the "imminent" tranche of aircraft for which we have greater confidence in our analysis.

Sustainable Aviation Fuels

We have retained the same assumptions in this category. We note considerable technical progress since 2012 in this area, but much remains to be done to enable large-scale adoption of sustainable aviation fuels.

Market-Based Measures

The global aviation industry has a stated goal to reduce net CO_2 emissions from aviation to half of 2005 levels by 2050. Our 2016 Road-Map, similar to its 2012 predecessor, illustrates the scale of net carbon reduction that remains, after implementation of the above within-sector improvements, if UK aviation is also to reach 50% of 2005 levels by 2050. However in our 2016 Road-Map, we have accounted for the recently agreed CORSIA scheme by extending to 2035 the period of “carbon-neutral growth”. An as-yet-undetermined scheme will be required to bring about further reductions post 2035.

Summary

<table>
<tr><th colspan="3">Edition of SA CO_2 Road-Map:</th><th>2012</th><th>2016</th></tr>
<tr><td colspan="3">Period</td><td colspan="2">2010 – 2050</td></tr>
<tr><td colspan="3">Average demand-growth rate</td><td>2.32 % p.a.</td><td>2.37 % p.a</td></tr>
<tr><td rowspan="6">Reduction in Fleet Average Carbon Intensity in 2050 (vs 2010)</td><td colspan="2">ATM / Operations</td><td>8.9 %</td><td>8.7 %</td></tr>
<tr><td rowspan="3">Aircraft and Engine</td><td>“Imminent”</td><td>17.0 %</td><td>22.0 %</td></tr>
<tr><td>“Future”</td><td>25.9 %</td><td>21.4 %</td></tr>
<tr><td>Total</td><td>38.5 %</td><td>38.7 %</td></tr>
<tr><td colspan="2">Sustainable Aviation Fuels</td><td>18%</td><td>18%</td></tr>
<tr><td colspan="2">TOTAL</td><td>54.0 %</td><td>54.1 %</td></tr>
<tr><td colspan="3">Market-Based Measures</td><td>As required to reduce net emissions to half of 2005 levels</td><td>As required to reduce net emissions to half of 2005 levels, following a net-carbon-neutral period to 2035</td></tr>
</table>

Table 11 – comparison of assumptions used in the 2012 and 2016 Sustainable Aviation CO_2 Road-Maps.

APPENDIX B – Hypothetical "No-Improvements" Scenario – Details

B.1 Growth in RPKs on Passenger Flights

In the previous issue of our CO_2 Road-Map (2012), we made use of demand growth forecasts from the UK's Department for Transport, taking the most recent forecasts available at the time [DfT, 2011]. As the basis for our growth trajectory, we used the DfT's "central" case which assumed no new runway capacity in the South East of England, consistent with Government policy at the time[121]. DfT has since updated its forecasts [DfT, 2013] to take account of the long-term impact of the recent economic downturn. However, those revised forecasts are now over three years old and furthermore comprise two options in which runway capacity is either "constrained" (i.e. no new runway capacity at all) or "unconstrained" (i.e. runway capacity is allowed to expand as necessary to accommodate demand growth wherever it may occur). A more recent forecast, in which the underlying assumptions of additional runway capacity focus on specific options in the South East of England, has been published by the Airports Commission [AC, 2015], and it is primarily upon that document that we base our calculations.

The Airports Commission document includes aviation demand growth forecasts for a variety of situations, covering combinations of four runway-capacity options with five economic growth scenarios, in either a "carbon-capped" framework or a "carbon-traded" framework.

- In the Airports Commission's "carbon-capped" framework, UK aviation CO_2 emissions in 2050 were constrained in the demand forecast model to no more than 2005 levels, with permitted levels of aviation activity being impacted as appropriate. In the corresponding "carbon-traded" framework, CO_2 emissions were subject to a price that exerted downward pressure on demand but did not place a hard limit on emissions.
- The "carbon capped" approach required the Airports Commission to make assumptions concerning the carbon-efficiency of future aviation activity in order to assess how much activity could be accommodated within the carbon cap, and therefore to calculate how much growth could be permitted. Since it is a primary purpose of our CO_2 Road-Map to set out Sustainable Aviation's own assumptions about the future carbon-efficiency of UK aviation, use of the "carbon-capped" demand growth scenarios would be inappropriate for our purposes. Therefore in our Road-Map, we use the Airports Commission's scenarios corresponding to the "carbon-traded" framework, in which growth in demand for aviation is stronger than in the capped case.
- Of the five economic growth scenarios presented by the Airports Commission, we have chosen for our Road-Map the "Global Growth" scenario which corresponds to the strongest growth in aviation activity.
- The Airports Commission's runway capacity options comprised a baseline of no new capacity, and three increased-capacity options. Sustainable Aviation does not have a position concerning the relative attractiveness of the three increased-capacity options, although we do support the general principle that additional runway capacity is required to support the UK's economic growth and to alleviate congestion associated with running existing runways at or very close to their capacity limits. We have therefore taken an average of the three demand-growth trajectories corresponding to the Airports Commission's three additional-runway-capacity options. More specifically, the procedure detailed below has been carried out for each of the three additional-runway-capacity options (to derive a year-by-year RPK trajectory for each such option, assuming in each case the "Global Growth" economic scenario and the "carbon-traded" framework) and then we have taken the arithmetic mean of those three trajectories. It should be noted that the difference in levels of aviation activity between the three additional-capacity options is in general less significant than that between the various

121 This did not and does not imply our support for a "no new runways" policy

economic scenarios, and is also less significant than that between the baseline (no-additional-capacity) scenario and each of the additional-capacity options. We note that although the UK Government has recently[122] indicated a preference for one of the additional capacity options, this is subject to consultation. We therefore retain our approach of averaging the growth trajectories corresponding to the three additional runway capacity options, while noting that future issues of our Road-Map may be able to use a growth forecast corresponding to one specific additional-runway capacity option. Our demand-growth trajectory, being based on the average of three additional-runway-capacity options, is marginally lower than a corresponding demand growth trajectory based solely on the option for which the UK Government recently expressed a preference, the difference being less than 2% in 2050, and less than 3% at all points on the path to 2050.

To summarise, we have selected - as the basis for our trajectory of growth in demand for passenger aviation - the Airports Commission's scenario corresponding to 1) increased runway capacity (average of three options), 2) high economic-growth, and 3) uncapped carbon emissions. In other words our choice of demand growth scenario is very close to[123] the highest-aviation-growth scenario amongst all those presented in [AC, 2015]. This can therefore be viewed as being towards the upper end of the demand growth that we are likely to observe in practice.

Recent figures for 2015 and 2016 [CAA] show terminal passenger numbers higher than those for the corresponding years in the trajectories set out by the Airports Commission. However, we should be wary of assuming that this constitutes a trend. Possible explanations include the recent low price of oil which may temporarily be stimulating demand for aviation. To SA's knowledge, the Airports Commission's forecast is the UK's most up to date formal demand growth forecast for aviation activity, and our Road-Map will make use of it until such time as it is superseded.

For each of the scenario combinations considered by the Airports Commission, [AC, 2015] provides RPK data only for a selection of years, namely 2011, 2030, 2040 and 2050. For our Road-Map, we require yearly data from 2010 to 2050. This requires two sources of adjustment, as follows:

- [AC, 2015a] provides detailed year-by-year forecasts of passenger numbers from 2011 to 2050. We use these to derive intermediate-year RPK values for use in our Road-Map. This avoids a simple linear or exponential curve fit between the given points for RPK values, and instead allows us to capture in our model the expected slower growth in the years prior to 2025. Although the use of passenger-number ratios to derive RPK values for intermediate years does not reflect year-to-year changes in the market structure, and therefore may introduce small errors, we emphasise that the resulting curve is anchored at the four points 2011, 2030, 2040 and 2050 for which [AC,2015] does provide RPK forecasts, and furthermore any resulting errors for the intervening years are likely to be very small in comparison with uncertainties related to differences between the assumed economic conditions and the actual economic conditions.
- We must also derive a corresponding year-2010 figure for use in our Road-Map. The data source used above for estimating intermediate year RPK values from passenger number ratios does not provide passenger numbers for 2010. However, these are available from [CAA]. **Figure 9** shows the level of agreement between the two sources of passenger-number data for the first few years, indicating adequate agreement in the overlapping years

[122] https://www.gov.uk/government/collections/heathrow-airport-expansion , dated 25th Oct 2016

[123] Since we have taken an average of the three additional-capacity options, our chosen trajectory cannot by definition be identically equal to the highest-growth scenario considered by the Airports Commission. But due to the similarities in forecast growth associated with each of the additional-capacity options, our average is close to the highest-growth scenario.

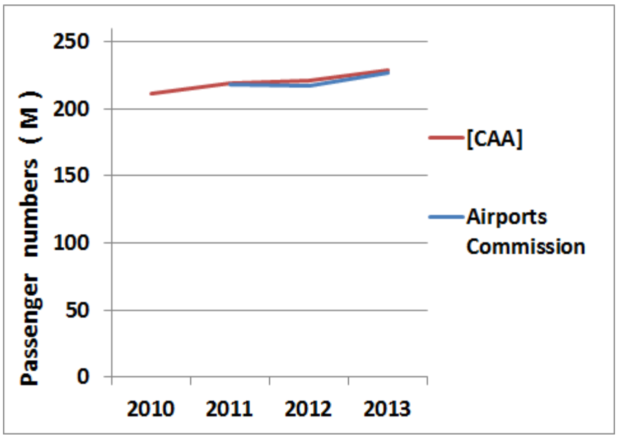


Figure 9 – passenger numbers (millions) according to [CAA] and [AC, 2015a].
Scope: UK aviation.

Our resulting trajectory of growth in RPKs on passenger flights is shown in **Figure 10**, alongside the RPK forecasts [AC, 2015] (average of the 3 additional-runway-capacity options) for 2011, 2030, 2040 and 2050, from which our trajectory is derived using scaling data from [AC,2015a] and [CAA] as described immediately above.

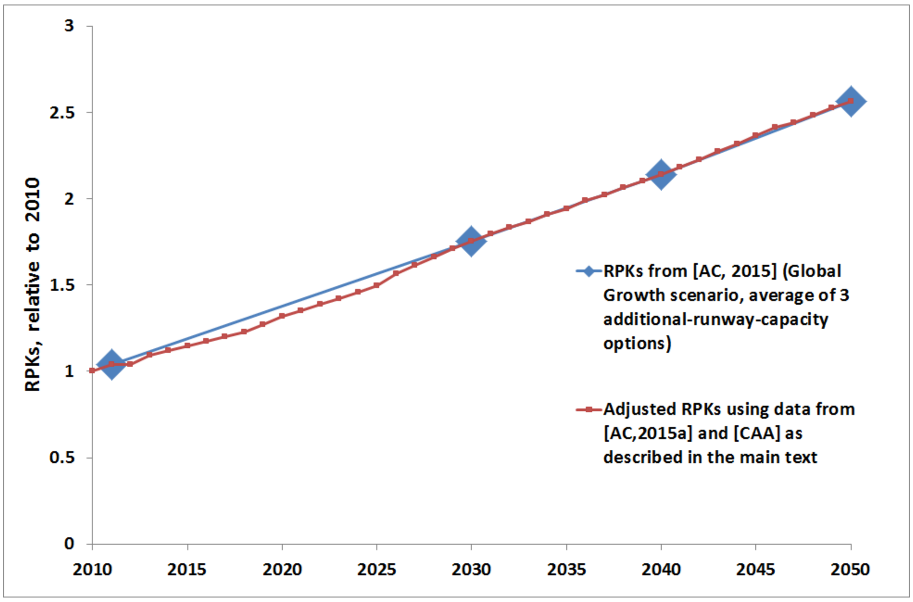


Figure 10 – trajectory of growth in RPKs (relative to 2010) on passenger flights. See main text for details. Scope: UK aviation.

B.2 Growth in FTKs on Freight-Only Flights

Globally, there is strong evidence that the rate of growth in air freight has slowed in recent years, and that it is expected to lag behind passenger transport in the years ahead. Furthermore, a transition from freighter-flights towards bellyhold freight is also in evidence.

- Airbus forecasts that the global passenger aircraft fleet will increase by 109% from 2015 to 2035, while the freighter fleet will grow by only 35%[124]. Similarly, Boeing forecasts 2015-2035 growth in the passenger fleet as being 104%, with growth in the freighter fleet of only 70%[125].

[124] See page 2 of http://www.airbus.com/company/market/global-market-forecast-2016-2035/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=109228, viewed 30th Sept 2016

[125] See page 53 of http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/cmo_print_2016_final_v6.pdf, viewed 30th Sept 2016

- Boeing forecasts that RPKs will grow at 4.8%p.a. from 2015 to 2035, while FTKs will grow by only 4.2%p.a. over the same period[126].
- Airbus forecasts that RPKs will grow at an average of 4.5%p.a.[127] from 2016 to 2035, while FTKs will grow at an average of only 4.0%p.a.[128] over the same period
- Furthermore, Boeing also forecasts for 2015-2035 that bellyhold FTKs will grow at a faster rate than total freight FTKs, implying a slower rate of growth for freighter FTKs[129].
- IATA presents data showing that although historically growth in FTKs has matched that in RPKs, over the past few years there has been a significant decoupling of the two, with growth in FTKs being much lower in recent years[130].
- IATA also shows how the balance of delivered payload capacity on wide-body aircraft has in recent years moved away from freighters relative to passenger aircraft[131].

In the UK:

- Figures from [CAA] for freight tonnes uplifted from UK airports show that freighter tonnage declined by over 4% between 2010 and 2015, while in the same period, bellyhold tonnage remained approximately stable, as shown in **Figure 11**.

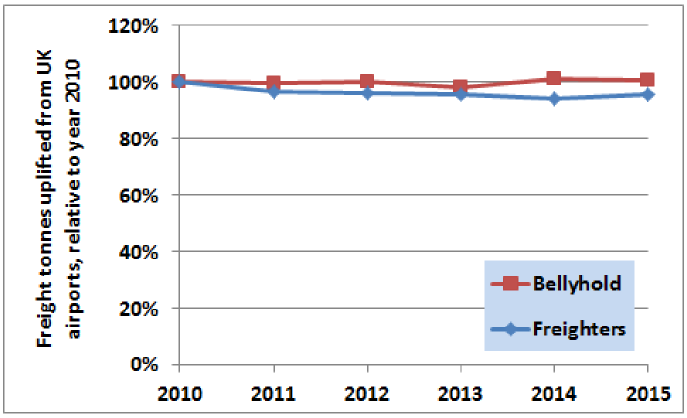


Figure 11 – tonnes of freight uplifted from UK airports . Scope: UK aviation. Data source: [CAA]

- Furthermore, as shown in **Figure 12** there is an apparent migration (in terms of tonnes uplifted) of freighter activity away from international destinations outside Europe, and towards destinations within Europe and the UK. While this does not prove beyond doubt that average freighter-flight distances are reducing, it does provide us with some reason to believe that they are not materially increasing, and that a reduction in freighter tonnes uplifted therefore probably also means a reduction in freighter FTKs. We note that this situation could change if there is a shift in the UK's trading patterns arising from the outcome of the 2016 referendum concerning the UK's membership of the EU. However it is too early to make predictions concerning the scale or impact of such effects. Future updates of our Road-Map will take account of the latest information available at the time of their preparation.

126 See page 8 of http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/assets/downloads/cmo_print_2016_final_v6.pdf, viewed 30th Sept 2016

127 Page 25 of http://www.airbus.com/company/market/global-market-forecast-2016-2035/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=111117, viewed 14th Nov 2016

128 Page 101 of http://www.airbus.com/company/market/global-market-forecast-2016-2035/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=111117, viewed 14th Nov 2016

129 See page 59 of http://www.boeing.com/resources/boeingdotcom/commercial/about-our-market/cargo-market-detail-wacf/download-report/assets/pdfs/wacf.pdf, viewed 30th Sept 2016

130 See figure 12 of http://www.iata.org/whatwedo/Documents/economics/cargo-chartbook-Q1-2016.pdf, viewed 30th Sept 2016

131 Ibid, figure 13

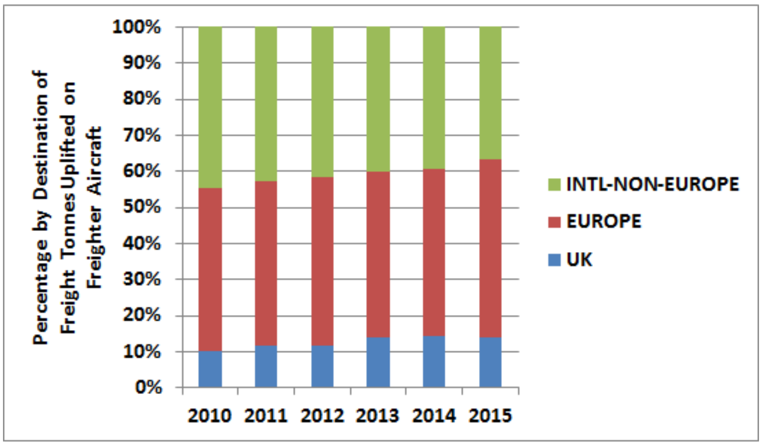


Figure 12 – share by destination category of tonnes of freight uplifted on freight-only flights. Scope: UK aviation, freight-only flights. Data source: [CAA]

We are therefore confident that, for the foreseeable future, growth in FTKs on freight-only flights is very unlikely to proceed at a higher rate than that in RPKs on passenger flights. This means that although we do not have access to detailed forecast data for UK freighter activity, we can nonetheless identify an upper bound, representing a growth trajectory which freighter activity is unlikely to exceed.

- In the period 2010-1015, we use out-turn data from [CAA] for freight tonnes uplifted on freighter aircraft as a proxy for the growth in freighter activity. This may result in an over-estimate of the corresponding growth in FTKs, due to the apparent migration away from longer-haul freight-only flights during that same period (discussed above).
- From 2015 onwards we assume, based on the evidence set out above, that growth in freighter FTKs is no more rapid than that in RPKs on passenger flights. Again, this is probably an over-estimate of the likely growth in freighter FTKs.

Our assumed trajectory for growth in FTKs on freighter aircraft, shown in **Figure 13**, should thus be seen as an upper bound rather than as a central estimate. Despite this, the assumed growth in freighter FTKs used here in our 2016 Road-Map is significantly less rapid than that based on [DfT, 2011] used in our 2012 CO_2 Road-Map[132].

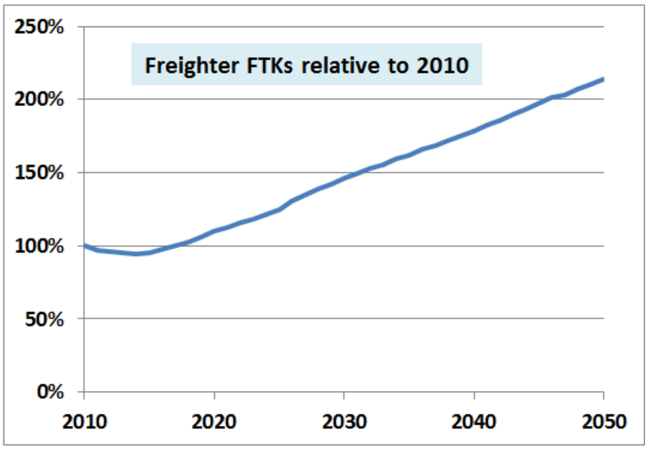


Figure 13 – growth trajectory of freighter FTKs. See main text for derivation. Scope: UK aviation. Source: SA analysis of data from [CAA] and [AC, 2015]

132 Paragraph 8.11 of [DfT, 2013] presents reasons why the [DfT, 2011] freighter growth forecast has subsequently been revised significantly downward.

B.3 Combining Passenger and Freight Flights

Table G.2 of [DfT, 2013] states that in year 2010 (the baseline year of our CO_2 Road-Map), freighter flights accounted for 0.8 $MtCO_2$ out of a total of 33.2 $MtCO_2$ for UK aviation. In other words, freighters accounted for 2.4% of UK aviation CO_2 in 2010.

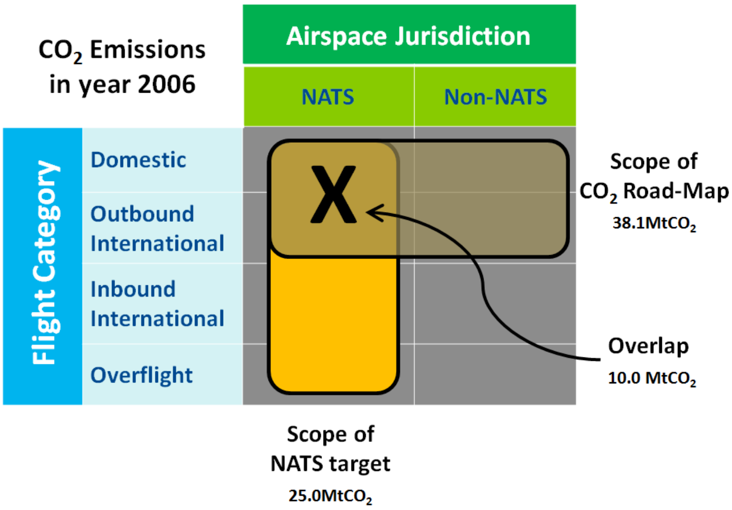
We can use this fact to combine our separate RPK and freighter-FTK forecasts, multiplying the FTKs "forecast" set out in **section B.2** by a factor of 0.024 (corresponding to 2.4%) and the RPKs "forecast" set out in **section B.1** by a factor of 0.976 (corresponding to the remaining 97.6%), before adding the two scaled trajectories together.

Results are shown in **section 2.4** of the main text.

APPENDIX C – NATS 10% Target and UK Aviation CO_2 Emissions

This appendix relates to and should be read in conjunction with **section 3.2.2** of the main text.

In 2008, NATS committed to a target of reducing CO_2 emissions from aircraft under NATS control by 10% per flight by 2020 relative to a 2006 baseline. [NATS, 2012][133] shows the expected delivery profile of the 10% saving, indicating that the overwhelming majority of the improvements will be delivered post 2010. In other words, the delivery of the NATS-driven CO_2 savings can be viewed as occurring entirely within the timeframe spanned by our CO_2 Road-Map, without introducing material error.



Although CO_2 emissions from UK aviation in 2006 were 38.1 Mt[134], emissions in the same year from aircraft under NATS control were 25.0 Mt[135], as reported in our 2012 Road-Map. Full achievement of the NATS 10% target would thus save 2.5 $MtCO_2$ from flights under NATS control, relative to the 2006 baseline aviation activity level. Subsequent growth or contraction of aviation activity would increase or decrease the absolute saving but we assume the relative saving is approximately constant, which therefore implies an assumption on our part that the distribution of aviation activity between different markets remains approximately constant between 2006 and 2020.

NATS calculates that 10.0 $MtCO_2$ of the 25.0 $MtCO_2$ was attributable to domestic flights and outbound international flights (i.e. lying within scope of our Road-Map, and corresponding to the “X” in the figure above) while the remainder was attributable to overflights and inbound international flights which are out of scope. This 10.0 $MtCO_2$ is a little smaller than the figure of 12.3 $MtCO_2$ which was the best available information at the time of our 2012 Road-Map. However, the impact of this change upon the CO_2 mitigation potential for UK aviation is minimal, since the change relates to within-scope activity in the North Atlantic part of NATS airspace which is predominantly cruise activity for which the likely savings are small compared with those in other phases of flight, as discussed immediately below.

[NATS, 2009][136] lists the proportion of the NATS 10% target that is expected from each of the phases of flight, as follows: climb 3.25%, cruise 1.5%, descent 4.75%, airport 0.5%. It should be noted that even though an individual aircraft will use substantially more fuel per unit distance in its climb phase of flight than when descending, the opportunities for saving CO_2 are greater in the descent phase due to greater levels of inefficiency. **Table 12** shows how these percentages can be re-expressed as a proportion of UK aviation emissions in the same year 2006.

133 page 18 thereof
134 Source: [NAEI]
135 Source: NATS analysis
136 Page 15 thereof

Flight Phase	NATS target saving as % of 2006 NATS baseline[137]	NATS target $MtCO_2$ saving relative to NATS 2006 baseline of 25 $MtCO_2$[138]	NATS target % saving vs 2006 UK aviation emissions of 38.1 $MtCO_2$[139]
Climb	3.25	0.8125	2.13
Cruise	1.5	0.375	0.98
Airport	0.5	0.125	0.33
Descent	4.75	1.1875	3.12
TOTAL	**10 %**	**2.5 $MtCO_2$**	**6.56 %**

Table 12 – target savings by phase of flight, expressed relative to NATS baseline and relative to UK aviation in the same year 2006.

We can then establish how much of each line of **Table 12** lies within scope of our Road-Map i.e. applies to flights which depart from UK airports (domestic flights and outbound international flights).

- For "**climb**", some 85%[140] of fuel burned in the climb phase within the UK FIR[141] is attributable to flights which have departed from UK airports, and thus lies within scope of our Road-Map. The other 15% is attributable to flights originating from nearby non-UK airports (such as Dublin, Brussels, Amsterdam and others).

- For "**cruise**", the situation is a little more complicated. [NATS, 2009][142] details the breakdown between flight categories of 2006 CO_2 emissions from flights while under NATS control.
  - Overflights (out of scope) account for 23% of 2006 CO_2 emissions from flights while under NATS control - it is reasonable to assume that most of this is emitted during cruise since overflights have relatively little climb/descent activity within UK airspace.
  - Domestic flights (in scope) account for 14% of the 2006 CO_2 emissions under NATS control. However, only a relatively small proportion (around one third) of this will take place at cruise due to the short distances involved (most UK domestic flights are around 350nm or less, and so fuel burned in the non-cruise phases of light, particularly climb, dominates).
  - Inbound international flights (out of scope) may include a long cruise segment within NATS airspace (for example if approaching from North America), or very little (if approaching London from North-West Europe. However, averaged over all inbound international flights, the proportion of cruise fuel burn, relative to the descent and taxi-in fuel-burn, is likely to be fairly high, perhaps two thirds.
  - Similarly, outbound international flights (in scope) may or may not include a substantial cruise segment within NATS airspace. In either case climb fuel-burn is likely to be more material than was the case for descent fuel-burn on inbound flights. As a result, the proportion of CO_2 emissions from outbound-international flights under NATS control that is attributable to the cruise phase is likely to be somewhere in the range of one-third to one-half.
  - Combining the above suggests that around one third of CO_2 emissions from cruising aircraft under NATS control also lies within scope of our Road-Map.

- For "**descent**", CAA Airport data[143] for 2006 shows that some 36% of all air transport movements in 2006 were related to domestic flights, meaning that domestic flights accounted

137 Source: [NATS, 2009]
138 Baseline of 25.0 $MtCO_2$ (emissions in 2006 from flights while under NATS control).
139 UK aviation CO_2 emissions in 2006: 38.1 $MtCO_2$.
140 Source: NATS
141 FIR = flight information region
142 Pie chart of CO_2 emissions on page 09 thereof

for some 36% of all instances of descent into UK airports. However, since aircraft used for domestic flights are generally smaller and lighter than those used for international flights, and particularly for long-haul flights, the materiality of domestic flights within the CO_2 associated with the descent phase of flight in 2006 is materially less than 36%. Data from OAG[144] for year 2006 scheduled flights can be used to show that the frequency-weighted average seat count for domestic arrivals in 2006 was 87.8 seats while that for international arrivals in the same year was 162.0 seats. Using seat-count as a proxy for materiality with respect to CO_2 emissions in the descent phase, domestic descents can be assigned a materiality of 23.3%[145] (i.e. rather less than 36%) for year 2006. Therefore the fraction of the target CO_2 saving in the descent phase that also lies within scope of our Road-Map is around 23% for year 2006. A similar calculation for year 2014 yields a value of 17%, reflecting the relative decline of domestic flights within the overall mix. We shall use a value of 15% in anticipation of a further continuation of that trend to 2020.

- For "**airport**" - we might simplistically assume that half (i.e. 50%) of the CO_2 attributable to aircraft ground movements lies within scope of our Road-Map, since for every departure (within scope) there is a corresponding arrival (out of scope except for domestic arrivals). However, we note that departing aircraft are subject to considerably more ground holding than arriving flights. We estimate that this raises the materiality of departing flights to around two thirds rather than half, i.e. we are assuming that each aircraft emits around twice as much CO_2 from its departure-related ground movements as from its arrival-related ground movements. Taking domestic arrivals into account as well, we estimate that some 70%[146] of total CO_2 emissions from aircraft ground movements fall within scope of the Road-Map.

The results are summarised in **Table 13**.

Flight Phase	NATS Target % saving vs 2006 UK aviation emissions[147]	Fraction of line within scope of UK aviation (see text)	Within-Scope % saving vs 2006 UK aviation emissions
Climb	2.13	0.85	1.81
Cruise	0.98	0.33	0.32
Airport	0.33	0.7	0.20
Descent	3.12	0.15	0.47
		TOTAL	**2.83 % vs 2006**
		Used for Road-Map	**2.8 % vs 2010**

Table 13 – estimation of available percentage saving of 2010 UK aviation CO_2 emissions arising from achievement of the NATS 10% target.

As explained above, the delivery of the NATS target is largely post-2010, and so we can assume that the overwhelming majority of the 2.83% relative to 2006 emissions also applies to the Road-Map's 2010 baseline. We shall assume a likely saving of **2.8%** relative to the 2010 baseline in our Road-Map calculations.

143 https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-1990-onwards/, Table 05 ("Air Transport Movements") of data for full-year 2006.

144 http://analytics.oag.com, accessed 14th July 2016

145 (36%*87.8seats) / [(36%*87.8) + (64%*162.0)] = 23.3%

146 In the above discussion, we have estimated for the descent phase that domestic arrivals have a materiality of around 15% of the descent CO_2 of all arrivals. We can reasonably assume the same level of materiality for domestic arrivals within the ground-movement CO_2 of all arrivals. We have also estimated that arrival-related ground movements account for about one third of CO_2 from all aircraft ground movements. Taking 15% of one third gives 5% which when added to the other two thirds (66% of ground-movement CO_2 related to departures which lie entirely within scope) yields about 70% of CO_2 emissions from aircraft ground movements being within scope.

147 From **Table 12**

APPENDIX D – Characteristics of "Imminent" Aircraft Types

This appendix relates to and should be read in conjunction with **section 4.4** of the main text.

D.1 Fuel-Efficiency Improvements

Manufacturers' claims for the fuel-efficiency of their respective products falling within scope of our "imminent" category are as follows:

1. The Bombardier C Series reduces CO_2 emissions per seat by 20% compared with in-production aircraft in the same class[148].
2. The Embraer E2 aircraft offer fuel-burn per seat improvements relative to their respective predecessors of 16% (E190-E2 vs E190)[149], 16% (E175-E2 vs E175)[150] and 24% (E195-E2 vs E195)[151] on a 600nm flight.
3. The Boeing "*737 MAX will be 14 percent more fuel-efficient than today's most efficient Next-Generation 737s – and 20 percent better than the original Next-Generation 737s when they first entered service*"[152].
4. The Boeing 737 MAX 200 offers "*up to 20 percent better fuel efficiency per seat than today's most efficient single-aisle airplanes*"[153].
5. "*Improvements for the A320neo Family result in a per-seat fuel burn saving of 20 per cent compared to current engine option (CEO) jetliners by 2020*"[154], the neo vs ceo per-seat fuel burn saving being 19% for the A319, 20% for the A320 and 23% for the A321[155].
6. The Airbus A321LR offers "*30% lower fuel burn per seat than 757-200W* "[156,157].
7. The Airbus A330neo "*delivers fuel savings of 14 per cent per seat compared to in-production A330s*"[158].
8. Boeing 787-9 aircraft offer "*20 percent less fuel use and 20 percent fewer emissions than the airplanes they replace*"[159].
9. The Boeing 787-10 "*will deliver 25 percent better fuel use and emissions than the airplanes it will replace*"[160].
10. The Airbus A350 XWB offers "*25 per cent lower fuel consumption compared to its current aluminium long-range competitors*"[161].
11. The Boeing 777X "*reduces fuel use and CO_2 emissions by 20% compared to previous generation aircraft*"[162].

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148 http://commercialaircraft.bombardier.com/en/cseries/Environment.html, viewed 26 Apr 2016

149 http://www.embraercommercialaviation.com/Pages/Ejets-190-E2.aspx#aFuel_Burn, viewed 17 May 2016

150 http://www.embraercommercialaviation.com/Pages/Ejets-175-E2.aspx#aFuel_Burn, viewed 17 May 2016

151 http://www.embraercommercialaviation.com/Pages/Ejets-195-E2.aspx#aFuel_Burn, viewed 17 May 2016

152 http://boeing.mediaroom.com/2014-10-31-Boeing-Monarch-Airlines-Finalize-Order-for-30-737-MAX-8s, viewed 26 Apr 2016

153 http://boeing.mediaroom.com/2014-12-01-Boeing-Ryanair-Finalize-Order-for-100-737-MAX-200s, viewed 26 Apr 2016

154 http://www.airbus.com/aircraftfamilies/passengeraircraft/a320family/spotlight-on-a320neo/, viewed 26 Apr 2016

155 http://www.airbus.com/presscentre/hot-topics/annual-press-conference-2016/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=104646, slide 18, viewed 26 Apr 2016

156 https://asfaarbyairbus.com/asfaar/february-2015/a321lr-extending-market-reach/, viewed 24 May 2016

157 http://www.airbus.com/presscentre/corporate-information/key-documents/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=104646, (page 20), viewed 23 May 2016

158 http://www.airbus.com/aircraftfamilies/passengeraircraft/a330family/spotlight-on-a330neo/, viewed 26 Apr 2016

159 http://boeing.mediaroom.com/2015-10-22-Boeing-Norwegian-Finalize-Order-for-19-787-9-Dreamliners, viewed 26 Apr 2016

160 http://boeing.mediaroom.com/2016-03-15-Boeing-787-10-Dreamliner-Begins-Major-Assembly, viewed 26 Apr 2016

161 http://www.airbus.com/aircraftfamilies/passengeraircraft/a350xwbfamily/, viewed 26 Apr 2016

162 http://aviationbenefits.org/media/100195/aviation-climate-solutions_web-114.pdf, viewed 19 July 2016

12. "*At 544 seats layout - 4-class, the A380 has: 40% lower fuel burn per seat than 747-400*"[163].

It will be noticed that we have not included the Boeing 747-8 Intercontinental in the above list. Although that aircraft entered service several years ago and is in regular commercial use by several airlines on many routes[164] globally, none of those routes currently serve the UK. In the specific context of UK aviation therefore, at the present time the materiality of the 747-8 Intercontinental for reducing CO_2 through the displacement of UK aviation activity from older aircraft types (such as the Boeing 747-400) is low. Furthermore, the Boeing order-book[165] for the 747-8 Intercontinental currently shows no orders from UK-based airlines and only a relatively small number of orders remaining to be fulfilled from other airlines. Of course, this situation may change in the future and we shall update as necessary our analysis in future issues of our CO_2 Road-Map to reflect the prevailing situation at the time of their preparation. Nonetheless, this 2016 version of our CO_2 Road-Map does not take account of the 747-8 for the reasons given immediately above. Note that the remarks made in this paragraph concern the passenger version of the 747-8 and not the freighter version.

D.2 Entry Into Service (EIS) Dates and Fleet Refresh Periods

EIS dates of the "imminent" aircraft types listed above are easily obtained from manufacturers' websites and/or a variety of other sources, and are listed in **Table 4**.

As a default value, we assume that the time taken to displace older aircraft in a particular category from the fleet, once a new aircraft of that category becomes available, is in the region of 25 years. However, in certain aircraft categories we have modelled the fleet turnover as taking a shorter or longer period, for reasons discussed below.

- **Turboprops** and **regional jets**– we use the default fleet refresh period of 25 years.

- **Airbus A320 family** – in our 2012 Road-map we assumed a substantial transition period during which production of A320-family ceo and neo variants would proceed side by side, and as a result our assumed fleet transition period in this category was 30 years from EIS of the neo, rather than the default of 25 years. However, the remaining order book[166] for conventional engine option (ceo) variants now suggests a much shorter transition period than we had previously assumed. So in our 2016 Road-Map we use the default fleet refresh period of 25 years from EIS of the neo variant.

- **Boeing 737 family** – in our model we assume that fleet refresh is complete within 25 years of EIS of the "imminent" aircraft (737 MAX, 2017). This is shorter than we assumed in our 2012 Road-Map, for similar reasons to those outlined immediately above[167]. However, we also take account of substantial improvements in the efficiency of the in-service 737 fleet during the period 2010-2017, arising from replacement of 737 Classics with 737 Next Generation aircraft as is evident from **Figure 15**. As a result we model the fleet turnover as spanning a 32-year period from 2010.

[163] http://www.airbus.com/presscentre/corporate-information/key-documents/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=104637, viewed 19 July 2016

[164] See for example http://www.gcmap.com/featured/20151129

[165] http://www.boeing.com/commercial/?cm_re=March_2015-_-Roadblock-_-Orders+%26+Deliveries/#/orders-deliveries, viewed 18 July 2016

[166] http://www.airbus.com/company/market/orders-deliveries/?eID=maglisting_push&tx_maglisting_pi1%5BdocID%5D=110412, viewed 12th Sept 2016

[167] http://www.boeing.com/commercial/?cm_re=March_2015-_-Roadblock-_-Orders+%26+Deliveries/#/orders-deliveries, viewed 12th Sept 2016

- **Boeing 757** – since the build years[168] of current in-service 757 aircraft worldwide span 1983-2004, and since the earliest corresponding “imminent” aircraft (A321LR) will not become available until 2019, even the youngest members of the 757 fleet will be well into middle age by the time the replacement aircraft start to enter service. As a result, we assume a short fleet refresh period of 10 years, starting in 2019.

- **Small/Medium Twin Aisle (SMTA)** – we use the default of 25 years, starting at EIS of the first “imminent” aircraft types (Boeing 787, 2011). This choice means that we do not capture the swift reduction in Boeing 767 activity that has become apparent in the short time since the Boeing 787 entered service (see **section 7.3.1**). As a result our Road-Map is likely to under-predict reductions in CO_2 intensity (i.e. to over-predict emissions) in the early years after 2010.

- **Large Twin Aisle (LTA)** – as with the 737, we assume fleet refresh is completed within 25 years of EIS of the first available “imminent” aircraft type (A350 XWB, 2015), but we also take account of fleet efficiency improvements taking place from 2010, as 777-200 and -200ER aircraft are replaced with 777-300ER aircraft. As a result our model assumes a 30-year transition from the baseline fleet to an all-“imminent” fleet, starting in 2010 and lasting until 2040.

- **Boeing 747-400** – the number of ASKs delivered on UK-departing flights by 747 aircraft are shown in **Figure 14**, which reveals a consistent downward trend over the past decade or more which, if linearly extrapolated, reaches zero around 2021 or 2022. We could therefore assume a fleet refresh period of 12 years (from 2010), motivated also by the age of the fleet[169] and by drivers for replacement that include not only fuel costs but also the noise footprint of that aircraft relative to more modern and/or smaller alternatives. However, almost all of the ASKs currently being delivered by 747-400 aircraft are attributable to only two operators, of which one, British Airways, has recently announced a life-extension[170] to its 747 fleet. Hence in this category we shall assume a fleet refresh period of 15 years, i.e. that replacement of 747-400 aircraft is largely complete by 2025.

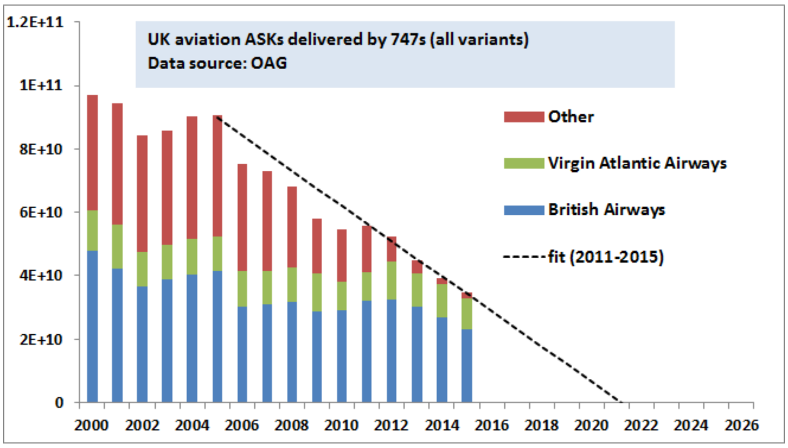

Figure 14 – ASKs delivered by 747 aircraft. Scope: UK aviation. Data source: OAG

A summary of the above discussion is included in **Table 5** in the main text.

Our fleet transition model assumes a linear transition between generations of aircraft types, as described in section 5.6 of our 2012 CO_2 Road-Map.

168 Source: Ascend, accessed 14th Sept 2016, including all 757 variants excluding pure freighters

169 Data from Ascend (accessed 29th Sept 2016) show that the build years of 747-400 aircraft currently in service with British Airways and Virgin Atlantic span the period 1990-2001, meaning that even the youngest of those aircraft will be over 20 years old by 2022 .

170 For details see page 107 of 118 of http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9MzU3NDQzfENoaWxkSUQ9LTF8VHlwZT0z&t=1&cb=636138423067231682

APPENDIX E – Fleet Fuel-Efficiency Impact of "Imminent" Aircraft

This appendix relates to and should be read in conjunction with **section 4.5** of the main text.

The following discussions draw upon the data presented in **Table 4** and **Figure 3**

Turboprops

We are unaware of any "imminent" aircraft types in this category. As a result, we envisage no improvement to the efficiency with which ASKs are delivered by turboprop aircraft until such time as "future" aircraft types become available in this category. Since turboprops are responsible for only a small fraction of UK aviation, the impact on the outcome will be very small.

Regional Jets

In this category we apply a 20% fuel-efficiency saving, based upon the expected fuel-efficiency improvements offered by the Bombardier C Series and Embraer E2 aircraft.

737 Family

The distribution of UK aviation ASKs between various members of the 737 family is shown in **Figure 15**. A clear trend is evident of migration towards the more fuel-efficient 737-800 from other family members. In particular, the 2010 fleet comprises a substantial component of Boeing 737 Classics[171] which preceded the 737 NG[172], which in turn is the predecessor of the 737 MAX. The 737 NG is 9-14% more fuel-efficient per seat than 737 Classics[173]. The 9% comparison relates to early examples of the 737 NG, while the 14% relates to more recent examples of the NG. We know from **APPENDIX D** that the 737 MAX is 20% more fuel efficient than early examples of the 737 NG. Hence the fuel efficiency improvement between 737 Classics and the 737 MAX is 27%[174].

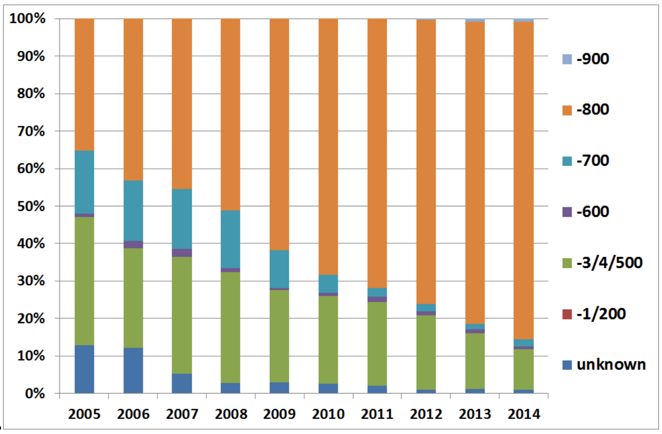

Figure 15 – distribution of ASKs between different members of the Boeing 737 family. Scope: UK aviation (flights which depart from UK airports). Source: SA analysis of OAG data.

171 737 Classics = 737-300, 737-400 and 737-500

172 737 NG (Next Generation) = 737-600, 737-700, 737-800 and 737-900

173 http://www.boeing.com/commercial/737ng/#/design-highlights/environmentally-progressive/cleaner-for-the-community/more-efficient-operations, viewed 18th May 2016

174 9% combined with a further 20% means that fuel use per seat is multiplied by 0.91 and 0.8 respectively, so the post-improvement fuel use per seat is 0.91 * 0.8 = 0.728 i.e. a reduction of 27%

Table 14 shows the year-2010 distribution of ASKs between different generations of the 737 family. Where the available data do not allow us to identify which member of an aircraft family is responsible for flights, we make the most conservative assumption concerning the fuel-efficiency improvement opportunity associated with its replacement. Specifically, this means that a generic or "unknown" 737 is assumed to be a recent example of a 737 NG, in which case the fuel efficiency opportunity associated with its replacement by a 737 MAX is assumed to be 14%. Although this could be a substantial underestimate (14% vs up to 27%), the low materiality of "unknown" 737s within the total of year-2010 737 ASKs means that the error it introduces is small.

Type	Unknown	Classics	NG
% of 737-family 2010 ASKs	2.5	23.4	74.1

Table 14 – share of year-2010 ASKs within the B737 aircraft family. Scope and source – as **Figure 15**

In 2010, the vast majority of ASKs delivered by 737 NGs were attributable to 737-800 aircraft, of which most were operated by Ryanair and Thomson Airways, as shown in **Table 15**.

Operator	Ryanair	Thomson Airways	Other
Share of year-2010 UK aviation ASKs delivered by Boeing 737-800s	81.7%	11.5%	6.8%

Table 15 – share by operator of year 2010 ASKs delivered by 737-800 aircraft. Scope: UK aviation. Source: SA analysis of data from OAG

Given the dominance of the 737-800 within the overall 737 picture in our baseline year, it is worth delving a little more deeply into the age distribution and configuration of those aircraft, and also considering what they may be replaced with.

We note that Ryanair has a substantial order[175] for 737 MAX 200 aircraft which offer improved fuel efficiency per seat relative to the standard 737 MAX. Comparing the size of that order with the size of Ryanair's fleet[176], and observing the high materiality of Ryanair 737-800s within overall year 2010 UK aviation 737-800 usage, we make the simple but conservative assumption that around one third of 737-800 aircraft used within UK aviation will be replaced by 737 MAX 200 aircraft, with the other two-thirds being replaced by 737 MAX aircraft.

We now consider the characteristics of the 737-800 aircraft being replaced. For very recently manufactured 737 NGs, we know from **APPENDIX D** that the fuel-improvement opportunity associated with their replacement is 14% (737 MAX) or 20% (737 MAX 200). For the very early 737 NGs we know, again from **APPENDIX D**, that the fuel-efficiency improvement associated with their replacement by 737 MAX aircraft is 20%. It follows that the replacement of early 737 NGs by 737 MAX 200 aircraft gives a fuel-efficiency improvement opportunity of some 26%. 737 NGs manufactured between those two extremes present opportunities lying between the two.

Figure 16 shows the age distribution of the year-end-2010 737-800 fleets of Ryanair and Thomson Airways. We assume that half of that fleet (build year 2008 onwards) can be described as "recent" 737 NGs offering 14-20% fuel-efficiency improvement opportunity, and that the other half (build-year 2007 or earlier) can be described as "early" 737 NGs.

175 http://boeing.mediaroom.com/2014-09-08-Boeing-Launches-737-MAX-200-with-Ryanair, viewed 13th Sept 2016

176 Source: Ascend

However, by 2010, the overwhelming majority of 737-800 aircraft in use by Ryanair and Thomson Airways had winglets fitted[177], yielding a fuel-efficiency improvement (relative to no winglets) of some 1.5% to 4% depending on mission length[178]. We assume a central value of 3%, implying that the fuel-efficiency opportunity in upgrading from older 737 NGs (with winglets) to the 737 MAX or the 737 MAX 200 is respectively 17 and 23% rather than the 20 and 26% which would be possible if those older aircraft lacked winglets. "Recent" 737 NGs have winglets fitted as standard and the 14-20% improvement opportunity applying to those aircraft takes account of that.

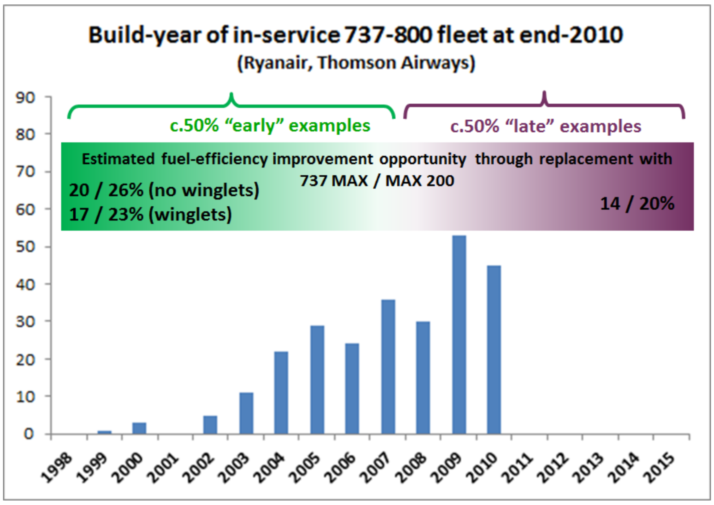

Figure 16 – range of build years of 737-800 aircraft at year-end 2010, and the estimated fuel-efficiency improvement opportunity associated with replacement of those aircraft by 737 MAX or by 737 MAX 200. Scope: UK aviation. Source: SA assumptions based on data from Ascend and Boeing data as discussed in the main text

Table 16 shows how the above discussion is translated into a single fleet-wide fuel-efficiency opportunity related to replacing the baseline (year 2010) 737 fleet with 737 MAX and 737 MAX 200 aircraft, according to the assumptions set out above.

<table>
<tr><th colspan="2">B737 Type</th><th colspan="3">Materiality</th><th colspan="2">Efficiency improvement</th><th rowspan="2">Fleet-wide saving (fraction of pre-improvement total)</th><th></th></tr>
<tr><th>Old</th><th>New</th><th colspan="2">share of year-2010 ASKs[179]</th><th>share of year-2010 fuel-burn[180]</th><th>%</th><th>factor</th><th></th></tr>
<tr><td>**Unknown**</td><td>MAX</td><td colspan="2">0.025</td><td>0.0237</td><td>14</td><td>0.86</td><td>0.020</td><td></td></tr>
<tr><td>**Classics**</td><td>MAX</td><td colspan="2">0.234</td><td>0.2613</td><td>27</td><td>0.73</td><td>0.191</td><td></td></tr>
<tr><td rowspan="2">**NG (new)**</td><td>MAX</td><td rowspan="4">0.741</td><td>0.247</td><td>0.2341</td><td>14</td><td>0.86</td><td>0.201</td><td></td></tr>
<tr><td>MAX 200</td><td>0.1235</td><td>0.1171</td><td>20</td><td>0.8</td><td>0.094</td><td></td></tr>
<tr><td rowspan="2">**NG (old) (winglets)**</td><td>MAX</td><td>0.247</td><td>0.2426</td><td>17</td><td>0.83</td><td>0.201</td><td></td></tr>
<tr><td>MAX 200</td><td>0.1235</td><td>0.1213</td><td>23</td><td>0.77</td><td>0.093</td><td></td></tr>
<tr><td colspan="2" rowspan="2">TOTAL</td><td colspan="2" rowspan="2">1</td><td rowspan="2">1</td><td colspan="2" rowspan="2"></td><td>0.801</td><td>Factor</td></tr>
<tr><td>**19.9**</td><td>**%**</td></tr>
</table>

Table 16 - calculation of total B737 fleet-wide saving achievable from replacement of 737 aircraft with 737 MAX aircraft. Scope – UK aviation. Baseline – year 2010.

177 Source: Ascend

178 Source: http://www.aviationpartnersboeing.com/products_737_800.php, viewed 12th Sept 2016

179 Source: SA analysis of data from OAG

180 Derived from previous column using relative fuel efficiency of the various "old" types

A320 family

The distribution, between various members of the A320 family, of UK aviation ASKs is shown in **Figure 17**, with the corresponding values for year 2010 given in **Table 17**.

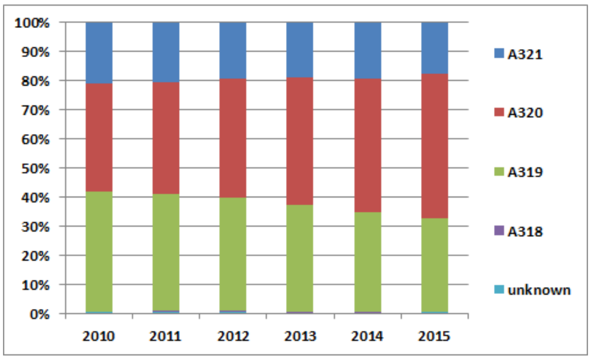

Figure 17 – distribution of ASKs between different members of the Airbus A320 family. Scope: UK aviation. Source: SA analysis of OAG data.

Type	Unknown	A319	A320	A321
% of A320-family 2010 ASKs	0.7	41.3	37.1	20.8

Table 17 – share of year-2010 ASKs within the A320 aircraft family. Scope and source – as **Figure 17**.

Using data from **Table 4** in conjunction with the fuel-efficiency improvements given in **APPENDIX D**, we can perform a weighted sum as shown in **Table 18** to show that the fuel-efficiency improvement associated with the replacement of A320ceo family members with corresponding A320neo family members is **20.7%**. Where the available data do not allow us to identify which A320 family member is responsible for flights performed in the baseline year of 2010, we make the most conservative assumption concerning the fuel-efficiency improvement opportunity associated with its replacement. Specifically, a generic A320 (labelled as "unknown" in **Table 17** and **Table 18**) is assumed to yield only a 19% improvement opportunity when replaced with its corresponding re-engined aircraft. This is potentially a small under-estimate (19% vs up to 23%), and applies only to a very small percentage of year-2010 A320-family ASKs, hence the error it introduces is very small.

A320 family member	Materiality (share of year-2010 ASKs)[181]	Efficiency improvement (ceo to neo)		Fleet-wide saving (fraction of pre-improvement total)	
		%[182]	factor		
Unknown	0.007	19	0.81	0.006	
A319	0.413	19	0.81	0.335	
A320	0.371	21	0.79	0.293	
A321	0.208	23	0.77	0.16	
TOTAL	1			0.793	Factor
				20.7	**%**

Table 18 – calculation of total A320 family fleet-wide saving achievable from replacement of A320ceo family aircraft with corresponding members of the A320neo family. Scope – UK aviation. Baseline – year 2010.

[181] Source: **Table 17**

[182] Source: **APPENDIX D**

757

Although some migration away from the 757 is evident between 2010 and 2014, we envisage that in the medium term much of the activity performed in 2010 by the 757 will migrate to A321LR aircraft (offering a 30% fuel efficiency improvement) and an as-yet undefined equivalent from Boeing.

Small-Medium Twin-Aisle

In this size category, we have Airbus A300/A310, A330, A340-200/300 and Boeing 767 aircraft being replaced by Airbus A330neo and Boeing 787 aircraft. We are not able to predict, nor would Sustainable Aviation adopt a position regarding, the likely market share between the Airbus A330neo and the Boeing 787. So here we assume an equal market split between the two families.

From **APPENDIX D**, the A330neo offers a 14% improvement relative to the A330ceo, while variants of the 787 family offer a 20% improvement (787-8 and 787-9) or a 25% improvement (787-10) relative to the aircraft they will replace.

As of June 2016, 787-10 aircraft accounted for around 13% of the global 787 order book[183]. Looking specifically at UK-based airlines (June 2016), 16% of the 787s ordered by British Airways, TUI travel and Virgin Atlantic Airways are the -10 variant. As the -10 is the most recently-launched variant of the family, it is reasonable to assume that the proportion of global 787 orders it accounts for may rise a little over time.

Based on the current situation, we assume that around 15% of 787 activity will be due to the -10 variant, offering a 25% fuel-efficiency improvement over aircraft it will replace, while the remaining 85% of 787 activity will offer a 20% fuel-efficiency improvement over the displaced aircraft types.

In this category therefore, we are assuming that 50% of the fleet achieves a 14% efficiency improvement over replaced aircraft, 42.5% of the fleet achieves a 20% improvement, and 7.5% achieves a 25% improvement. The weighted average is therefore **17.3%**.

Note that this approach is slightly conservative because it does not take account of the fact that displaced aircraft include older aircraft types such as the A300/A310, as well as more recent types such as the A330 and Boeing 767.

Large Twin Aisle

In this category, we again assume a 50:50 market split between the two competing aircraft families, in this case the Airbus A350 XWB family and the Boeing 777X family. From **APPENDIX D**, the Airbus A350 XWB offers "*25 per cent lower fuel consumption compared to its current aluminium long-range competitors*" while the Boeing 777X "*reduces fuel use and CO_2 emissions by 20% compared to previous generation aircraft*". However, we can use additional information to take more complete account of the baseline fleet composition in 2010

- The Boeing 777X is 20% more fuel efficient than the 777-300ER[184]
- The 777-300ER is 10% more fuel-efficient on a per-seat basis than the 777-200ER[185], hence the 777X is some 28% more fuel efficient than the 777-200ER[186].

[183] http://www.boeing.com/commercial/?cm_re=March_2015-_-Roadblock-_-Orders+%26+Deliveries/#/orders-deliveries, viewed 21 Jun 2016

[184] source: Boeing

[185] http://www.boeing.com/commercial/777/#/design-highlights/unmatched-capabilities/profitability/fuel-efficiency/, viewed 12th Sept 2016

[186] 0.9 * 0.8 = 0.72 i.e. 28% reduction in fuel burn per passenger kilometre

- The 777-200LR is 1% more fuel-efficient on a per-seat basis than the 777-200ER[187], while the 777-200 has a very similar fuel-efficiency to the 777-200ER.
- In year 2010, at least 59% of UK 777 ASKs were attributable to the -200, -200ER and -200LR variants[188].

Replacement of 777 aircraft from the baseline (year 2010) fleet by 777X aircraft can thus be shown to offer an approximately 25% fuel-efficiency opportunity.

We have no precise information regarding the 25% fuel-efficiency improvement offered by the A350 XWB in terms of what the specific comparison aircraft is, so we take the 25% as is.

Overall, assuming a 50:50 market split between the two "imminent" aircraft families in this category, we assume in our Road-Map model a 25% fuel-efficiency opportunity.

B747-400

In our 2012 CO_2 Road-Map, we made the assumption that 747-400 activity in year 2010 would, over time, migrate to newer aircraft in the same size category, specifically a mixture of the Airbus A380 and the Boeing 747-8. However, as explained in **APPENDIX D**, current evidence suggests that the 747-8 is unlikely, in the short-to-medium term, to take on a material role in UK passenger aviation, despite its substantial use in other parts of the world. If we were to follow the same approach taken in our 2012 Road-Map therefore, we would in our 2016 Road-Map simply assume that 747-400 activity would be replaced exclusively by A380 activity.

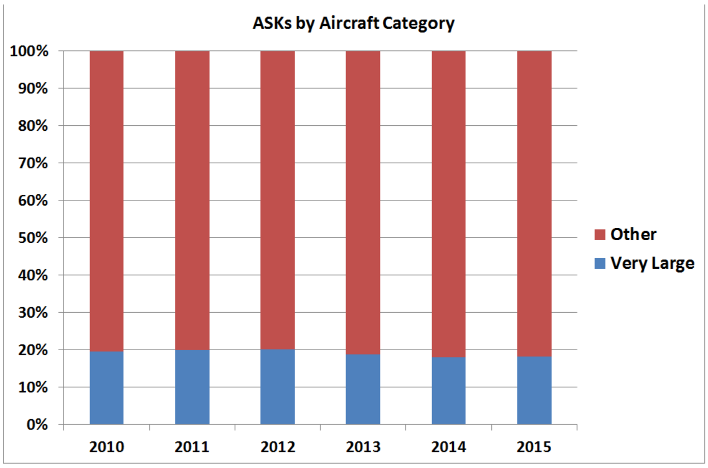

Figure 18 – Changing materiality of very large aircraft (Boeing 747, Airbus A380) within UK aviation, as measured by available seat kilometres. Data source: OAG.

However, **Figure 18** shows a slight decline since 2010 in the percentage of UK aviation ASKs delivered by very large aircraft (Boeing 747-400 and Airbus A380 combined). Based on this, and unlike our 2012 Road-Map, we do not assume that all 2010 747-400 activity will be replaced by large 4-engined aircraft. Instead we allow in our assumptions for some migration to aircraft in other aircraft categories. Specifically, we assume that over time 747-400 activity from our baseline year of 2010 will be replaced with ASKs delivered on a variety of aircraft including the A380, B777, B777X, A350 XWB, and perhaps others.

We cannot predict what the mix between those aircraft types will be, nor does SA have a position concerning the relative fuel efficiency of large twin-engined aircraft versus very large 4-engined

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187 http://www.boeing.com/commercial/777/#/design-highlights/unmatched-capabilities/profitability/fuel-efficiency/, viewed 12th Sept 2016

188 Source: OAG, plus data from Heathrow, Gatwick and Manchester airports

aircraft. As a result, we conservatively assume a fuel-efficiency improvement of 25% arising from migration of B747-400 activity to a mix of primarily “imminent” aircraft types.

A380

A380 aircraft within the baseline (year 2010) fleet represent the first examples of “imminent” aircraft types entering the fleet. As a result, these aircraft will not be displaced during the “baseline” to “imminent” fleet transition and so no fuel-efficiency improvement is assumed relative to these aircraft.

Other

We do not take account of any fuel-efficiency improvements in this category associated with the transition from “baseline” to “imminent” aircraft types. This is a very conservative assumption but, due to the very low materiality of this category, the error it introduces is tiny.

Summary

Table 5 in the main text summarises the above discussion.

APPENDIX F – Deriving "Future" Aircraft Assumptions

In this appendix, which relates to **section 4.7** of the main text, we follow the approach set out in **section 4.6** in order to derive assumptions for the fuel-efficiency and entry into service dates of "future" aircraft in each of the four aircraft size categories used in our Road-Map model. These assumptions are then sense-checked and placed into context in **APPENDIX G.**

Step 1 – Definition of Prototypical Reference Aircraft

Table 19 shows the characteristics of our "reference" aircraft for each of the four aircraft categories. Each of the four "reference" aircraft is intended to be an average of the corresponding types entering service in the years immediately prior to 2000.

Aircraft Category	Candidates (new aircraft in 2000) aircraft type (EIS-date)	"Reference" Aircraft	
		EIS	Fuel-Burn per ASK[189]
NB	A320 (1988), 737-800[190] (1998)	1993	100%
SMTA	767-200 (1984), 767-300 (1988), 767-400 (2000) A330-200 (1999), A330-300 (1995)	1993	100%
LTA	777-200 (1995)	1995	100%
VL	747-400 (1989)	1989	100%

Table 19 – "reference" aircraft characteristics derived from typical new aircraft in 2000

Step 2 – Definition of Representative "Imminent" Aircraft

- **NB** - From **APPENDIX D**, the Airbus A320neo offers 21% fuel-efficiency improvement relative to the A320ceo, the Boeing 737 MAX offers 14% relative to recent 737 NGs and 20% relative to early 737 NGs (without retrofitted winglets), while the 737 MAX 200 offers 20% relative to the latest 737 NGs. Hence the 737 MAX 200 offers some 26% improvement relative to early 737 NGs which, along with the A320, are relevant for our "reference" aircraft. Assuming that the MAX 200 accounts for around one third of the "imminent" 737 fleet[191], then the average fuel-burn saving from early 737 NGs to a mixture of 737 MAX and MAX 200 aircraft is around 22%[192]. Combining this with the A320's 21% saving (and assuming an equal weighting of the two aircraft families) gives an average fuel saving of around 21.5%. Averaging the EIS dates of the 3 aircraft types gives an EIS for our representative "imminent" aircraft of 2017.

- **SMTA** – for fuel-efficiency improvement we can simply use the figure of 17.3% from **APPENDIX E** and **Table 5**, since that figure was derived without specific reference to the 2010 fleet composition. For EIS of our representative "imminent" aircraft we average the A330neo (2017) with the 787 (2011) and a small component[193] of the 787-10 (2018) to give 2015.

[189] 100%, by definition of the "reference" aircraft

[190] Without winglets

[191] consistent with our assumption in **APPENDIX E**

[192] Note that this is a little larger than the 20.4% we derived relative to the baseline (year 2010) fleet in **APPENDIX E**, This is because our "reference" aircraft is an early 737 NG without winglets, i.e. the "typical new aircraft of year 2000" in this category, while the baseline fleet comprises a large percentage of recent-model 737 NGs as well as early 737 NGs that have been retrofitted with winglets (both types being more fuel efficient than the "reference" aircraft), along with a small percentage of 737 Classics (less efficient than the "reference" aircraft).

[193] As discussed in **APPENDIX E**, the 787-10 currently accounts for only a small proportion of the total 787 order-book. Hence its weighting in the averaging performed here is small.

- **LTA** – From **APPENDIX E** and **Table 5**, we have a 25% improvement from our "reference" aircraft to the representative "imminent" aircraft. For EIS we average those of the A350 XWB (2015) and the B777X (2019) to give 2017.

- **VL** – from **APPENDIX E** and **Table 5** our representative "imminent" aircraft offers a 25% improvement over the "reference" aircraft in this category. A suitable EIS date takes into account those of the A380, A350 XWB and B777X – we choose 2013 as an average

Table 20 summarises the above.

Aircraft Category	Candidates ("imminent" aircraft) aircraft type (EIS-date)	Representative "imminent" aircraft	
		EIS	Fuel-Burn per ASK[194]
NB	A320neo (2015), 737 MAX (2017), 737 MAX 200(2019)	2017	78.5%
SMTA	A330neo (2017), 787-8 (2011), 787-10 (2018)	2015	82.7%
LTA	A350 XWB (2015), 777X (2019)	2017	75%
VL	A380 (2007), A350 XWB (2015), B777X (2019)	2013	75%

Table 20 – representative "imminent" aircraft characteristics

Step 3 – Bounding the Space of Likely options

Regarding potential EIS dates, we have made the following assumptions

- **NB** - the substantial market success of both the Airbus A320neo family and the Boeing 737 MAX family means that we now consider it unlikely that a successor aircraft will appear before 2030. We consider it unlikely that a successor aircraft would remain unavailable beyond 2040.
- **SMTA** - we judge that the 2030s is the most likely period within which a new aircraft will appear, given the EIS dates of the all-new Boeing 787 (2011) and the re-engined A330neo (2017).
- **LTA** – given EIS dates spanning 2015-2019 for "imminent" aircraft in this category, it again seems unlikely that an all-new aircraft will appear before 2030. However, the continued absence beyond 2040 of a successor aircraft in this category is not consistent with past experience of inter-generational periods.
- **VL** - in this category we assume that a new aircraft will emerge in the period 2035 to 2045.

Regarding worst-case fuel-efficiency improvements, in most aircraft categories we assume a default threshold of acceptability of 20%, based on observations of the extent to which successive generations of aircraft typically improve upon their predecessors. However, in the NB category we consider that a 15% improvement might be viewed as sufficient to allow the launching of a new aircraft model.

We can then simply follow the method set out for step 3b in **section 4.6.3 above** to establish our best-case fuel-efficiency assumptions corresponding to the "earlier" and "later" EIS dates.

Table 21 summarises the outcome of this step.

194 Relative to that of the corresponding "reference" aircraft which is 100% by definition

Category	EIS dates		Fuel-Efficiency Improvement % vs representative "imminent" aircraft			Fuel-Burn per ASK vs "reference" aircraft[195]		
	Earlier	Later	Worst	Best-Earlier	Best-Later	Worst	Best-Earlier	Best-Later
NB	2030	2040	15	40.7%	51.8%	66.7%	46.6%	37.9%
SMTA	2030	2040	20	43.7%	54.2%	66.2%	46.6%	37.9%
LTA	2030	2040	20	36.8%	49.0%	60%	47.4%	38.3%
VL	2035	2045	20	45.4%	55.0%	60%	41.0%	33.7%

Table 21 – extreme-case assumptions for "future" aircraft, collectively forming the corners of regions providing context for the central case assumptions used within the Road-Map.

Step 4 – EIS Dates and Fleet Transition Periods

We choose EIS dates, shown in **Table 22**, corresponding to the half-way point between the "earlier" and "later" scenarios identified immediately above.

Fleet transition periods are taken as being 25 years in the NB category and 20 years in the remaining categories, for reasons explained in Appendix A of our 2012 Road-Map [SA, 2012].

Step 5 – Fuel-Efficiency Improvement Assumptions

In this step we define our "central" case assumptions which will be used as input to the Road-Map model in determining the impact upon UK aviation CO_2 of the "future" generation of aircraft.

As with our 2012 Road-Map, we assume an underlying rate of improvement in fuel-efficiency between aircraft generations of 1.3% each year. We supplement this with a "step-change" improvement element intended to capture the deployment of a combination of one or more significant new technologies and/or design configurations such as those described in **section 4.10 above**. The size of the supplemental step-change is assumed to be 10% (NB) or 15% (SMTA, LTA and VL).

These assumptions lead us to define our central case for future aircraft types as shown in **Table 22**.

Category	EIS	Central case: Fuel-efficiency % improvement vs…		Central case: Fuel-burn per ASK vs "reference" aircraft
		…representative "imminent" aircraft	…"reference" aircraft	
NB	2035	28.9	44.2	55.8%
SMTA	2035	34.6	45.9	54.1%
LTA	2035	32.8	49.6	50.4%
VL	2040	40.3	55.2	44.8%

Table 22 – characteristics of "future" aircraft (central case) used in the Road-Map model. This table is repeated as Table 8 in section 4.7 of the main text

[195] `Note that this equals 100% minus (fuel efficiency improvement relative to "reference" aircraft). Its value determines the vertical height of the corners of the bounding boxes in **Figure 19** to **Figure 22**.

APPENDIX G – "Future" Aircraft Assumptions: Sense-Check

This appendix relates to **section 4.8** of the main text.

In **Figure 19** through to **Figure 22** we illustrate our central case assumptions in the context of the "worst" and "best" cases defined above, and where possible, with reference to the NASA technology targets (N+2, N+3) for civil aircraft (described in **section 4.2.5**). In the charts we use the abbreviation G0 to refer to the "reference" aircraft, G1 to mean the representative "imminent" aircraft, and G2 to refer to the various options for the "future" aircraft.

In the case of the NASA technology targets, which refer to a target of TRL 4-6, we have assumed a lag of 8 years between achieving that TRL and the entry into service of an aircraft achieving a similar level of fuel-efficiency.

In each of the charts, we show an extrapolation of the rate of improvement in fuel-efficiency observed between the "reference" aircraft and the representative "imminent" aircraft (blue crosses), as well as a curve representing a constant rate of improvement of 1.3% per annum from the representative "imminent" aircraft (red dots). These set the context for the worst case and central case assumptions.

- **Figure 19** shows for **narrow-body (NB)** aircraft the central case we use in our Road-Map, along with the bounding box of best/worst cases described above. It is clear that the level of ambition of our central case is substantially less optimistic than either an aircraft based on the NASA N+3 goal, or the "best-earlier" and "best-later" cases derived with reference to the ACARE FlightPath2050 goal. Note also that in the NB category, the representative "imminent" aircraft[196] is a re-engined variant of the "reference" aircraft[197], and so a corresponding "future" aircraft would be able to benefit not only from a further generation of engine technology but also from two generations of airframe and aircraft systems technologies and/or design configurations. For this reason, it is to be expected that our central case is substantially more ambitious than a simple extrapolation of the rate of progress observed from "reference" to representative "imminent" aircraft.

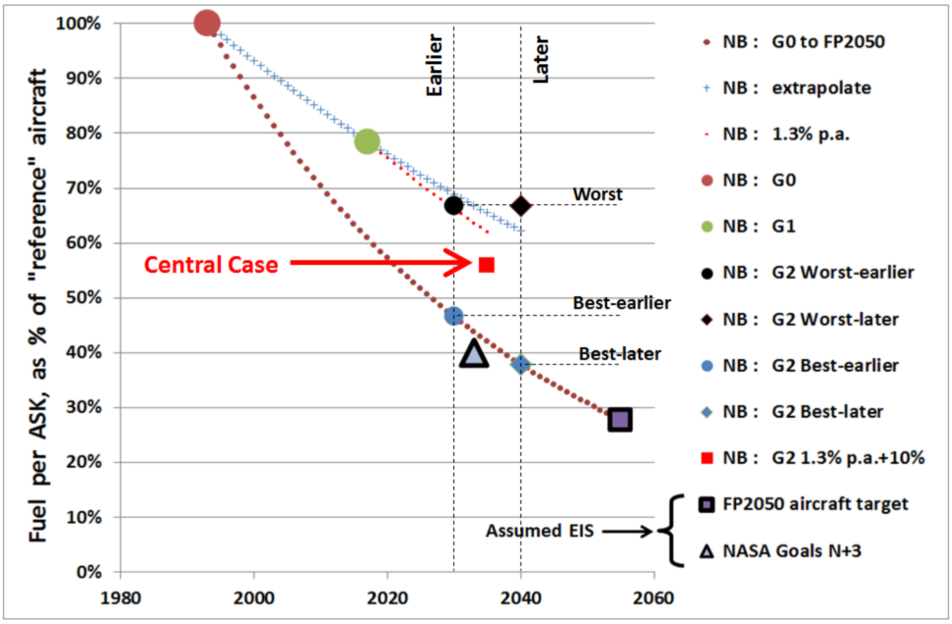

Figure 19 – narrow-body (NB) aircraft central-case assumptions regarding EIS date and fuel-efficiency, shown in the context of 1) previous generations of aircraft in the same size category and 2) best/worst case possibilities.

196 A representation of the average characteristics of the A320neo / 737 MAX

197 A representation of the average characteristics of the A320ceo / 737 NG

- **Figure 20** shows the corresponding chart for **small/medium twin-aisle (SMTA)** aircraft. As with our NB category, the central case is more ambitious than a simple extrapolation of recent observed rates of progress (which takes account of the fact that at least one of the contributing aircraft types was a re-engined aircraft), but very much less ambitious than the "best-earlier" or "best-later" cases derived with reference to the ACARE FlightPath2050 goal.

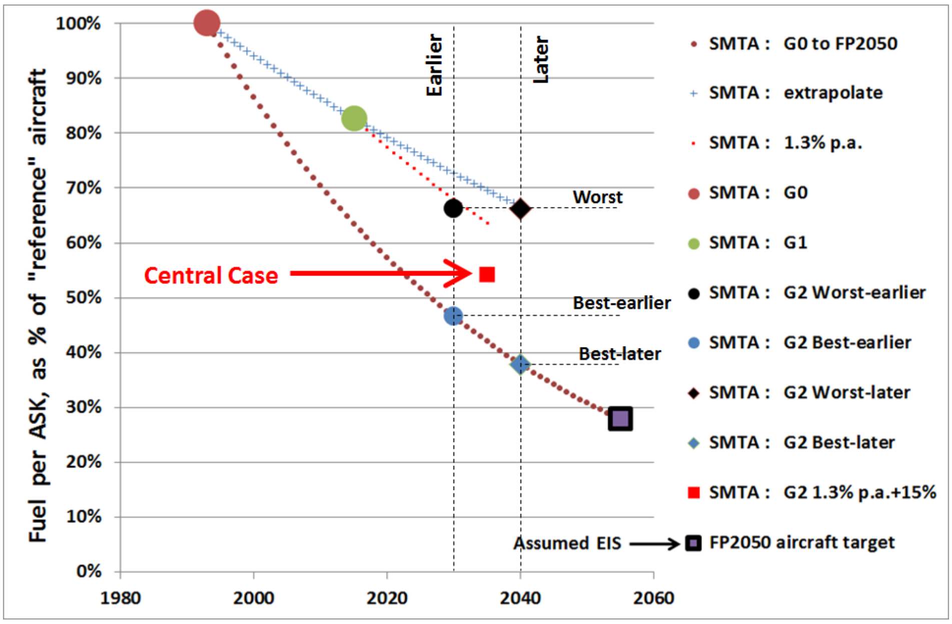

Figure 20 – small/medium twin aisle (SMTA) aircraft central-case assumptions regarding EIS date and fuel-efficiency, shown in the context of 1) previous generations of aircraft in the same size category and 2) best/worst case possibilities.

- **Figure 21** shows the corresponding chart for **large twin-aisle (LTA)** aircraft. Here the rate of improvement between "reference" and representative "imminent" aircraft is a little higher than in the NB and SMTA categories. Our central case lies approximately mid-way between on the one hand an extrapolation of that rate and on the other hand the best-case targets derived with reference to the FlightPath2050 goal.

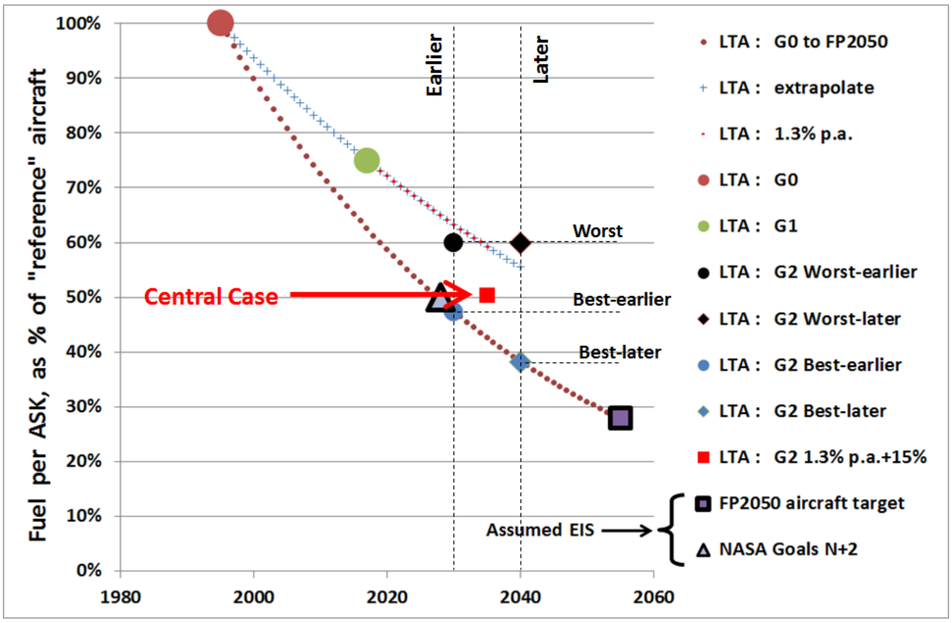

Figure 21 – large twin-aisle (LTA) aircraft central-case assumptions regarding EIS date and fuel-efficiency, shown in the context of 1) previous generations of aircraft in the same size category and 2) best/worst case possibilities.

- Finally, **Figure 22** shows the corresponding chart for **very-large (VL)** aircraft. In this category the time period between EIS of the representative "imminent" aircraft and assumed EIS of our central case "future" aircraft is substantially longer than for the other categories[198]. As a result the worst-earlier and worst-later cases[199] fall substantially above the extrapolation curve and the 1.3% per annum curve. Our central case lies approximately mid-way between the 1.3% p.a. curve and the "best-earlier" / "best-later" cases defined with regard to the Flightpath 2050 goal.

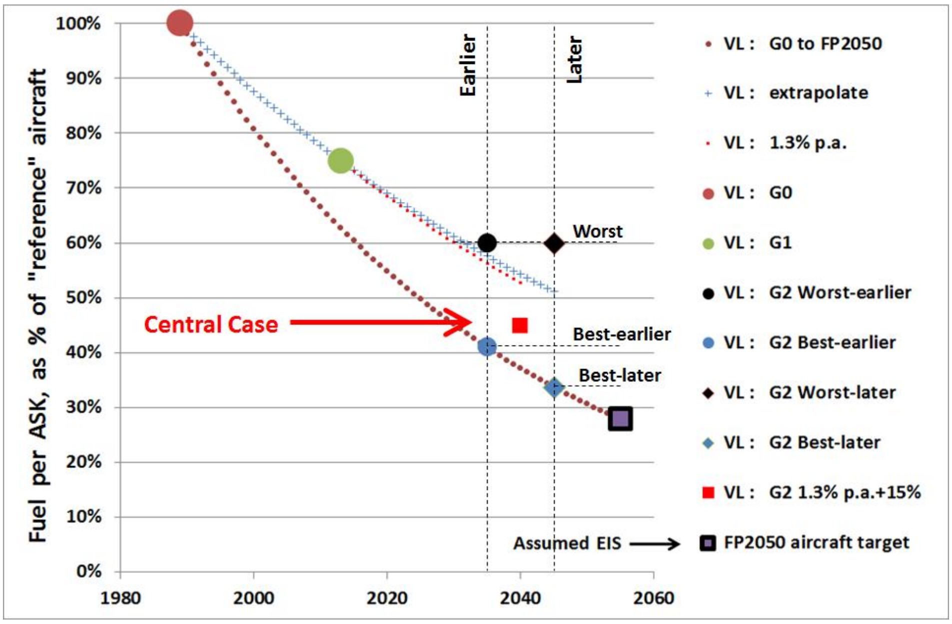

Figure 22 – very large (VL) aircraft central-case assumptions regarding EIS date and fuel-efficiency, shown in the context of 1) previous generations of aircraft in the same size category and 2) best/worst case possibilities.

From the above charts, we conclude that our central case assumptions for "future" aircraft fuel-efficiency are challenging compared with the rates of improvement observed between the "reference" aircraft and representative "imminent" aircraft. Nonetheless they fall far short of the rates of improvement that would be required to produce aircraft characterised by fuel-efficiencies consistent with the NASA N+2/N+3 goals or with steady progress towards the FlightPath2050 goal.

Furthermore, [ICCT, 2016] takes the view that "*the fuel consumption of new aircraft can be reduced by approximately 25% in 2024 and 40% in 2034 compared with today's aircraft by deploying emerging cost-effective technologies. The latter value….may be conservative because of the modeling assumptions used and the exclusion of non-conventional airframes like blended wing body or strut-based wings.*"

Our assumptions (set out in **Table 8**) for new aircraft fuel-efficiency in 2035-2040, relative to our "reference" aircraft, involve higher percentage savings than those suggested by [ICCT, 2016], but we do not exclude non-conventional airframe configurations.

In **section 4.10** we explore the upcoming technologies which may contribute towards enabling these assumed levels of fuel-efficiency to become reality.

198 27 years (VL) vs 18-20 years (NB, SMTA, LTA)

199 Which - as with the SMTA and LTA categories - are based on a 20% fuel-efficiency improvement of the "future" aircraft relative to the corresponding representative "imminent" aircraft

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