# A Comparison of Aviation Greenhouse Gas Emission Mitigation Policies for Europe

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**This paper integrates the results of a set of studies looking at UK and European aviation environmental policy measures. It uses a model of the European air transport system to assess the economic costs and environmental benefits associated with proposed emission mitigation strategies. In particular, we concentrate on the potential penetration of fuel-saving technologies and operations, lower carbon alternative fuels and high-speed rail in response to the European Union Emissions Trading Scheme, and the effect on $CO_2$ emissions that this has in both the UK and Europe. A special emphasis is placed on the interaction effects of multiple mitigation policies. We find that a combination of policies could potentially allow UK and European lifecycle aviation $CO_2$ emissions in 2050 to be reduced to below year-2005 levels. Although other operational and technological measures can reduce aviation $CO_2$ emissions by up to 15% compared to an unconstrained base case, the largest part of this reduction comes from the interaction between carbon trading and cellulosic biomass fuels.**

## I. Introduction

THE European air transport system faces a number of significant challenges. Although continuing growth of 3-4% per year in intra-European RPKM is forecast[1,2], that growth is subject to strong political and environmental pressures. As the world region with the highest current level of political and journalistic concern about aviation's environmental impact, it may also present a test case for the future evolution of the global aviation system under climate policy constraints. Recently, the inclusion of aviation emissions into the European Union (EU) Emissions Trading Scheme (ETS) in 2012 has been confirmed[3]. In order to fulfill its obligations under this scheme, European aviation must either reduce its $CO_2$ emissions to a level consistent with the EU-specified cap, buy allowances from other sectors, or apply some combination of emissions reductions and allowance purchases. Impact analyses of the effect of adding aviation to the EU ETS have suggested that aviation is likely to be a net purchaser of allowances[4] because of the high cost of emissions mitigation in the aviation sector relative to other sectors. In this case it is possible that only a limited number of technology-based mitigation strategies will be adopted in aviation. Similarly, the introduction of alternative fuels with lower fuel lifecycle carbon emissions may be limited. Such a scenario, in which aviation emissions continue to grow but aviation carbon trading funds extra emission reductions in other sectors, is in conflict with the UK's aviation-specific emission reduction goal to reduce aviation $CO_2$ to below year-2005 levels by 2050[5].

The choice of an airline to adopt fuel and emission-saving measures in the presence or absence of emissions trading is primarily an economic one. Currently, there exist a range of fuel-saving measures which are adopted by different airlines, depending on their business model and fleet. For example, older aircraft may be retrofitted with winglets or re-engined, maintenance intervals may be decreased to reduce the effects of engine and/or airframe deterioration with time, and airlines may promote continuous descent approaches or attempt to increase passenger load factors. A number of other promising technological and operational measures designed to reduce fuel consumption and emissions are currently under development. For example, the SESAR project aims to reduce European air traffic control inefficiencies[6], and could potentially deliver a fuel saving of up to 10%[7]. Radical new airframe and engine designs, such as blended wing body aircraft and open

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rotors, may deliver even larger fuel savings. One potential major resource available to airlines looking to lower their lifecycle carbon emissions is the development of cellulosic biomass-based biofuels. An aircraft using drop-in biofuels does not have lower airborne emissions for the same utilization, but total fuel lifecycle emissions may be significantly reduced compared to conventional jet fuel due to the extraction of carbon dioxide from the atmosphere during the growth of the biofuel feedstock, with the amount of reduction depending on the specific biofuel selected[8]. However, there remain land use and production problems which must be overcome before widespread aviation biofuel usage can become a feasible option.

In the absence of regulation requiring airlines to adopt a specific emission reduction measure, each of these options will only be implemented by airlines if it is cost-effective for them to do so. This decision will be strongly affected by the anticipated oil price and, in the case where carbon trading is applied, by carbon prices. Recent studies[9,10] have suggested that significant present-day, near-future and long-term aviation emissions reductions are potentially achievable from a combination of technological and operational mitigation measures. Should these measures be cost-effective, aviation may be able to fulfill some of its emissions trading responsibilities by reducing emissions rather than purchasing allowances, and the UK's aviation emission reduction target may be achievable.

However, the interaction between different mitigation measures, and between those measures and scenario variables such as population, gross domestic product (GDP) and oil price, is potentially complex. Some of the mitigation measures that are induced by the ETS may interact with each other and with other, less environmentally-motivated policies (e.g. decisions about whether or not to add capacity at congested airports) to produce results which are not as expected. For example, widespread adoption of biofuels may make some other fuel-saving measures no longer cost-effective. Capacity increases may increase demand by reducing delay levels, but can also reduce emissions on a per flight basis by lowering the amount of delay incurred with the engines running. A high oil and/or carbon price may induce manufacturers and airlines to invest in open rotor engines, which will then remain in the fleet even if the oil and/or carbon price subsequently drops. A further complicating interaction is the promotion of High-Speed Rail (HSR) by European governments. For example, the UK government has proposed a high-speed rail link joining London, Manchester and Scotland by 2030[11]. These links could significantly lower demand for domestic UK air travel, and hence reduce emissions from aviation. It is therefore useful, in a situation where multiple policies are likely to be applied, to assess their impact by simultaneous modeling of these policies which also takes into account capacity, delay and demand-related issues.

As a methodological framework, we use a model of the global aviation system developed under the Aviation Integrated Modelling (AIM) project[12]. Established in 2006, the AIM project has the objective of developing a modular policy assessment tool to simulate the interplay between aviation's operational, economic and environmental aspects. It has recently been used to analyze emissions trading policies in the US, India[13] and Europe[14]. In the study presented in this paper, we use the AIM project model of Europe to provide a balanced assessment of the separate and combined effects of different mitigation policies in the UK and Europe. Many of the technology and fuel options considered in this study were prepared by the UK's Omega consortium, a group of nine universities with expertise in aviation and environmental issues. Among the more than 40 Omega studies, some have focused on costing the environmental effects of aviation[15], assessing the climate impacts of non-optimal ATM procedures[7], looking at the potential for utilizing sustainable fuels[8], estimating marginal abatement cost curves (MACs) for mitigation procedures[9], and looking at the environmental effects of fleet turnover[16]. Outputs from these studies include models and quantitative results which are suitable for incorporation into wider modeling and have been adopted for this paper.

The structure of this paper is as follows: A brief description of the components of AIM and of the separate Omega studies relevant to this study is given in Section II. Section III presents results for UK and European aviation to 2050 under different background scenario and policy combinations, and includes a discussion of policy interaction effects and target achievability. Finally, Section IV summarizes the paper, and draws conclusions.

## II. Modeling

### A. AIM

The Aviation Integrated Model is a modular tool intended to simulate the interaction between the global operational, economic, technological and environmental aspects of aviation. It consists of seven separate modules: Aircraft Technology and Cost, Air Transport Demand, Airport Activity, Aircraft Movement, Regional Economics, Air Quality and Noise, and Global Climate. To reduce the scope of this study, we use the initial four modules only and output total pollutant release by location rather than the climate effect (e.g. in terms of radiative forcing) of these pollutants. The interactions between the modules, and the policy levers which may be applied in each case, are illustrated in Figure 1. Further details of the model structure and the modeling carried out within each module may be found in Refs. 12-14; however, a brief summary of each of the modules used in this study is given below.

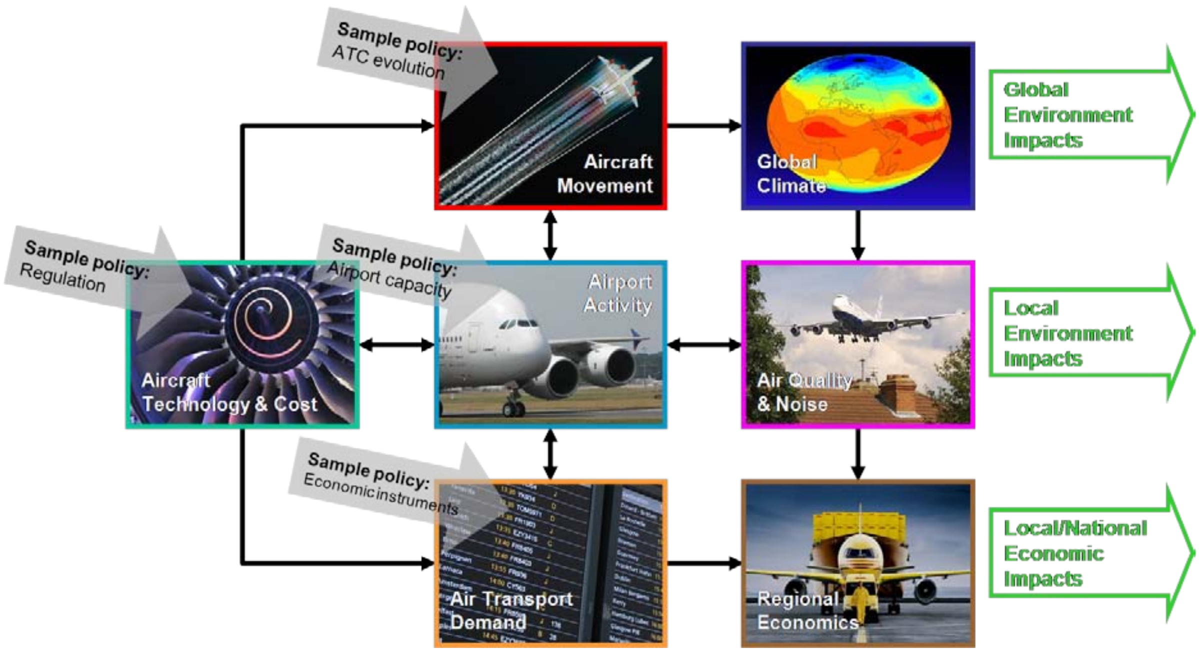


**Figure 1. The Aviation Integrated Model modular structure, outputs and policy lever input sites.**

*1. Aircraft Technology and Cost Module*

The fuel burn, emissions and costs associated with operating a given aircraft model by stage length and load factor are simulated by the Aircraft Technology and Cost Module. Aircraft performance modeling below 3,000 feet is based on the ICAO engine exhaust emission data[17] and the ICAO reference Landing and Take-Off cycle[18], with taxi times determined by the Airport Activity Module. Above 3,000 feet, all flight phases are modeled using the Eurocontrol Base of Aircraft Data (BADA)[19]. Route-specific airborne delays and routing inefficiencies are obtained from the Airport Activity and Aircraft Movement Modules.

The global fleet is modeled using six reference aircraft types for old/new (pre-/post-1995) technology and small/medium/large (under 190 seats, 190-299 seats, over 300 seats) size classes: the B737-300/A319, B767-300ER/A330-300, and B747-400/B777-300. Fleet turnover and incremental improvements in new aircraft technology are accounted for using a simple stock model based on Ref. 16. It is assumed that incremental improvements in new aircraft model fuel burn (specifically excluding radical technology changes and retrofits which are treated as an airline choice, as described in Section IIC) proceed at a rate of 1% reduction per year. For already-existing aircraft, an increased fuel burn of 0.2% per year of age is assumed to account for performance deterioration.

The costs associated with owning and operating aircraft by model are taken from US Form 41 data[20], adjusted for regional differences in operating costs[21]. Navigation charges are obtained from Ref. 22 and the extra costs associated with delays are obtained from the Airport Activity Module.

*2. Air Transport Demand Module*

The Air Transport Demand Module simulates the demand for passenger air travel by true origin-ultimate destination city-pair, based on city characteristics, the background socioeconomic scenario, the airline costs obtained from the Aircraft Technology and Cost Module and the travel times calculated in the Airport Activity Module. A simple gravity model is utilized to project demand by city-pair:

$$D_{ij} = (I_i I_j)^{\alpha} (P_i P_j)^{\gamma} e^{\delta A_{ij}} e^{\varepsilon B_{ij}} e^{\varphi S_{ij}} e^{\omega DF_{ij}} e^{\theta R_{ij}} e^{\beta H_{ij}} C_{ij}{}^{\tau} \quad , \tag{1}$$

where $D_{ij}$ is the passenger demand between cities i and j; $I_i$ and $P_i$ are the population and per capita income associated with city i; $A_{ij}$ and $B_{ij}$ indicate whether one or both of the cities i and j is a major tourist or business center; $S_{ij}$ indicates whether one of the cities is a major international hub airport; $DF_{ij}$ indicates whether the journey is a domestic one; $R_{ij}$ indicates whether a road link exists between i and j; $H_{ij}$ indicates whether a high-speed rail link exists between i and j; and $C_{ij}$ is the generalized cost of travelling by air between i and j, including fare and time (and delay) costs. $\alpha/2$, $\gamma/2$, $\delta$, $\varepsilon$, $\varphi$, $\omega$, $\theta$, $\beta$ and $\tau$ are the elasticities associated with each of these terms. Base year city data was obtained from country-specific censuses and surveys (e.g. Ref. 23). Base year fares and journey times were estimated using published information on yields by flight distance[24], delays, differences between low-cost and legacy carriers[25] and schedules[26]. Elasticities were estimated using an assignment matrix approach as in Ref. 13, using segment passenger number data from Ref. 27. All parameters are significant at the 95% level and are reasonable in comparison to literature values[28]. The $R^2$ obtained was 0.47.

For years after the 2005 base year, population and income were adjusted to reflect the scenario inputs described in Section IIB. Proposed future high-speed rail links were obtained from press releases and government feasibility studies by country (e.g. Ref. 11). Future journey times including delays and airline costs were obtained from the Airport Activity and Aircraft Technology and Cost Modules. Obtaining fares from airline costs requires making assumptions about airline profits and competition. For this study, we assume that airline rates of return remain constant in all markets, as modeled in Ref. 29. All base year and scenario currency totals are converted to year 2005 dollars using market exchange rates.

### 3. *Airport Activity Module*

Taking passenger demand from the Air Transport Demand Module, the Airport Activity Module generates the resulting global air traffic schedules, aircraft movements by city-pair, delays and capacity requirements. Passenger routing is assumed to remain unchanged from the 2005 base year. Schedules by aircraft size are then generated as a function of passenger demand, segment length and network type (hub-hub, hub-spoke or point-to-point) according to a multinomial logit regression on historical data[26], with base year segment passenger load factors used to obtain flight frequencies. These approaches are similar to those used in Ref. 30. To estimate delays, airport capacities are required. Published airport capacities were used where available[31]. Where these were not obtainable, capacities were estimated using simple runway capacity models[32] and standard capacity estimation charts corresponding to different airport runway configurations[7]. Ground and airborne holding delays due to airport capacity constraints were then estimated as a function of capacity and flight frequencies using queuing theory, applying the cumulative diagram approach and classical steady state simplifications described by Ref. 33. These were added to gate departure delays, which were assumed to remain at current levels. The distribution of runway departure delays between the taxiway and departure gate was calculated according to a taxi-out threshold based on historical US taxi-out data[34], above which delay was assumed to be propagated upstream to the departure gate. A similar procedure was used to distribute destination airport delays between the air and the ground, using US enroute delay data[34].

Future projections of airport capacity tend to be short-term and focused on capacity expansions which are already in the planning or construction stage. Rather than use external projections of capacity, we therefore simulate future airport capacity expansion within the Aviation Integrated Model by assuming that capacity expansion will occur as required to serve forecast demand such that delays remain close to present-day levels. In Europe, this capacity expansion may come from more intensive use of runways and increased use of secondary airports, as well as possible infrastructure expansion.

### 4. *Aircraft Movement Module*

The Aircraft Movement Module takes the schedules generated by the Airport Activity Module and generates the location and amount of emissions released by the simulated aircraft, using data from the Aircraft Technology and Cost Module. Flight routing inefficiencies, in the form of extra distance flown beyond the shortest ground track distance above the theoretical optimum for a given aircraft and airport-pair, are modeled as in Refs. 35-36, using archived European flight track and flight data recorder data. These inefficiencies come from a variety of sources including separation requirements, standard procedures in terminal and en route airspace, avoidance of restricted airspace or adverse weather, and congestion. Inefficiencies arising from technological limits within the present-day air traffic control system will be partly addressed by SESAR, as described in Section IIC, but safety constraints, such as separation requirements, cannot be completely removed from the system.

## B. Scenarios

### 1. *City Set*

The global AIM model uses a set of 700 cities for which airport-level, demographic and socioeconomic data have been gathered, containing 1127 airports and accounting for about 95% of global scheduled revenue passenger-kilometers (RPKM)[26]. For modeling Europe we use the corresponding European subset, which contains 173 cities and 337 airports. The corresponding UK subset, for which we also present results, contains 17 cities and 36 airports. Although the European subset includes some countries of the Former Soviet Union, we present results only for the European Union region. In order to adequately calculate delay and capacity requirements, we also need to know the number of passengers and flights entering and leaving the European set of airports. For the purposes of this paper, base year demand to and from regions outside Europe is stored by region-city pair (e.g. South America – London). In years after the base year, this demand is scaled up using a simple income elasticity-based model and income projections by world region.

### 2. *Future population, growth and capacity assumptions*

To model future growth we need scenario-based projections of some key variables. The main scenario inputs required by AIM are population and income growth (for estimating passenger demand), future airport capacity scenarios (for estimating flight delays), and oil and carbon prices (for calculating airline costs). In this paper, we use scenarios of future UK region, European and world region growth from the UK Climate Change Committee (CCC)[**]. Three main background scenarios are utilized, with high, medium and low fuel+carbon prices. A brief summary of the main characteristics of these scenarios is given in Table 1. Population growth for regions outside the UK is taken from the UN World Population Prospects Medium Variant[37].

**Table 1. Selected characteristics of the socioeconomic scenarios used in this paper.**

| Scenario | Average annual GDP/capita growth rate (UK, 2005-2050) | Average annual GDP/capita growth rate (EU, 2005-2050) | 2020 Oil Price, \$2005/bbl | 2020 Carbon Price, \$2005/tonne $CO_2$ |
|---|---|---|---|---|
| **Central** | 1.4% | 1.9% | 74 | 63 |
| **Low** | 1.2% | 1.7% | 56 | 27 |
| **High** | 2.1% | 2.2% | 139 | 86 |

## C. Policy and Mitigation Inputs

Strategies aimed at reducing aviation's environmental impact fall into three main categories: economic, technological and operational. In this paper we consider the EU ETS as a sample economic strategy; retrofits, maintenance changes, open rotors and biofuels as sample technological strategies; and SESAR as a sample operational strategy. In addition, demand for aviation can be reduced by the provision of suitable alternatives to flying, such as high-speed rail or videoconferencing. In this paper we consider high-speed rail as such an alternative.

Economic measures, such as taxes, local emissions-based charges and emissions trading, typically seek to lower passenger demand by increasing the cost of flying, and/or incite airlines to take other fuel-saving measures which will reduce their fuel and/or carbon costs. Technological measures (which may be prompted by economic measures) include aircraft retrofits and the development of new, lower-carbon models of engines and airframes. In particular, biofuels offer the potential to reduce total lifecycle carbon emissions through the use of renewable feedstocks. Operational measures seek to reduce emissions by changing the way that existing aircraft are used, for example implementing continuous descent arrivals or reducing routing inefficiencies. High speed rail offers an alternative, potentially low-$CO_2$ emissions transportation alternative which may reduce demand for aviation on some routes. In this paper, we model a range of measures based primarily on outputs from the Omega studies detailed in Section I. They are applied cumulatively, with each new measure adding to the effect of previously-applied measures.

[**] These were CCC working assumptions as of Spring 2009 and are subject to change.

The inclusion of aviation in the EU ETS in 2012 is now confirmed[3] and emissions monitoring and reporting programs associated with the ETS are already being put in place. Therefore we include the EU ETS in our models as the first major policy option, and it is modeled in all policy scenarios considered. Likely future levels of carbon charging in the EU ETS are uncertain. Based on present-day permit prices, a near-future mid-range price of around €10-40 (year 2008 euros, corresponding to around $15-60 year 2005 dollars) per tonne of $CO_2$ seems reasonable[38]. The scenario values reported in Table 1 mainly fall close to this range. However, the exact values for carbon prices in any given year may be volatile[39] and will depend on future changes to the EU ETS. For example, if a global emissions trading scheme is established, carbon prices are likely to be lower than in a comparable Europe-only scheme, due to the increased availability of low-cost mitigation options in the developing world. However, if emissions caps are tightened significantly (perhaps in response to a specific atmospheric carbon concentration or global temperature change goal[40]), carbon prices are likely to rise beyond these levels. It is assumed that airlines pay in full for the allowances they receive.

The second major mitigation option we consider is a set of technological and operational abatement measures which may be introduced by airlines in response to increased fuel and carbon costs. The options we make available from the present day to airlines are retrofitting winglets to aircraft which do not already have them, applying engine upgrade kits, increasing airframe maintenance and increasing engine maintenance. After 2020, airlines are also given the option of adapting their aircraft, supplying crew training and paying greater navigation costs to take advantage of the improved routing offered by SESAR, and purchasing short-range aircraft with open rotor engines. Assumptions about the costs, introduction timescales and benefits of these mitigation options are taken from Refs. 9 and 41. It should be noted that the modeling of SESAR contains significant simplifications; in reality, some components of SESAR will be available well before 2020. One finding of Ref. 9 was that there are a number of measures, such as more frequent engine maintenance, which may be economic to introduce straight away but have not been widely introduced. We assume that these measures will be introduced, i.e. we do not consider extra barriers to technology adoption. To calculate the uptake of each option, we also require assumptions about how airlines will decide whether a technology option is economic for them to introduce. For simplicity, we use a payback period of seven years, i.e. it is assumed that airlines will invest in fuel-saving technology only if fuel and maintenance cost savings over seven years are equal to or greater than the up-front costs of installing the technology (plus any resulting maintenance or navigation cost increases).

The third major mitigation option we consider is the development of an aviation-suitable drop-in biofuel. Suitable alternative fuels for aviation were identified by the Omega project *Sustainable Fuels for Aviation*[8]. In particular, costs and lifecycle emissions were estimated for those alternative fuels that met the stringent aviation requirements for fuel suitability. Future alternative fuels scenarios can vary widely in terms of airline costs and emissions depending on the fuel assumed. We take as our main alternative fuels case the effect of introducing synthetic aviation jet fuel from cellulosic biomass in a 50% blend with Jet A, available from 2020. Aviation biofuel prices are assumed to be at least 70 US cents per litre[8] or – following the profit-maximizing behavior of the fuels industry – equivalent to the costs of Jet A, whichever value is higher. One major obstacle to the introduction of aviation biofuels is likely to be production capacity. If production begins in 2020, it is unlikely that a large enough volume of fuel will be produced to serve the entire European aviation industry for some years, even if aviation is the main consumer of biofuel. Therefore we limit yearly production increases limited to historically-observed rates from the Brazilian proEthanol program[42]. In order to capture the full impact of alternative fuels, we consider lifecycle $CO_2$ emissions from aviation, which include the upstream emissions associated with the production of the synthetic jet fuel, its delivery to the airport and the combustion process, *i.e.*, a well-to-wake analysis.

The fourth and final major mitigation option we consider is the introduction of new high-speed rail networks over the period 2005-2030. In Europe, a number of high-speed rail (here defined as rail lines capable of handling 300 $kmh^{-1}$ traffic for all or nearly all of the city-pair routes in question) networks exist. These include the French TGV and Spanish AVE systems, and the High-Speed 1 Eurostar route linking London with Paris and Brussels. Further development of high-speed rail has been promoted as an option for reducing aviation demand and hence emissions. For example, a high-speed route between London and Scotland, via Manchester, has been proposed for 2030[11]. We include development of high-speed rail links as an additional option that governments may take to lower aviation demand and hence emissions, as specified in Section IIA.2. Whilst currently-existing high-speed links are modeled in all scenarios, proposed extensions to the French TGV, Spanish AVE, Italian TAV, German ICE and Eurostar high-speed networks are modeled only when high-speed rail is specified as a policy option. We do not model emissions from high-speed rail networks; when interpreting the results from the high-speed rail scenarios it should be borne in mind that these scenarios will have increased ground-level emissions.

## III. Sample Case Studies

Full simulations of the UK and European aviation systems were run for all combinations of the background scenario and policy cases. In summary these are, for each of the high, low and central background scenarios:

- The unconstrained base case in which no policies are applied.
- The EU ETS is applied to aviation, but no other policies are applied.
- As well as the ETS, the uptake of operational and technological mitigation measures by airlines is modeled, with the exception of alternative fuels.
- In addition, the adoption of alternative fuels is modeled.
- All mitigation measures, including future high-speed rail networks, are modeled.

Caution should be taken when interpreting these results as the different reductions in lifecycle emissions are not independent. For example, although biofuels have, as shown, a significant emission reduction effect when carbon trading is also in place, the impact of biofuels without carbon trading is minimal, because airlines have zero carbon costs and hence much lower pressure to reduce their emissions. Different mitigation measures may also have strongly differing effects on $CO_2$ emissions and RPKM. For example, carbon trading without any other measures lowers $CO_2$ primarily by increasing fares and hence reducing the total RPKM flown. Making biofuels available in a carbon trading scenario lowers lifecycle $CO_2$ emissions but raises RPKM compared to a trading case without biofuels, because airline carbon costs and hence fares are lowered. It should also be noted that, where results are presented for European 'domestic' traffic, this refers to flights within and between the set of European cities mentioned in Section IIB.

Figure 2 shows the RPKM response in each combination of background and policy scenarios. The corresponding fuel lifecycle $CO_2$ emissions response is shown in Figure 3. Background data from ICAO[43] (for Europe), Transport Statistics Great Britain[44] and the UK Department for Transport[46], as well as projected growth rate trends from Airbus[1] and Boeing[2] are also shown, for comparison.

A number of general points are notable. RPKM in both the UK and Europe continues to grow in all scenarios, even when all policy measures are applied. As discussed in Ref. 14, the growth rates we predict are lower than those projected by Airbus and Boeing, although not outside the range of those projected for the European region (e.g. Ref. 45). Whilst the UK Department for Transport projections for UK travel[46] do not report UK domestic RPKM, their UK domestic central base case $CO_2$ emissions as shown in Figure 3 are very similar to those found in this study, as shown in Figure 3. Our total base case demand growth is similar in the Central, High and Low scenarios; in the High scenario, higher income growth rates encourage air travel but high oil and/or carbon prices result in higher fares, whereas in the Low scenario fares are lower but so is income growth. However, the policy response of these scenarios is significantly different. For example, in the High scenario, airlines have a much greater incentive to adopt new technologies which could lower their fuel and carbon costs. Whilst this does not produce a strong difference in response in terms of RPKM, it does produce a large difference in terms of emissions and fleet composition by 2050.

For Europe, the policy scenario which decreases RPKM by the greatest amount is the case in which only emissions trading is applied. However, even in this case RPKM is reduced by less than 10% from the unconstrained base case. The effect of emissions trading is directly linked to the allowance price, with the Low scenario showing a decreased response. For the UK, the decrease in RPKM demand from 2030 of around 15% from the base case in the 'all policies' scenario is mainly due to the implementation of high-speed rail on several major UK routes (e.g. London-Manchester, London-Edinburgh). The RPKM increases, and the relatively small response of RPKM totals to policy, are demonstrated by the required capacities at major airports as shown in Table 2. Although the majority of airports in the set modeled in this paper do not require capacity expansion before 2050 under the assumptions used here, most major international hub airports do. As discussed in Section IIA, the need for extra capacity at these airports may be met by changes in usage or by increased use of secondary airports rather than necessarily by new runways. Typically, the airports listed in Table 2 require up to a doubling of capacity by 2050 in the unconstrained base case. However, when all mitigation policies are applied, the required capacities are only a few movements per hour lower. As most of the mitigation measures investigated here reduce emissions by technological and/or operational means rather than reducing demand, numbers of aircraft movements and hence required capacities remain large; reducing required capacities significantly below this level would require either economic measures specifically aimed at reducing passenger numbers, or widespread provision of high-speed rail.

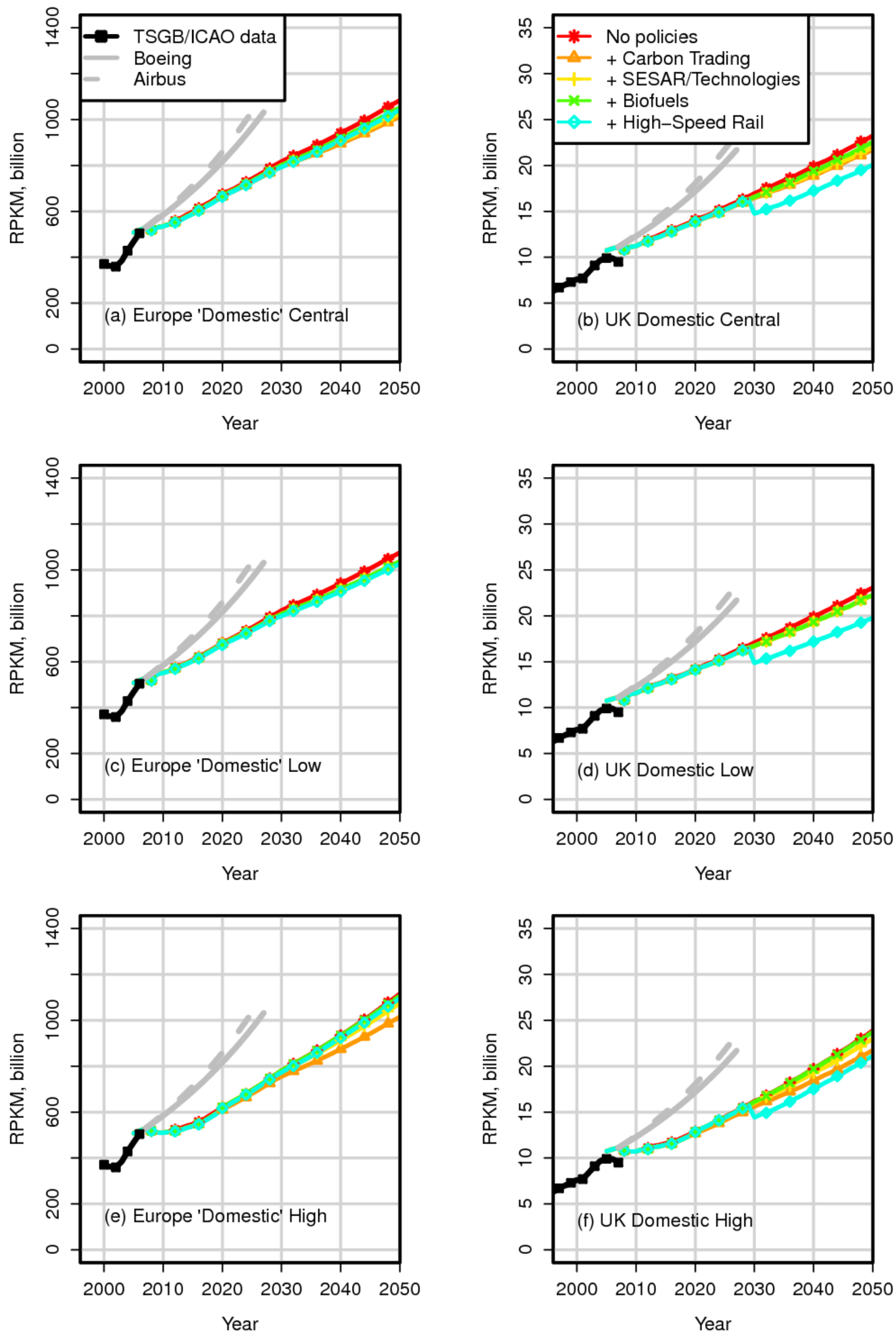


**Figure 2. European (panels (a), (c) and (e)) and UK (panels (b), (d) and (f)) domestic RPKM under different policy scenarios.**

**Table 2. Required capacities at some major airports in 2050 under different scenarios.**

| Airport | 2005 capacity , movements per hour | 2050 capacity, movements per hour | | | | | |
|---|---|---|---|---|---|---|---|
| | | Unconstrained Case | | | All Policies | | |
| | | Central | Low | High | Central | Low | High |
| **London Heathrow** | 75 | 143 | 141 | 147 | 137 | 133 | 143 |
| **London Gatwick** | 48 | 84 | 84 | 86 | 80 | 78 | 82 |
| **London Stansted** | 45 | 83 | 81 | 85 | 79 | 77 | 83 |
| **Paris Charles de Gaulle** | 110 | 198 | 194 | 206 | 188 | 184 | 196 |
| **Frankfurt am Main** | 75 | 129 | 123 | 135 | 127 | 123 | 135 |
| **Amsterdam Schiphol** | 100 | 164 | 162 | 168 | 160 | 158 | 166 |

Fuel lifecycle $CO_2$, as shown in Figure 3, however, does display significant reductions from the base case. In the case of carbon trading alone, the observed reduction in emissions is similar to the reduction in RPKM, as no extra fuel-saving measures are adopted in this scenario. However, when the airline response to emissions trading in terms of investing in retrofits, new technologies and operational measures is considered, reductions in airborne and lifecycle $CO_2$ emissions of around 15% (in the central case) can be obtained. Most of these benefits are the result of airlines adapting their aircraft to take advantage of SESAR, and occur after 2020. This is illustrated by Figure 4, in which the uptake of different mitigation measures by aircraft in the case that all policies are applied is shown. Before 2020, a small number of aircraft apply winglet retrofits and/or increased engine maintenance, but no measure is economic for the entire fleet to adopt. After this point, the response of the Central, Low and High scenarios differs. In the Central and High scenarios, SESAR's assumed introduction in 2020 prompts the adaptation of almost the entire fleet. As we assume a 10.5% reduction in fuel burn is achievable for a given aircraft through improved air traffic control[14], this translates to a significant decrease in overall fleet emissions. In addition, the substantial oil and carbon costs in the High scenario lead to the introduction of open rotor engines for the short-haul aircraft fleet. However, in the Low scenario, the mitigation measures considered here are not cost-effective to implement for most of the fleet (it is likely in reality that SESAR compliance would be required to fly in Europe from some threshold date, so the low SESAR uptake in this scenario may not be realistic).

If, in addition, biofuels are assumed to be made available to aviation from 2020, significant reductions in lifecycle $CO_2$ emissions can be made. In both the European and UK Central and High cases, 2040 aviation fuel lifecycle emissions are well below year-2005 levels if biofuels are available. This is a result specifically of the lifecycle emission characteristics of the chosen cellulosic biomass fuel blend[8]. As airlines are able to lower their carbon costs by adopting biofuels in this scenario, fares are reduced and hence demand, as shown in Figure 2, is actually higher than in the carbon trading only or carbon trading plus SESAR/technologies cases. In Figure 4, it can be seen that biofuels become economic to adopt for aircraft in the central scenario around 2026, 6 years after their introduction (note that it is assumed that biofuel production capacity grows from 2020). After this time, biofuel usage in the European aviation fleet grows at a rate which is limited only by the assumed increases in production rate. Similarly, biofuels are adopted as soon as they become available in 2020 in the High scenario. However, they are not cost-effective before 2050 in the Low scenario.

As the addition of high-speed rail networks affects aviation emissions by reducing passenger demand for air trips, the effect of high-speed rail on airborne emissions is similar to its effect on RPKM, as discussed above. However, it should be noted that extra ground emissions, not modelled here, are likely to result as part of this scenario. As low-speed rail passengers also shift to high-speed rail, if it is provided, these extra emissions may potentially be significant.

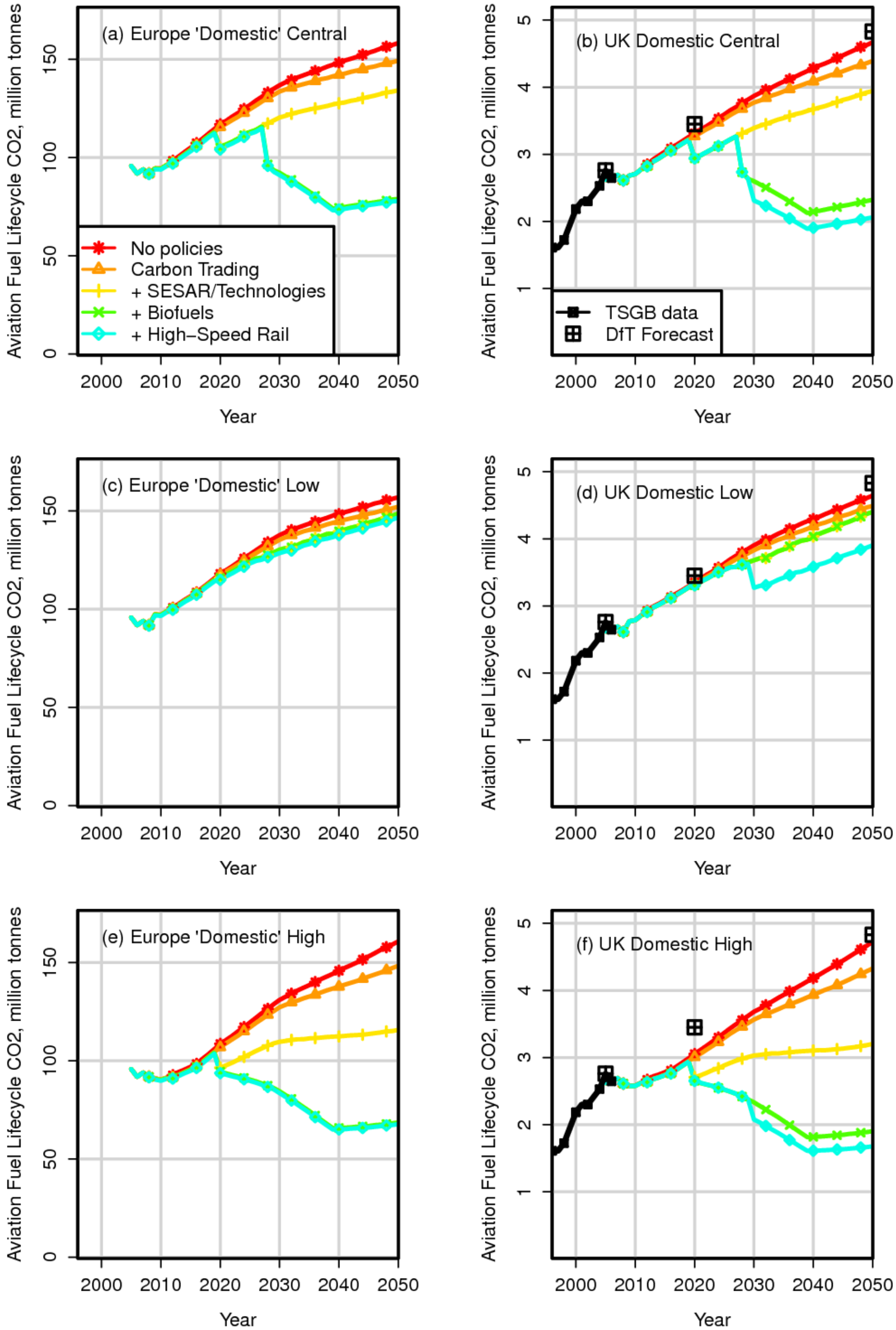


**Figure 3. European (panels (a), (c) and (e)) and UK (panels (b), (d) and (f)) domestic fuel lifecycle $CO_2$ under different background scenarios and policy options. Step-changes in the curves in 2020 correspond to the introduction of SESAR, in 2026 (Central scenario) to biofuel adoption at 2026 production capacity, and in 2030 to the opening of the UK high-speed rail network. The DfT Forecast shown in all panels is the central base case.**

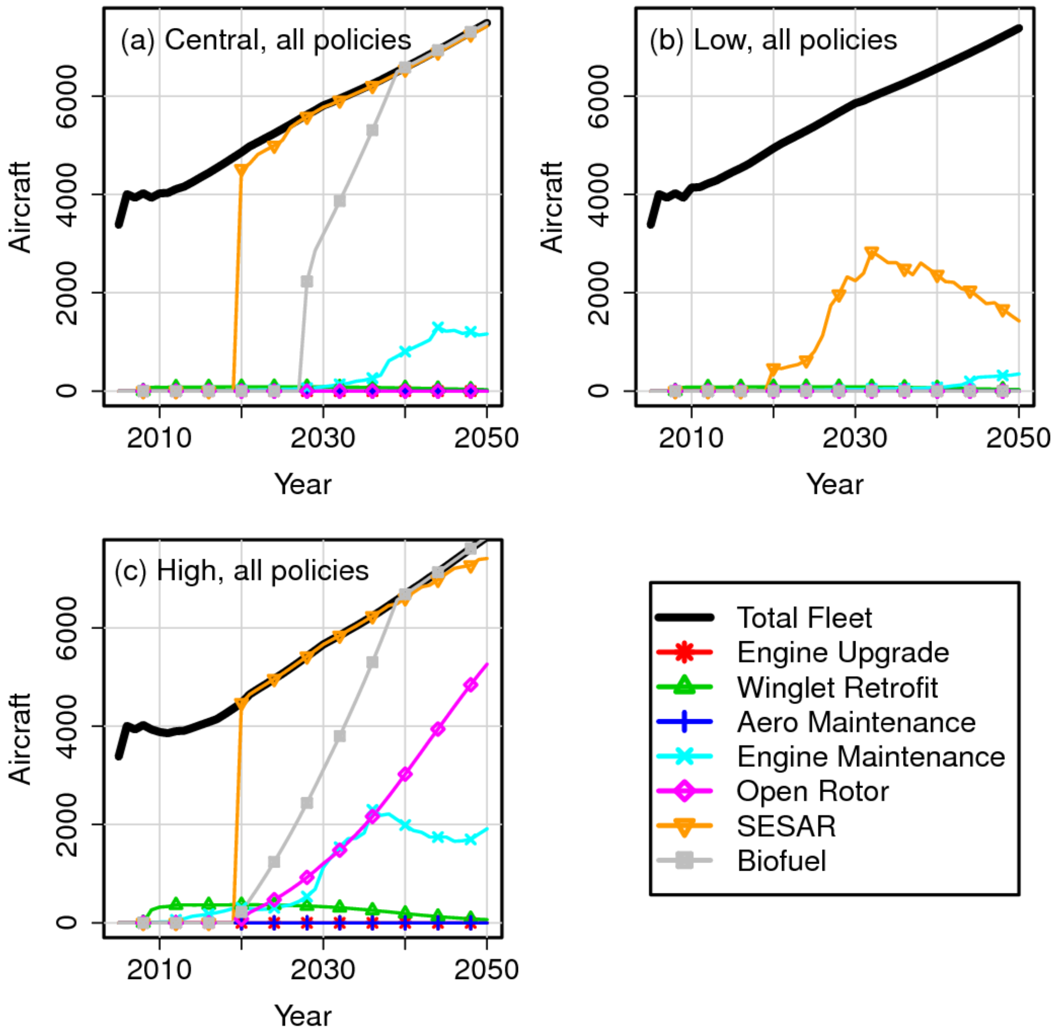


**Figure 4. Uptake of different mitigation measures by aircraft in the case that all policies are applied. Panels (a), (b) and (c) refer to the Central, Low and High background scenarios respectively.**

It is notable that none of the policies considered here produces a significant effect on emissions before 2020. However, the UK government's goal of reducing aviation emissions in 2050 to below year-2005 levels appears to be achievable provided aviation is included in the EU emissions trading scheme and suitable biofuels can be developed and made available for aviation. Whilst other mitigation measures can produce valuable contributions to UK and European $CO_2$ mitigation, the UK goal is not straightforwardly achievable under the scenarios studied here without biofuel usage. In addition, aviation biofuel usage in these scenarios is dependent on fuel and carbon costs. Where these are small, as in the Low scenario, aviation biofuels are not widely adopted and the total lifecycle $CO_2$ reductions are hence much smaller.

Although the role of biofuels in reducing aviation fuel lifecycle emissions is very promising, there are a number of potential problems which should be noted. Whilst fuel lifecycle $CO_2$ is reduced to below year-2005 levels in 2050, this reduction is almost entirely due to the ground-level production characteristics of cellulosic biomass. Airborne emissions, including $CO_2$ and $NO_x$, will remain little-changed from the unconstrained base case. This is illustrated in Figure 5 for the Central scenario, which shows what the effect on Figure 3 would be if airborne (i.e. "wing to wake") rather than lifecycle ("well to wake") $CO_2$ emissions were considered. Airborne emissions in the biofuel adoption case are slightly higher than in the case in which non-biofuel technologies only are made available because airlines are assumed to only adopt biofuels if by doing so they can lower their total costs, i.e. biofuel adoption tends to decrease fares and hence increase demand and operations. In the case of Europe, the policy option with the lowest airborne $CO_2$ emissions is in fact the non-biofuel SESAR/technologies scenario. Similarly, other negative externalities of aviation, such as local area pollution and the climate effects of contrails, will be reduced by only small amounts from the unconstrained base case in the biofuel case.

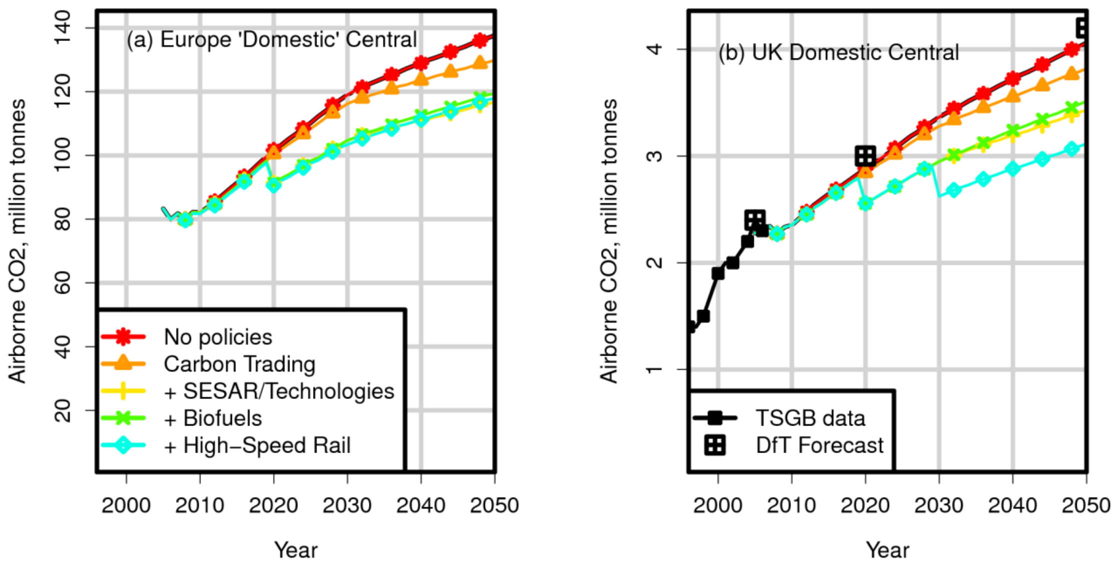


**Figure 5. Airborne $CO_2$ for the Central background scenario under different policy options. Panel (a): European domestic. Panel (b): UK domestic. Step-changes in the curves in 2020 result from SESAR, and in 2030 from the introduction of an UK high-speed rail network. The DfT forecast shown is the central base case.**

Another potential problem associated with widespread biofuel adoption is that of land use. As noted in Ref. 14, fuelling the entire European fleet in 2050 with a 50:50 biofuel:Jet A blend would require a land area roughly the size of England. This suggests that, if the use of biofuels for aviation needs to be a part of emissions reduction strategies in order to meet climate goals, the development of higher-yield biofuels needs to be a key research priority.

## IV. Conclusions

In this study, we have investigated the total effect of, and interactions between, a range of economic, technological and operational $CO_2$ emission mitigation measures for the UK and European aviation sectors. Although we find that no single measure is likely to allow the projected year-2050 aviation fuel lifecycle $CO_2$ emissions of the baseline scenario to be reduced to below year-2005 levels, this goal seems possible if a combination of policies, including emissions trading and biofuel availability, are adopted. Depending on the economic scenario and geographic region considered, a combination of SESAR, high-speed rail networks and open rotor aircraft may also be required to meet this goal. The adoption of each of these measures is, however, highly sensitive to GDP and oil and carbon prices. While SESAR compliance is adopted in all scenarios, biofuels are only adopted in the central and high GDP, oil and carbon price scenarios. The adoption of open rotor technology is only adopted under the high GDP, oil and carbon price scenario.

The paper also illustrates the complexity of the system and its sensitivity to key parameters. It is also noted that the land use requirements to supply sufficient biofuel for aviation are potentially significant. As the combination of emissions trading and biofuels represents the most promising option investigated in this paper for large-scale aviation lifecycle $CO_2$ reductions before 2050, this suggests that continued research into higher-yield biofuels for aviation should be prioritized.

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## Appendix: RPKM and Emissions for UK-Europe Flights

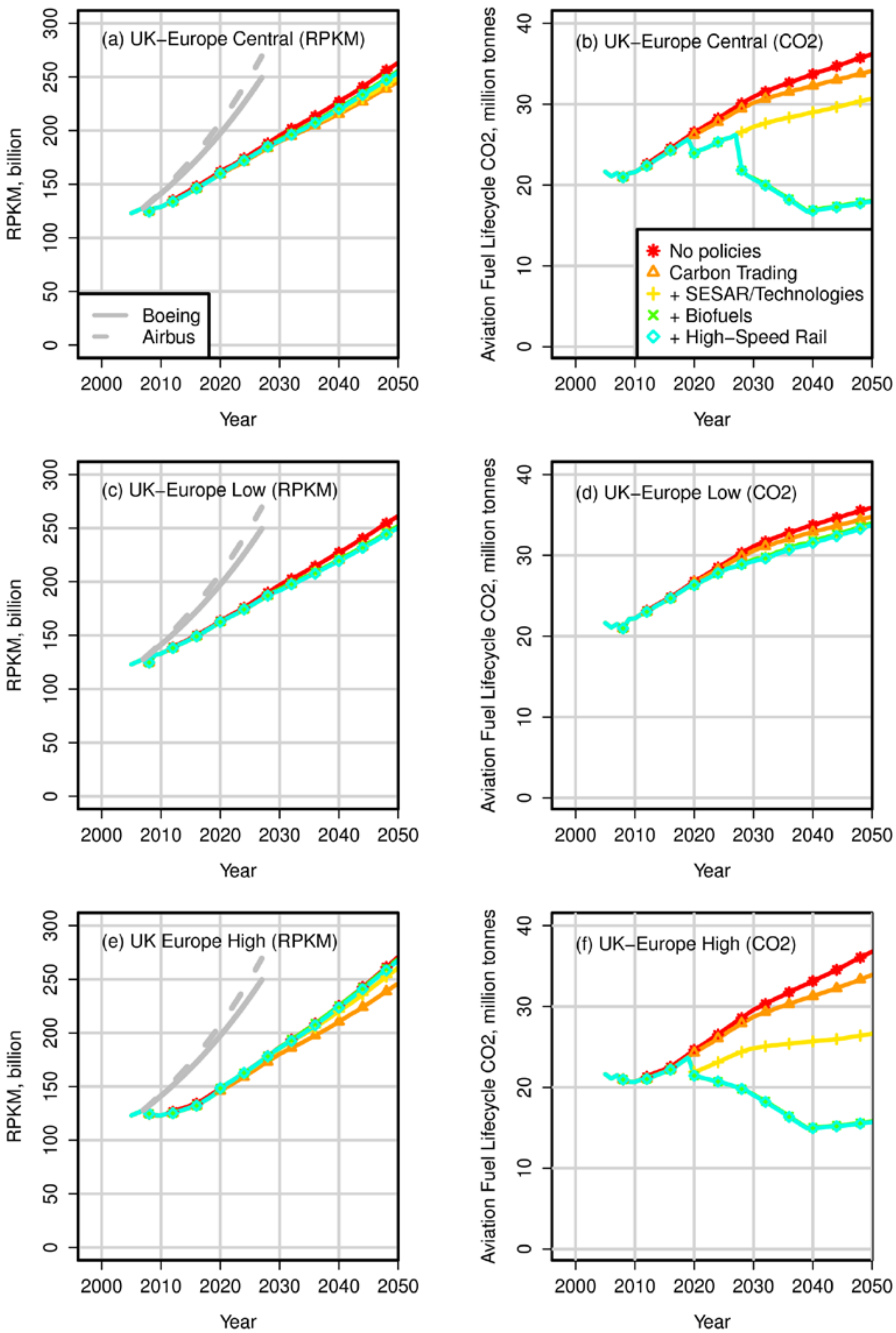


**Figure 6: RPKM and $CO_2$ emissions for international flights from the UK to the European city set modelled in this paper. For comparison, UK international $CO_2$ emissions from flights to all (global) destinations were 35.6 Mt $CO_2$ in 2006, and are projected to rise to 55.7 Mt $CO_2$ in 2050 (UK DfT central base case)[46].**

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