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Direct Carbon Dioxide Emissions from Civil Aircraft

“International air transport has helped bring our world closer together……Yet, these advances have not been without cost. Looking forward, we must ensure that international aviation is as energy-efficient as possible and minimizes harmful impacts on our climate and ecosystems” – UN Secretary-General Ban Ki-moon.

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# Abstract

Global airlines consume over 5 million barrels of oil per day, and the resulting carbon dioxide (CO2) emitted by aircraft engines is of concern. This article provides a contemporary review of the literature associated with the measures available to the civil aviation industry for mitigating CO2 emissions from aircraft. The measures are addressed under two categories – policy and legal-related measures, and technological and operational measures. Results of the review are used to develop several insights into the challenges faced.

The analysis shows that forecasts for strong growth in air-traffic will result in civil aviation becoming an increasingly significant contributor to anthropogenic CO2 emissions. Some mitigation-measures can be left to market-forces as the key-driver for implementation because they directly reduce airlines’ fuel consumption, and their impact on reducing fuel-costs will be welcomed by the industry. Other mitigation-measures cannot be left to market-forces. Speed of implementation and stringency of these measures will not be satisfactorily resolved unattended, and the current global regulatory-framework does not provide the necessary strength of stewardship. A global regulator with ‘*teeth*’ needs to be established, but investing such a body with the appropriate level of authority requires securing an international agreement which history would suggest is going to be very difficult.

If all mitigation-measures are successfully implemented, it is still likely that traffic growth-rates will continue to out-pace emissions reduction-rates. Therefore, to achieve an overall reduction in CO2 emissions, behaviour change will be necessary to reduce demand for air-travel. However, reducing demand will be strongly resisted by all stakeholders in the industry; and the ticket price-increases necessary to induce the required reduction in traffic growth-rates place a monetary-value on CO2 emissions of approximately 7 to 100 times greater than other common valuations. It is clear that, whilst aviation must remain one piece of the transport-jigsaw, environmentally a global regulator with ‘*teeth*’ is urgently required.

# Keywords

Aviation

Carbon

Emissions

Mitigation

ICAO

# Highlights

* Impacts of technological, operational and policy mitigation-measures are reviewed.
* Aviation growth-rates will continue to out-pace emissions reduction-rates.
* Specific measures reduce airline fuel-bills and can be driven by market-forces.
* A global regulator with ‘*teeth*’ is required but likely to be resisted.
* Constraining demand with price-rises gives up to 100-fold increases in CO2 values.

# 1. Introduction

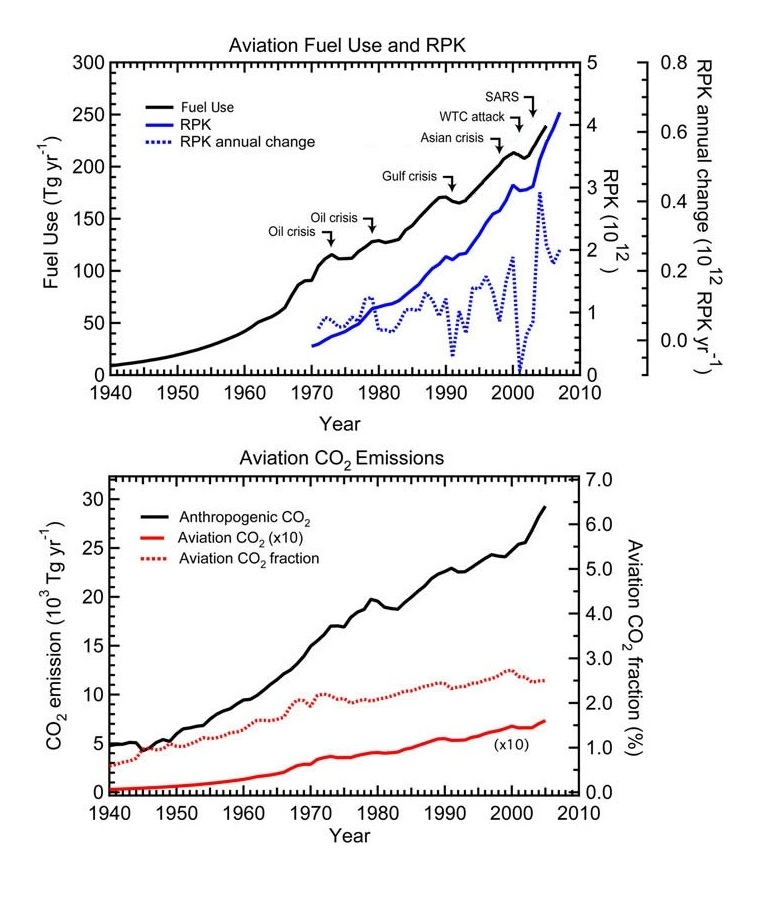
The beginning of significant aviation activity is commonly held to be 1940 ([Lee *et al.* 2010](#_ENREF_66)). In 1944, the Convention on International Civil Aviation (the Chicago Convention) was signed by 52 nations. In 1947, the International Civil Aviation Organisation (ICAO) was established to set necessary standards and regulations, becoming a specialised agency of the United Nations (UN) in the same year ([ICAO 2013c](#_ENREF_56); [ICAO 2013e](#_ENREF_58)). Growth of the civil aviation industry since 1940, in terms of fuel-consumed, is shown in Figure 1.

Growth in passenger traffic since 1970, in terms of Revenue-Passenger-Kilometres (RPKs), is also shown in Figure 1. More recently, the International Transport Forum (ITF) at the Organisation for Economic Co-operation and Development (OECD) report that from 1999 to 2008 scheduled passenger air-travel, measured in RPKs, grew at an average rate of 4.8% per annum; and that over the same period, air freight, measured in Freight-Tonne-Kilometres (FTKs), grew at an average rate of 4.1% per annum ([ITF 2012](#_ENREF_60)). The 2008 financial crisis, and subsequent global recession, reduced air traffic growth-rates ([ICAO 2010c](#_ENREF_48)). However, the ITF predict continued fast growth in the sector is likely over the next decades ([ITF 2012](#_ENREF_60)). Various key industry stakeholders agree with this prediction ([e.g. ICAO 2010c](#_ENREF_48); [IATA 2014](#_ENREF_44); [Airbus 2013](#_ENREF_3); [Boeing 2012](#_ENREF_13)), forecasting RPK and FTK growth-rates of approximately 4-5%; additionally, Boeing predicts the number of aircraft in service will double from 19,890 in 2011, to 39,780 in 2031.

The global airline industry now consumes in excess of 5 million barrels of oil per day ([IATA 2013](#_ENREF_43)). Emissions of CO2 from aircraft engines are proportional to fuel-used by a factor of approximately 3.15 ([Lee *et al.* 2009](#_ENREF_64)). CO2 is the most important anthropogenic greenhouse gas (GHG) ([IPCC 2007](#_ENREF_42)), and is the principal GHG emitted by powered aircraft ([Atma *et al.* 2013](#_ENREF_11)). Growth in aviation fuel-use and the associated CO2 emissions are shown in Figure 1. The Figure also shows that civil aviation’s contribution to total anthropogenic CO2 emissions is approximately 2-2.5%. Aviation could progressively become a dominant CO2 emissions source ([Bows and Anderson 2007](#_ENREF_14)), particularly if forecast sector-growth is realised.

It is recognised that non-CO2 emissions from aircraft also have climate impacts. These emissions include water vapour, oxides of nitrogen (NOx), soot and sulphates ([Wood *et al.* 2010](#_ENREF_84)). Aviation’s total instantaneous warming impact has been estimated at 2-4 times that of CO2 emissions alone ([Bows and Anderson 2007](#_ENREF_14)); although there is still some uncertainty surrounding such estimates ([Wood *et al.* 2010](#_ENREF_84)). However, the focus of the civil aviation industry’s effort to mitigate its climate-warming impact is on reducing CO2 emissions from aircraft; hence this is also the scope of this article.

The methodology used in this study is a detailed review of contemporary literature in order to enable critical evaluation of the various measures available to the global civil aviation industry for reducing CO2 emissions from aircraft. The results are presented in the next two sections – the first dealing with policy and legal-related measures, and the second with technological and operational measures. In the Discussion section, the results are used to develop several insights into the challenges faced by the civil aviation industry as it attempts to address global CO2 emissions.



**Figure 1.**

Top: Aviation fuel-use starting in 1940, the beginning of significant aviation activity. Growth in passenger traffic from 1970 is shown in terms of RPKs, alongside annual change in RPK (far right hand axis, with offset zero). The arrows indicate the timings of significant world events which potentially threatened global aviation: oil crises in the 1970s, the Gulf war crisis in the early 1990s, the Asian financial crisis in the late 1990s, the World Trade Center attack in 2001, and the global health crisis resulting from Severe Acute Respiratory Syndrome (SARS).

Bottom: Growth in aviation CO2 emission rate (scaled x10) over the same period as the growth of aviation fuel-use. Also shown is the rise in total anthropogenic CO2 emission rate, alongside aviation’s fraction of the total.

Adapted from: [Lee *et al.* (2009)](#_ENREF_64).

# 2. Policy and Legal-Related Measures

Civil aviation is a global industry, so its challenges are global in scale. The ICAO serves as the global forum for its 191 member-nations, bringing them together alongside key industry organisations and setting standards and recommended practices for the development of civil aviation. As such, the ICAO has a leadership-role in addressing aviation’s global challenges, which include addressing CO2 emissions ([ICAO 2011](#_ENREF_49); [ICAO 2013e](#_ENREF_58)).

The ICAO’s most recent Assembly Session (the 38th) finished in October 2013. At this Assembly, draft Resolution A38-17/2: ‘*Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change*’ was approved by the Executive Committee and recommended for adoption by the Plenary. The Resolution includes the following key points:

1. That nations and relevant organisations will work through the ICAO to achieve the goal of a global average fuel-efficiency improvement of 2% per annum up to 2050 (based on the volume of fuel-used per Revenue-Tonne-Kilometre).
2. That nations and relevant organisations will work through the ICAO to achieve the goal of keeping global net CO2 emissions from international aviation from 2020 at the same level.
3. That the ICAO has decided to develop a global market-based measures (MBM) scheme for international aviation. This involves finalising work on assessment of the possible options for a global MBM scheme, including consultation with nations and relevant organisations. Then making a recommendation on which the 39th Session of the Assembly in 2016 can make a decision, with implementation of the scheme to follow in 2020.
4. To continue development of a global CO2 standard for aircraft, aiming for adoption by the ICAO Council in 2016.
5. Encouragement for nations to voluntarily submit to the ICAO their Action Plans, outlining national policies and actions on CO2 emissions from international aviation. This will allow the ICAO to compile information on progress towards achieving global goals.

Similar to the “common but differentiated responsibilities” provision of the United Nations Framework Convention on Climate Change (UNFCCC) ([UN 1992](#_ENREF_79)), the draft Resolution suggests that when working towards these goals account should be taken of the circumstances and capabilities of nations, in particular developing-countries ([ICAO 2013a](#_ENREF_54)).

The ICAO has a leading role in formulating global CO2 reduction policies, and in providing advice and assistance to their member-nations in setting national-level policies that are consistent with global policies. However, in setting policy goals, and then determining and implementing the actions necessary to achieve those goals, the ICAO must rely on securing international agreements from member-nations. Ultimately, if nations (and hence relevant organisations within those nations) do not want to co-operate with the ICAO, the ICAO lacks the legal authority to force compliance.

### 2.1 Fuel-efficiency improvement goal

The Air Transport Action Group (ATAG) is a coalition representing the commercial aviation industry, focused on the sustainable development of air transport. The ATAG is a global organisation made up of aviation industry bodies such as: the Airports Council International (ACI); the Civil Air Navigation Services Organisation (CANSO); the International Air Transport Association (IATA); the International Coordinating Council of Aerospace Industries Associations (ICCAIA); and the International Business Aviation Council (IBAC). The ATAG has set a goal of an average improvement in fuel-efficiency of 1.5% per annum up to 2020, which is comparatively less challenging than the corresponding ICAO goal. Figures from the ATAG give the average annual fuel-efficiency improvement achieved since 2010 as 2.1% per annum ([ATAG 2013a](#_ENREF_1)), which exceeds both the ATAG and the ICAO goals.

However, if the ultimate goal is to stabilise and then reduce aviation’s CO2 emissions, the ICAO has stated that its policy goal of 2% per annum fuel-efficiency improvement is unlikely to deliver the necessary reductions in the face of forecast sector-growth ([ICAO 2013a](#_ENREF_54)). In other words, an average fuel-efficiency improvement >2% per annum is likely to be the minimum requirement. It seems likely that key organisations in the industry would resist this, as the ATAG has already set a less challenging fuel-efficiency improvement goal of 1.5% per annum.

According to the ITF, average fuel-efficiency improvement between 1960 and 2008 was 1.5% per annum; although the average disguises the fact that the rate of improvement has slowed over time after the introduction of several important technological developments in the 1970s and 1980s ([ITF 2012](#_ENREF_60)). The ITF also suggests that the high oil-price of 2008, and the following recession, have led to the retirement of older, less fuel-efficient aircraft from the global fleet ([ITF 2012](#_ENREF_60)). This is likely to have increased recent fuel-efficiency improvement rates, and produced the ATAG figures (2.1% p.a. since 2010) which show both ATAG and ICAO goals have been exceeded since 2010. In short, it would appear likely that sustained average annual fuel-efficiency improvements greater than 2% are going to be difficult to achieve.

### 2.2 Global net CO2 emissions held at 2020-levels

The ICAO goal of capping net aviation CO2 emissions at 2020-levels is also shared by the ATAG ([ATAG 2013b](#_ENREF_2)). The reference to ‘*net*’ rather than ‘*absolute*’ emissions means aviation can include emissions-trading activities within this target. In other words, aviation’s absolute emissions may increase from 2020, but it could be claimed the goal has been achieved because excess emissions have been offset by trading with other sectors where emissions have been reduced. This allows those mitigation-measures aimed at reducing absolute emissions to be less stringent.

The goal is also somewhat watered-down with caveats. The draft Resolution from the 38th Assembly states that the ICAO, member-nations and relevant organisations should all work towards this aspirational goal; but at the same time also take into account “the sustainable growth of the international aviation industry; and that emissions may increase due to the expected growth in international air traffic until lower emitting technologies and fuels and other mitigating measures are developed and deployed” ([ICAO 2013a](#_ENREF_54)).

Additionally, the ATAG has gone beyond net carbon-neutral growth from 2020 and set a further goal of reducing aviation’s net CO2 emissions by 50% by 2050, compared to a 2005 baseline ([ATAG 2013a](#_ENREF_1)). This aligns with the G8 leaders’ call for a global GHG emissions reduction target of 50% by 2050, although the baseline for this target was not made explicit ([G8 2009](#_ENREF_34)). In contrast to the ATAG’s position, the ICAO has not set this as a goal.

### 2.3 Market-based measures

Emissions from domestic aviation arise from flights departing and arriving within the same nation; and, as such, can easily be allocated to that nation. Therefore, whilst not specifically targeted, CO2 emissions from domestic aviation are included when calculating a nation’s total GHG emissions for the purposes of assessing performance against legally-binding reduction targets under the Kyoto Protocol to the UNFCCC ([Owen and Lee 2005](#_ENREF_72); [Webb *et al.* 2013](#_ENREF_83)). In this way, domestic aviation emissions are included in the global MBM created by the Kyoto Protocol, based on a national approach – i.e. Annex 1 nations are the participating entities ([UN 1998](#_ENREF_80)).

In contrast, international aviation crosses national borders and the high-seas, making allocation of emissions to a particular nation difficult. The Kyoto Protocol recognised this complexity, and excluded international aviation emissions from nations’ legally-binding targets ([Preston *et al.* 2012](#_ENREF_73)). As a guide to the scale of emissions currently excluded, international emissions were 47% and 55% of total global civil aviation emissions in 1990 and 2000 respectively ([Lee *et al.* 2005](#_ENREF_65)). Research into the most suitable method of allocating international aviation emissions has been carried-out, notably by the UNFCCC’s Subsidiary Body for Scientific and Technological Advice (SBSTA) ([Preston *et al.* 2012](#_ENREF_73)). However, no methodology has yet been internationally agreed, and international aviation emissions are currently excluded from nations’ Kyoto targets.

Following the 38th Assembly Session in September/October 2013, the ICAO has now decided to develop a global MBM to include international emissions, and has identified three potential options: Global Mandatory Offsetting; Global Mandatory Offsetting with Revenue (the revenue generated through an additional fee on each offset purchased, and then used for agreed purposes); or a global Emission Trading Scheme (ETS). Consistent methods for monitoring, reporting and verification (MRV), along with methods for enforcement at national or global-level will all require international agreement. A decision must also be made on whether nations or aircraft-operators will be the participating entities – i.e. a national or sectorial approach ([ICAO 2013f](#_ENREF_59)). Given the complexity associated with allocating responsibility for international emissions to nations, it would appear simpler to choose aircraft-operators.

The airline industry, through the ATAG, has expressed a willingness to implement a global MBM. However, the ATAG has indicated that the industry’s preferred option is for Global Mandatory Offsetting, with aircraft-operators as participating entities ([ATAG 2013b](#_ENREF_2)). Therefore, the ICAO may encounter difficulty in securing the necessary international agreements if they decide on a different preferred option.

The timetable for introducing the global MBM is to finalise work on the feasibility of the 3 options in time for a decision by the 39th Session of the ICAO Assembly in 2016, followed by implementation in 2020 ([ICAO 2013a](#_ENREF_54)). New national reduction targets for the 2nd Kyoto commitment period from 2013 to 2020 have recently been set in the Doha Amendment to the Kyoto Protocol ([UN 2012](#_ENREF_81)) (adopted, but not yet entered into force). So, if the ICAO can adhere to their timetable, their global MBM would be implemented as the 2nd Kyoto commitment period was finishing. However, in the meantime from now until 2020, it would seem to be a priority to agree an allocation methodology so global international emissions can be included in nations’ new Kyoto targets.

#### 2.3.1 EU Emission Trading System

The ICAO has been criticised for having a poor track-record in driving through MBMs ([Preston *et al.* 2012](#_ENREF_73)). Frustrated with slow progress from the ICAO, the European Union (EU) took the lead and acted unilaterally to include the aviation sector in the EU Emission Trading System (EU-ETS). Civil aviation was brought into the EU-ETS on 1st January 2012, in the last year of the 2nd trading period. The scheme covers CO2 emissions from all flights (domestic and international) originating or terminating within the EU-ETS, with aircraft-operators as the participating entities ([EC 2013c](#_ENREF_29)).

The inclusion of civil aviation in the EU-ETS highlights the challenges of taking unilateral action without full international agreement; with retaliatory measures having been threatened by, among others, the USA and China ([Preston *et al.* 2012](#_ENREF_73)). For example, in November 2012 the USA passed a law entitled ‘*European Union Emissions Trading Scheme Prohibition Act of 2011*’ which allows the Secretary of Transportation to “prohibit an operator of a civil aircraft of the United States from participating in the emissions trading scheme unilaterally established by the European Union” ([Congress.gov 2012](#_ENREF_18)). It was claimed by the Air Transport Association of America (now called Airlines for America) that including USA airlines in the EU-ETS was illegal under international law ([Preston *et al.* 2012](#_ENREF_73)). However, the European Court of Justice ruled in favour of the EU legislation, finding that inclusion of aviation “infringes neither the principle of territoriality, nor the sovereignty of third countries” ([EC 2013a](#_ENREF_27)).

As yet, no attempt has been made to apply the scheme to flights with an origin or destination outside the EU-ETS because the European Commission (EC) decided to defer the scheme’s application to these flights to allow time for the ICAO to reach agreement on a global MBM at the 38th Assembly in October 2013 ([EC 2012](#_ENREF_26)). Now that the ICAO has agreed a global MBM will be introduced, the EC have proposed that from 2014 until the global MBM is implemented in 2020, flights with an origin or destination outside the EU-ETS will once-again be included under the scheme. However, the proposal is that only emissions from the proportion of the flight within the EU-ETS airspace are to be included ([EC 2013b](#_ENREF_28)). This is less stringent than the original scheme, where emissions from the entire flight were included. With this less stringent scheme the EU can argue that they are only addressing those emissions that arise within their geographic-area. Whether this argument will be enough to convince nations outside the EU-ETS to agree to comply with the scheme remains to be seen.

Studies have indicated that the reduction in CO2 emissions resulting from including aviation in the EU-ETS is expected to be small ([Anger 2010](#_ENREF_7); [Anger and Köhler 2010](#_ENREF_8)), and it has been argued that more effective measures are available ([King *et al.* 2010](#_ENREF_62)). However, maybe the most important role it will play is as a flagship scheme, pushing international aviation emissions up the political agenda ([Preston *et al.* 2012](#_ENREF_73)), and demonstrating that it is feasible to address these emissions with an agreed multi-national MBM (albeit international agreement between nations that have pre-existing close-ties through the EU). It could be argued that the flagship-role played by the EU-ETS provided some of the leverage required for the ICAO to finally reach agreement on the introduction of a global MBM.

### 2.4 Global CO2 standard

The ICAO has been making progress towards agreement on a global CO2 emissions certification standard for aircraft. For example, a significant milestone was achieved in July 2012, when the ICAO’s Committee on Aviation Environmental Protection (CAEP) unanimously agreed on a metric system for the standard. The metric addresses emissions from a wide variety of aircraft on a fair and transparent basis, and includes factors accounting for fuselage geometry, maximum take-off weight, and fuel-burn performance in three different cruise conditions ([ICAO 2012d](#_ENREF_53)).

A further milestone was achieved in February 2013, when the CAEP unanimously agreed on the certification procedures for the standard; leaving only agreements on stringency and scope of applicability remaining ([ICAO 2013d](#_ENREF_57)). An appropriate regulatory limit for the standard will be established using the ICAO criteria of technical feasibility, environmental benefit, cost effectiveness, and the impacts of inter-dependencies on other performance indicators covered by other standards ([ICAO 2012d](#_ENREF_53)). The CAEP agree that the standard should be applicable to new aircraft-types. Potentially, it could also apply to newly-manufactured examples of existing aircraft-types, although this is yet to be finalised. If the standard only applies to new-types, there will be a need to determine when modifications to an existing-type are extensive enough to warrant classification as a new-type, and therefore become eligible for compliance ([Holland *et al.* 2011](#_ENREF_39)).

In the climate change Resolution A37-19 adopted at the ICAO’s 37th Assembly in 2010, the stated aim was to introduce the CO2 standard by 2013 ([ICAO 2010a](#_ENREF_46)). Whilst progress has been made, following the 38th Assembly in October 2013 the timetable for introduction of the standard has now slipped to 2016 ([ICAO 2013a](#_ENREF_54)). This 3-year delay in introduction serves to highlight the time-consuming difficulties inherent in trying to get all the key actors (airlines, aircraft and engine manufacturers, environmental groups, etc.), with their range of different vested-interests, to agree on the form and implementation of CO2-reducing regulations.

When finally agreed and implemented, if the standard is stringent enough, the effect may be to accelerate the introduction of fuel-efficient aircraft technology beyond what would have been achieved anyway by the drivers of reducing fuel-costs and reducing costs from MBMs. If the standard is less stringent, the effect would be limited to stopping production of older, non-compliant aircraft, either enforced through the regulation or through a lack of orders from aircraft-operators ([Holland *et al.* 2011](#_ENREF_39)).

### 2.5 Submission of national Action Plans

Submission of Action Plans to the ICAO is voluntary, and allows nations to showcase the specific mitigation-measures they intend to take, and also to include information on any specific assistance they may require. Action Plans should also include international RTKs, fuel consumption, and projected future CO2 emissions, ideally to 2050. Receipt of Action Plans allows the ICAO to monitor nations’ progress towards global goals, and identify where targeted technical and financial assistance is required ([ICAO 2012a](#_ENREF_50)).

During 2012, the ICAO stated that, by the end of the year, it expected to receive Action Plans from member-nations representing 85% of global international air traffic ([ICAO 2012c](#_ENREF_52)). In fact, progress has been slower than hoped, with the ICAO reporting that, as of 30th June 2013, 61 member-nations representing 78.89% of global international air traffic have voluntarily submitted their Action Plans ([ICAO 2013a](#_ENREF_54)). The ICAO has 191 member-nations, so this statistic also demonstrates that there are 130 member-nations who have not yet submitted Action Plans. As submission is voluntary, the ICAO has no process available to enforce submission from those member-nations yet to do so.

# 3. Technological and Operational Measures

### 3.1 Aircraft technology

Civil aviation is likely to depend on fossil fuels for the foreseeable future ([Kahn Ribeiro *et al.* 2007](#_ENREF_61)). Therefore, improved fuel-efficiency is a key method for reducing CO2 emissions. Fuel represents approximately 20% of total operating costs for modern aircraft ([Kahn Ribeiro *et al.* 2007](#_ENREF_61)), so market forces act on airlines to minimise fuel consumption and provide a financial incentive to pursue fuel-efficient fleets through incorporating new aircraft technology ([Holland *et al.* 2011](#_ENREF_39)). Since 1960, aircraft fuel-efficiency has improved by approximately 70-80% ([ITF 2012](#_ENREF_60)), and some estimates suggest a further 40-50% improvement is achievable by 2050 ([Kahn Ribeiro *et al.* 2007](#_ENREF_61)). The main areas for improving overall aircraft fuel-efficiency are:

1. Reducing basic aircraft weight.
2. Improving aircraft aerodynamics to reduce drag.
3. Improving specific engine efficiency, to reduce fuel burn per unit thrust ([King *et al.* 2010](#_ENREF_62)).

#### 3.1.1 Weight reductions

Aircraft weight reductions have been achieved through the introduction of light-weight advanced alloys and composite materials, new designs for aircraft systems, and improved and new manufacturing processes. For example, the Boeing 787 entered service in 2011 and has an airframe comprised of nearly 50% carbon-fibre reinforced plastic and other composites, offering average weight-savings of 20% over equivalent conventional aluminium designs ([Boeing 2006](#_ENREF_12)).

#### 3.1.2 Drag reductions

Lift-dependent drag and friction drag are the greatest contributors to aircraft aerodynamic drag, approximately 21% and 50% of total drag respectively ([King *et al.* 2010](#_ENREF_62)). Advances in materials, structures, and aerodynamics are already allowing significant reductions in lift-dependent drag to be achieved. Over the next 10-20 years, friction drag offers the most potential for further improvements ([ICAO 2010c](#_ENREF_48)), with computational fluid dynamics modelling suggesting it can be reduced by 20-70% ([King *et al.* 2010](#_ENREF_62)). Beyond that time-frame, more radical re-designs of the conventional airliner airframe-layout are currently being researched, such as the blended-wing-body (BWB) design. Sometimes called a flying-wing design, the BWB approach increases aerodynamic efficiency through minimising any aircraft surfaces that do not contribute to lift-generation, and potentially offers large fuel-efficiency improvements. However, BWB must overcome issues such as passenger acceptance of windowless designs, the difficulties inherent in pressurising non-cylindrical shapes ([King *et al.* 2010](#_ENREF_62)), and current airport-infrastructure needing to be reconfigured to load/unload BWB designs. Additionally, although there is no definitive demarcation between large and small aircraft or long and short range, the BWB is seen as being best-suited to larger aircraft over longer distances ([Morris *et al.* 2009](#_ENREF_70)). Therefore, the BWB approach is less likely to offer potential for smaller aircraft on shorter flights.

#### 3.1.3 Specific engine efficiency improvements

Specific engine efficiency improvements can be achieved for in-service, in-production and new aircraft-types. For example, multiple engine-upgrade programs over the last decade have delivered up to 2% fuel-consumption reductions. Engine technologies, such as materials, coatings, combustion-techniques, sensors, and cooling-techniques, mean that the engines and APUs for new aircraft are expected to give at least 15% fuel-consumption savings over the aircraft they replace ([ICAO 2010c](#_ENREF_48)). For the longer-term, more radical engine designs, such as open-rotor engines, are under consideration. If issues of noise and vibration can be overcome, open-rotor engines potentially offer step-change improvements in fuel-efficiency ([Lee *et al.* 2009](#_ENREF_64); [King *et al.* 2010](#_ENREF_62)).

#### 3.1.4 Barriers to aircraft technology

Over recent decades, jet engine technology development has involved a trade-off between fuel-efficiency and production of NOx. Increases in fuel-efficiency tend to result in higher temperatures and pressures at the combustor inlet, thus increasing NOx formation. Therefore, the challenge is to reduce fuel-consumption whilst also guarding against a tendency for increased NOx production. For example, combustor designs that keep NOx emissions down through incorporating additional cooling ([Lee *et al.* 2010](#_ENREF_66)).

When developing new aircraft technologies, overall aircraft optimum is not achieved through simply combining individual optimal components. Instead, a fully integrated approach to designing the aircraft as a whole leads to overall optimal-performance. In this process fuel-efficiency and emissions are major design-drivers, but they must sit alongside other drivers such as aircraft noise, operability, safety, reliability, costs, comfort, etc. For example, increasing the fan-diameter of an engine would normally decrease engine noise; but this is also likely to increase weight and drag, and could therefore reduce fuel-efficiency ([ICAO 2010c](#_ENREF_48)).

Civil aviation technology developments are only allowed on to the market after rigorous safety testing. Levels of engineering excellence and stringent safety requirements are beyond those normally demanded by other vehicle-types. This results in significant development costs, and slows the rate at which technology improvements can be delivered ([Kahn Ribeiro *et al.* 2007](#_ENREF_61)). A further factor slowing the rate at which improvements can be delivered is the long product life-cycles of aircraft, compared to land-based transport. Technology introduced today is likely to last the next 30-50 years. So, for example, BWB aircraft are unlikely to make any significant contribution to reducing CO2 emissions for many decades to come ([Bows and Anderson 2007](#_ENREF_14)).

### 3.2 Alternative fuels

Alternative fuels for aviation, with lower carbon-intensities, have been examined by many nations, both for potential environmental benefits and to address security of supply ([Kahn Ribeiro *et al.* 2007](#_ENREF_61)). Alternative fuels are also a focus for the ICAO, who established a global framework for their development at the 2009 ‘*Conference on Aviation and Alternative Fuels (CAAF)*’.

Examples of the alternatives to conventional jet-fuel (mineral-kerosene) that have been investigated include:

* Liquefied hydrogen (LH2).
* Methane.
* Methanol.
* Ethanol.
* Bio-diesel (methyl esters) from processing plant-oils and animal-fats.
* Nuclear power.
* Synthetic Paraffinic Kerosene (SPK), created either by:
* the Fischer-Tropsch (F-T) process from feedstocks such as biomass, natural gas, or coal;
* or Hydroprocessing of plant-oils and animal-fats to Hydroprocessed Renewable Jet (HRJ), sometimes called Bio-SPK or Hydroprocessed Esters and Fatty Acids (HEFA).

Of this list, most options have been found to be currently unsuitable for a variety of different reasons such as: costs; lack of fuel production and delivery infrastructure; larger fuel-tanks necessitating larger fuselage-volumes, leading to increased weight and drag; low energy densities; or safety-concerns ([Lee *et al.* 2010](#_ENREF_66); [Kahn Ribeiro *et al.* 2007](#_ENREF_61); [ICAO 2010c](#_ENREF_48); [Van Gerpen 2005](#_ENREF_82); [Allen *et al.* 2012](#_ENREF_6); [FAA 2011](#_ENREF_31)).

However, use of synthetic-kerosene is making progress. Drop-in fuels are alternative fuels that meet existing jet-fuel specifications, and hence are interchangeable with mineral-kerosene. In 2009, a new jet-fuel specification was introduced: ASTM International Standard D7566 “*Standard Specification for Aviation Turbine Fuel Containing Synthesised Hydrocarbons*”. Introduction of this specification enabled SPK (from the F-T process or HRJ process) to be used up to 50% blended with mineral-kerosene, making this the easiest alternative fuel for aviation-use in the short and medium-term, with a good number of demonstration flights already having taken place ([Lee *et al.* 2010](#_ENREF_66); [ICAO 2010c](#_ENREF_48); [FAA 2011](#_ENREF_31); [King *et al.* 2010](#_ENREF_62); [ASTM International 2011](#_ENREF_10)).

Any large-scale cultivation of biofuel-crops for the production of biomass feedstock would require large areas of agricultural land, creating competition with food production. Land-use changes from wet-lands, rainforests, peat-lands, savannahs, and grasslands to cultivating biofuel-crops could involve net increases in GHG emissions ([Subhadra and Edwards 2010](#_ENREF_78)). Also, nitrous oxide (N2O), emitted as a result of biofuel-crop production, is a GHG and could negate any CO2 savings ([Lee *et al.* 2010](#_ENREF_66)). These problems are avoided if using other sources of biomass feedstock, such as waste-biomass or algae.

Algae, both macro (seaweed) and micro, have rapid growth-rates, high photon-conversion efficiency, high oil-yields, and high CO2 absorption ([Singh and Olsen 2011](#_ENREF_77); [Subhadra and Edwards 2010](#_ENREF_78)). They can be grown in coastal-seawater or on barren land, removing competition with food production. Shell, ExxonMobil, and British Petroleum have all recently invested substantial resources in developing algae-based biofuels ([Subhadra and Edwards 2010](#_ENREF_78)). However, high costs are a key problem, with processing and infrastructure challenges remaining to be overcome before commercial viability can be reached (ICAO [2010c](#_ENREF_48); [Hendricks *et al.* 2011](#_ENREF_36)).

Additionally, carbon-reduction strategies for other transport-modes, and in other sectors such as power generation or other industrial processes, often include increased use of biomass fuels. For example, the UK Statutory Instrument ‘*The Renewable Transport Fuel Obligation Order 2007*’ (RTFO) requires that a percentage (currently approximately 5%) of total road-transport fuel supplied in the UK is sustainable fuel derived from biomass ([HMG 2007](#_ENREF_37); [HMG 2011](#_ENREF_38); [DfT 2013b](#_ENREF_22)). Biomass is a resource for which aviation will have to compete, and alternative uses of this scarce resource could have the potential to offer greater emission savings than use as a feedstock for aviation biofuel.

### 3.3 Efficient aircraft operational procedures

Theoretical CO2 emissions performance is determined by the technology embodied in an aircraft. However, actual achieved-performance will be dictated by how the aircraft is operated subject to ‘*real world*’ constraints. Efficient operational procedures are those that allow an aircraft to be operated so that actual fuel-used (and associated CO2 emissions) approaches as closely as possible to the theoretical minimum.

Allowing an aircraft to fly at its optimum trajectory (vertically, horizontally, and at the most fuel-economic speed) translates into fuel-efficiency. Accordingly, one method to reduce aircraft CO2 emissions is through efficient flight management, commonly known as Air Traffic Control (ATC) or Air Traffic Management (ATM). The current ATM-system is largely based on airspace organised around national borders leading to inefficient routings that impose mileage-penalties. Studies of the European route network suggest ATM-related impediments increase flight-distances by an average of 9-10%. Additionally, at certain times of day, a lack of airport capacity can be an issue causing congestion and delays; with each minute spent flying a holding-pattern awaiting a landing-slot producing an average 160kg of CO2 emissions ([King *et al.* 2010](#_ENREF_62)).

The ICAO’s response to ATM-related inefficiencies is the Global ATM Operational Concept. This is a vision of an interoperable global ATM-system that “meets agreed levels of safety, provides for optimum economic operations, is environmentally sustainable, and meets national security requirements”. Environmental-sustainability is a key factor, and it is recognised that the ATM system must contribute to reducing CO2 emissions. However, achieving optimal system performance necessitates balancing environmental-sustainability against other, often competing, expectations ([ICAO 2010c](#_ENREF_48)).

The Global Air Navigation Plan is the roadmap towards the ICAO’s vision of the Global ATM Operational Concept. The Global Plan assists nations and regions in identifying the most suitable improvements to their ATM systems; and also considers harmonisation of regional programmes already in place, such as the SESAR (Single European Sky ATM Research Programme), NextGen (Next Generation Air Transportation System), AIRE (Atlantic Interoperability Initiative to Reduce Emissions), and ASPIRE (Asia and Pacific Initiative to Reduce Emissions). In Europe, the SESAR is designed to eliminate fragmentation of airspace across the many national borders. One of the performance goals of achieving this is a 10% reduction in CO2 emissions per flight by 2020, against a 2005 baseline. In the USA, NextGen will allow more direct aircraft trajectories, both in-flight and also during ground-movements before take-off and post-landing. Both AIRE and ASPIRE are demonstration-projects showing the potential fuel-efficiency benefits of a gate-to-gate approach to handling flights; including pre-flight operations, aircraft ground-movements at both ends of a flight, and interoperability between the different ATM units handling a flight en-route ([ICAO 2010c](#_ENREF_48); [King *et al.* 2010](#_ENREF_62); [FAA 2013](#_ENREF_32); [SESAR JU 2011a](#_ENREF_75); [SESAR JU 2011b](#_ENREF_76); [ASPIRE 2013](#_ENREF_9)).

Reduced Vertical Separation Minimum (RVSM) has reduced the required vertical separation between aircraft, thus allowing more aircraft to operate closer to their optimum fuel-economy cruising-level. Hence fuel-burn is reduced, and consequently so are emissions. Global coverage was completed when the Eurasia region became the last region to complete RVSM implementation in 2011 ([ICAO 2012b](#_ENREF_51)). Environmental studies have concluded that RVSM has reduced fuel-use ([Owen 2008](#_ENREF_71)); and therefore reduced both CO2 emissions and aircraft-operators’ fuel-costs. Following on from RVSM’s improvements to vertical flight-profiles, Performance Based Navigation (PBN) is being used to improve efficiency in the horizontal-plane through employing more flexible use of airspace, allowing aircraft to fly even closer to their optimum trajectories. PBN is also one of the main features of both NextGen and SESAR (FAA [2013](#_ENREF_32); [Eurocontrol 2013](#_ENREF_25)).

Operational measures are particularly attractive, as there is less likelihood of meeting resistance to implementation from aircraft-operators. Indeed, operational measures which reduce emissions through reducing fuel-use are likely to be championed by aircraft-operators. This is because of the downward impact on their fuel-costs, and the fact that operational measures can often be implemented without the need for large investments in new technology. Some operational measures are lengthy projects that may be able to deliver year-on-year fuel-efficiency improvements over the project-lifetime, as progress is made towards the maximum benefits. Conversely, a project such as implementation of RVSM, now that global coverage is complete, is unlikely to deliver further fuel-efficiency improvements in future years ([Owen 2008](#_ENREF_71)).

### 3.4 Aggregated impact study

A recent study by [King *et al.* (2010)](#_ENREF_62) aggregated all the potential impacts of aircraft technology, alternative fuels, and efficient aircraft operational procedures, and produced both short-term (5 years) and long-term (40 years) forecasts for potential CO2 emissions reductions.

#### 3.4.1 Short-term forecast

The measures feasible for implementation in the short-term were considered to be: evolution of current fuel-efficient aircraft technologies; aircraft routinely flying on a 95-5 mix of mineral-kerosene and biofuel; and operational efficiency improvements leading to greater use of optimal trajectories. If all these measures could be realised, then new aircraft would offer an estimated 28% reduction in CO2 emissions over today’s current aircraft. However, new aircraft will only constitute part of the global airline fleet, because many current aircraft will still be in service in 5-years’ time. Assuming all new aircraft entering the fleet include all available technology improvements (seen as an optimistic assumption), then it was estimated a 6% reduction in CO2 emissions could be achieved for the global airline fleet as a whole over a 5-year time-period ([King *et al.* 2010](#_ENREF_62)). The 6% estimated reduction on current fleet-performance approximates to a reduction-rate of 1.2% per annum, compounded over the 5-year period.

#### 3.4.2 Long-term forecast

For the long-term, feasible-measures were considered to be: fuel-efficiency technologies requiring fundamental aircraft-architecture changes; 100% biofuel-use; and a fully integrated global ATM system. If these measures could be realised, it was estimated a 60-95% reduction in CO2 emissions could be achieved compared to current aircraft, over a 40-year time period. However, the likelihood that this best-case scenario would occur was assessed as “slim” ([King *et al.* 2010](#_ENREF_62)). The 60-95% estimated reduction on current fleet-performance approximates to a reduction-rate of 2.3-7.2% per annum, compounded over the 40-year period.

#### 3.4.3 Comparison with the ICAO policy goals

Various industry bodies are all forecasting air traffic growth-rates in the region of 4-5% per annum. If comparison is made with the CO2 emission reduction-rates estimated above, then it appears likely that, in all but the most highly-optimistic scenarios, traffic growth-rates will out-pace emission reduction-rates. Hence, aviation’s absolute emissions will grow. The ICAO and the ATAG share the goal of keeping aviation’s net CO2 emissions from 2020 at the same level; and this goal will only be achievable through offsetting growth in absolute emissions with emissions-trading.

The ICAO also has a goal of 2% per annum fuel-efficiency improvement. The estimated CO2 emission reduction-rates derived from the aggregated impact study include the effects of both fuel-efficiency improvements (aircraft technology and efficient aircraft operational procedures) and increasing use of alternative fuels. In fact, for the long-term forecast, nearly half the total emissions-reduction benefit is derived from use of alternative fuels alone ([King *et al.* 2010](#_ENREF_62)). Therefore, the forecasts from the aggregated impact study indicate that achieving 2% per annum improvements from fuel-efficiency alone will be difficult to sustain, especially as the forecasts are based on optimistic assumptions.

The implementation of both regional and/or global MBMs and a global CO2 certification standard were not explicitly included in the aggregated impacts study. These measures have the potential to provide additional incentives for the up-take of aircraft technology, efficient operational procedures, and alternative fuels. If the stringency of these measures can be set appropriately, they could lead to increased emissions reduction-rates and the possibility of closing the gap to traffic growth-rates. However, as an example of the potential impact of an MBM, studies have indicated that the reduction in CO2 emissions resulting from including aviation in the EU-ETS is expected to be small (as discussed in Section 2.3.1).

# 4. Discussion

### 4.1 Measures that reduce fuel-costs

Any measures that directly improve the fuel-efficiency of aircraft operations (aircraft technology and efficient operational procedures) are not likely to encounter resistance from the civil aviation industry, and can be left to market forces as the key driver for implementation. Measures that reduce the amount of fuel an aircraft consumes will also reduce its CO2 emissions, and more importantly (from the airlines’ point of view) also reduce airline fuel-bills. If the initial cost to the airline of implementing a measure does not outweigh the on-going fuel-bill reductions, any attempt to implement such a measure would be pushing against an ‘*open-door*’. In one of the authors’ personal experience of flying aircraft for a large UK airline (Grote), airline policies aimed at reducing fuel-use were always near the top of the agenda, probably second only to the paramount concern of flight-safety. The reason given for the importance placed on fuel-saving policies was always the cost of fuel, rather than any mention of concern for reducing CO2 emissions – this was just a happy by-product. Inclusion of aviation in MBMs such as the EU-ETS and the ICAO’s planned global MBM, will more directly relate CO2 emissions to an airline’s costs, and explicit concern for reducing CO2 emissions may become increasingly important.

Of the measures that can provide fuel-efficiency improvements, it is implementation of fuel-efficient operational procedures that offer the most immediate benefits. In contrast, aircraft technology measures are constrained by the lengthy product-lifecycles of aircraft. However, the fuel-cost savings available from new, more fuel-efficient aircraft may provide enough incentive for airlines to speed-up the rate of fleet-renewal, with early retirement of old, less fuel-efficient aircraft becoming the cost-effective option. However, forecasting the benefits that may accrue from fleet-renewal is challenging because the rate of fleet-renewal is obviously highly dependent on future oil prices; and forecasting oil prices over the timescales of aircraft product-lifecycles is difficult because it depends on unknowns, such as future global economic growth-rates, technology development, climate change policies, strategies of resource-holders, etc. For example, the UK government’s projection of the oil price in 2030 ranges from $75-$195 per barrel ([DECC 2013](#_ENREF_24)).

The combination of evidence from the historic average fuel-efficiency improvement rate (1.5% per annum) and the aggregated impact forecasts, indicates that even if all measures delivering fuel-efficiency improvements (aircraft technology and efficient operational procedures) are embraced and fully implemented by the civil aviation industry, it will still be difficult to sustain the ICAO’s goal of 2% per annum fuel-efficiency improvement. This is of concern because, as previously mentioned (Section 2.1), the ICAO itself has stated that achieving this goal is unlikely to be sufficient to deliver the necessary reductions to stabilise and then reduce civil aviation’s absolute emissions in the face of forecast sector-growth.

### 4.2 Measures that do not reduce fuel-costs

Measures that do not directly increase the fuel-efficiency of aircraft operations cannot be left to market forces as the driver for implementation. For measures not directly acting to reduce airline fuel-bills (MBMs, national Action Plans, and alternative fuels), the industry requires a global regulator with ‘*teeth*’. In other words, a regulator that can impose global regulations aimed at achieving their stated global policies, backed with the authority to impose penalties on the participating entities (nations or organisations) in the event of non-compliance. The ICAO would seem the obvious candidate for this role, but to strengthen their authority to appropriate levels would require international agreement from many different parties, all with their own vested interests. Historically, such international agreements have proved difficult to secure. Some examples highlighting the inherent difficulties include: the implementation-date of the global CO2 standard slipping from 2013 to 2016; the reaction of China and the USA to the inclusion of international aviation in the EU-ETS; the length of time it has taken the ICAO to secure agreement on a global MBM; and the lack of agreement on how emissions from international aviation should be allocated to nations under the Kyoto Protocol, thus preventing international emissions from being addressed by the Protocol in the interim before the ICAO’s global MBM planned for implementation in 2020.

The situation regarding tax on aviation-fuel further illustrates the difficulties surrounding international agreements. The current circumstances are that fuel for international aviation is, in general, exempt from tax. This is based on a principle of reciprocal-exemption between nations, and long-standing maritime practice. The ICAO support this policy because they see it as the only practical option that can assure international aviation is treated equitably in the many national jurisdictions into which it operates ([ICAO 2000](#_ENREF_45); [ICAO 2010b](#_ENREF_47); [ICAO 2013b](#_ENREF_55)). In other words, under the current global regulatory-framework the only feasible option is tax-exemption. If the ICAO were to conclude that a global tax on international aviation fuel was an appropriate measure to mitigate CO2 emissions, they do not regard securing the necessary international agreement as feasible. To introduce a tax on international aviation fuel that was seen as equitable and was global in extent would require a global regulator with the necessary authority to impose such a tax.

Currently, the ICAO is heavily reliant on voluntary cooperation and piecemeal agreements from member-nations when setting global policies on CO2 emissions reductions, and implementing measures in support of those policies. Authority to enact legislation to ensure compliance with measures tends to reside at a national-level, with national governments having the power to impose regulations on organisations within their national-borders. An example of national legislation from the UK would be the compulsory use of biofuel for road-transport through the RTFO. If agreement could be secured to invest the ICAO with the appropriate level of authority, then they could impose the less ‘*popular*’ measures, and speed-up the implementation process through removal of the need to secure piecemeal agreements for each measure in-turn. However, realistically the ICAO would still need to perform the difficult diplomatic task of operating in such a way that all the interested parties in the civil aviation industry felt their concerns were being addressed in a fair and transparent fashion. Otherwise support for agreements could be withdrawn, leading to the collapse of the ICAO’s authority.

For the global CO2 certification standard, it is less clear whether or not this measure is an ‘*open-door*’. Aircraft which are compliant with the standard are likely to be more fuel-efficient than those which are not, and this is likely to be welcomed by airlines. However, depending on the final agreements on scope of applicability and stringency, the standard may force airlines into engine-upgrade or fleet-replacement timetables in advance of original plans, which could incur unwelcome additional costs. It remains to be seen how wide-ranging and stringent an agreement the ICAO can secure from the interested parties.

### 4.3 Requirement for behaviour change

The results of the literature review suggest that traffic growth-rates are likely to out-pace CO2 emission reduction-rates. Implementation of MBMs and a global CO2 standard will provide additional incentives for greater emission reduction-rates to be ‘*squeezed*’ from the combination of aircraft technology, efficient operational procedures, and alternative fuels. Another potential emission-saving option would be, for a given level of demand, to increase passenger load-factors by reducing the Available-Seat-Kilometres (ASKs, i.e. the total passenger capacity available) which would reduce CO2 emissions per RPK. For example, global average load-factors increasing from 68% in 1989 to 79.3% in 2012 has placed some constraint on the growth in aviation’s CO2 emissions ([Lee *et al.* 2009](#_ENREF_64); [IATA 2014](#_ENREF_44)). However, it is by-no-means certain that a combination of these measures will be sufficient to close the gap between traffic growth-rates and emission reduction-rates. If not, then behaviour change to reduce the underlying demand for air-travel becomes necessary if a cut in aviation’s absolute CO2 emissions (or at least remaining constant at 2020-levels) is to be realised.

#### 4.3.1 Options for inducing behaviour change

To induce behaviour change, measures are needed that provide potential users of air-travel with incentives to make the environmentally ‘*correct*’ choice, or disincentives to make the ‘*wrong*’ choice. For example, as well as precipitating technological and operational measures to reduce CO2 emissions, MBMs can act as a disincentive to choose air-travel through passing on to the consumer the increased costs due to the MBM, thereby reducing demand ([Anger and Köhler 2010](#_ENREF_8)). Modal-shift towards transport-modes with better carbon-efficiency is a further way of reducing aviation demand. For example, it is generally acknowledged that High-Speed Rail (HSR) emits less CO2 per passenger-kilometre in comparison to aviation ([Campos and de Rus 2009](#_ENREF_17)). A national government policy of investing in new HSR services, or promoting existing HSR services, could induce modal-shift away from aviation. In 1992, when HSR was introduced to Spain on the Madrid-Sevilla route, the rail share of the total rail-and-air market increased from 21% in 1991 to 82% in 1993 ([Fu *et al.* 2012](#_ENREF_33)). The optimal whole-journey time for HSR is 3-4 hours, with its time-advantage over aviation disappearing when the whole-journey time by train exceeds 4 hours ([Fu *et al.* 2012](#_ENREF_33)). Additionally, it is often argued that information and communication technology (ICT) can reduce the demand for work-related travel through replacing physical-mobility with virtual-mobility ([Lassen *et al.* 2006](#_ENREF_63); [Lu and Peeta 2009](#_ENREF_69)).

#### 4.3.2 Barriers to behaviour change

For obvious reasons, any measure designed to reduce civil aviation demand would be very likely to meet strong resistance from within the civil aviation industry, and from the ICAO who also have a vested interest in a thriving and growing commercial aviation sector. Taking MBMs’ potential to reduce demand as an example, the ATAG’s position is that whilst they support a global MBM, unsurprisingly they also explicitly state that it must “not be designed to……suppress demand” ([ATAG 2013a](#_ENREF_1)).

National governments could implement measures aimed at reducing demand for air-travel. However, national governments tend to attach high importance to a strong civil aviation industry, as evidenced by these quotes concerning the three nations with the largest aviation networks (based on ASKs) ([WEF 2013](#_ENREF_85)): in the USA, the “aviation industry is important to the U.S. economy and is a critical link in the nation’s transportation infrastructure” ([GAO 2013](#_ENREF_35)); the Chinese Government see the airline industry as a “strategically important asset to national competitiveness and regional development” ([Lei and O’Connell 2011](#_ENREF_67)); and the UK Government “believes that aviation needs to grow” and recognises the vital contribution regional airports “can make to the growth of regional economies” ([DfT 2013a](#_ENREF_21)). Therefore, the likelihood that a national government would implement measures explicitly targeted at reducing demand for air-travel doesn’t appear high.

It would also seem optimistic to expect individual consumers to take responsibility for behaviour change and, of their own volition, elect to avoid air-travel. A review of passenger-attitude surveys in the UK revealed that, despite being aware that aviation contributes to the problem of climate change, passengers are reluctant to reduce air-travel. Rather than change their own behaviour, passengers are more likely to see other bodies, such as governments or airlines, as having responsibility for finding solutions ([Hooper *et al.* 2009](#_ENREF_40)). A further factor affecting individual behaviour is the world-wide rise of Low Cost Carriers (LCCs), which began with deregulation of the domestic market in the USA and liberalisation of the European market. The rapid growth of the LCC business model has driven down the cost of air-travel; and this reduction of any affordability-barrier has stimulated demand, and made individual consumers less likely to avoid air-travel ([Lei and Papatheodorou 2010](#_ENREF_68); [de Wit and Zuidberg 2012](#_ENREF_19)).

Regarding virtual-mobility, [Randles and Mander (2009)](#_ENREF_74) argue that a ‘good society’ is one that recognises the well-being benefits for its members of enabling physical-mobility as opposed to virtual-mobility. More specifically, other research has identified a number of factors that drive a continued-preference for physical-mobility. For example, networking was found to be an important reason for going on work-related trips, and networking relies on informal relations that are strongly dependent on physical proximity ([Lassen *et al.* 2006](#_ENREF_63)).

In general, the causes of behaviour are likely to lie deep within complex interactions between numerous political, economic, social, and technical factors. As a result, behaviour becomes ‘*instituted*’ leading to an inherent resistance to change ([Randles and Mander 2009](#_ENREF_74)). For the global aviation industry as a whole, growth is forecast to be strong over the coming decades, and it would seem optimistic to expect behaviour change to have any significant downward-impact on this.

The situation is further complicated if growth-rates are considered at a national-level, rather than globally. It could be argued that it is equitable to curb growth in nations where per capita flying is already high, in order to allow growth to continue in other nations. However, securing and enforcing the necessary agreements in a fashion that all parties perceive as fair appears likely to be a difficult task for a global regulator.

#### 4.3.3 Ticket price-increase necessary to induce behaviour change

As an illustrative example of the difficulties faced, consider the following scenario for passenger air-travel. Some simple calculations have been performed to estimate the annual air-ticket price-increase that would be necessary to achieve absolute carbon-neutral growth in aviation from 2020 onwards. It is assumed that the growth-rate for RPKs is 4% per annum (the lower-end of the forecasts), and that passenger load-factors remain constant. A CO2 emissions reduction of 2.3% per annum is assumed (the 40-year forecast from the King *et al*. study was considered to have a “slim” chance of occurring, so it would seem prudent to select an emissions reduction-rate from the lower-end of this highly-optimistic scenario). Therefore, the following equation would give absolute carbon-neutral growth:

1.04 (from RPK growth) x 0.977 (from CO2 reduction) x Behaviour Change Factor = 1

Rearranging this equation gives: Behaviour Change Factor = 0.984. In other words, a 1.6% per annum demand-reduction from behaviour change is required.

Using a meta-analysis of studies on the price-elasticity-of-demand for passenger air-travel, a representative value for the overall mean price-elasticity-of-demand is taken as -1.146 ([Brons *et al.* 2002](#_ENREF_16)). Hence, a demand-decrease of 1.6% per annum would require a price-increase, in real-terms, of 1.4% per annum.

Compare this required price-increase with historical air-ticket price-data from the USA, the nation with the largest aviation network ([WEF 2013](#_ENREF_85)). From 1979 ($442.88 in year 2000 dollars) to 2012 ($283.97 in year 2000 dollars), the average domestic air-ticket price has **reduced** in real-terms at an average of 1.3% per annum ([A4A 2013a](#_ENREF_4)). From 1990 ($1029.84 in year 2000 dollars) to 2012 ($926.66 in year 2000 dollars) (the available data-range), the average international air-ticket price has also **reduced** in real-terms at an average rate of 0.5% per annum ([A4A 2013b](#_ENREF_5)). It would seem a challenging task to turn this historic downward price-trend into the upward trend required to produce the necessary reduction in demand-growth.

Using international passenger travel from the USA in 2012 as an example, it is also instructive to consider the approximate value that the required annual price-increase would place on the annual CO2 emissions-saving. For the average USA international air-ticket price in 2012 of $1,235.51 ($926.66 in year 2000 dollars) ([A4A 2013b](#_ENREF_5)), a change from a 0.5% per annum reduction to a 1.4% per annum increase, equates to a $23.47 price rise. Multiplying the average distance for the trip (7,696 miles = 12,386 km) ([A4A 2013b](#_ENREF_5)) by a representative average emission factor for long-haul aviation (0.1176 kg CO2/passenger-km for 2012) ([DEFRA 2013](#_ENREF_20)) gives 1,457kg CO2 per passenger; so a 2.3% per annum reduction in CO2 emissions equates to 34kg. Therefore, the value of CO2 implied is $23.47/34kg, or $690/tonne (in year 2012 dollars). This result shows consistency with a 2009 study into aviation in a low-carbon EU which found that carbon-prices well in excess of $400/tonne (€300/tonne) were required to constrain emissions within acceptable limits ([Bows *et al.* 2009](#_ENREF_15)).

For comparison, examples of CO2 values from different areas around the world are as follows: EU emission allowances for the EU-ETS are currently approximately $6.50/tonne ([EEX 2013](#_ENREF_30)); emissions from non-traded sectors (i.e. sectors not included in the EU-ETS) are valued by the UK government for 2012 at $92/tonne (£56/tonne) ([DECC 2011](#_ENREF_23)); and the USA government values 2012 emissions at $37/tonne ($33/tonne in year 2007 dollars) ([IWG SCC 2013](#_ENREF_41)). So, the value placed on CO2 by the annual price-increase required to produce the necessary reduction in demand-growth ($690/tonne) ranges from approximately 7 to 100 times greater than these examples.

In the above scenarios the assumption was made that passenger load-factors would remain constant. If the result of price-increases is only to reduce load-factors, rather than reducing the number of ASKs, this is likely to produce greater CO2 emissions per RPK due to the increased number of empty seats; which, in-turn, will offset some of the gains made by reducing the growth in demand.

# 5. Conclusions

There are a number of important conclusions that can be drawn from this analysis of civil aviation’s direct CO2 emissions. In light of the unanimous forecasts for strong growth in demand for air transport, civil aviation is going to become an increasingly significant contributor to anthropogenic CO2 emissions.

The civil aviation industry is aware of this problem, and is taking steps to address the issue. Some mitigation-measures can be left to market-forces as the driving-force towards implementation. They are fuel-efficient aircraft technology and fuel-efficient operational procedures. These measures directly reduce airlines’ fuel consumption, and their impact on reducing fuel-costs will be welcomed by the industry.

Other mitigation-measures cannot be left to market-forces. They are MBMs, national Action Plans, alternative fuels, and possibly the global CO2 standard. Issues surrounding the speed of implementation and stringency of these measures will not be resolved unattended; strong stewardship is required because these issues will not work themselves out. Under the current global regulatory-framework, stewardship is not as strong as it needs to be. A global regulator with ‘*teeth*’ is required, but investing such a body with the appropriate level of authority requires securing an international agreement which history would suggest is going to be difficult (impossible?) to achieve.

Even if all the mitigation-measures currently on the table were to be successfully implemented, it is doubtful that a reduction in civil aviation’s overall absolute CO2 emissions could be achieved if forecast traffic-growth in the sector is realised. The gap between traffic growth-rates and emissions reduction-rates will remain, unless it can be closed through behaviour change to reduce demand for air-travel. However, reducing demand will be strongly resisted by all stakeholders in the civil aviation industry, including national governments and consumers; and the ticket price-increases necessary to induce the required reduction in traffic growth-rates value the CO2 emissions saved at 7 to 100 times greater than other common valuations.

The benefits of an extensive, well-connected aviation network are difficult to dispute, particularly for longer-distance travel where practical alternatives become limited. However, it is clear that, whilst aviation must remain one piece of the transport-jigsaw, from an environmental perspective there is an urgent requirement for a global regulator with ‘*teeth*’ to be established.

# References

Air Transport Action Group (ATAG) (2013a) *Flightpath - ICAO 38th Assembly September 2013*, Geneva, Switzerland and Montreal, Canada: Air Transport Action Group.

Air Transport Action Group (ATAG) (2013b) *Reducing emissions from aviation through carbon-neutral growth from 2020 - Working paper developed for the 38th ICAO Assembly September/October 2013*, Geneva, Switzerland and Montreal, Canada: Air Transport Action Group.

Airbus (2013) *Global Market Forecast - Future Journeys 2013 2032*, Blagnac, France: Airbus.

Airlines for America (A4A) (2013a) *Annual Round-Trip Fares and Fees: Domestic* [Online], Washington D.C., USA: Airlines for America. Available at: http://www.airlines.org/Pages/Annual-Round-Trip-Fares-and-Fees-Domestic.aspx [Accessed 09 December 2013].

Airlines for America (A4A) (2013b) *Annual Round-Trip Fares and Fees: International* [Online], Washington D.C., USA: Airlines for America. Available at: http://www.airlines.org/Pages/Annual-Round-Trip-Fares-and-Fees-International--.aspx [Accessed 09 December 2013].

Allen C, Toulson E, Edwards T and Lee T (2012) 'Application of a novel charge preparation approach to testing the autoignition characteristics of JP-8 and camelina hydroprocessed renewable jet fuel in a rapid compression machine', *Combustion and Flame,* 159(9)**,** 2780-2788.

Anger A (2010) 'Including aviation in the European emissions trading scheme: Impacts on the industry, CO2 emissions and macroeconomic activity in the EU', *Journal of Air Transport Management,* 16(2)**,** 100-105.

Anger A and Köhler J (2010) 'Including aviation emissions in the EU ETS: Much ado about nothing? A review', *Transport Policy,* 17(1)**,** 38-46.

Asia and Pacific Initiative to Reduce Emissions (ASPIRE) (2013) *Annual Report 2012*, Tokyo, Japan: Asia and Pacific Initiative to Reduce Emissions.

ASTM International (2011) *Aviation Fuel Standard Takes Flight* [Online], West Conshohocken, USA: ASTM International. Available at: http://www.astm.org/SNEWS/SO\_2011/enright\_so11.html [Accessed 06 June 2013].

Atma P, Kadambari L, Kamthe A and Sethi V. Advanced Novel Jet Engines Emission Modelling to Predict NOX & CO2 by Physics Based Model. 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 14-17 July 2013, San Jose, USA. American Institute of Aeronautics and Astronautics.

Boeing (2006) *Aero magazine - Qtr\_04 06*, Seattle, USA: The Boeing Company.

Boeing (2012) *Current Market Outlook*, Seattle, USA: Boeing.

Bows A and Anderson K (2007) 'Policy clash: Can projected aviation growth be reconciled with the UK Government's 60% carbon-reduction target?', *Transport Policy,* 14(2)**,** 103-110.

Bows A, Anderson K and Footitt A (2009) *Aviation in a Low-carbon EU. In: Climate Change and Aviation [Stefan Gössling and Paul Upham (eds.)]*, London, UK: Earthscan.

Brons M, Pels E, Nijkamp P and Rietveld P (2002) 'Price elasticities of demand for passenger air travel: a meta-analysis', *Journal of Air Transport Management,* 8**,** 165–175.

Campos J and de Rus G (2009) 'Some stylized facts about high-speed rail: A review of HSR experiences around the world', *Transport Policy,* 16(1)**,** 19-28.

Congress.gov (2012) *S.1956 - European Union Emissions Trading Scheme Prohibition Act of 2011* [Online], Washington D.C., USA: Congress.gov. Available at: http://beta.congress.gov/bill/112th-congress/senate-bill/1956 [Accessed 18 October 2013].

de Wit J G and Zuidberg J (2012) 'The growth limits of the low cost carrier model', *Journal of Air Transport Management,* 21**,** 17-23.

Department for Environment Food and Rural Affairs (DEFRA) (2013) *Greenhouse Gas Conversion Factor Repository* [Online], London, UK: Department for Environment Food and Rural Affairs. Available at: http://www.ukconversionfactorscarbonsmart.co.uk/ [Accessed 09 December 2013].

Department for Transport (DfT) (2013a) *Aviation Policy Framework*, Norwich, UK: The Stationery Office.

Department for Transport (DfT) (2013b) *RTFO Guidance Part Two: Carbon and Sustainability Guidance - RTFO Year 6: 15 April 2013 to 14 April 2014*, London, UK: Department for Transport.

Department of Energy & Climate Change (DECC) (2011) *A brief guide to the carbon valuation methodology for UK policy appraisal*, London, UK: Department of Energy & Climate Change.

Department of Energy & Climate Change (DECC) (2013) *Fossil Fuel Price Projections*, London, UK: Department of Energy & Climate Change.

Eurocontrol (2013) *Single European Sky (SES) regulations - Regulatory approach for the: Draft Interoperability Implementing Rule on Performance Based Navigation*, Brussels, Belgium: Eurocontrol.

European Commission (EC) (2012) *Decision of the European Parliament and of the Council - derogating temporarily from Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowance trading within the Community*, Brussels, Belgium: European Commission.

European Commission (EC) (2013a) *Compatible with international law* [Online], Brussels, Belgium: European Commission. Available at: http://ec.europa.eu/clima/policies/transport/aviation/index\_en.htm [Accessed 18 October 2013].

European Commission (EC) (2013b) *Directive of the European Parliament and of the Council - amending Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community, in view of the implementation by 2020 of an international agreement applying a single global market-based measure to international aviation emissions*, Brussels, Belgium: European Commission.

European Commission (EC) (2013c) *The EU Emissions Trading System (EU ETS)*, Brussels, Belgium: European Commission.

European Energy Exchange (EEX) (2013) *EU Emission Allowances - Primary Market Auction* [Online], Leipzig, Germany: European Energy Exchange. Available at: http://www.eex.com/en/Market%20Data/Trading%20Data/Emission%20Rights/EU%20Emission%20Allowances%20%7C%20Spot/spot-eua-table/2013-12-06 [Accessed 09 December 2013 2013].

Federal Aviation Administration (FAA) (2011) *Special Airworthiness Information Bulletin: Semi-Synthetic Jet Fuel*, Washington D.C., USA: Federal Aviation Administration.

Federal Aviation Administration (FAA) (2013) *NextGen Implementation Plan*, Washington D.C., USA: Federal Aviation Administration.

Fu X, Zhang A and Lei Z (2012) 'Will China’s airline industry survive the entry of high-speed rail?', *Research in Transportation Economics,* 35(1)**,** 13-25.

G8 Summit Declaration (2009) *Responsible Leadership for a Sustainable Future*, L’Aquila, Italy: G8 Summit 2009.

Government Accountability Office (GAO) (2013) *Aviation - Status of DOT’s Actions to Address the Future of Aviation Advisory Committee’s Recommendations (GAO-13-657)*, Washington DC, USA: Government Accountability Office.

Hendricks R C, Bushnell D M and Shouse D T (2011) 'Aviation fueling: A cleaner, greener approach', *International Journal of Rotating Machinery,* 2011**,** 1-13.

Her Majesty's Government (HMG) (2007) *The Renewable Transport Fuel Obligations Order 2007*, Norwich, UK: The Stationery Office.

Her Majesty's Government (HMG) (2011) *The Renewable Transport Fuel Obligations (Amendment) Order 2011*, Norwich, UK: The Stationery Office.

Holland M, Mann M, Ralph M, Owen B, Lee D, Horton G, Dickson N and Kollamthodi S (2011) *A marginal abatement cost curve model for the uk aviation sector. DfT aviation MACC study: Technical report: Final*, London, UK: Department for Transport.

Hooper P, Preston H, Wiles R and Thomas C (2009) *Omega Project - People Issues: Incorporating Passenger Expectation and Airline Business Models Workshop*, Manchester, UK: Manchester Metropolitan University.

Interagency Working Group on Social Cost of Carbon (2013) *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis - Under Executive Order 12866*, Washington D.C., USA: United States Government.

Intergovernmental Panel on Climate Change (IPCC) (2007) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri RK and Reisinger A (eds.)]*, Geneva, Switzerland: Intergovernmental Panel on Climate Change.

International Air Transport Association (IATA) (2013) *Fact sheet - Fuel*, Montreal, Canada: International Air Transport Association.

International Air Transport Association (IATA) (2014) *Fact sheet - Industry statistics*, Montreal, Canada: International Air Transport Association.

International Civil Aviation Organization (ICAO) (2000) *ICAO's Policies on Taxation in the Field of International Air Transport*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2010a) *Assembly 37-Resolution 19: Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2010b) *Assembly 37-Resolution 20: Consolidated statement of continuing ICAO policies in the air transport field - Appendix E - Taxation*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2010c) *Environmental Report - Aviation and Climate Change*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2011) *ICAO Strategic Objectives 2011-2013*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2012a) *Climate Change: Action Plan* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.icao.int/environmental-protection/Pages/action-plan.aspx [Accessed 18 October 2013].

International Civil Aviation Organization (ICAO) (2012b) *The EURASIA Reduced Vertical Separation Minima (RVSM) Task Force holds its last meeting after the successful implementation of RVSM and ICAO-compliant cruising levels in the Eastern Part of the ICAO European Region* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.paris.icao.int/news/20120404-rvsm.htm [Accessed 12 March 2013].

International Civil Aviation Organization (ICAO) (2012c) *International Civil Aviation Organization Submission to the Thirty-seventh Session of the United Nations Framework Convention on Climate Change Subsidiary Body for Scientific and Technological Advice (SBSTA 37) (26 November to 1 December 2012 – Doha, Qatar) - Agenda Item 11 (d): Emissions from fuel used for international aviation and maritime transport*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2012d) *New Progress on Aircraft CO2 Standard* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.icao.int/Newsroom/Pages/new-progress-on-aircraft-CO2-standard.aspx [Accessed 18 October 2013].

International Civil Aviation Organization (ICAO) (2013a) *A38-WP/430 Assembly 38th Session - Report of the Executive Commitee on Agenda Item 17 (Section on Climate Change)*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2013b) *Assembly 38th Session - Report of the Economic Commission on Agenda Item 40: Economic Development of Air Transport - Policy*, Montreal, Canada: International Civil Aviation Organization.

International Civil Aviation Organization (ICAO) (2013c) *Convention on International Civil Aviation* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.icao.int/publications/pages/doc7300.aspx [Accessed 18 October 2013].

International Civil Aviation Organization (ICAO) (2013d) *ICAO Environmental Protection Committee Delivers Progress on New Aircraft CO2 and Noise Standards* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.icao.int/Newsroom/Pages/ICAO-environmental-protection-committee-delivers-progress-on-new-aircraft-CO2-and-noise-standards.aspx [Accessed 18 October 2013].

International Civil Aviation Organization (ICAO) (2013e) *ICAO in Brief.* [Online], Montreal, Canada: International Civil Aviation Organization. Available at: http://www.icao.int/about-icao/Pages/default.aspx [Accessed 18 October 2013].

International Civil Aviation Organization (ICAO) (2013f) *Report on the Assessment of Market-based Measures*, Montreal, Canada: International Civil Aviation Organization.

International Transport Forum (ITF) (2012) *Transport Outlook 2012*, Paris, France: International Transport Forum - Organisation for Economic Co-operation and Development.

Kahn Ribeiro S, Kobayashi S, Beuthe M, Gasca J, Greene D, Lee D S, Muromachi Y, Newton P J, Plotkin S, Sperling D, Wit R and Zhou P J (2007) *Transport and its infrastructure. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)]*, Cambridge, UK and New York, USA: Cambridge University Press.

King D, Inderwildi O, Carey C, Santos G, Yan X, Behrendt H, Holdway A, Owen N, Shirvani T and Teytelboym A (2010) *Future of Mobility Roadmap - Ways to Reduce Emissions While Keeping Mobile*, Oxford, UK: Smith School of Enterprise and the Environment.

Lassen C, Laugen B T and Næss P (2006) 'Virtual mobility and organizational reality – a note on the mobility needs in knowledge organisations', *Transportation Research Part D: Transport and Environment,* 11(6)**,** 459-463.

Lee D S, Fahey D W, Forster P M, Newton P J, Wit R C N, Lim L L, Owen B and Sausen R (2009) 'Aviation and global climate change in the 21st century', *Atmospheric Environment,* 43(22-23)**,** 3520-3537.

Lee D S, Owen B, Graham A, Fichter C, Lim L L and Dimitriu D (2005) *Study on the Allocation of Emissions from International Aviation to the UK Inventory–CPEG7 - Final Report 2 of 3 to Defra - Allocation of International Aviation Emissions from Scheduled Air Traffic - Present Day and Historical*, Manchester, UK: Centre for Air Transport and the Environment.

Lee D S, Pitari G, Grewe V, Gierens K, Penner J E, Petzold A, Prather M J, Schumann U, Bais A and Berntsen T (2010) 'Transport impacts on atmosphere and climate: Aviation', *Atmospheric Environment,* 44(37)**,** 4678-4734.

Lei Z and O’Connell J F (2011) 'The evolving landscape of Chinese aviation policies and impact of a deregulating environment on Chinese carriers', *Journal of Transport Geography,* 19(4)**,** 829-839.

Lei Z and Papatheodorou A (2010) 'Measuring the effect of low-cost carriers on regional airports' commercial revenue', *Research in Transportation Economics,* 26(1)**,** 37-43.

Lu J-L and Peeta S (2009) 'Analysis of the factors that influence the relationship between business air travel and videoconferencing', *Transportation Research Part A: Policy and Practice,* 43(8)**,** 709-721.

Morris J, Rowbotham A, Morrell P, Foster A, Poll I, Owen B, Raper D, Mann M and Ralph M (2009) *UK Aviation: Carbon Reduction Futures. Final Report to the Department for Transport*, Manchester, UK: Centre for Air Transport and the Environment & Cranfield University.

Owen B (2008) *Omega Project - Fuel efficiency development and prediction*, Manchester, UK: Manchester Metropolitan University.

Owen B and Lee D S (2005) *Study on the Allocation of Emissions from International Aviation to the UK Inventory–CPEG7 - Final Report 1 of 3 to Defra - International Aviation Emissions Allocation - Allocation Options 2 and 3.*, Manchester, UK: Centre for Air Transport and the Environment.

Preston H, Lee D S and Hooper P D (2012) 'The inclusion of the aviation sector within the European Union's Emissions Trading Scheme: What are the prospects for a more sustainable aviation industry?', *Environmental Development,* 2**,** 48-56.

Randles S and Mander S (2009) 'Aviation, consumption and the climate change debate: ‘Are you going to tell me off for flying?’', *Technology Analysis & Strategic Management,* 21(1)**,** 93-113.

SESAR Joint Undertaking (2011a) *Atlantic Interoperability Initiative to Reduce Emissions (AIRE) - Summary of results 2010/2011*, Brussels, Belgium: SESAR Joint Undertaking.

SESAR Joint Undertaking (2011b) *SESAR - Modernising the European sky*, Brussels, Belgium: SESAR Joint Undertaking,.

Singh A and Olsen S I (2011) 'A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels', *Applied Energy,* 88(10)**,** 3548-3555.

Subhadra B and Edwards M (2010) 'An integrated renewable energy park approach for algal biofuel production in United States', *Energy Policy,* 38(9)**,** 4897-4902.

United Nations (UN) (1992) *United Nations Framework Convention on Climate Change*, New York, USA: United Nations.

United Nations (UN) (1998) *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, New York, USA: United Nations.

United Nations (UN) (2012) *Doha amendment to the Kyoto Protocol*, New York, USA: United Nations.

Van Gerpen J (2005) 'Biodiesel processing and production', *Fuel Processing Technology,* 86(10)**,** 1097-1107.

Webb N, Broomfield M, Cardenas L, MacCarthy J, Murrells T, Pang Y, Passant N, Thistlethwaite G, Thomson A, Gilhespy S, Goodwin J, Hallsworth S, Hobson M, Manning A, Martinez C, Matthews R, Misselbrook T, Salisbury E, Venfield H and Walker C (2013) *UK Greenhouse Gas Inventory, 1990 to 2011 - Annual Report for Submission under the Framework Convention on Climate Change*, London, UK: Department of Energy and Climate Change.

Wood F R, Bows A and Anderson K (2010) 'Apportioning aviation CO2 emissions to regional administrations for monitoring and target setting', *Transport Policy,* 17(4)**,** 206-215.

World Economic Forum (WEF) (2013) *The Global Competitiveness Report 2012-2013*, Geneva, Switzerland: World Economic Forum.