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Review

Direct carbon dioxide emissions from civil aircraft



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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.

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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 7–100 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.

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"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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1. Introduction

The beginning of significant aviation activity is commonly held to be 1940 (Lee et al., 2010). 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, 2013e). Growth of the civil aviation industry since 1940, in terms of fuel-consumed, is shown in Fig. 1.

Growth in passenger traffic since 1970, in terms of Revenue-Passenger-Kilometres (RPKs), is also shown in Fig. 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). The 2008 financial crisis, and subsequent global recession, reduced air traffic growth-rates (ICAO, 2010c). However, the ITF predict continued fast growth in the sector is likely over the next decades (ITF, 2012). Various key industry stakeholders agree with this prediction (e.g. ICAO, 2010c; IATA, 2014; Airbus, 2013; Boeing, 2012), 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.

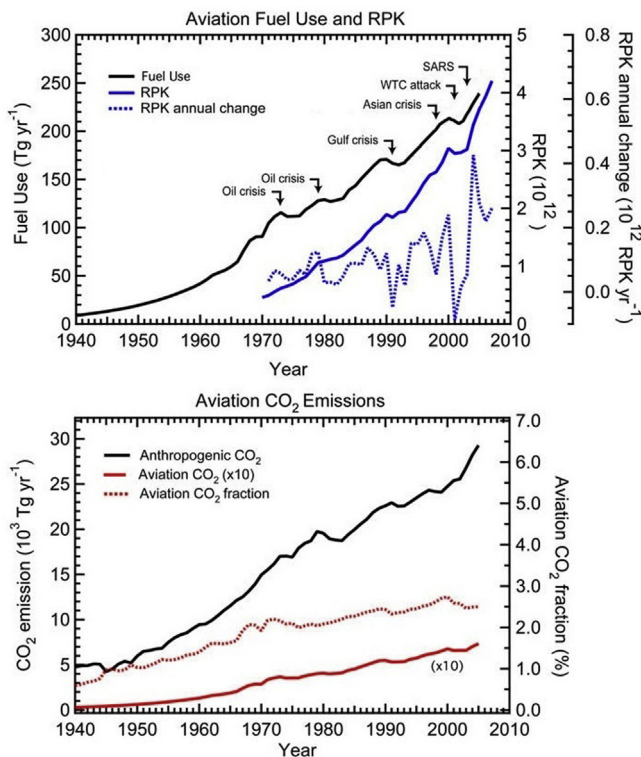


Fig. 1. Top: Aviation fuel-use starting in 1940, the beginning of significant aviation activity. Growth in passenger traffic from 1970 is shown in terms of RPKs, alongside annual change in RPK (far right hand axis, with offset zero). The arrows indicate the timings of significant world events which potentially 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 $\times 10$) 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).

The global airline industry now consumes in excess of 5 million barrels of oil per day (IATA, 2013). Emissions of CO₂ from aircraft engines are proportional to fuel-used by a factor of approximately 3.15 (Lee et al., 2009). CO₂ is the most important anthropogenic greenhouse gas (GHG) (IPCC, 2007), and is the principal GHG emitted by powered aircraft (Atma et al., 2013). Growth in aviation fuel-use and the associated CO₂ emissions are shown in Fig. 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), 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 (NO_x), soot and sulphates (Wood et al., 2010). Aviation's total instantaneous warming impact has been estimated at 2–4 times that of CO₂ emissions alone (Bows and Anderson, 2007); although there is still some uncertainty surrounding such estimates (Wood et al., 2010). 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.

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; ICAO, 2013e).

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), 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).

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), 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). 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). 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). 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). 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).

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). 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). 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; Webb et al., 2013). 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).

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). 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). 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). 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). 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). 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). 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) (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). 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).

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). 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). 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). 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).

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). 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). 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; Anger and Köhler, 2010), and it has been argued that more effective measures are available (King et al., 2010). 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), 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).

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). 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). 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).

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). 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). 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).

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).

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). 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). 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). 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), 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). Since 1960, aircraft fuel-efficiency has improved by approximately 70–80% (ITF, 2012), and some estimates suggest a further 40–50% improvement is achievable by 2050 (Kahn Ribeiro et al., 2007). 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).

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).

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). 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), with computational fluid dynamics modelling suggesting it can be reduced by 20–70% (King et al., 2010). 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), 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). 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). 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; King et al., 2010).

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 NO_x. Increases in fuel-efficiency tend to result in higher temperatures and pressures at the combustor inlet, thus increasing NO_x formation. Therefore, the challenge is to reduce fuel-consumption whilst also guarding against a tendency for increased NO_x production. For example, combustor designs that keep NO_x emissions down through incorporating additional cooling (Lee et al., 2010).

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).

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). 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).

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). 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; Kahn Ribeiro et al., 2007; ICAO, 2010c; Van Gerpen, 2005; Allen et al., 2012; FAA, 2011).

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; ICAO, 2010c; FAA, 2011; King et al., 2010; ASTM International, 2011).

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). 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). 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; Subhadra and Edwards, 2010). 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). However, high costs are a key problem, with processing and infrastructure challenges remaining to be overcome before commercial viability can be reached (ICAO, 2010c; Hendricks et al., 2011).

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; HMG, 2011; DfT, 2013b). 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 160 kg of CO₂ emissions (King et al., 2010).

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).

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; King et al., 2010; FAA, 2013; SESAR JU, 2011a, 2011b; ASPIRE, 2013).

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). Environmental studies have concluded that RVSM has reduced fuel-use (Owen, 2008); 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; Eurocontrol, 2013).

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).

3.4. Aggregated impact study

A recent study by King et al. (2010) 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). 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). 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). 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 ongoing 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).

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, 2010b, 2013b). 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; IATA, 2014). 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). 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). 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). The optimal whole-journey time for HSR is 3–4 h, with its time-advantage over aviation disappearing when the whole-journey time by train exceeds 4 h (Fu et al., 2012). 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; Lu and Peeta, 2009).

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).

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): 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); the Chinese Government see the airline industry as a "strategically important asset to national competitiveness and regional development" (Lei and O'Connell, 2011); 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). 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). A further factor affecting individual behaviour is the worldwide 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; de Wit and Zuidberg, 2012).

Regarding virtual-mobility, Randles and Mander (2009) 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).

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). 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:

$$1.04 \text{ (from RPK growth)} \times 0.977 \text{ (from CO}_2 \text{ reduction)} \\ \times \text{Behaviour Change Factor} = 1$$

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 (Bronson et al., 2002). 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). 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). 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). 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 \$1235.51 (\$926.66 in year 2000 dollars) (A4A 2013b), 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 (7696 miles = 12,386 km) (A4A 2013b) by a representative average emission factor for long-haul aviation (0.1176 kg CO₂/passenger-km for 2012) (DEFRA, 2013) gives 1457 kg CO₂ per passenger; so a 2.3% per annum reduction in CO₂ emissions equates to 34 kg. Therefore, the value of CO₂ implied is \$23.47/34 kg, 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).

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); 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); and the USA government values 2012 emissions at \$37/tonne (\$33/tonne in year 2007 dollars) (IWG SCC, 2013). So, the value placed on CO₂ by the annual price-increase required to produce the necessary reduction in demand-growth (the \$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.

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