Aviation in a sustainable world Omega

Opportunities for Reducing Aviation-Related GHG Emissions: A Systems Analysis for Europe

Main Thematic Area: Mitigation Policies

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Executive Summary

Context and Aim

The current size and projected growth of the European air transport system creates a number of environmental challenges. Although aviation makes significant contributions to economic growth, it also has direct and well-publicised impacts on the global climate and on communities around airports. Any successful policy measure aimed at mitigating these effects must balance the beneficial economic effects of expanding access to aviation with the unwelcome environmental consequences.

A number of policy options have been proposed or are in the planning stage to reduce aviation emissions. In Europe, aviation is to be included in the EU Emissions Trading Scheme (ETS) from 2012. Participants in an ETS can either purchase permits from other sectors or instead reduce their emissions. It is expected that aviation will primarily follow the first course, as it is currently relatively expensive to reduce emissions from aviation in comparison to many other sectors. However, a recent Omega study (Morris et al. 2009) suggested that there do exist a number of cost-effective direct mitigation options which airlines can apply at present-day or near-future oil prices. In this case, the higher effective fuel prices resulting from emissions trading will prompt airline actions such as retrofitting winglets on older aircraft or increasing passenger load factors. The interaction between emissions trading and airline responses (and passenger responses if airline costs are passed on to ticket prices) is potentially complex and also depends on the underlying trends in European population and GDP and global oil price over the time period considered.

Further promising mitigation options (each also with their own associated costs and difficulties) are likely to become available over the next 20 years. Open rotor engines are likely to offer a significant decrease in fuel burn, but may only be suitable for shorter-haul routes because of the slower cruise speeds at which they must be operated. The introduction of improved European air traffic management from the SESAR project will reduce the extra fuel burn aircraft currently incur by flying non-optimal routes, although significant costs may be incurred through adapting aircraft avionics and providing flight crew training to take advantage of SESAR. A potentially large saving in lifecycle carbon emissions may be achieved by introducing aviation-suitable biofuels. However, doubts exist over the feasibility of biofuel production is at a large enough scale to fuel a sizeable proportion of the global aircraft fleet. All of these mitigation options may also interact with each other. For example, an airline adopting biofuels may make a large saving on its emissions trading costs. It therefore has a much lower incentive to adopt other mitigation measures. It is for this reason that a fully integrated model capable of capturing the combined effects of different policies and available mitigation options is desirable. This study aims to apply such a model to look at how different mitigation options combine, what actions they prompt by airlines and passengers, and what the resulting effect on total carbon emissions is for a range of different future scenarios.

Approach

This study uses the Aviation Integrated Model (Reynolds et al. 2007), a global aviation-environment systems model, to investigate the separate and combined effects of a number of emissions mitigation strategies on the European air transport system. To achieve this, the results of a set of studies looking at European aviation-environment issues, commissioned by the Omega consortium, are incorporated into the model. These studies include a detailed analysis of the marginal costs of abatement measures (Morris et al. 2009); an assessment of the availability, lifecycle emissions and cost-effectiveness of aviation biofuels (Wilson et al. 2009); a study of global airline fleet acquisition, modification and retirement behaviour (Morrell & Dray 2009); a study assessing the present-day inefficiencies in European air traffic management (Reynolds et al. 2009); and a study incorporating research into what range of carbon prices is likely in the near-future EU ETS (Allen et al. 2009).

A scenario-based approach is adopted to assess the separate and combined effects of a range of policies. Using three separate integrated projections of underlying population, GDP, oil price and carbon price, the unconstrained reference case in which no interventions or mitigation options are made available is simulated. This is contrasted with a range of policy scenarios. In particular, we investigate cases in which: mitigation options, including SESAR and open rotors, are made available to airlines; the EU ETS is applied to aviation; both the ETS and mitigation options are applied; and the ETS and mitigation options are combined with aviation biofuel availability.

Results and Conclusions

The objective of this study is to identify the interactions between different mitigation options for aviation emissions, and the resulting level of absolute reductions in carbon emissions. A number of broad conclusions can be drawn from the simulations carried out.

Firstly, the uptake by airlines of the range of mitigation options (e.g. winglet retrofits, increased maintenance, open rotor engines) simulated in this study varies strongly depending on the option and scenario. In all cases uptake is increased if the ETS is applied. Under the assumptions about costs, benefits and introduction times used in this study (described in the body of the report), winglets and SESAR compliance are economic for at least a portion of the fleet to adopt in most scenarios, as is increased engine maintenance. However, open rotors are only economic to adopt over the period to 2050 if there is both a high oil price and emissions trading. The interaction between the uptake of different mitigation options can be complex and is dependent on the order in which options become available or economic to adopt. The mitigation options we simulate in this study can result in an 8-15% decrease in 2050 CO_2 emissions relative to the unconstrained reference case where these options are not made available (in the absence of emissions trading).

Secondly, we predict non-negligible reductions in emissions to 2050 from the EU ETS applied on its own. These reductions mainly arise from decreases in demand in response to increases in ticket price from airlines passing on a portion of their incurred costs to passengers. In the highest carbon price scenario (culminating in a carbon price of €124 (year 2008 euros) per tonne of CO_2) direct reductions in airborne CO_2 emissions of 20% relative to the unconstrained base case are possible in addition to the reductions in other sectors from airline permit purchases. However, significant reductions in emissions primarily occur after 2030 and only in response to carbon prices which have increased to at least 2-3 times present-day levels.

Thirdly, strong reductions can be made in fuel lifecycle CO_2 emissions if second-generation biofuel-to-liquids (BTL) can be made available in sufficient quantities. We assume a 50-50 blend of BTL and Jet A can be made available from 2020. BTL usage will be small if no ETS is applied, because BTL fuel prices are likely to be higher than or at a similar level to projected Jet A prices. However, if an ETS is applied, airlines may reduce their carbon trading costs significantly by adopting fuels with lower lifecycle emissions. In this case, it is likely that a large portion of the fleet will adopt BTL blends, if they are available in sufficient quantity. Biofuel use may reduce the number of other mitigation options adopted, and has little effect on airborne or local area emissions (for example, local NO_x emissions do not decrease significantly from the base case). Significant land-use issues may also arise from the quantities of biofuels required unless their yields can be increased from present-day estimates. For example, a land area the size of England would be required to grow sufficient quantities of cellulosic biomass to fuel the intra-European aviation fleet in the highest-growth scenario in 2050. However, aviation lifecycle CO_2 emissions in 2040-2050 can be reduced to below year-2005 levels in this scenario, depending on the underlying economic conditions.

Finally, a consequence of the modelling approach is that we are also able to identify the increases in airport capacity that would be required to serve the forecast demand, if delay levels remain similar to those experienced today. These capacity increases do not account for any policy scenarios relating to airport expansion, but only provide an indication of the increases in airport capacity that would be required to serve the forecast demand at current delay levels. Such increases in capacity may be achieved through airport expansion, but may also be achieved through growth at secondary airports. Also, if less or no capacity is added (which is highly plausible), it is likely that higher delays, constrained schedules and greater costs will lead to demand increases lower than those predicted here. Consideration of specific airport expansion scenarios is, however, outside the scope of this study.

In the unconstrained reference case we find that the majority of minor European airports would require only incremental capacity increases to serve forecast increases in demand at current delay levels. However, the major hub airports would require larger capacity increases. For example, Paris Charles de Gaulle would require a 2.4 times increase in capacity by 2050 in the highest-growth scenario (with Western European GDP growth of around 2.7% per year) in order to serve forecast increases in demand at current delay levels. London Heathrow would require a doubling of capacity, either at the airport itself or by switching some operations to other airports. Typically, we find low to moderate passenger demand growth rates of around 2% per year for intra-European revenue passenger-kilometres (RPKM) flown to 2050 in the scenarios we model. This demand growth is driven by increases in population and income and changes in fares. If demand growth rates are higher, the projected capacity requirements will also increase. Alternatively if less or no capacity is actually added, these increases in demand will not be realised.

1 Introduction

1.1 Context

The European air transport system faces a number of challenges. Although continuing growth of around 3% per year in RPKM is forecast (e.g. Airbus 2007, Boeing 2007), 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 decision to include aviation CO_2 emissions into the EU Emissions Trading Scheme (ETS) in 2012 has been made. Participants in emissions trading have the option of reducing their own emissions by applying mitigation measures, or purchasing permits from other sectors with lower mitigation costs. However, the mitigation options available to aviation are relatively limited and/or costly in comparison to those in other sectors. Therefore, aviation is likely to be a net purchaser of permits, and it is likely that only a limited number of technology-based mitigation strategies will be adopted.

Similarly, total (lifecycle) aviation emissions might be lowered by the adoption of a suitable alternative fuel with lower lifecycle emissions than petroleum-derived Jet A. However, at present it is unclear whether alternative fuels with aviation-suitable properties will be available in sufficient quantities and at costs that make widespread adoption feasible. If the combined refined oil and

ETS price of Jet A remains below that of lower carbon alternative fuels, then their uptake will be limited.

A further complication is that some of the mitigation measures that are induced by the ETS may interact with each other as well as with 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. It is therefore useful, in a situation where multiple policies are likely to be applied, to assess their impact by simultaneous modelling of these policies which also takes into account capacity, delay and demand-related issues.

1.2 Study Objectives

The purpose of this study is to jointly evaluate the results of a number of Omega studies focused on individual opportunities for mitigating CO_2 emissions in the European aviation system (listed in Section 1.3). This analysis is carried out using an aviation systems model for Europe (described in Section 2), that accounts for the likely interaction between these measures, and the likely uptake of a selection of voluntary measures by the aviation sector under different growth assumptions. In particular, there are a number of key questions and interactions this study examines:

- How might the European aviation system change by 2050?
- How will the EU ETS affect the uptake of aircraft retrofit and new technology options?
- At what rate will fuel-saving technologies percolate into the European fleet?
- What levels of CO_2 emission reductions are practically achievable for aviation from measures such as the ETS and SESAR, now and into the future?
- How will the availability of biofuels and/or improved ATM interact with other measures?
- What is the sensitivity of these measures to the underlying fuel price and GDP growth scenarios?
- And finally, what is the consumer response in such constrained scenarios?

Answering these questions requires the integration of environmental, economic and engineering systems modeling. For this study, we take an existing systems model, the Aviation Integrated Model (Reynolds et al. 2006), and adapt it for the European air transport system. We then integrate the results of a set of relevant studies recently carried out by the Omega Consortium describing individual mitigation options. The aviation systems model is used to project future air travel demand, CO_2 emissions, airport capacity requirements, fares and uptake of mitigation options to 2050 for different background scenarios projecting population, GDP, oil prices and carbon prices. We then explore the effects of making different technology and policy measures available during this time period. The outputs are used to inform a discussion of which policy options and areas of technological development offer the best mitigation potential in the short-, medium- and long-term.

1.3 Omega Study Inputs

The UK's Omega consortium is formed by nine universities with expertise in aviation environmental issues. This study draws upon the considerable range of information and expertise made available by the recent sets of studies commissioned by Omega covering the main technological, scientific and economic aspects of aviation's environmental impacts and potential emissions mitigation measures. Of the more than 40 Omega studies, some have focused on assessing the climate impacts of non-optimal ATM procedures (Reynolds et al. 2009), the potential for utilizing sustainable fuels (Wilson et al. 2009), estimating marginal abatement curves (MACs) for mitigation options (Morris et al. 2009), likely carbon prices and effects of the EU ETS (Allen et al. 2009), and the environmental effects of fleet turnover (Morrell & Dray 2009). The results from these studies have been subject to stakeholder review at a series of workshops, and most include significant industry input. Study outputs include models and quantitative results which are suitable for incorporation into wider modelling. Table 1 reports the studies along with the key outputs that were used for this analysis.

Table 1: Omega studies and related key outputs used for this analysis.

	Study title	Key outputs used for this study
1	A Framework for Estimating the Marginal Costs of Environmental Abatement for Aviation	Main economic and technological characteristics of selected mitigation technologies
2	Sustainable Fuels for Aviation	Fuel-cycle characteristics of second-generation (cellulosic) biofuels
3	Environmental Aspects of Fleet Turnover, Retirement and Life Cycle	Retirement of existing aircraft and market penetration characteristics of new aircraft
4	Climate Related Air Traffic Management	Aircraft fuel efficiency improvement potential due to advanced ATM & capacities of European airports
5	Air Transport in the European Emissions Trading Scheme	Range of carbon prices to prioritize emissions trading scenarios
6	Environmental Effects of Aircraft Operations and Airspace Charging Regimes	Air navigation charges

The structure of this report is as follows: A description of the Aviation Systems Model used and the specific inputs required to model European aviation are presented in Section 2. Section 3 presents in more detail the individual inputs used from each Omega study and the way that they are integrated into AIM. In Section 4, we use the updated systems model to examine a range of separate and combined mitigation scenarios for Europe. Conclusions, and a discussion of policy and technological development options, are presented in Section 5.

2 The Aviation Systems Model

As the methodological framework, we use a model of the global aviation system developed under the Aviation Integrated Modelling (AIM) project (Reynolds et al. 2007). Established in 2006, the AIM project has the objective of developing a modular policy assessment tool to simulate the interplay between aviation's technological, operational, economic and environmental aspects. The Aviation Integrated Model has recently been used to analyze the potential effect of global emissions trading policies on the US and Indian air transport systems (Dray et al. 2009). In the study presented in this report, we use the recently-developed AIM project model of Europe to provide a balanced assessment of the separate and combined effects of different mitigation policies.

The basic structure of the Aviation Integrated Model is shown in Figure 1. The model 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. Each module may have a number of policies or scenario variables applied to it. In Figure 1 the applicable policy and scenario variables used in this study are shown as grey arrows pointing to the relevant module. For example, the EU ETS will, as a first order effect, influence passenger demand in the Demand Module via an increase in airline fuel costs, some portion of which will be passed on to passenger fares. As a second order effect, the higher fuel prices experienced by the airline industry will lead to the adoption of more fuel-efficient technology in the Technology and Cost Module. This module also allows the simulation of the impacts of aircraft retrofits. Decisions about whether or not to add capacity to congested airports will affect the Airport Activity Module. Changes in air traffic management, such as brought about through the SESAR project, will affect the aircraft movement module.

For this study, we use primarily the Aircraft Movement, Airport Activity, Technology and Cost and Demand modules. More detailed descriptions of these modules including methodology, data sources, assumptions used in adapting the model to Europe and references are presented in Appendix 1.

Therefore, only a brief description of the modules and their interaction is provided below.

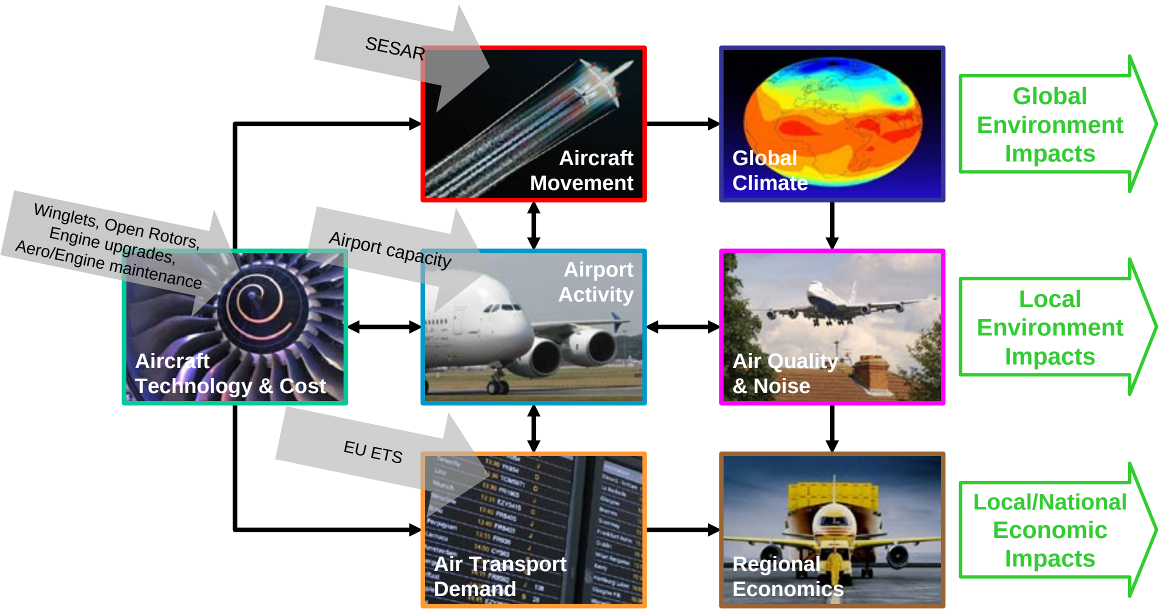

Figure 1: The Aviation Integrated Model structure.

The Aviation Integrated Model is run in a two-stage process. Initially, the first four modules (Aircraft Movement, Airport Activity, Technology and Cost and Demand) are run in an iterative fashion. These modules simulate the operational and economic aspects of the air transport system and produce as an output a matrix of passenger movements and aviation emissions by location, given scenario input about demographic and socioeconomic conditions, airport capacity and available technology. True origin-ultimate destination (i.e. from the first airport a passenger leaves to the last one (s)he arrives at, whatever the route taken) passenger demand by city-pair for a given set of cities is first generated by the Air Transport Demand Module using scenario data about population, income and costs. This demand is then assigned routing by the Airport Activity Module, allowing the passenger numbers by flight segment to be calculated. The Airport Activity Module then assigns a flight schedule for each segment based on this data. Simulating this schedule in combination with airport capacity assumptions allows the resulting flight delay levels to be calculated. The Aircraft Movement Module calculates the likely airborne trajectories for this schedule taking into account the effects of flight inefficiencies due to factors such as weather and ATM. The resulting emissions, revenues and costs are calculated by the Aircraft Technology and Cost Module using data about currently-available and potential future technology. This information, along with the estimated delays, is fed back into fares and journey times for the Air Transport Demand module. To do this, an assumption is needed about how airlines pass incurred costs on to passengers. This behaviour varies depending on the airline and world region, and is typically not publically available. However, model results can be sensitive to the degree to which costs are passed on. In this study, we assume perfect competition, i.e. that the fare charged equals the marginal cost of carrying a passenger on a given route. This means that the proportion of costs passed on to passengers may vary depending on the underlying oil and carbon price scenarios. For example, 10-30% of carbon costs were passed on in the US scenarios (also assuming perfect competition) analysed by Dray et al. (2009), with a greater proportion of costs passed on when oil and carbon prices were higher. Higher passed-on costs induce a larger response in terms of demand reduction.

As described above, the first four modules in Figure 1 are run as an iterative loop. They produce output to be fed to the latter three modules only when a system equilibrium has been reached between travel demand and the supply of flights. The Global Climate Module takes as input the gridded emissions produced when AIM is run on a global scale and produces a range of metrics indicating what effect aviation emissions (including non-CO_2 environmental impacts of aviation such as NOx and contrails) in each scenario are likely to have on climate change. The Air Quality and Noise Module takes local area emissions and aircraft tracks for specific airports, along with meteorological data and information on runway alignment and usage, and produces detailed emissions and noise footprints. It also calculates the global impacts of health-impacting emissions, such as particulates, which are released during cruise. The health and economic impacts of the local air quality and noise footprints can then be calculated and monetized by the Regional Economics Module. In this study, in order to limit the project scope, we do not use the latter three modules. Instead, intermediate-stage data such as the total CO_2 emissions from aviation, total local area NO_x emissions from aviation and total revenue passenger kilometres (RPKM) flown are presented.

In this study we focus on the European region, using the city set described in Section 2.2. Only flights within this city set are directly simulated. Data is included on the number of flights entering and leaving the European city set so that capacity requirements and delays can be accurately calculated, and these numbers are scaled according to demand growth in the set of routes which are modelled. However, the numbers of flights flown to or from the European region are not included in the results presented. Similarly, where figures for RPKM and emissions are presented, they include only flights within the city set used and not flights into and out of that set.

2.1 Background Scenarios

Underlying the projection of future aviation growth are scenario-based projections of key variables. As predicting the future is an inherently uncertain process, it is useful to use a range of scenarios with different characteristics. The main scenario inputs required by AIM are population and income growth (for estimating passenger demand) and future airport capacity scenarios (for estimating flight delays). In addition, applying the results of the Omega studies requires projections of the oil price and carbon prices. These factors are interdependent, with (for example) high carbon prices potentially lowering GDP. Therefore any scenarios used need to incorporate integrated economic modeling which considers all these factors simultaneously.

Table 2: Main scenario input data used in this study, following the US Climate Change Science program study.

		2000	2020	2040
Population, millions				
Western Europe[1]	IGSM	390	388	368
	MERGE	390	397	397
	MiniCAM	457	486	481
Eastern Europe	IGSM	97	91	83
	MERGE	411	393	393
	MiniCAM	124	119	111
GDP per capita, $(2005)				
Western Europe	IGSM	19437	33554	60457
	MERGE	22163	31992	44211
	MiniCAM	16598	15607	24387
Eastern Europe	IGSM	2548	5433	11913
	MERGE	2145	4264	8079
	MiniCAM	2845	5188	11124
World Oil Price, $/bbl				
	IGSM	33.1	88.8	125.5
	MERGE	33.1	71.7	98.0
	MiniCAM	33.1	62.3	77.8
Carbon Price[2], $/t$CO_2$				
	IGSM	0	23.0	46.0
	MERGE	0	33.7	112.5
	MiniCAM	0	28.5	94.3

We use scenarios for Western and Eastern European growth from the US Climate Change Science Program (CCSP, 2007). The three models used to generate the scenarios within that report are:

- MIT “Integrated Systems Model” (IGSM)
- Stanford “Model for Evaluating Regional & Global Effects of GHG Reduction Policies” (MERGE)

[1] Country lists for Western and Eastern Europe are given in CCSP (2007) and references therein. Note that MiniCAM includes Turkey in Western Europe, whereas the other scenarios do not, MERGE includes the Former Soviet Union region in the country group containing Eastern Europe, etc. However, as we use only the growth rates from these scenarios (which are then applied to city-level base year data) the different aggregrations of countries in different scenarios affect only which city has which growth rate applied to it.

[2] The carbon price scenarios shown are IGSM 550 ppm, MERGE 450 ppm and MiniCAM 450 ppm. See Section 3.5 for details why these carbon price scenarios were chosen.

- Pacific Northwest Laboratory “Mini Climate Change Assessment Model” (MiniCAM)

These scenarios cover a wide range of economic growth and oil price projections. A summary of each scenario is presented in Table 2. Broadly, IGSM generates a high-growth scenario with strong economic performance, particularly in Western Europe, high emissions and also high oil prices. MiniCAM presents a scenario for Europe with much lower growth rates, but higher growth in the developing world. MERGE is approximately between the other two scenarios. In addition to the base IGSM, MERGE and MiniCAM scenarios, which do not include climate policy, a number of sub-scenarios are available which apply carbon trading to each unconstrained base scenario and calculate the resulting changes in key variables. These scenarios are based on an open (all sectors) global (all countries) carbon trading scheme, assumed to be introduced in 2012 and aimed at stabilizing atmospheric CO_2 concentrations at set targets of 450, 550, 650 and 750 ppm. The carbon prices are calculated as part of each scenario and typically increase over time, as greater pressure needs to be applied to keep emissions down. These scenarios have previously been applied in the Aviation Integrated Model to investigate the effects of emissions trading on the US and Indian air transport systems (Dray et al. 2009). Our use of these scenarios in this study is discussed in section 3.5.

Current European airport capacities were taken from a harmonized assessment conducted as part of the Omega study “Climate Related ATM” (Reynolds et al. 2009, discussed further in section 3.4), supplemented with numbers from the IATA airports database where needed. 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. This study does not comment on whether infrastructure expansion, such as building new runways, is a good policy solution or not. Instead it only indicates the airport system capacity increases that would be required to serve forecast demand at current delay levels.

2.2 City Set

The global AIM model concentrates on 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 RPKM (OAG, 2005). For the Europe model we use the corresponding European subset, which contains 173 cities and 337 airports. These airports are shown in Figure

2. Although this subset includes some countries of the Former Soviet Union, we present airport-level results for the European Union (EU-27) region and closely associated airports (e.g. Olso, Zurich) only. Where the EU ETS is applied we assume that all flights to or from an EU-27 airport are subject to carbon charging. Further details, including a list of the EU-27 cities and airports modeled, are presented in Appendix 2.

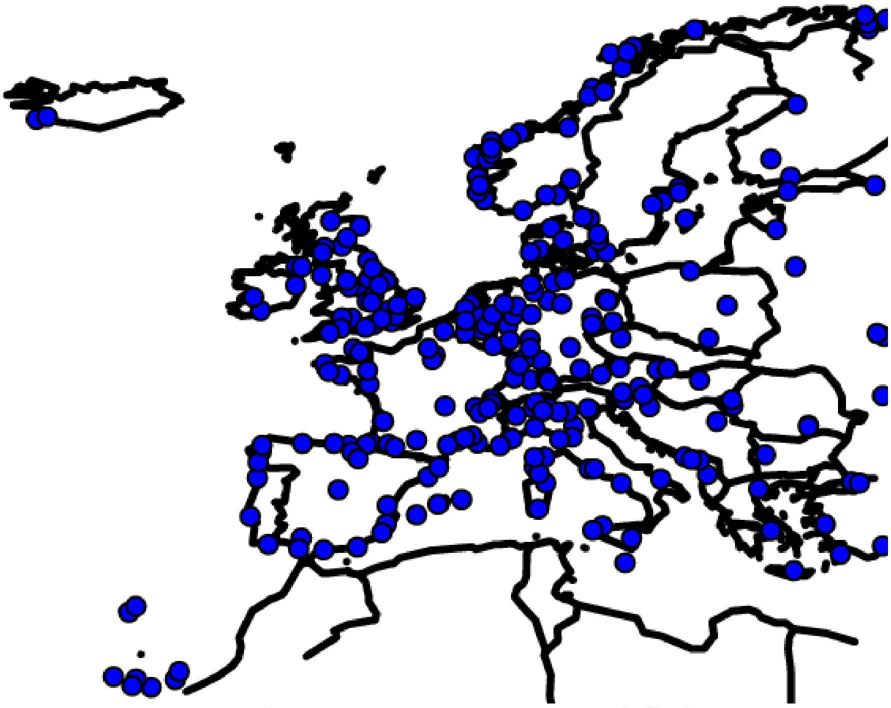

Figure 2: The European airport set modelled.

3 Mitigation – Policies, Technologies and Scenarios

The Aviation Integrated Model as described above is able to simulate the business-as-usual case for aviation growth, either with or without a global emissions trading scheme. However, airlines and manufacturers as well as policymakers are likely to respond to pressures in the European aviation system. Under rising fuel prices, as for example induced through the carbon price in an emissions trading system, airlines may choose to retrofit older aircraft or invest in new technology aircraft in order to reduce their emissions. The range and efficacy of options available to airlines will change over time, as biofuels, improved air traffic management and radical new airframe and engine technologies which are currently under early-stage development become available.

In order to address these issues and to adapt the Aviation Integrated Model to a European context, we apply data and formulae from the Omega studies listed in Table 1 addressing different aspects of the European aviation system and its interaction with environmental pressures. More details on these individual studies and their integration into AIM are presented in Sections 3.1 – 3.6 below.

3.1 Marginal Abatement Curves

For a given range of emission-reducing interventions, Marginal Abatement Curves (MACs) indicate the extra cost per unit of emission reduction by successive amounts within a given time period. For example, the retrofitting of winglets to an aircraft might cost £400,000 and reduce cruise fuel use and CO_2 emissions by 4%. These values combined with fuel and carbon prices and the fuel use of the aircraft in question allow the marginal cost of reducing CO_2 emissions by one tonne, using winglets, to be calculated. If a range of measures are evaluated in this way then they can be ranked in order of increasing cost per tonne of CO_2 saved. The curve of increasing cumulative abatement of CO_2 with increasing cost per tonne of CO_2 abated allows the likely airline response to increasing fuel and carbon prices, in terms of mitigation measures, to be transparently evaluated.

MACs for the European aviation system are calculated in the Omega study "A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector" (Morris et al. 2009). This study assessed the individual mitigation potential, related up-front and yearly costs, and the applicability of abatement measures to the European aircraft fleet, as well as their likely introduction timescale. Significant industry and academic input was used to identify the most likely mitigation measures to be adopted over the short-, medium- and longer-term in response to increasing oil and carbon prices. A large number of abatement policies are included in the curves given in this report, ranging from operational changes and aircraft retrofits to new aircraft technologies.

For the purposes of this study, we have identified a reduced set of representative mitigation measures covered by Morris et al. (2009) which span the range of intervention types considered. These are: retrofitting winglets; engine upgrades; more frequent engine maintenance; more frequent airframe maintenance; open rotors; adaptation to comply with SESAR requirements; and biofuels. Although the Morris et al. study finds significant present-day mitigation potential may be achieved by increasing passenger load factors, we do not apply this measure directly as its achievability depends strongly on airline business model, scheduling, available aircraft and pricing strategies. Similarly, we neglect the options of lowered reserve fuel requirements and increased use of turboprops because of their complicated interaction with demand, airline competition, regulation and political factors. Because we have chosen a reduced set of measures, the mitigation potential we estimate will be lower than the true potential when all measures are taken into account.

Table 3: Main characteristics of mitigation measures considered in this study.

Mitigation Technology	Availability (year, proportion of fleet)	Fuel Burn Mitigation Potential (% per aircraft)	Upfront Costs	Yearly Costs	Comment
Existing technology					
Winglets	Now, up to 25% depending on size	1.2 - 2.4 depending on route flown	£400,000	£8,000 extra maintenance costs	Costs in year 2008 UK pounds.
More frequent engine maintenance	Now, all	Up to 2.5	-	85% increase in engine maintenance costs	Depends on aircraft age.
More frequent airframe maintenance	Now, all	Up to 1	-	Function of MTOW and fuel saving achievable[3]	Depends on aircraft age.
Engine upgrades	Now, up to 37.5% depending on size	1	15% of new engine costs	5% reduction in engine maintenance costs	
Future technology					
Open rotor engines	2020, all new <190-seat aircraft	30	£4,000,000 extra on purchase price	Engine maintenance cost increase of £400,000	Journey time increase assumed small.
Improved air traffic management	2020, all	10.5	£250,000 for avionics upgrade	£45,000 for equipment and training, 30% increase in navigation costs	Reversible.
Second generation biofuels	2020, all (limited availability before 2040)	85	-	Biofuel costs	Mit. pot. relative to petroleum-derived jet fuel on lifecycle basis. Reversible.

Notes: The reference point for the mitigation potential is the 2005 fleet average for existing technology and the average new aircraft put into service in 2005 for future technology.

In order to implement these options within AIM, we apply data on costs, applicability, introduction date and potential fuel and carbon price savings from Morris et al. (2009) for the chosen mitigation options. A summary of the assumptions used is presented in Table 3. Additional data and formulae that underlie these numbers are derived from Henderson et al. (2005) and Morris et al. (2008). In the case of increased engine and airframe maintenance, where mitigation values in the source reports are given for the whole fleet,

[3] See Henderson et al. (2005) for detailed cost formulae.

we estimate mitigation per aircraft assuming that the fuel burn deterioration recoverable by increased maintenance is a constant fraction of the total fuel burn deterioration with aircraft age, with the given maximum values of recoverable fuel burn in Henderson et al. (2005) being achievable for 30 year-old aircraft.

Table 4: AIM reference aircraft models.

	<190 Seats	190-300 Seats	>300 Seats
Old Technology	B737-300	B767-300	B747-400
New Technology	A319	A330-300	B777-300

As in Morris et al. (2009) we base our cost analysis on a set of sample aircraft types for different size/range classes and technology levels. The AIM model sample aircraft types are given in Table 4[4]. Since these aircraft are being used to represent a fleet which has changing fuel burn over time, when considering aircraft manufactured in a given year we adjust the fuel burn of the sample aircraft types to reflect the distribution appropriate to that manufacture year, as given in Morrell & Dray (2009) and described further in Section 3.3. Maintenance costs for these aircraft types are obtained from the US Form 41 database (BTS 2009) and adjusted for Europe using the regional cost comparisons in ICAO (2003). Navigation costs are obtained from Gillingwater et al. (2009) as described further in Section 3.4. Capital costs for new aircraft purchase are estimated from list prices assuming a 20% discount, and oil prices are obtained from the scenarios described in Section 2.1 and adjusted to European Jet A costs per gallon using the regional comparisons in ICAO (2003).

To integrate the Omega MAC study transparently into AIM, 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 for new aircraft technology, i.e. it is assumed that airlines will invest in fuel-saving technology only if fuel and maintenance cost savings over the first seven years are equal to or greater than the up-front costs of installing the technology (plus any resulting maintenance or navigation cost increases). For each simulation year, the cost-effectiveness of available mitigation options is then assessed separately for each aircraft technology class, size and manufacture year. Thus, for example, in 2010 it might be economic to apply winglets to old technology planes with 190-300 seats manufactured in 1980, but not to new technology planes in the same size class manufactured in 2003, even if both aircraft operate under similar conditions, because the aircraft will have different starting values of fuel burn. We consider some options to be reversible, as noted in Table 3; a given aircraft has the option of stopping using these options (for example, an

[4] In the stock model described in Section 3.4 the <190-seat class is split into <100 seats and 100-190 seats so as to capture the regional jet market more closely. For cost calculations here we consider the sample <190-seat aircraft to be used on both short-haul and regional jet-type missions so that the cost model aircraft set is compatible with that used in the rest of the Aviation Integrated Model.

aircraft is unlikely to have winglets removed, but may cease using biofuels relatively easily).

In applying the different mitigation options, there are also a number of other assumptions that need to be applied. These are discussed individually below.

3.1.1 Winglets

A number of different assumptions can be made about which aircraft would benefit from retrofitting with winglets. In particular, aircraft which already have winglets may or may not be candidates for the retrofit of better winglets, and there are significant differences between Boeing and Airbus aircraft as to the applicability of winglet upgrades. In this study we follow the applicability assumptions used by Morris et al. (2009), who assume a relatively small range of aircraft are suitable for winglet retrofits. In addition, we assume that new aircraft types manufactured after the present day will likely be manufactured with winglets if winglets can provide a significant fuel burn advantage. This is considered to be part of the background trend in decreasing fuel burn for new models of aircraft (see section 3.3), so for these new aircraft the applicability of retrofit winglets is assumed to be zero.

3.1.2 Open Rotors

Conventional turboprops present a higher propulsive efficiency – lower specific thrust – than turbofan engines and benefit from the absence of the drag and weight associated with a nacelle. The main disadvantages of this technology are the reduced flight Mach number and the propeller noise. Given the potential reduction in fuel consumption, estimated to be about 20-30% in comparison to a similar thrust turbofan, efforts are being made to overcome these disadvantages. Hence, a number of new technologies are being considered for the design of advanced turboprops. Examples are the use of counter-rotating propellers to recover the swirl from the upstream propeller blade row and therefore increase the efficiency, and swept wing technology to delay compressibility effects and increase the flight Mach number without incurring a loss penalty (Strack et al., 1982). Open rotor engines are assumed to become available from 2020. Due to the reduced flight Mach number, the advanced turboprops will be best suited for shorter-haul routes for which the journey time difference is small and for <190 seat aircraft types. We assume that noise regulations will not present a significant obstacle to open rotor adoption.

3.1.3 ATM Improvements

ATM improvements from the Single European Sky (SESAR) are assumed to become available from 2020. An aircraft has the option of taking advantage of these improvements if the airline operating the aircraft invests in suitable avionic equipment and crew training. However, we assume that these measures are optional and that there will be no extra policy incentives to comply with SESAR requirements. In addition, we assume that aircraft which do not comply with those requirements have city-pair journey times and fuel burn which are unchanged from the case in which SESAR was not available.

Aircraft which do comply with SESAR requirements are assumed to benefit from a 10.5% decrease in fuel burn, as assumed by Morris et al. (2009) and consistent with the results of Reynolds et al. (2009); however, this is assumed to come primarily from better airborne vs. ground delay management, i.e. journey times are assumed to remain similar to the non-SESAR case.

3.1.4 Biofuels

Many different biofuel options have been suggested for aviation, with different applicability, adoption timescales, associated costs and lifecycle emissions. For this study, we use data from Wilson et al. (2009) to simulate the availability of second generation biofuels, i.e., biomass-to-liquids, as detailed further in Section 3.2. Although we assume biofuels become available for aviation use in 2020, it is likely that their initial availability will be limited. We model the gradual introduction of biofuels assuming that the biofuel production increase per year in the highest-demand scenarios will be similar to the production increase per year observed in the most ambitious biofuel program in history, i.e., the ethanol-based ProAlcohol program in Brazil during the 1980s (Moreira and Goldemberg, 1999).

Aircraft using drop-in biofuels will still emit similar amounts of airborne CO_2 to those using Jet A. However, the lifecycle emissions may be significantly reduced, depending on which biofuel is used. It is assumed here that the ETS charge applied to aircraft using biofuels will be based on the comparative difference between lifecycle emissions of Jet A and the selected biofuel.

3.1.5 Additivity and Trade-offs

As noted by Morris et al. (2009), the issue of whether any two mitigation measures are additive in their effects is not necessarily straightforward. For example, re-engining an aircraft removes any previous benefit that the aircraft had from engine upgrades applied to the old engine. In addition, each measure already adopted by an aircraft changes the cost-effectiveness of any later measures to be evaluated for potential adoption. Although we apply the effects of previously adopted measures on costs and fuel burn before calculating whether extra measures are economic to adopt, we assume that the set of measures we have chosen do not interact with each other in any other way.

In addition, there may exist trade-offs between different environmental impacts for any given mitigation option. For example, open rotors provide considerable fuel use advantages at the expense of increased noise. In this study, we concentrate on CO_2 impacts, and CO_2-reducing measures are encouraged by the EU ETS. We do not consider local airport NO_x or noise charges which might encourage specifically NO_x or noise-reducing measures, but the implications of the CO_2 mitigation options on these other environmental issues are briefly discussed later in this document.

3.2 Alternative Aviation Fuels

Suitable alternative fuels for aviation were identified by the Omega project "Sustainable Fuels for Aviation" (Wilson et al., 2009). In particular, costs and lifecycle emissions were estimated for those alternative fuels that meet the stringent aviation requirements for fuel suitability. Future alternative fuel 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. 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. Aviation biofuel prices are assumed to be at least 70 US cents per litre (Wilson et al., 2009) or — following the profit-maximizing behavior of the fuels industry — equivalent to the costs of Jet A, whichever value is higher.

3.3 Aircraft Fleet Turnover

The aircraft fleet turnover modelling is derived from the Omega study "Environmental Effects of Fleet Turnover, Retirement and Life Cycle" (Morrell & Dray, 2009). This study examined economic and historical trends in various factors affecting fleet emissions, including the distribution of fuel burnt per RPK for new aircraft orders, the frequency of freighter conversions with aircraft age, and retirement/survival curves by aircraft type. A net present value (NPV) model was also presented to assess the economic case for early aircraft retirement by type, fuel price and characteristics of replacement aircraft.

Results from this study were integrated into a simple stock model, which in turn was integrated into the main AIM architecture. Aircraft in the fleet are considered separately by size class (<100 seats, 100-190 seats, 191-300 seats and >300 seats), by technology class and by manufacture year. For each aircraft cohort within this framework, the fuel burn with respect to the base year sample aircraft for that class is calculated, as well as the likely proportion of freighters. These values are then used by the Technology and Cost Module within the Aviation Integrated Model to follow the change in fleet fuel burn over time as older aircraft are retired and new aircraft are purchased. For the purposes of this study, the most relevant assumptions are that fuel burn per RPK for new models of aircraft is assumed to decrease by 1-1.5% per year[5] over the study period, and that fuel burn per RPK for existing aircraft is assumed to *in*crease by 0.2% for each year of increasing age unless those aircraft are subjected to some form of maintenance over

[5] This value depends on the oil price trend to 2030, i.e. it is assumed that higher oil prices will prompt more rapid technology development. See Dray et al. (2009) for more details. It is also implicitly assumes that airlines and manufacturers know about future oil and carbon price trends, i.e. they have reasonably accurate forecasts.

and above normal maintenance schedules. It should be noted that the background trend in fuel burn per RPK is separate from the improvements which can be made by retrofits and radical new technologies, as discussed in Section 3.1. Instead, the background trend represents the future decreases in fuel burn which will become available for new models of aircraft only, resulting from incremental changes in technology only. To avoid double-counting, we specifically exclude from the analysis in Section 3.1 any technologies which are likely to come fitted on new aircraft models as standard, e.g. winglets are not considered as a retrofit option for future models of aircraft, but only as an option for present-day existing aircraft without winglets.

3.4 ATM and Airspace Charging

The Omega study “Climate Related ATM” (Reynolds et al. 2009) identified the levels, locations and sources of inefficiencies in the European air traffic management system. Data from this study is incorporated into the AIM Airport Activity and Aircraft Movement Modules to account for extra emissions due to aircraft flying longer distances than the great circle distance, because of airborne routing, holding, weather or other factors.

The European lateral-based airspace inefficiency metrics identified by Reynolds et al. (2009), both en route and in the terminal area, were applied directly within AIM to increase airborne fuel burn, emissions and travel time of all flights simulated:

- In the departure terminal area an average extra distance flown of 9.0 nm was added to the climb out phase of each flight, increasing travel time, fuel burn, and emissions accordingly.

- En route, the average extra distance flown was calculated as a function of great circle stage length according to the best fit line described by Reynolds et al. (2009) (a straight line with intercept of 12 nm and a slope of 0.02 nm extra distance for each nm of great circle route distance). This was added to the cruise phase of each flight, increasing travel time, fuel burn, and emissions accordingly.

- In the arrival terminal area an average extra distance flown of 26.9 nm was added in this phase of flight, increasing travel time, fuel burn, and emissions accordingly. The amount of airborne holding required as a result of airport capacity constraints was estimated independently by the Airport Activity Module, as described below.

Airspace holding is a major source of inefficiency in the arrival flight phase. As described by Reynolds et al. (2009), airspace holding is a direct function of airport capacity constraints. The impact of airport capacity constraints on the European system was modelled by applying airport capacity constraints within the AIM Airport Activity Module, and calculating the delays – both in airborne holding and on the ground. This is described in detail in Appendix 1 (Section A1.3). The primary input to this modelling is airport capacity.

Base year airport capacities were based on values identified by Reynolds et al. (2009) for 35 airports in Europe, and calculated according to an approach described by the FAA (1983, 2002) and Horonjeff & McKelvey (1994: 348-350), as well as a combination of available data, expert judgment and informed guesswork.

Future year airport capacities are also discussed by Reynolds et al. (2009). According to EUROCONTROL (2008) already existing airport capacity expansion plans could result in a 41% increase in system capacity, but this is likely to fall short of unconstrained demand in 2030 by as much as 11%. This only accounts for already existing plans, however, and any number of other plans may complete by 2050. The timing and characteristics of the existing plans are also highly subject to change. For these reasons, instead of explicitly modelling the increases in airport capacities discussed by Reynolds et al. (2009) and EUROCONTROL (2008), this project follows a different approach: Airport capacities are assumed to increase over time in such a way as to maintain average arrival delays at base year levels. The means by which this increase in capacity is achieved is not identified, although it is likely to be through construction of additional infrastructure at major airports (such as described by Reynolds et al., 2009 and EUROCONTROL, 2008) and increased use of secondary airports (Bonnefoy & Hansman, 2007). Instead, the results here indicate how much extra airport capacity would be required to serve the forecast demand at current delay levels.

The impact of reductions in airspace inefficiencies in the European air traffic management system resulting from major ATM modernization initiatives, such as the Single European Sky ATM Research (SESAR, EUROCONTROL, 2009-1), were also accounted for in this project. This was done by reducing average fuel burn for complying aircraft (by 10.5%, as described in Section 3.1.3), according to Morris et al. (2009) and consistent with Reynolds et al. (2009), instead of directly reducing the inefficiency metrics estimated by Reynolds et al. (2009), presented above. As discussed in Section 3.1.3, ATM improvements from SESAR are assumed to become available from 2020. SESAR compliance is assumed to require an upfront avionics upgrade per aircraft, costing £250,000; annual training and equipment costs of £45,000 per aircraft; and a 30% increase in navigation costs.

Navigation costs vary throughout Europe by member state. As described by Gillingwater et al. (2009), navigation costs can most accurately be calculated using EUROCONTROL's RSO Distance Tool (EUROCONTROL, 2009-2), which accounts for each member state's specific navigation charge formula, for each flight segment modelled. The modelling is greatly simplified, however, by applying an average rate, estimated from the 100 flight plans analysed by Gillingwater et al. (2009) of \$1.17E-05 per km per kg MTOW (Maximum Take-Off Weight), in year 2004 US dollars.

3.5 Emissions Trading

Likely future levels of carbon charging in the EU ETS, as well as implementation timescales for adding aviation and applicable flights, were investigated by the Omega project “Aircraft Emissions Trading” (Allen, Köhler & Anger 2009). This project utilised a range of likely carbon prices between €5 and €40 (year 2008 euros) per tonne of CO_2, with a mid-range price of €20. This mid-range price is similar to those identified by various other studies (e.g. European Commission, 2005; Ernst and Young, 2007), which specify a range of likely carbon prices of €10 - €30 per tonne of CO_2. We therefore take €20 as a suitable value for the near-future ETS carbon price.

Future trends in oil prices, carbon prices, and per person GDP are likely to be highly interdependent. For example, higher permit prices in the EU ETS may lead to reductions in the GDP of EU countries, and high oil prices may reduce demand for petroleum fuels and ultimately lower the carbon price. Therefore, in order to model carbon trading within AIM, we need integrated, internally consistent scenarios of all of these quantities over the time horizon studied across multiple economic sectors which may be participating in an ETS. The U.S. Climate Change Science Program (CCSP) scenarios for future growth described in Section 2.1 above do not include local carbon charging, but they do include trajectories for global carbon charging schemes at a range of stabilization targets integrated with corresponding population, GDP and oil price projections, including the effect of carbon trading on European GDP growth. Although the effect of a global scheme is likely to differ from a local one in several ways (e.g. the availability of permits from countries with significantly lower mitigation costs) the broad effects will be similar[6]. Therefore we choose the CCSP stabilisation scenarios with the closest carbon price trajectories during the 2020-2030 period to those identified for Europe by Allen, Köhler & Anger (2009), and apply those as our carbon trading scenarios. The carbon price trajectories applied to aviation are shown in Figure 3. As the inclusion of aviation into the EU ETS has already been agreed, we include its effects, assuming a 2012 start date, in all policy scenarios (See Section 3). However, to allow an assessment of the effect that carbon trading will have by itself, the base case scenarios do not include carbon trading.

[6] The main difference is likely to be that any given emissions reduction target will result in lower carbon prices within a global scheme than a Europe-specific one, due to the availability of low-cost mitigation measures in the developing world. The atmospheric CO_2 stabilization levels associated with each global CCSP scenario and carbon price trajectory are therefore likely to be significantly higher (i.e. less stringent) if that scenario is only applied regionally.

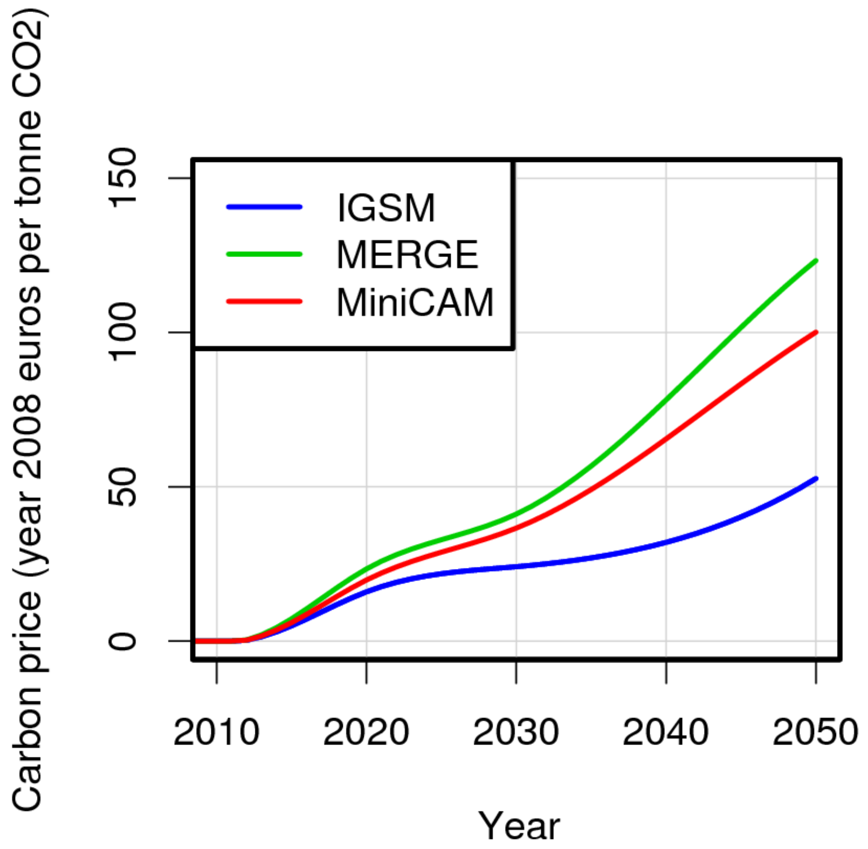

Figure 3: Carbon prices applied to aviation over time, by scenario.

3.6 Interactions and Combined Mitigation Effects

The policies, scenarios and mitigation measures discussed in Sections 3.1 – 3.5 above are not independent. For example, the reductions in emissions gained by adding winglets to an aircraft would be reduced if improved air traffic management meant that flight times were lowered for the routes flown by that aircraft. In addition, there are many mitigation measures which cannot be applied jointly at all, or for which the order of application of the measures is highly important (e.g. an engine upgrade followed by re-engining). Although we have attempted to choose mitigation measures which are less affected by these issues and to account for the fuel burn changes from already-applied measures when evaluating subsequent ones, it is still likely that the true mitigation potential of the set of measures modelled may differ from that predicted by our model. In addition, as noted above, we model only a subset of the measures that may be available to aviation over the next 40 years. Finally, as noted by Morris et al. (2009), it is not straightforward to estimate costs and benefits of mitigation measures for periods which may be 20 or more years after the present day. Therefore the results of this study should be regarded with caution, particularly with regard to the latter part of the time period modelled.

4 Case Studies

A large number of policy scenarios for separate and combined mitigation efforts are possible using the results of the studies described above. We simplify these into a set of five basic scenarios for combined mitigation:

Scenario B1: An unconstrained reference scenario in which no policies are applied and no mitigation measures are made available.

Scenario B2: Similar to scenario B1, but retrofit and new technology mitigation measures are made available to airlines.

Scenario P1: The EU ETS is applied to aviation, but no other measures are applied.

Scenario P2: As well as the ETS, the mitigation measures from scenario B2 are made available. Second generation biofuels are not made available.

Scenario P3: As scenario P2, but in addition second generation biofuels are made available, as detailed in Section 3.2 above.

These scenarios are discussed in order below. The base case (B1) is discussed in Section 4.1. In section 4.2 we consider the uptake of mitigation measures if they are made available in the base case (B2). Sections 4.3 and 4.4 consider the case in which the EU ETS is applied, without and with mitigation measures being made available to airlines (P1 and P2 respectively). Finally, Section 4.5 considers the case in which the ETS, biofuels and other mitigation measures are all active (P3). Although in theory we could also consider a case in which the ETS was not applied but biofuels were made available, in practice the uptake of biofuels under the assumptions made here in such a scenario would be minimal because the extra incentive to make savings in carbon costs by adopting biofuels would not be in place. In all cases results are presented separately for each of the three underlying demographic and socioeconomic scenarios (IGSM, MERGE and MiniCAM).

4.1 Scenario B1: Base Case

Results for the base case Europe model in the scenario where no policies are applied (B1) are presented in Figure 4 in terms of revenue passenger km (RPKM) in the top left; total fuel burn in the top right; airport capacity required relative to 2005 to maintain average arrival delay in the bottom left; and average fare per km in the bottom right. In general, we predict relatively low growth rates for Europe in comparison to other studies (e.g. Airbus 2007, Boeing 2007). Typically, the scenarios we model have yearly RPKM growth rates of around 2%, whereas the Boeing and Airbus forecasts have growth rates of over 3%. However, our results are within the range of RPKM growth rates that have been predicted for Europe. For example, ICAO (2004) predict domestic European RPKM growth rates of 1.4% per year to 2015[7].

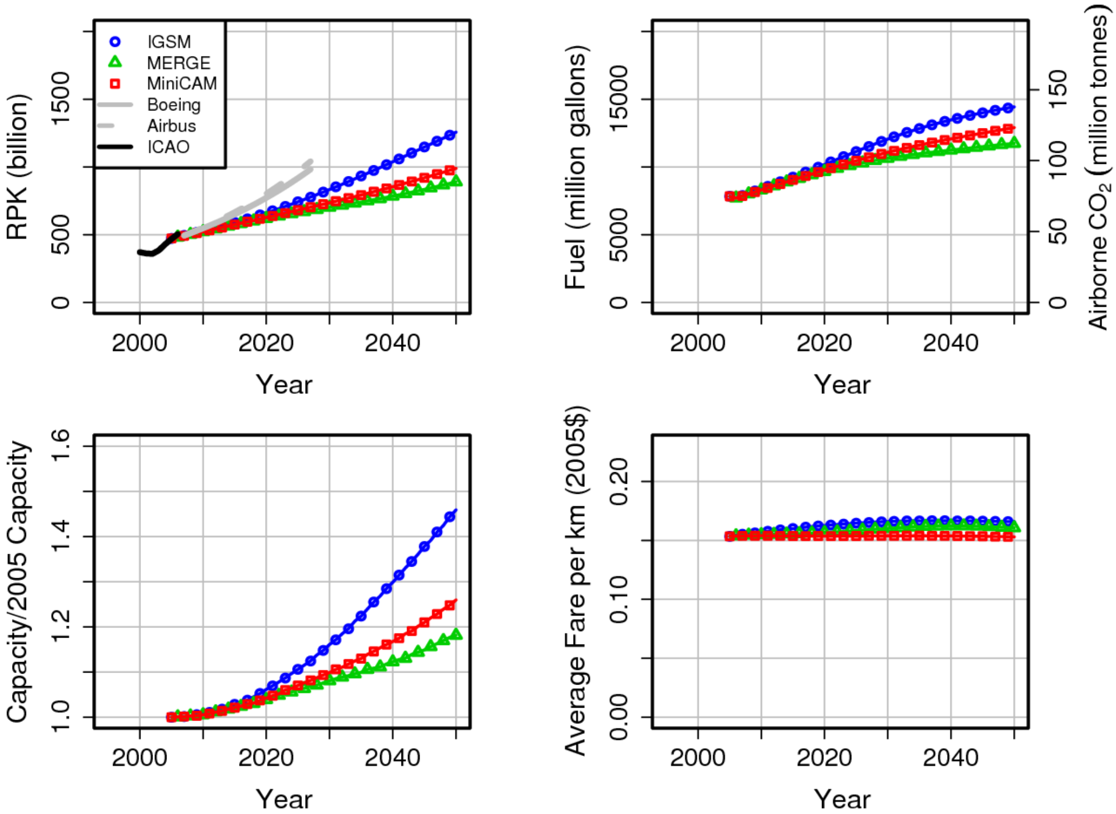

Figure 4: Comparison of RPKM, Fuel use, required capacity and fare for European scenarios in scenario B1 (no policies).

The low growth is a result of several combined factors. Firstly, our assumptions about competition and the passing back of costs to consumers (Section 2) lead to fares per km travelled which remain at roughly constant levels over the time period modelled. This results in lower demand growth than scenarios which assume a long-term decreasing trend in fares. Secondly, the elasticities estimated for this study (Table 5) will affect demand growth rates[8]. RPKM growth rates are also a strong function of the different GDP per capita growth rates of the underlying scenarios. For example, by 2040 the IGSM model assumes a GDP per capita for Western Europe which is nearly a third higher than that in the MERGE model. The differences in RPKM and capacity requirements between the different projection scenarios give a clear indication of the range of uncertainty that may be expected from applying

[7] This number does not include flights between different European countries, which make up a part of the RPKM projection for international flights. Although the projected value in ICAO (2004) for international flights is significantly higher (4.6%) than that for European domestic flights, this number includes flights into and out of Europe, which can make up a large proportion of the RPKM total because of the long distances flown. ICAO (2004) predict routes into and out of Europe to have emplanement growth rates to 2015 of over 5%, depending on the route group. Therefore the RPKM growth rate for intra-European flights is likely to be significantly lower than 4.6%, but it is difficult to estimate its exact value.

[8] Elasticities estimated were checked against literature values (e.g. Gillen at al. 2007). However, a relatively wide range of values exist in the literature so any two given studies may use different values.

different projections of future demographic and socioeconomic growth. As noted above, uncertainties are typically higher after 2020. Before this time, the three scenarios are relatively close.

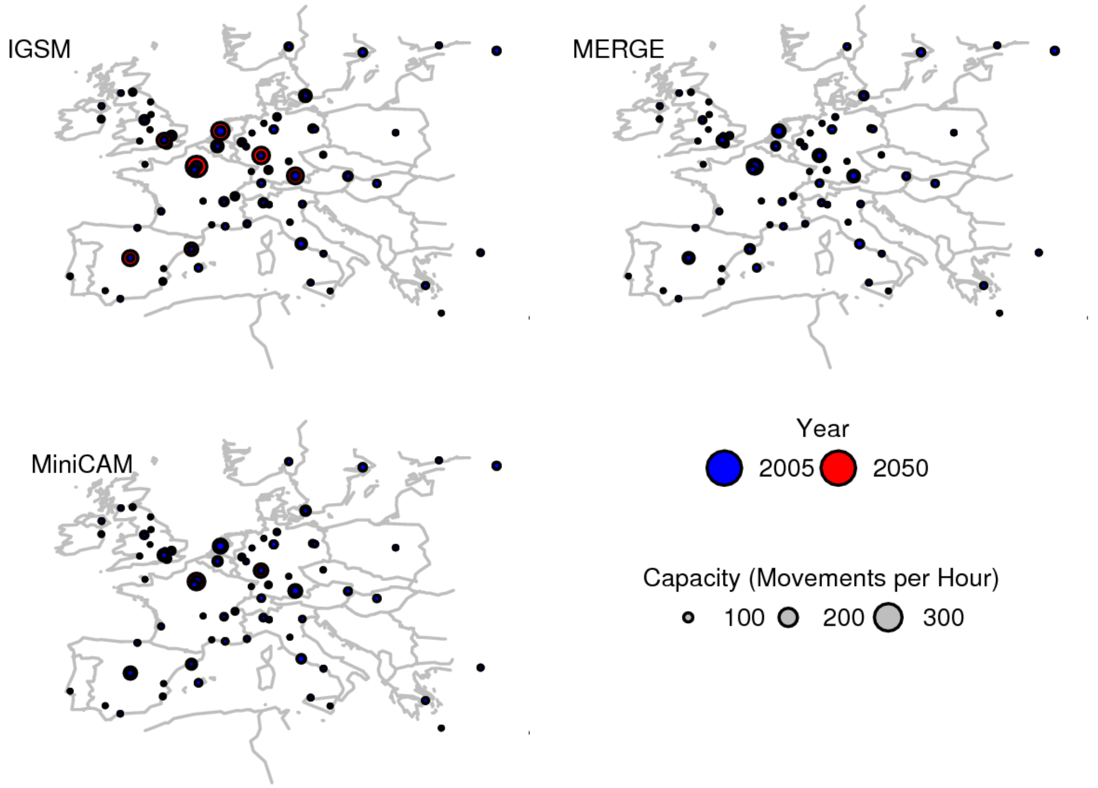

Figure 5: Airport capacity, 2005, and airport capacity requirements, 2050, for major European airports.

The slow demand growth in combination with fleet turnover and assumed rates of new aircraft technology improvement lead to a growth in system fuel burn and emissions which is relatively small and, even in the highest-growth scenarios, Europe's aviation emissions do not quite reach a doubling over present-day levels by 2050. Similarly, the required system airport capacity increases (shown in the bottom left panel of Figure 4 for the top 50 airports only) to keep delay at present-day levels are relatively moderate and concentrate primarily at or around major hub airports. Also shown in Figure 4 are historical RPKM figures for European domestic and international flights from ICAO (2008). As the underlying figures do not distinguish between intra-Europe international flights and flights to and from Europe, we apply a correction factor to international RPKM based on the ratio of seats available in these different classes of flights from OAG (2005).

In Figure 5 we break down the capacity requirements shown above into those for individual airports. Base year capacities (blue) and 2050 required capacities (red) are shown for a selection of the most-used airports. It is notable that the largest required capacity increases are concentrated around a small number of major hub airports, most notably in London, Paris, Frankfurt and Amsterdam. Whilst the majority of European airports may be able to carry on operating with only incremental capacity increases, the major hub airports would require larger capacity expansions to serve the forecast demand at current delay levels (for example, Paris Charles de Gaulle requires a 2.4 times increase in capacity to 2050 in the highest-growth scenario, and London Heathrow a doubling), or would require the expansion of nearby secondary airports instead. However, one assumption that we make is that routing, and in particular the hub airports operated by airlines, remains the same as in the base year. Therefore if airlines decide to change routing or move operations to a less-congested hub the extra capacity requirements could decrease significantly. However, moving hubs can result in considerable expense for an airline and busy hubs provide a commercial advantage for airlines if they can take advantage of the large number of connecting flights available, so congestion alone may not be enough to prompt such changes.

4.2 Scenario B2: Base Case with Abatement Measures

In the results in the previous section it was assumed that abatement measures such as aircraft retrofits and SESAR compliance are not made available to airlines. This is unrealistic, as retrofits (e.g. of winglets) can and do take place in the present day. As noted in Morrell & Dray (2009) there may however be substantial complicating factors relating to aircraft leasing and ownership which prevent full uptake of retrofit options even when they are economic, and many past retrofit options (e.g. re-engining) have only had limited uptake. In this section, we assume that a range of mitigation options as described in section 3.1 will be made available to airlines and will be adopted for applicable aircraft if it is economic to do so, ignoring leasing and ownership issues. As noted in Section 3.3, these options include retrofits, operational changes and the adoption of radical new technology options only, and are separate from the assumed trend in incremental-technology fuel burn reductions for new aircraft models. As the ETS is not active in this scenario, the main factor driving airlines to adopt retrofits is the chance of making savings on fuel costs by reducing total fuel burn. This means that the uptake is sensitive to the oil price trajectory in each scenario.

In Figure 6 the uptake of abatement measures in the IGSM scenario B2 is presented over time by aircraft size. As is apparent, not all mitigation options are economic to adopt, and those that are are not always adopted by the whole fleet (uptake is dependent on the size and age of each aircraft). Typically, those measures found to be economic here were also judged to be economic by Morris et al. (2009). These include winglet retrofits, which come in for nearly all applicable aircraft as soon as mitigation measures are made active. Note that we have assumed that the number of aircraft which can be retrofitted with winglets is relatively small; we do not assume that aircraft which already have winglets can be retrofitted with better winglets; and we assume that future aircraft models will already be fitted with winglets where they can provide a fuel burn advantage (see Section 3.1.1). These assumptions lead to an adoption of retrofit winglets which is relatively small and declines over time.

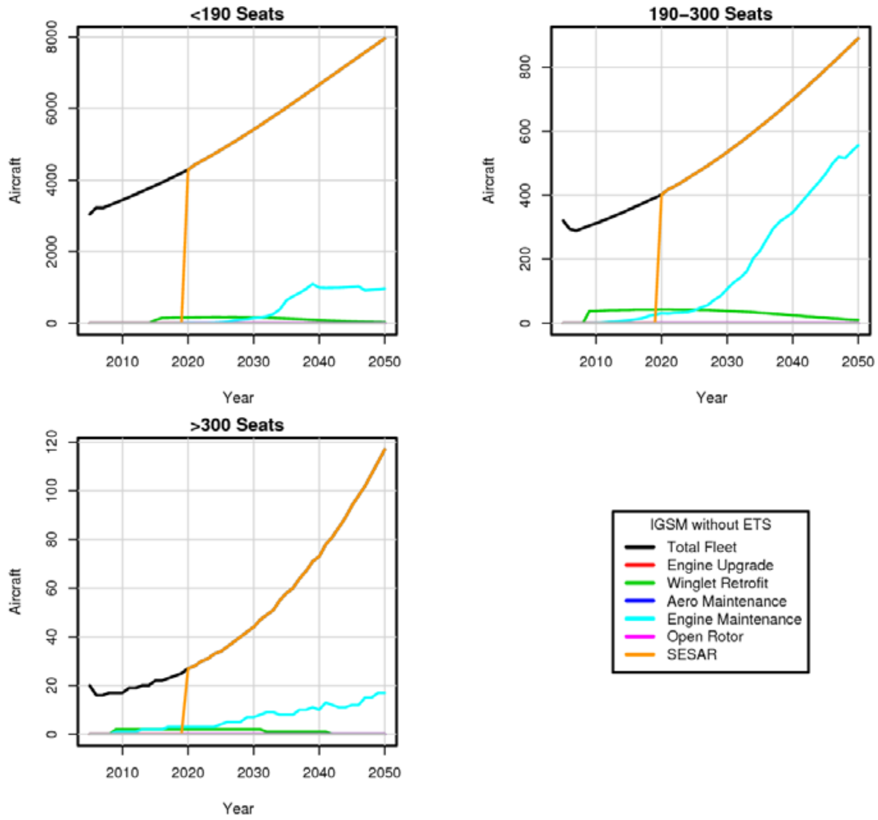

Figure 6: Uptake of abatement measures by aircraft size class in the IGSM scenario B2 (no ETS).

SESAR compliance, as described in Section 3.1.3, is assumed to be optional with no policy incentives for aircraft adaptation to take advantage of improved air traffic management. We find strong uptake of SESAR-compatible adaptations in the IGSM scenario B2, quickly increasing to the whole fleet, after SESAR is introduced in 2020. The other option which we find some uptake of is increased engine maintenance. Usage of this option is highest amongst medium-sized aircraft but still does not reach 100% of the fleet by 2050. In general, uptake of all mitigation options starts in and is highest amongst older aircraft, which have higher fuel burn and stand to gain most from the fuel burn reductions on offer. However, engine upgrades, increased aerodynamic maintenance and open rotors are not adopted by any airlines in this scenario. For the case of open rotors, this is due to the high upfront costs associated with adopting open rotor technology; engine upgrades and increased aerodynamic maintenance are unpopular options in this scenario because they are assumed to provide only small benefits in terms of reduced fuel burn.

In Figure 7, the corresponding chart for the MERGE scenario B2 is shown. Oil prices are lower in the MERGE scenario, providing less of an incentive to adopt mitigation measures. Note that total fleet growth is also lower, i.e. the axis scales are different between Figure 6 and Figure 7. Similar measures are adopted to those found economic in the IGSM scenario, but typically their uptake is lower or over a longer time period. For example, although winglets are still economic to fit to larger aircraft, no small aircraft are fitted with them.

SESAR uptake is slightly slower and fewer aircraft take up increased engine maintenance.

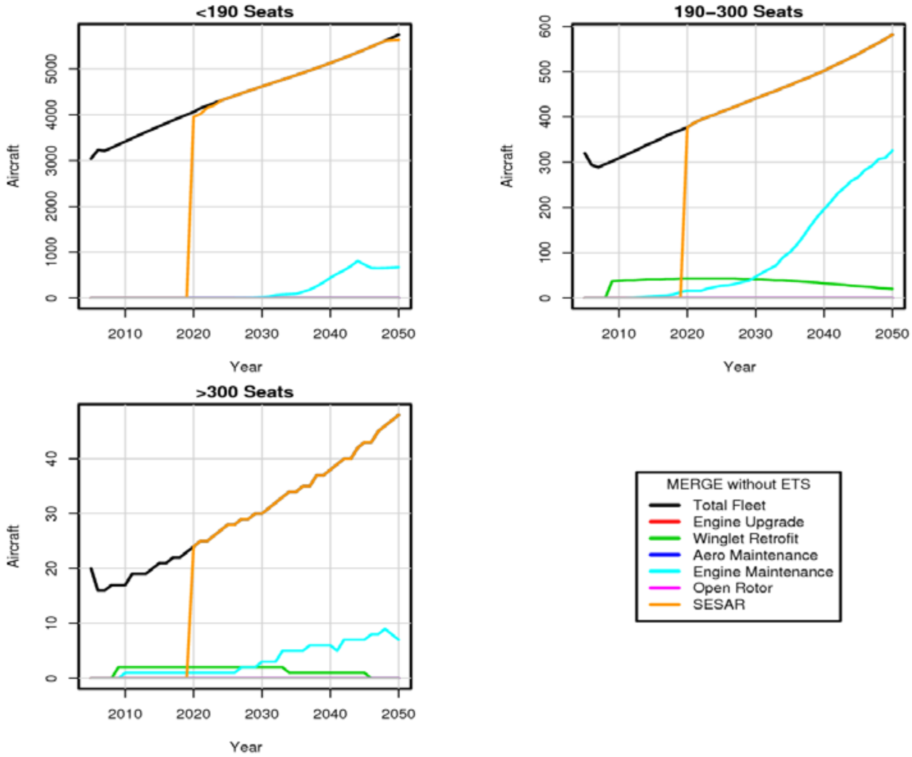

Figure 7: Uptake of abatement measures by aircraft size class in the MERGE scenario B2 (no ETS).

Similarly, the MiniCAM scenario B2 (Figure 8) has an even lower oil price and less extensive uptake of abatement measures. In particular, SESAR uptake is not 100% in this scenario with some aircraft, particularly those in the small aircraft class, choosing to opt out. This suggests that in a low-growth, low fuel cost future extra incentives may need to be applied to get the entire fleet to adapt to SESAR usage.

The corresponding RPKM and fuel lifecycle (i.e. including processes such as extraction, refining and transportation) emissions in each case in comparison to scenario B1 are shown in Figure 9. For Jet A, the total fuel lifecycle emissions are around 1.15 times the airborne emissions. Hence the emissions shown in Figure 9 are not equal to the airborne-only emissions shown in Figure 4. In general, those abatement measures which are adopted in this scenario are only just economic, and there is only a small difference in fare and hence RPKM between the two scenarios. RPKM is higher in the abatement cases because some of the money that airlines save on reduced fuel costs is being used to lower ticket prices slightly. None of the scenarios show appreciable reductions in fuel lifecycle CO_2 emissions until 2020, when SESAR is assumed to come into effect. This is because the fuel burn decrease per aircraft offered by SESAR compliance is significantly higher than that available for measures adopted before 2020 (e.g. 10.5% compared to up to 2.4% for winglet retrofits). By 2050 we see a reduction in emissions over the base case of around 9 - 15%, depending on scenario. However, there also exist other emission-reducing abatement measures which may offer cost-effective options for reducing aircraft fuel burn (Morris et al. 2009) so the true potential reduction in CO_2 emissions may be higher than this.

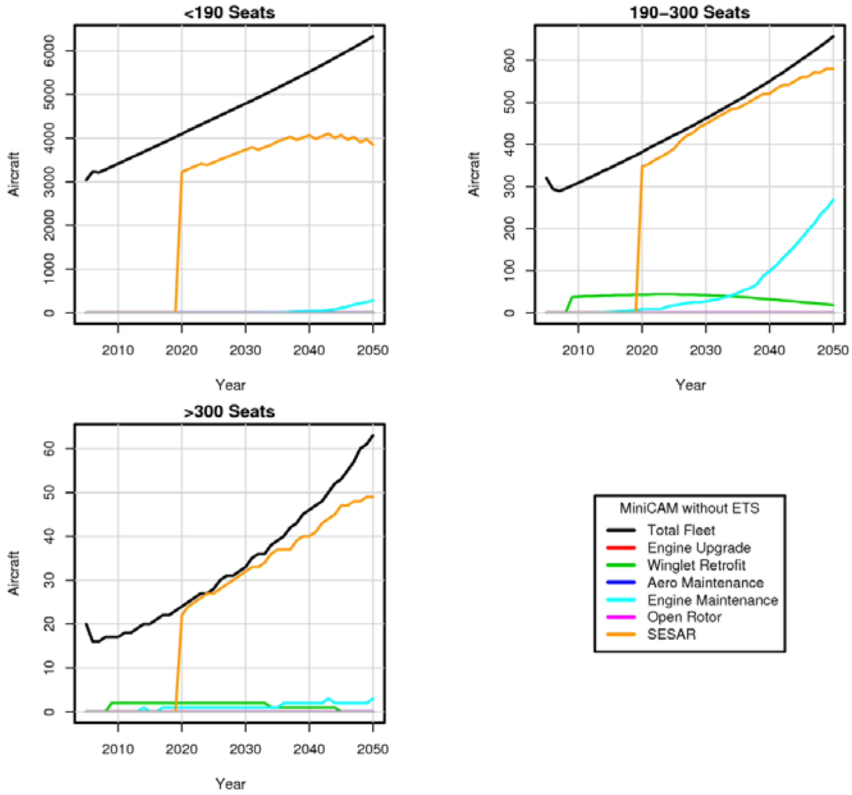

Figure 8: Uptake of abatement measures by aircraft size class in the MiniCAM scenario B2 (no ETS).

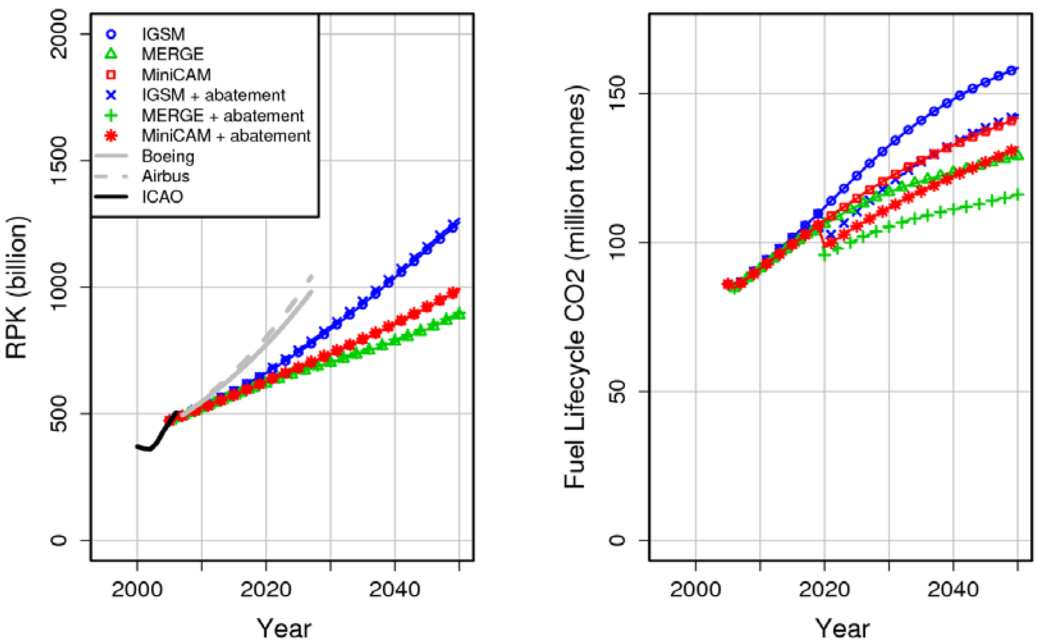

Figure 9: RPK and lifecycle CO2 emissions for Scenarios B1 (base) and B2 (base with abatement options).

4.3 Scenario P1: Emissions Trading

The inclusion of aviation in the EU ETS, beginning in 2012, has already been agreed by the EU (Allen et al. 2009). As it currently stands, all flights both within the EU and to and from the EU will be included, and no uplift factor to account for aviation's non-CO_2 emissions will be applied. We assume carbon trading applied to these flights beginning in 2012 as detailed in Section 3.5. Airlines may display a number of responses to the imposition of the ETS. If abatement measures are not available to airlines, as we assume in scenario P1, then their main response to increasing fuel costs from carbon trading is likely to be to increase ticket prices. Thus, there will likely be a reduction in airborne emissions, but it will result from decreased demand. At the same time, permits bought by aviation will contribute to the reduction in emissions from other sectors. One other possibility is that airlines may reconfigure their networks to take advantage of non-EU airports such as Zurich or Dubai. However, Albers et al. (2009) suggest that this is unlikely at present-day permit prices. We assume airline networks will remain unchanged by the introduction of the ETS in this study.

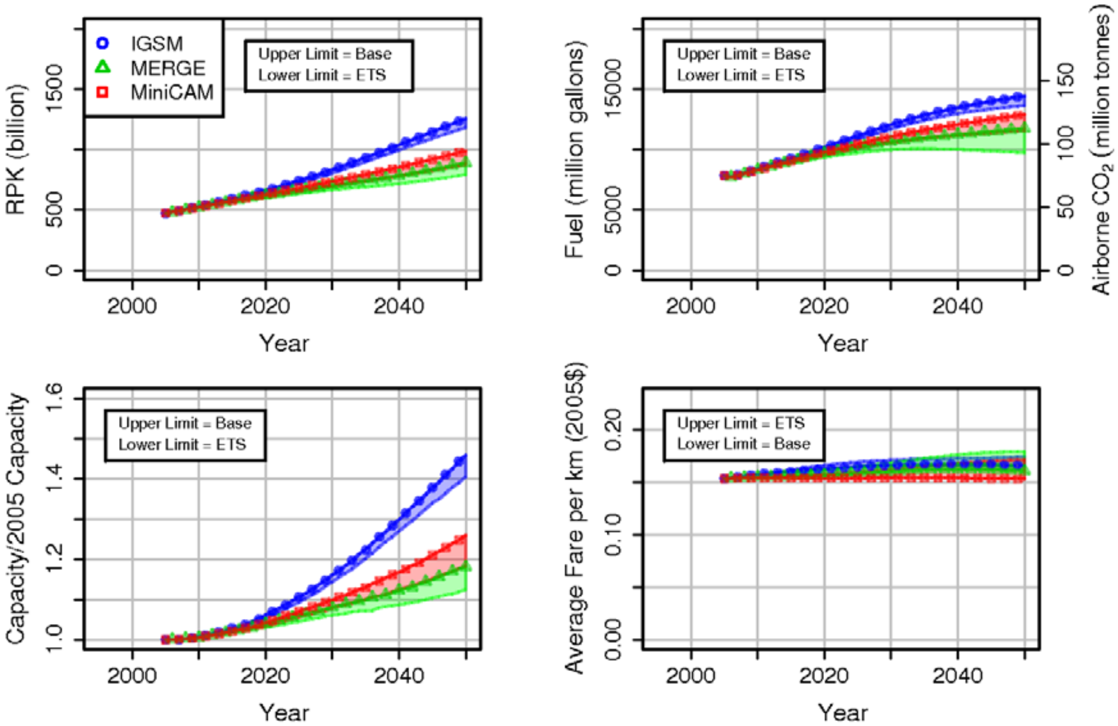

Figure 10: As Figure 4, but including also the effects of the EU ETS (Scenario P1) in comparison to the base case.

In Figure 10 we show the effect of applying emissions trading (scenario P1) in comparison to the base scenario (scenario B1), using the price trajectories outlined in section 3.5, as well as corresponding GDP and oil price projections. As can be seen, the effect is relatively small but not negligible at suggested near-future (2020-2030) carbon price levels. As the carbon price increases over time, greater reductions in demand and emissions are predicted at later dates. Demand reductions in the different scenarios are mainly related to the different carbon price trajectories assumed (Figure 3). However, the total emissions are also a function of the underlying economic scenario. In particular, the lower demand and relatively high carbon price in the MERGE ETS case results in roughly constant fuel use for the EU fleet after 2025, i.e. the rate of RPKM growth and the rate of fuel burn per RPKM decrease through fleet turnover are roughly equal. Reductions of up to 20% in CO_2 emissions compared to scenario B1 are possible in the MERGE scenario from the ETS alone, with no abatement measures made available to airlines. However, these reductions occur only near the end of the time period examined, in response to a carbon price which has risen to €124 (year 2008 euros) per tonne of CO_2.

4.4 Scenario P2: Emissions Trading with Abatement Measures

As noted in Section 4.2, it is unrealistic to assume that airlines will not make use of the abatement measures available to them, if those measures can offer them real economic benefit. If the EU ETS is applied to aviation, airlines will invest into fuel-saving measures, as long as the extra costs per tonne of CO_2 saved are lower than the permit price per tonne of CO_2 emitted. We repeat the analysis in Section 4.2 for the case in which the ETS is applied to aviation and mitigation measures (Scenario P2). Biofuels are not made available in this scenario.

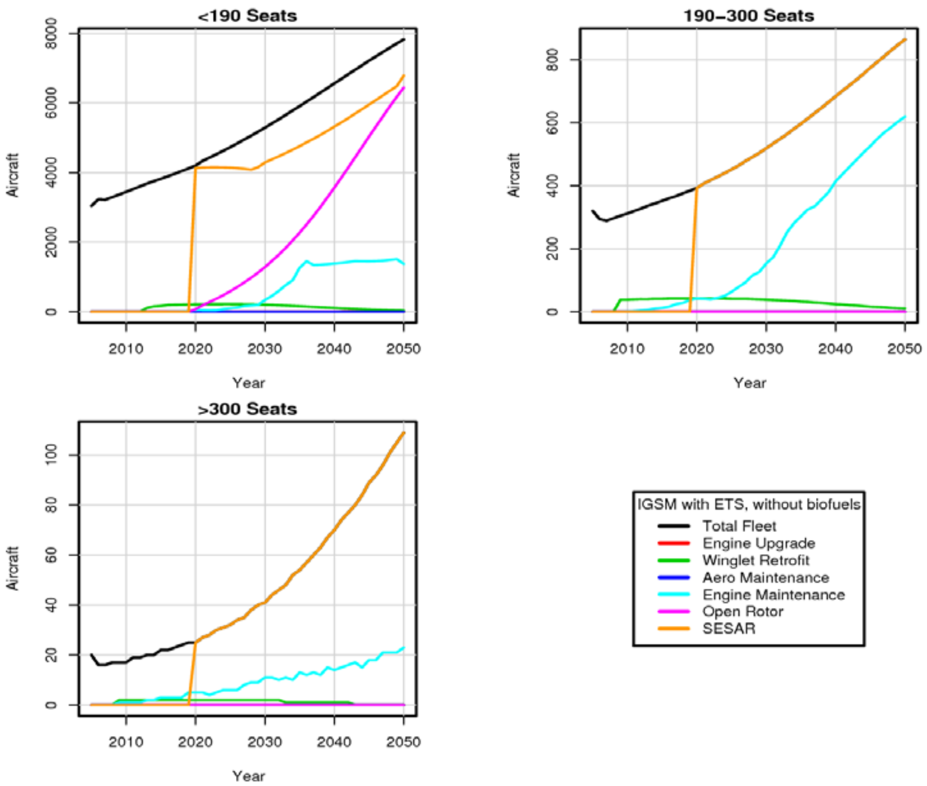

Figure 11: Uptake of abatement measures by aircraft size in the IGSM Scenario P2 (ETS + non-biofuel abatement measures).

The uptake of mitigation measures in the IGSM scenario P2 is shown in Figure 11. In comparison to the no-ETS case (Figure 6), uptake is slightly increased – for example, more medium-size aircraft adopt increased engine maintenance. However, the most notable change is the uptake of open rotors within the small aircraft class. As noted in Table 3, we assume open rotors to have high monetary costs but significant benefits (~30%) in terms of fuel burn reduction. Once open rotors have been adopted, this large reduction in fuel burn changes the cost-benefit analysis for other mitigation options. In particular, fuel cost savings from other potential mitigation options are reduced to 70% of what they would have been in the absence of open rotors. This leads to a SESAR uptake of below 100% for small aircraft in this scenario once open rotor technology starts to enter the fleet. Similarly, if other measures which significantly lower fuel use have already been adopted, the likelihood of then adopting open rotor technology is smaller. This means that two relatively similar scenarios can have quite different mitigation option uptake histories depending on the order in which different measures become available and/or economic to adopt.

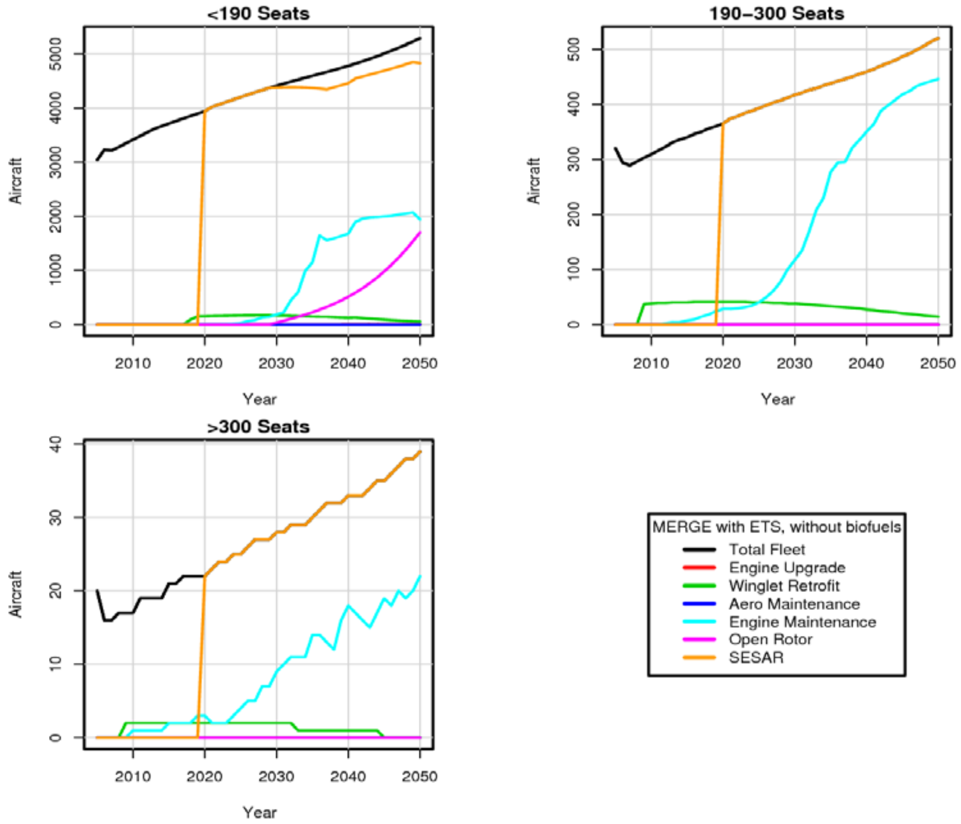

Figure 12: Uptake of abatement measures by aircraft size in the MERGE Scenario P2 (ETS + non-biofuel abatement measures).

The corresponding uptake of mitigation measures in the MERGE and MiniCAM scenario P2 are shown in Figure 12 and Figure 13. Again, uptake is increased over the base case. MERGE has the highest carbon price of the three scenarios, although combined carbon and fuel costs are still lower than the IGSM case. The high carbon price leads to a strongly increased uptake of the extra engine maintenance option over scenario B2. Open rotor technology is also adopted by small aircraft, but only after 2030. The MiniCAM scenario displays similar behaviour, with some open rotor aircraft entering the fleet in 2034. As in the IGSM scenario, SESAR compliance is lower than 100% for open rotor aircraft. Since SESAR will be well-established by 2030 under the assumptions used here, such non-compliance is unlikely to occur in practice – i.e. the infrastructure to allow aircraft to use non-complying equipment may no longer be in place.

Measures which are still not economic to introduce even with the ETS in any scenario include engine upgrades and increased aerodynamic maintenance. Typically, the ETS initially increases the effective oil price by only 10-30 dollars per barrel (year 2005 US dollars), with the effective oil plus carbon price in the highest-price scenario, IGSM in the year 2050, being around 175 dollars per barrel. In 2030, effective oil prices are around 100 dollars per barrel, with the IGSM scenario slightly higher and the MiniCAM scenario slightly lower. If oil or carbon prices increase beyond these levels, or airlines believe that they are going to, then engine upgrades and increased aerodynamic maintenance may also be adopted (see e.g. Morris et al. 2009).

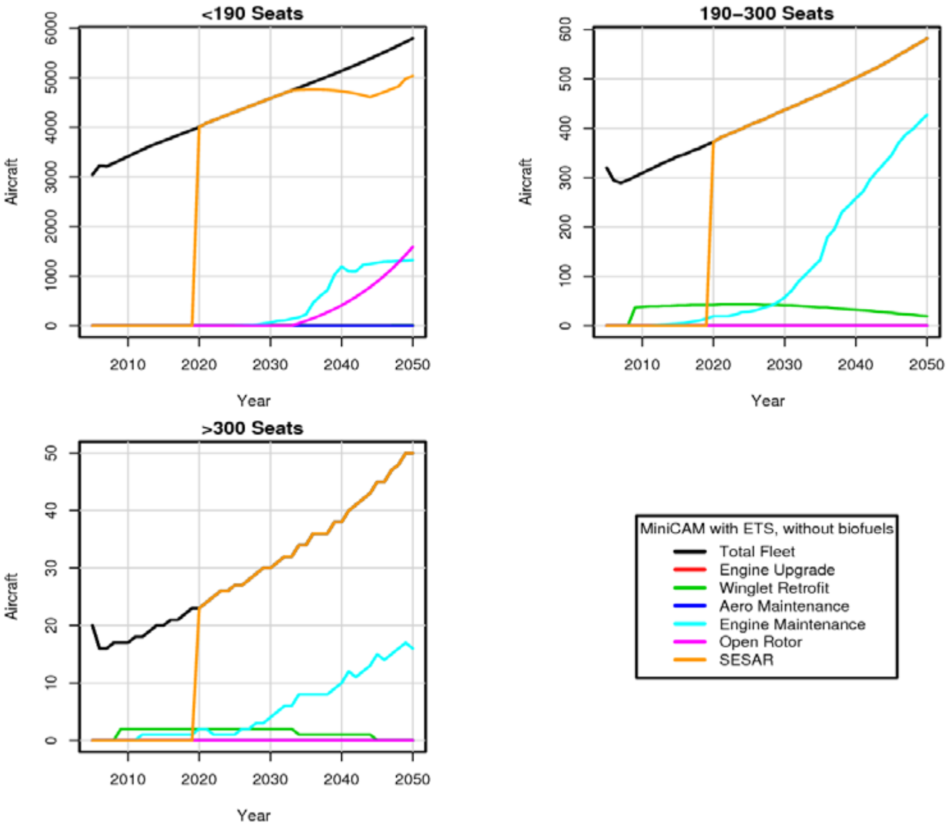

Figure 13: Uptake of abatement measures by aircraft size in the MiniCAM Scenario P2 (ETS + non-biofuel abatement measures).

In Figure 14, the RPK and fuel lifecycle CO_2 emissions for scenario P2 are shown, in comparison to the base case (scenario B1). As for the case with emissions trading alone, the RPK is lower than in the base case as airlines are purchasing permits as well as applying mitigation measures. However, the reductions in demand are less than in the ETS-only case (Scenario P1, Figure 10). Fuel lifecycle CO_2 emissions before 2020 are slightly lower than in scenario P1 due to the adoption of winglet retrofits and increased engine maintenance. After 2020, significant reductions in emissions are possible as open rotors and SESAR are adopted. In particular, the MERGE scenario emissions show a slight decreasing trend over time after 2030, and IGSM CO_2 emissions in 2050 are reduced by almost a third compared to the base case with no ETS or abatement measures.

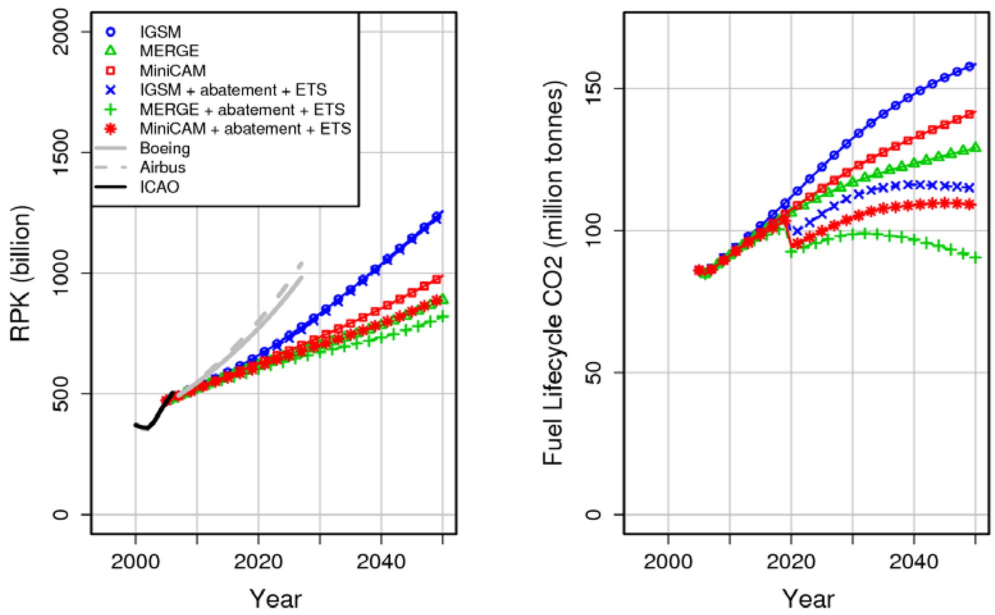

Figure 14: Comparison of the RPKM and fuel lifecycle emissions between the base case and scenario P2 (ETS+non-biofuel abatement measures).

4.5 Scenario P3: Emissions Trading and Biofuels

The final scenario considered here, scenario P3, is the case in which second-generation biofuels are made available to aviation from 2020 together with ETS and mitigation options. As discussed in Sections 3.1.4 and 3.2, we choose a 50-50 drop-in blend of cellulosic biomass-derived synthetic jet fuel with Jet A as our sample biofuel scenario. Other biofuels and blending assumptions may produce results which vary significantly from the scenario presented here. Although aviation biofuels have the potential to present a significant advantage over aviation kerosene in terms of lifecycle emissions, it is as yet uncertain as to whether suitable biofuels can be produced in sufficient quantities to supply the entire European aviation fleet. As noted in Section 3.1.4, we assume production growth rates based on historical data from biofuel programs. Biofuels are assumed to become available to aviation from 2020. However they may not be economic to adopt for aviation for some time after this date, depending on the underlying oil and carbon prices. We assume in this case that production capacity will still be increasing over the time period between 2020 and when biofuels become economic to adopt for airlines, potentially in anticipation of aviation demand or in response to demand from other sectors.

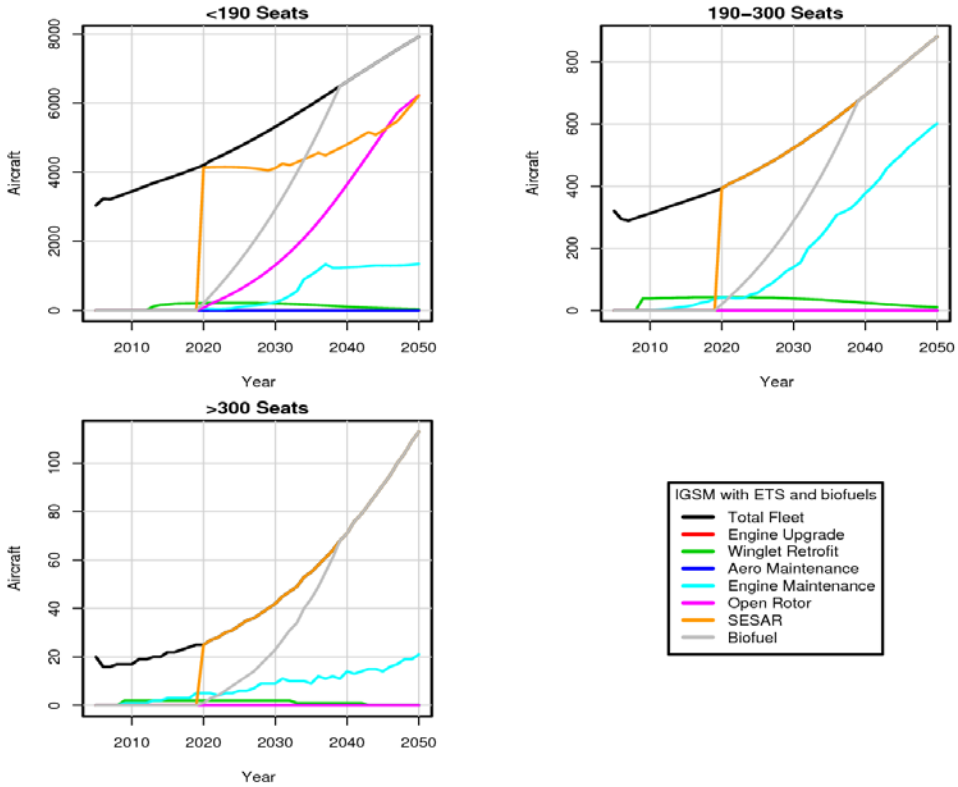

Figure 15: Uptake of abatement measures by aircraft size in the IGSM Scenario P3 (ETS + biofuels).

The uptake of abatement measures, including biofuels, over time by aircraft size class in the IGSM scenario P3 is presented in Figure 15. Two main points are notable. First, as IGSM is a relatively high oil price scenario, biofuels are economic to adopt as soon as they become available from 2020. Takeup is limited only by availability, and eventually the whole fleet adopts biofuels as production capacity increases. Secondly, after biofuels come into widespread use, uptake of other abatement measures is slightly reduced in comparison to the no-biofuels case (Figure 11). Airlines are able to make significant savings on carbon costs from biofuel usage. Therefore there is less pressure on them to adopt other mitigation measures. In particular, SESAR compliance is lower. As noted above, choosing not to adapt aircraft for SESAR may in practice be unrealistic once SESAR is well-established, and possibly mandated. In reality, SESAR compliance after 2030 is likely to be higher and adoption of other measures, such as open rotors, may be lower.

The corresponding MERGE and MiniCAM scenario results are presented in Figure 16 and Figure 17. Although MERGE has a lower oil + carbon price than IGSM, it is still economic to start adopting biofuels when they become available, in 2020. However, the lower oil prices in the MiniCAM scenario result in biofuel adoption only in 2027. After this date, uptake is similar to the IGSM scenario, i.e. only limited by availability. As in the IGSM case, uptake of biofuels also lowers the demand for other mitigation measures. For example, open rotors do not come into widespread usage, as they did in the no-biofuel case.

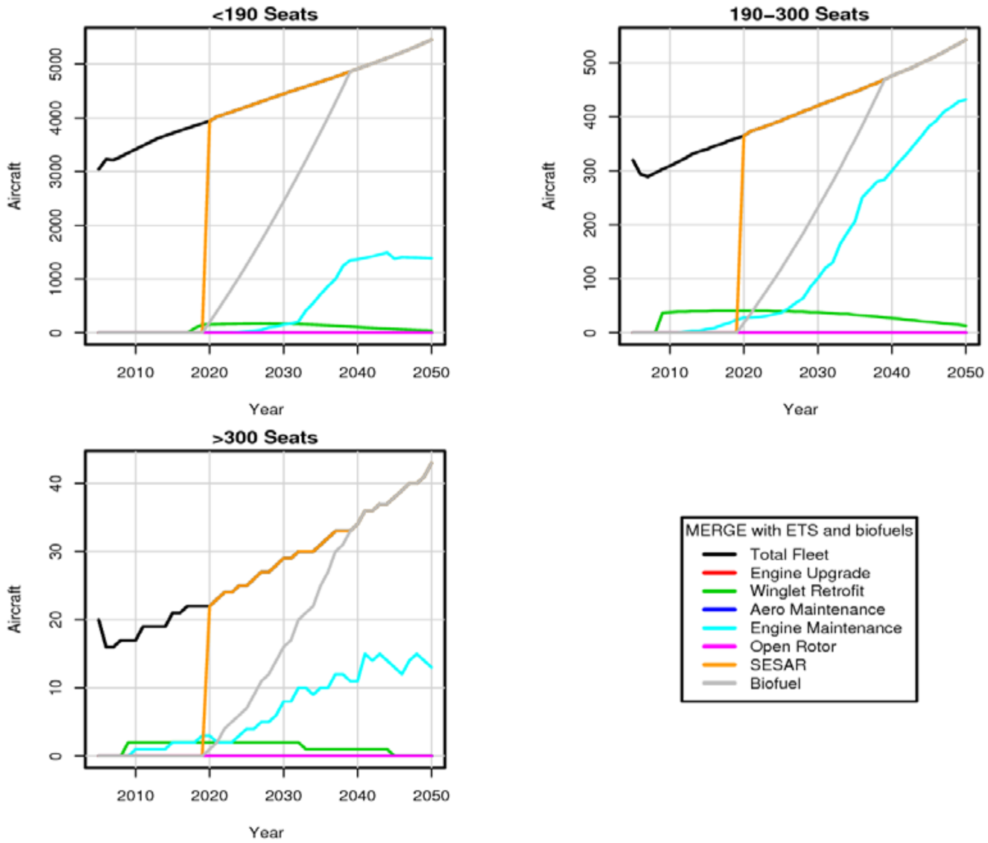

Figure 16: Uptake of abatement measures by aircraft size in the MERGE Scenario P3 (ETS + biofuels).

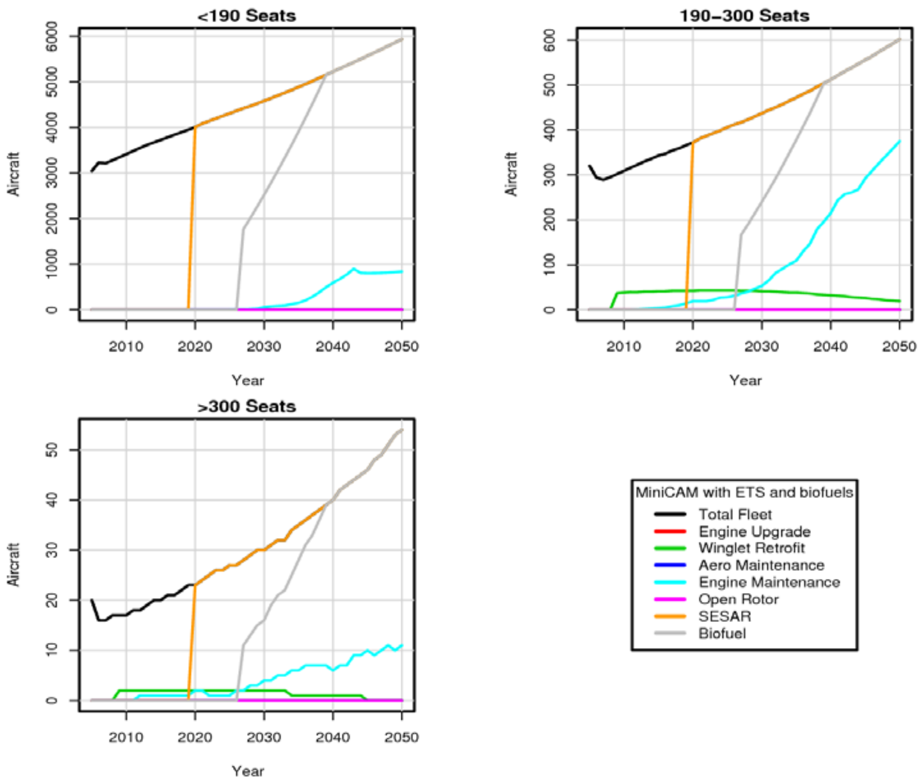

Figure 17: Uptake of abatement measures by aircraft size in the MiniCAM Scenario P3 (ETS + biofuels).

RPKM and lifecycle emissions from scenario P3 are given in Figure 18, in comparison to the base case (scenario B1). It is useful to compare these values with the scenario P2 case plotted in Figure 14, i.e. in which all other variables are the same, but biofuels are not made available. The availability of biofuels increases the RPKM flown, as airlines are able to use the savings made on emissions trading to lower ticket prices. However, RPKM typically does not increase back to base scenario levels, i.e. airlines are still subject to greater costs in the ETS + biofuels case than in the no-ETS, no-biofuel case as they cannot reduce their total emissions to zero. Lifecycle CO_2 emissions are, however, strongly reduced once biofuels are introduced. Even in the highest-growth scenario (IGSM), it is possible to reduce 2050 aviation lifecycle CO_2 emissions to below 2005 levels by making biofuels available. In lower-growth scenarios biofuels are adopted later, but could still potentially lower aviation fuel lifecycle emissions to around 20% below 2005 levels. Aviation-suitable biofuels may therefore present a “win-win” situation for airlines if they become available in sufficient quantities after the EU ETS has been applied to aviation, allowing both significant cost savings and large reductions in total emissions. However, it is important to note that airborne emissions will remain the same for an aircraft powered by a typical drop-in biofuel as one powered by Jet A – in fact, the slight increase in RPKM in scenario P3 over scenario P2 means that in fact airborne emissions will be higher in scenario P3, even though lifecycle CO_2 emissions are much lower. In such a case, the non-CO_2 effects of aviation on climate, which are not included in the EU ETS, must be carefully considered.

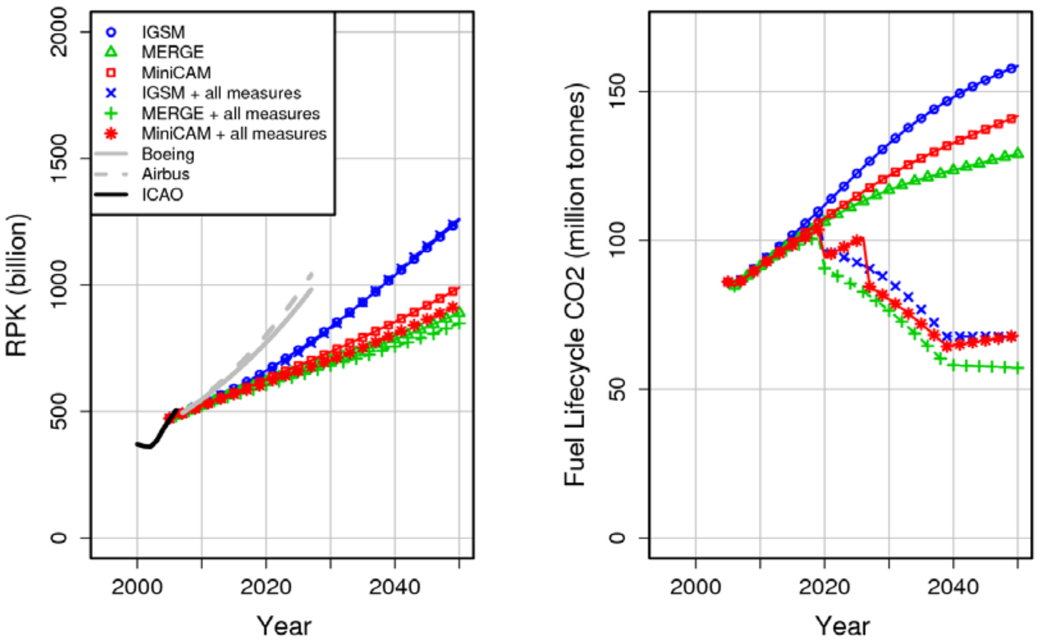

Figure 18: RPK and fuel lifecycle emissions for the base case and scenario P3 (ETS + biofuels).

4.5.1 Quantities of Biofuel Required

As noted in section 3.1.4, it is far from certain that biofuels can be produced in sufficient quantities to fuel the global aviation fleet. Figure 19 shows the quantities of Jet A and cellulosic biofuel required over time in scenario P3.

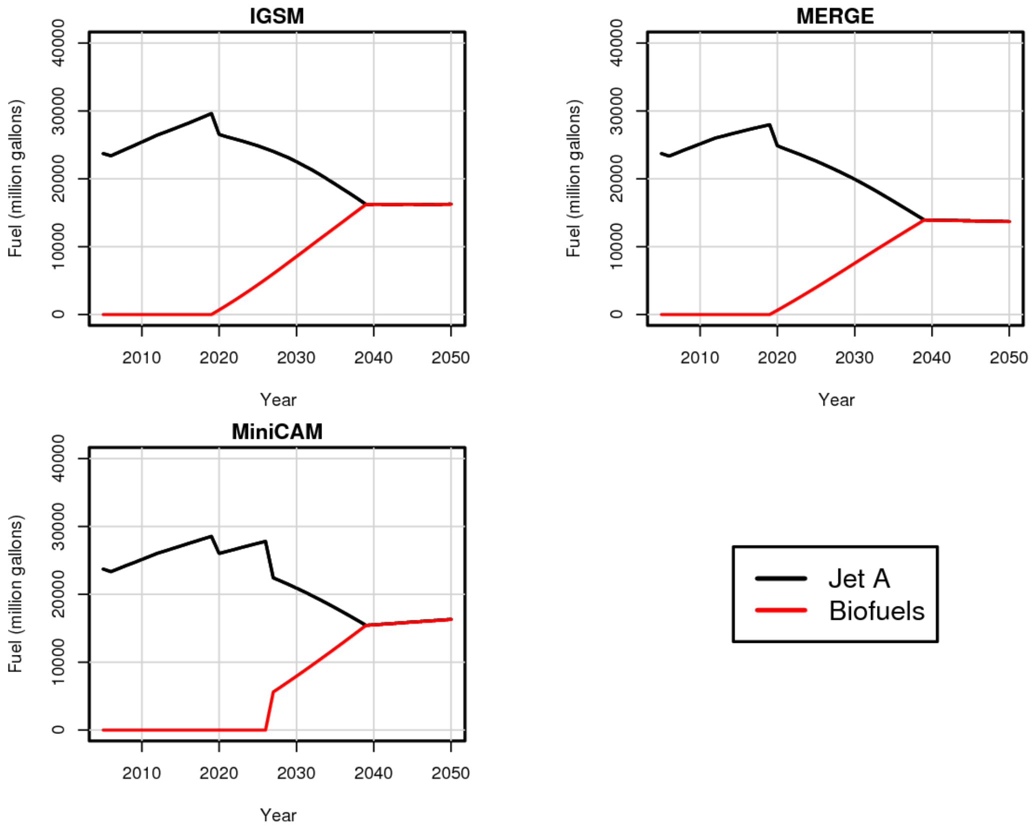

Figure 19: Jet A and biofuel usage by time in scenario P3 (ETS + biofuels).

Because the 2050 end result in the IGSM, MERGE and MiniCAM scenarios P3 is that the entire fleet comes to use a 50-50 blend of Jet A and cellulosic biomass-derived synthetic jet fuel, the quantities required of Jet A and biofuel are equal once full adoption has taken place. The scenarios differ only in the start date and timescale of adoption, and the maximum amount of biofuel required. In the highest-growth scenario this corresponds to just under 18 billion gallons in 2040-2050. To produce this much cellulosic biomass, a land area of about 14 million hectares (roughly the size of England), would be required. Given that this quantity of biofuel would supply intra-European aviation only, and that aviation is likely to be only one of a number of sectors interested in using biofuels, this suggests that the successful adoption of aviation biofuels may require research into higher-yield biofuel options than cellulosic biomass.

4.5.2 Noise and Air Quality Implications

This study has mainly concentrated on the implications of and reduction strategies for aviation CO_2 emissions. However, CO_2 and its associated climate impacts are far from the only environmental problems associated with aviation. Whilst air quality and noise effects may be smaller issues in terms of their potential for global economic impact (e.g. Stern 2006), they have a real and continuing negative impact on communities around airports. In addition, regulation has historically been focused on noise and local air quality issues rather than global climate issues. Thus, it is possible that the scenarios presented here may perform well in terms of reducing CO_2 emissions but not be implementable because the resulting local area NO_x emissions or noise levels breach pre-existing regulations. In the case of biofuel adoption, lifecycle CO_2 emissions may decrease strongly whilst aircraft movements and airborne/local area emissions remain similar to those in the non-biofuel case, or even increase, as discussed in section 4.3.

In Figure 20 the change in NO_x emissions between the base case (scenario B1) and the ETS+biofuels case (scenario P3) is plotted, by airport for major European airports in 2005 and 2050. We assume that the chosen biofuel blend has identical local and airborne emissions to Jet A. Yearly total airport-region NO_x emissions below 3000 feet are presented. Typically, those airports which have the highest required increases in capacity as indicated by Figure 5 also have the highest resulting NO_x increases. Similarly, the higher the demand growth resulting from a background scenario, the larger the increases in local emissions observed in that scenario. Local emissions are also affected by the amount of delay which is incurred with engines running. For example, holding and taxi delays (provided the engines remain on) are associated with much higher local emissions than delays incurred at the gate or in a parking area, where only the aircraft's Auxiliary Power Unity (APU) is run.

The left-hand panels in Figure 20 show local NO_x emissions in the case that no mitigation measures are applied at all (Scenario B1). It is immediately notable that only a small reduction in local NO_x is gained by applying the full suite of mitigation measures, as shown in the right-hand panels of Figure 20. As noted above, whilst airlines making extensive use of drop-in biofuels are able to strongly reduce their lifecycle fuel emissions, the emissions associated with aircraft in use will not be strongly changed and hence air quality impacts will increase with increasing RPK. Similar issues are likely to apply to aircraft noise. In the event of widespread biofuel adoption under an ETS, it may therefore be necessary to introduce new regulations or maintain or tighten older regulations in order to deal with the non-CO_2 impacts of aviation.

It is also noted that changes in airline routing may have a significant impact on local emissions aviation impacts. As discussed above, if airport capacity is not added to congested airports, airlines may shift operations to other airports, including secondary airports. This would change the distribution of local emissions and noise between airports, potentially limiting the negative impacts of non-CO_2 effects at the larger airports, but increasing it at the smaller airports. Such conclusions would, however, require further study for verification.

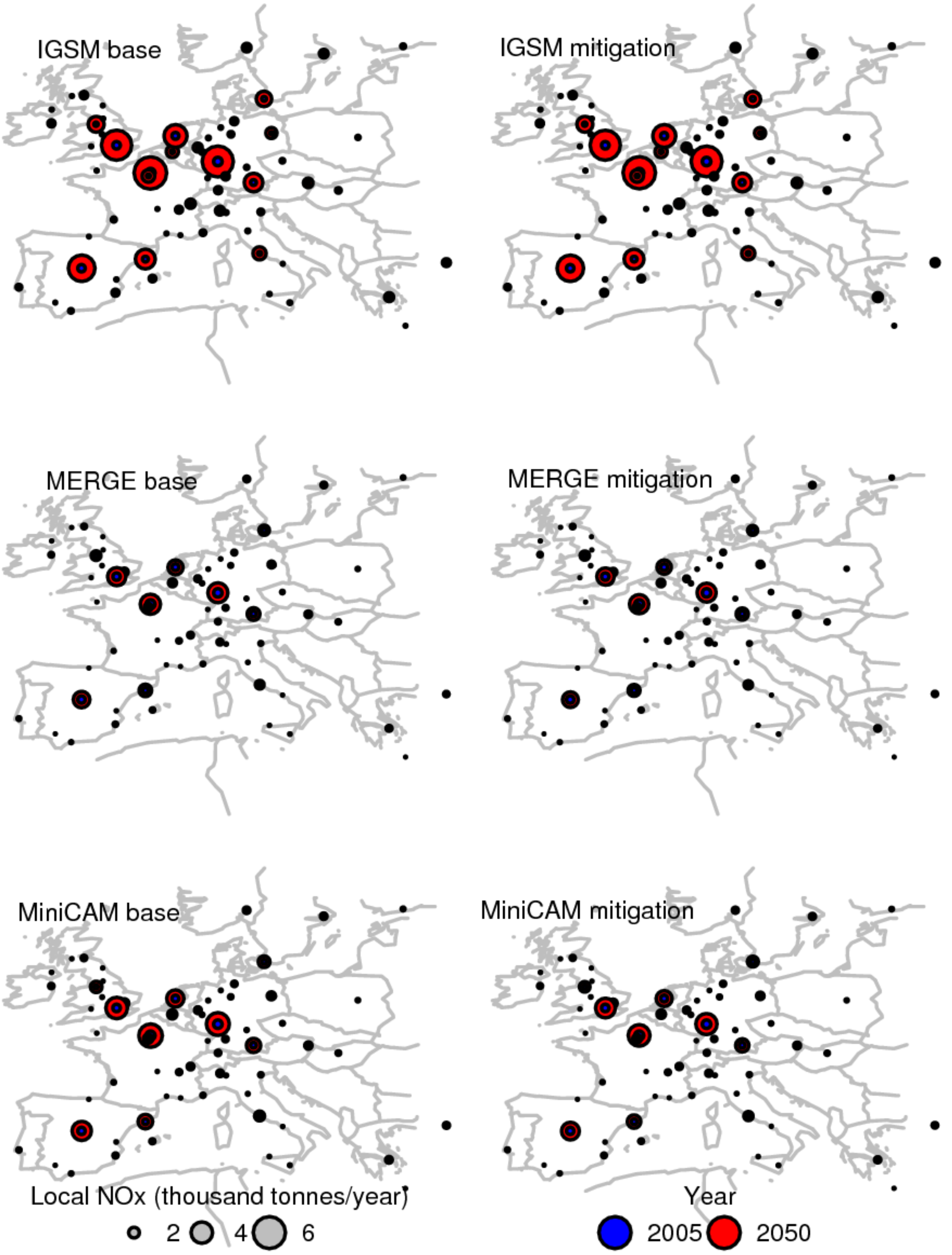

Figure 20: Increase in NOx emissions by for major airports, 2005 and 2050, for scenarios B1 (base) and P3 (ETS+biofuels).

5 Summary

In this report, we have attempted to assess the emissions mitigation potential of a number of policy and scenario options for the European air transport system, by applying the results of a set of studies examining individual aspects of the European aviation-environment issue to an aviation systems model. A number of conclusions can be drawn from this study as to the effectiveness of different mitigation options. It should be noted that these must be considered in the light of the significant uncertainties involved in projecting many of the key variables needed for modelling. In terms of the objectives set out at the beginning of this report, the main conclusions are:

How may the European aviation system change to 2050?

Initial results for unconstrained and ETS-only scenarios suggest that future European aviation system growth is likely to be modest in all scenarios, with the ETS initially having only a relatively small effect at projected carbon permit prices. Under the assumptions used in this study, a RPKM growth rate of around 2% per year for intra-European (including European domestic) traffic is projected. Congestion and capacity issues may play a strong part in shaping how the European aviation system evolves to 2050. Our analysis of capacity requirements in the unconstrained case suggests that the majority of minor European airports may be able to carry on operating with only incremental capacity increases. However, the major hub airports would require larger capacity expansions in order to serve forecast demand at current delay levels. If these capacity increases are not added, airline routing networks may change significantly, and the system growth would be less than presented in this report.

How will the EU ETS affect the uptake of aircraft retrofit and new technology options?

Uptake of the range of mitigation options simulated in this study varies with the underlying economic scenario. For the assumptions about costs, benefits and introduction timescales used in this study, options which are economic for some or all of the applicable fleet without the ETS include the retrofitting of winglets, compliance with SESAR avionic and crew training requirements, and increased engine maintenance. However, open rotors are typically not economic to adopt over the period to 2050 unless the EU ETS is applied, due to their high upfront cost. The number of aircraft adopting mitigation measures is sensitive to the underlying oil and carbon prices. The higher the oil price, and the higher the carbon price, the more likely it is that further fuel-saving technologies will be adopted. Thus the ETS is potentially a significant tool in getting airlines to adopt fuel-saving technology. However, at projected near-future carbon prices of around €20 per tonne of CO_2, carbon costs are relatively small compared to an airline's typical fuel costs. Thus oil prices are likely to have a more significant effect on aircraft retrofits and the adoption of new technology in the near future.

At what rate will fuel-saving technologies percolate into the European fleet?

As detailed above, the rate at which fuel-saving technology enters the fleet is dependent on the scenario oil and carbon prices. As noted by Morrell & Dray (2009), the rate of new aircraft technology entering the fleet is also a strong function of the rate of fleet growth. For example, regions of the world which have recent strong fleet growth (e.g. South and East Asia) have typically very young fleets with a high proportion of newer-technology aircraft. Therefore the most rapid uptake of fuel-saving technology is likely in a high-growth, high-cost scenario, because in such a scenario more new aircraft are purchased. However, the interaction between the adoption of different retrofit and new technology options is complex, with the order in which measures become available or economic to adopt potentially having a significant effect on their uptake within the fleet. In the case of biofuel availability at suitable prices combined with an ETS, widespread adoption is likely to be limited mainly by the rate that biofuel production can be increased.

What levels of emissions reductions are practically achievable for aviation from measures such as the ETS and SESAR, now and into the future?

Our analysis suggests that, if SESAR compliance is limited to adapting aircraft avionics and providing flight crew training to make use of SESAR's improved ATM, it is likely that all or a significant portion of the fleet will choose to comply. This is a result of the significant fuel burn advantages achievable by those aircraft, given our assumptions about costs and fuel prices. Emissions reductions from SESAR rapidly reach the maximum assumed attainable (10.5%) after its assumed introduction in 2020 in most scenarios. The ETS on its own can also produce non-negligible reductions in airborne CO_2, mainly by increasing ticket prices and hence reducing passenger demand. In the highest carbon price scenario direct reductions in airborne CO_2 emissions of 20% are possible in addition to the reductions in other sectors from airline permit purchases. However, these reductions in emissions primarily occur after 2030 and in response to carbon prices which have increased to at least 2-3 times present-day levels. If biofuels are available and oil and carbon prices are high enough that adopting biofuel usage becomes economic, highly significant savings in fuel lifecycle emissions can be made. In the scenarios considered here, the European aviation fleet was able to reduce its year 2050 fuel lifecycle emissions to below year 2005 levels by widespread adoption of a 50-50 blend of cellulosic biofuel with Jet A. This scenario does, however, depend on sufficient quantities of biofuel being made available. The land use requirements associated with the amount of cellulosic biofuel required are potentially prohibitive, in which case a biofuel option with significantly higher yield would be required. In addition, there may still exist significant air quality and noise problems associated with biofuel use scenarios.

How will the availability of biofuels and/or improved ATM interact with other measures?

Typically, as noted in Section 4.5, the availability of a cost-effective emissions mitigation measure tends to reduce the uptake of other emissions mitigation measures. Thus, for the assumptions used in this study, the rate of SESAR compliance went down in scenarios with biofuel availability because airlines used biofuels to significantly reduce their carbon costs. They therefore no longer had such a strong incentive to reduce these costs further by adopting other measures. However, as discussed, this may be an artifact of the assumptions used in the analysis and actual SESAR compliance is likely to be high or mandated for other reasons.

What is the sensitivity of these measures to the underlying fuel price and GDP growth scenarios?

As noted above, high carbon prices and high oil prices increase the probability that emissions reduction measures will be adopted, because the cost savings available on fuel are greater. Scenario GDP growth also has a strong effect, with higher-growth scenarios also having more rapid growth in aviation demand. Using a range of underlying scenarios for socioeconomic growth and fuel prices we found an approximately 40% difference in unconstrained reference case RPKM in 2050 between the highest- and lowest-growth scenarios. Therefore it should be no surprise that the uptake of emissions mitigation measures can also be strongly dependent on scenario. However, in some cases, most notably the adoption of biofuels, SESAR compliance, increased engine maintenance and winglet retrofits, measures were economic for at least some of the fleet in all scenarios in which they were made available.

And finally, what is the consumer response in such constrained scenarios?

Consumer response in the scenarios looked at in this study is largely a function of the costs that are applied to or incurred by airlines, and the competition assumptions that govern how much of that cost is passed on to ticket price. Typically, most of the mitigation measures examined are only just economic for airlines to adopt in the scenarios we run. Therefore there is no strong overall change in airline costs or passenger demand. The ETS-only scenario sees a reduction in passenger demand to 2050 of up to 20%, resulting from airlines passing on some of their carbon costs to passengers. However, if biofuels are also made available then airlines can reduce their carbon costs significantly by using them, and the reduction in RPKM from the base case is smaller.

Taking these conclusions as a whole, the most promising option for reducing aviation CO_2 emissions explored here is that of the EU ETS in conjunction with development of an aviation-suitable biofuel. Such a fuel would have to be introduced gradually, as production levels would initially not be high enough to provide fuel for the entire European fleet. In addition, other problems related to noise, yield, land use and air quality would need to be overcome. However, significant reductions in aviation fuel lifecycle CO_2 emissions – to below year-2005 levels or by 2050 – could potentially be achievable via this route.

5.1 Future Work

The work carried out for this Omega project represents a first step in the process of applying a fully integrated analysis of the options available for European aviation emissions reduction. There is significant future potential for refining and extending the work presented here. For example, investigating the sensitivity of the models to key assumptions is desirable and would present a clearer picture of the range of possible outcomes of any given policy. The range of mitigation measures studied in this report was also necessarily limited. Therefore significant scope exists to include other, potentially more complex, mitigation options that are or may become available to airlines (e.g. changing load factors, riblets, blended wing body aircraft, early retirement and so forth).

The results of the work presented here suggest that biofuel usage, though not without potentially significant problems, is a promising option for reducing European aviation emissions. However, the results in terms of uptake, cost and emissions reductions depend on the specific type of biofuel used. Therefore further study looking at a range of biofuel types and pricing scenarios would be useful in providing a recommendation to policymakers of what the potential CO_2 savings are from the range of proposed biofuels, and the sensitivity of those savings to economic and technology scenarios.

Finally, this study has concentrated on the intra-European region only. However the EU ETS is planned to apply to all flights entering or leaving the EU. With many regions outside the EU forecast to undergo rapid economic growth over the next 40 years, the impact of, for example, Europe-Asia flights may be significant. As a full global version of the Aviation Integrated Model is under development, this area is likely to form part of future AIM-related research.

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References

Airbus (2007), "Global Market Forecast 2007-2026," http://www.airbus.com/fileadmin/documents/gmf/PDF_dl/00-all-gmf_2007.pdf, [Cited 14 November 2008]

Albers, S., Bühne, J.-A. and Peters, H., 2009. "Will the EU-ETS Instigate Airline Network Reconfigurations?", Journal of Air Transport Management, 15:1-6.

Allen, P., Köhler, J. and Anger, A., 2009. "Aircraft Emissions Trading." Final Report for the Omega Consortium, to be made available at http://www.omega.mmu.ac.uk/aircraft-emissions-trading.htm.

Boeing, "Current Market Outlook 2007," 2007, http://www.boeing.com/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2007.pdf [Cited 3 February 2009].

Bonnefoy, P.A., R.J. Hansman, "Scalability and Evolutionary Dynamics of Air Transportation Networks in the United States," 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO), Belfast, Northern Ireland, Sept. 2007, AIAA 2007-7773.

BTS (US Bureau of Transportation Studies) 2009. Form 41, BA1A and T100 databases. http://www.transtats.bts.gov/ [Cited 20 February 2009]

CCSP (US Climate Change Science Research Program) 2007. "Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, Synthesis and Assessment Product 2.1a." http://www.climatescience.gov [Accessed 31 January 2009].

Dray, L. M., Evans, A., Reynolds, T., Rogers, H., Schäfer, A. & Vera-Morales, M., 2009. "Air Transport Within An Emissions Trading Regime: A Network-Based Analysis of the United States and India." TRB 88th Annual Meeting, Washington DC, 11-15 January 2009.

Ernst & Young, 2007. "Analysis of the EC Proposal to Include Aviation Activities in the Emissions Trading Scheme (with York Aviation)." Executive Summary. Ernst & Young, New York.

EUROCONTROL, 2008. "Challenges of Growth 2008," Brussels: European Organisation for the Safety of Air Navigation.

EUROCONTROL, "Single European Sky ATM Research", www.eurocontrol.int/sesar/ [accessed 23 Jan. 2009].

EUROCONTROL, "RSO Distance Tool", http://www.eurocontrol.int/crco/public/standard_page/rso_distance_tool.html [cited 19 Feb. 2009].

European Commission, 2005. "Reducing the Climate Change Impact of Aviation – Impact Assessment COM(2005) 459 Final," Annex to the Communication from the Commission, Commission Staff Working Document, SEC(2005) 1184. Brussels.

FAA, 1983. "Airport Capacity and Delay," AC 150/5060-5, Washington DC: Federal Aviation Administration.

FAA, 2002. "Airport Capacity Benchmark Report 2001," Washington DC: Federal Aviation Administration.

FAA JPDO, "Integrated Work Plan for the Next Generation Air Transportation System", 2008, http://www.jpdo.gov/iwp/IWP_Version_02_Master_w-o_appendix.pdf [Cited 27 June 2008].

Gillen D.W., W.G. Morrison, C. Stewart, 2007. Air Travel Demand Elasticities: Concepts, Issues and Measurement, in "Advances in Airline Economics Volume 2: The Economics of Airline Institutions, Operations and Marketing", D. Lee (Editor), Elsevier.

Gillingwater, D., Budd, L., Caves, R. & Reynolds, T. G., "Environmental Effects of Aircraft Operations and Airspace Charging Regimes", Omega Study 39 Final Report, 2009. To be made available at http://www.omega.mmu.ac.uk/environmental-effects-of-aircraft-operations-and-airspace-charging-regimes-.htm

Henderson, J., 2005. “Controlling Carbon Dioxide Emissions in the Aviation Sector,” Stratus Consulting for the US EPA.

Horonjeff, R., McKelvey, F.M., 1994. “Planning and Design of Airports,” 4th ed., New York: McGraw-Hill.

ICAO (International Civil Aviation Organisation), 2004. “Outlook for Air Transport to the Year 2015”, Clr 304 AT/127.

ICAO (International Civil Aviation Organisation), 2006. “Regional Differences in International Airline Operating Economics: 2002 and 2003,” Clr 310 AT/132.

ICAO (International Civil Aviation Organisation), 2008. ICAO Global Database. http://www.icaodata.com [Cited 20 February 2009]

Morrell, P. and Dray, L. M. “Environmental Aspects of Fleet Turnover, Retirement and Life Cycle.” Final Report for the Omega Consortium, 2009. To be made available at http://www.omega.mmu.ac.uk/environmental-aspects-of-fleet-turnover-retirement-and-life-cycle.htm.

Morris, J., Rowbotham, A., Morrell, P., Foster, A., Poll, I., Owen, B., Raper, D., Mann, M. and Ralph, M., “UK Aviation: Carbon Reduction Futures,” Final Report to the Department for Transport, 2008.

Morris, J., Rowbotham, A., Angus, A., Mann, M. and Poll, I. “A Framework for Estimating the Marginal Costs of Environmental Abatement for the Aviation Sector,” Final Report for the Omega Consortium, 2009. To be made available at http://www.omega.mmu.ac.uk/estimating-the-marginal-costs-of-aviation-environmental-abatement-measures.htm.

OAG, 2005. “Official Airline Guide 2005 Schedules,” Back Aviation database.

Reynolds, T. G., Barrett, S.,Dray, L. Evans, A., Köhler, M., Vera Morales, M., Schäfer, A., Wadud, Z., Britter, R., Hallam, H. & Hunsley, R. “Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Project”, 7th AIAA Aviation Technology, Integration and Operations Conference, Belfast, N. Ireland, Sep. 2007, AIAA-2007-7751.

Stern, N. (2006). Review on the Economics of Climate Change, H. M. Treasury, UK, http://www.sternreview.org.uk [accessed 20 January 2009].

Vera-Morales, M. and Schäfer, A., “Fuel-Cycle Assessment of Alternative Aviation Fuels,” OMEGA Alternative Fuels Report (Draft), February 2009. To be made available at http://www.omega.mmu.ac.uk/omega-alternative-aviation-fuels-data-centre-.htm

Wadud, Z. “Environmental Costs of Aviation,” Final Report for the Omega Consortium, 2009. To be made available at http://www.omega.mmu.ac.uk/environmental-costs-of-aviation-.htm.

Appendix 1 – The Aviation Integrated Model

In Section 2 of the main report, a brief description of the Aviation Integrated Model is given. This Appendix contains more detailed descriptions of the four main modules of the Aviation Integrated Model which are used for this study, including data sources, assumptions, references and aspects of the modelling which are specific to Europe.

A1.1 Aircraft Technology & Cost Module

The Aircraft Technology & Cost Module simulates fuel burn, emissions and operating costs as a function of stage length for airframe and engine technology levels likely to have an effect within the forecast horizon. In order to obtain a more realistic representation of the spectrum of commercial aircraft technologies operating within the world's air transport network, three size classes (small with up to 189 seats, medium with 190 to 299 seats and large with 300 or more seats) and two technology classes (pre-1995 and post-1995) were considered. Performance and emissions data for the Boeing 737-300, 767-300ER and 747-400 were used for the pre-1995 size classes respectively, and Airbus A319, A330-300 and Boeing 777-300 for the post-1995 types. The fuel burn and emissions calculations for these aircraft types below 3,000 feet were based on the ICAO engine exhaust emission data (ICAO, 2008). The ICAO reference Landing and Take-Off (LTO) cycle (ICAO, 2006-1) provided the time spent in each of the phases of the cycle, with the exception of the taxi/idle time which has been calculated by the Airport Activity Module. Above 3,000 feet, the performance during climb, cruise, descent, and airborne holding were modeled according to the parameters for the representative aircraft types from the EUROCONTROL Base of Aircraft Data (BADA) (EUROCONTROL, 2004). The introduction characteristics of new technology aircraft and retirement of old technology aircraft over the modelled period was considered to be similar to past fleet turnover characteristics determined from the OAG Back Aviation worldwide fleet database, as discussed further in the main report in section 3.3. Given the average lifetime for an individual jet aircraft is about thirty years, and successful technologies may remain available for purchase 15-20 years after their initial introduction, aircraft introduced over the next decade are likely to be representative of the future fleet throughout most of the period examined from 2005 to 2050, and hence no radically new technologies (e.g. blended wing body aircraft) were considered in the base case. However, the introduction of open rotor engines is considered as a scenario option, as discussed further in the main report in section 3.1.2.

The rate of technology development and improvements in fuel burn for future aircraft models is likely to be driven by future changes in fuel costs, including those from carbon trading. It is assumed here that fuel burn for the best available new aircraft technology (excluding retrofits or any radical new technology options such as open rotors) improves by 1%, 1.5% or 2% per year respectively for scenarios where the 2030 oil price plus associated carbon trading costs is below $100/bbl, between $100/bbl and $150/bbl or over $150/bbl in year 2005 dollars. However, the over $150/bbl case does not occur in the scenarios looked at for this study. These improvement rates represent low, medium and high values with respect to historical trends.

More information on the Aircraft Technology and Cost Module can be found in Reynolds et al. (2007).

A1.2 Air Transport Demand Module

The demand module estimates demand for passenger air travel between city-pairs in the simulation city set, given costs, travel time and delays from the Technology and Cost and Airport Activity modules. The demand (*D*) for true origin-ultimate destination passenger air trips between each pair of cities *i* and *j* is calculated using a simple one-equation gravity-type model given in the following equation:

$$D_{ij} = (I_i I_j)^{\alpha} (P_i P_j)^{\gamma} e^{\delta A_{ij}} e^{\varepsilon B_{ij}} e^{\varphi S_{ij}} e^{\omega DF_{ij}} C_{ij}^{-\tau} \quad .$$

The explanatory variables include base year metropolitan area population (*P*), associated per capita income (*I*) and generalized travel costs (*C*) consisting of fares, value of travel time and flight delay. The binary variables *A* and *B* indicate whether one or both cities in the pair have qualities which might increase visitor numbers (for example being a major tourist destination or capital city), while the binary variable *S* indicates whether road links exist between a given city pair. Similarly, binary variable *DF* indicates whether the city-pair journey is a domestic or international one. The elasticities 2α, 2γ, δ, ε, φ, ω and τ are estimated using ordinary least squares and available demand data for the 2005 base year.

Metropolitan area population and income data were derived from individual country censuses and household income surveys (e.g. ONS 2001, ISER 2005). Income values are converted to year 2005 US dollars using market exchange rates. Fares were obtained from base year surveys and published fare lists where possible. For Europe, fares were estimated using data on published airline yields by flight distance (AEA 2005), comparisons of low-cost and legacy carrier fares (AEA 1997), and base year schedules (OAG 2005). It was assumed that fares on multi-segment routes were equal to the single-segment alternative if one was available, and otherwise equal to the sum of fares on each individual segment. The fares resulting from this calculation were verified against present-day fare lists where available. Similarly, the demand module requires knowledge of base year routing for multi-segment journeys. Where this information was unavailable, routing was inferred using an analysis of available connection and journey times via different available hubs from schedule data (OAG 2005), based on an analysis of US routing using data collected by Jamin et al. (2004). The air traveller passenger values of time were estimated using US values (US DoT 1997) adjusted according to regional GDP per capita using the relationship given by INFRAS/IWW (2000).

To estimate elasticities the base year demand is also required. Base year passenger numbers by segment were obtained from Eurostat (2008). For segments not included in this database, passenger numbers are estimated using base year schedules (OAG 2005) and regional load factors (AEA 2006, ICAO 2006) adjusted for the variation in load factor by length of haul using relationships derived from US data (DoT 2008). As the elasticities we estimate are for true origin-ultimate destination travel demand, we use an assignment matrix approach to estimate true origin-ultimate destination demand elasticities from segmented passenger data and routing information. The demand on each segment is considered to be the sum of the true origin-ultimate destination demand on all the itineraries using that segment. This equation is then used for estimation. Table 5 gives the parameter estimates and standard errors for the European transport system using Equation 1. Note that τ is a generalized cost elasticity rather than a direct fare elasticity. All parameters in Table 5 are significant at the 95% level. The R^2 obtained for the combined estimation is 0.47, reflecting the specific uncertainties about routing and mode choice which apply for Europe. However, R^2 values in this range are considered reasonable for cross-sectional data. The elasticities are well within the ranges identified by other studies (e.g. Gillen et al. 2007; Oum et al. 1990; Jamin et al. 2004).

Table 5: Elasticity estimates and standard errors (in parentheses) for the European air transport system.

	2α	2γ	δ	ε	T	φ	ω
Short haul (<500 miles)	1.16 (0.04)	0.75 (0.05)	0.77 (0.10)	-0.90 (0.07)	-1.24 (0.09)	0.32 (0.07)	1.63 (0.06)
Medium haul (500-1000 miles)	1.09 (0.04)	0.85 (0.05)	0.70 (0.12)	-0.88 (0.07)	-1.27 (0.08)	0.24 (0.07)	2.19 (0.13)
Long Haul (> 1000 miles)	1.01 (0.03)	0.75 (0.03)	1.46 (0.19)	-0.36 (0.07)	-1.08 (0.05)	0.66 (0.07)	1.59 (0.14)

The base year elasticity, city- and city pair-level data described above can be used to calculate estimates of the city-pair demand in the base year. To project demand into the future, we need forecasts of the key explanatory variables. Among those, future fare trends depend on the change in operating costs (most notably the oil price) and market economics. For simplicity and transparency perfect competition is assumed between airlines on all routes. This means that fares between true origin-ultimate destination city pairs equal the marginal costs of carrying passengers between the respective cities, accounting for flights serving both direct and connecting itineraries. In Equation 1, the cost variable also includes the cost of journey duration via the value of a passenger's time. It is thus possible to include the demand-reducing effect of increased journey time as well as that of increased fares.

More information on the Air Transport Demand Module can be found in Reynolds et al. (2007) and Dray et al. (2009).

A1.3 Airport Activity Module

The Airport Activity Module forecasts global air traffic required to satisfy the demand projected by the Air Transport Demand Module and estimates the resulting ground delay given the airport capacity constraints within the European network.

The flight routing network was assumed to remain unchanged from the base year, with the proportion of the three different aircraft types used on the required flight segments estimated as a function of projected passenger demand, segment length and network type (hub-hub, hub-spoke, or point-to-point) according to a multi-nomial logit regression on historical data. According to this regression, aircraft size increases with passenger demand, segment length and on routes to or from hub airports. Flight frequencies were forecast by applying base year passenger load factors by segment (which were assumed to remain constant with time) to passenger demand estimated by the air transport demand module. These approaches are similar to those used by Bhadra et al. (2003).

Delays due to airport capacity constraints were estimated using queuing theory, applying the cumulative diagram approach and classical steady state simplifications described by Evans (2008). In this delay model, flight delays, both on the ground and in airborne holding before landing, were estimated as a function of flight frequencies and airport capacity constraints. These were added to gate departure delays (due to mechanical failures and late arrivals), which were assumed to remain at current levels (with schedule padding increasing to maintain schedule reliability). Runway departure delays were distributed between the taxiway and the gate according to a taxi-out threshold. This is estimated according to average US airport taxi-out thresholds (calculated from historical data – historical data is not available for European airports). Similarly, delays due to destination airport capacity constraints were distributed between the air and ground according to an airborne holding threshold estimated according to average US airport airborne holding thresholds (calculated from historical data), and above which delay was assumed to be propagated upstream to the departure gate.

Flight delays resulting from airport capacity constraints impose extra costs on airlines because of increased fuel burn and other per-hour operating costs. These extra costs increase fares as modelled by perfect competition. The costs associated with flight delays were modelled according to estimated fuel burn rates from the Aircraft Technology and Cost Module and published US airline cost inventories (DOT, 2008), but adjusted according to regional differences in international airline operating economics (ICAO, 2006-2).

More information about the Airport Activity Module can be found in Reynolds et al. (2007).

A1.4 Aircraft Movement Module

The air traffic by flight segment generated by the Airport Activity Module is the main input to the Aircraft Movement Module, which works in conjunction with the Aircraft Technology and Cost Module to identify the amount and location of emissions released from the required flight segments, accounting for inefficiencies introduced by the air traffic control system. These inefficiencies take the form of extra distance flown (and hence extra fuel burn and emissions produced) beyond the shortest ground track distance for any given airport pair in the schedule. These extra distances were estimated for different phases of flight by using archived flight track data, as described by Reynolds (2008), and Reynolds et al. (2009).

More information on the Aircraft Movement Module can be found in Reynolds et al. (2007).

A1.5 References

AEA (Association of European Airlines), 1997. "AEA Yearbook 1997". http://www.**aea**.be/**aea**website/datafiles/year97.pdf [Cited 21 Feb. 2009]

AEA (Association of European Airlines), 2006. "Operating Economy of AEA Airlines 2006". http://files.aea.be/RIG/Economics/DL/SumRep06.pdf [Cited 21 Feb. 2009]

Bhadra D., Gentry, J., Hogan, B. & Wells, M., "CAASD's Future Air Traffic Estimator: A Micro-Econometric Approach", 13th Annual Federal Forecasters Conference, BLS Training Center, 2003.

Dept. of Transportation, Bureau of Transportation Statistics, DB1B Survey, Form 41, T100 Traffic & Financial Data, www.transtats.bts.gov [Cited 27 June 2008] .

Dray, L. M., Evans, A., Reynolds, T., Rogers, H., Schäfer, A. & Vera-Morales, M., 2009. "Air Transport Within An Emissions Trading Regime: A Network-Based Analysis of the United States and India." TRB 88th Annual Meeting, Washington DC, 11-15 January 2009.

EUROCONTROL, "Base of Aircraft Data (BADA)", Version 3.6, July 2004.

Eurostat, 2008. "European Transport Statistics". http://epp.eurostat.ec.europa.eu/portal/ [Cited 21 Feb. 2009].

Evans, A.D., "Rapid Modelling of Airport Delay", 12th Air Transport Research Society World Conference, Paper 202, Athens, Greece, 6-9 July 2008.

Gillen D.W., W.G. Morrison, C. Stewart, 2007. Air Travel Demand Elasticities: Concepts, Issues and Measurement, in "Advances in Airline Economics Volume 2: The Economics of Airline Institutions, Operations and Marketing", D. Lee (Editor), Elsevier.

ICAO, "ICAO Annex 16, Volume II: Aircraft Engine Emissions", ICAO Publications, 2006.

ICAO, “Regional Differences in International Airline Operating Economics: 2002 and 2003”, Clr 310 AT/132, 2006.
ICAO, “ICAO Engine Emissions Databank” http://www.caa.co.uk/docs/702/080407%20%20ICAO_Engine_Emissions_Databank-Issue_15-C.xls, [Cited 27 June 2008].
INFRAS/IWW 2000. “External Costs of Transport: Accident, Environmental and Congestion Costs of Transport in Western Europe”, Karlsruhe/Zurich/Paris
ISER (University of Essex Institute for Social and Economic Research), 2005. British Household Panel Survey 2005. http://www.data-archive.ac.uk/findingData/snDescription.asp?sn=5151 [Cited 21 Feb. 2009].
Jamin S., A. Schäfer, M.E. Ben-Akiva, I.A. Waitz, 2004. Aviation Emissions and Abatement Policies in the United States: A City Pair Analysis, Transportation Research D, 9(4): 294-314.
Moreira J.R., Goldemberg J., 1999, The Alcohol Program, Energy Policy 27:229-245.
OAG 2005. “Official Airline Guide Schedule Database”. Back Aviation Solutions.
ONS (UK Office of National Statistics), 2001. UK Census 2001. http://www.statistics.gov.uk/census2001/access_results.asp [Cited 21 Feb. 2001]
Oum T.H., W.G. Waters, J.S. Yong, 1990. “A Survey of Recent Estimates of Price Elasticities of Demand for Transport, Infrastructure and Urban Development Department”, The World Bank, Washington, DC.
Reynolds T., S. Barrett, L. Dray, A. Evans, M. Köhler, M. Vera-Morales, A. Schäfer, Z. Wadud, R. Britter, H. Hallam, R. Hunsley, “Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Tool”, 7th AIAA Aviation Technology, Integration and Operations Conference, Belfast, 18-20 September 2007, AIAA-2007-7751.
Reynolds, T. G., “Analysis of Lateral Flight Inefficiency in Global Air Traffic Management”, 8th AIAA Aviation Technology, Integration and Operations Conference, Anchorage, Alaska, US, Sep. 2008, AIAA-2008-8865.
Reynolds, T. G., Gillingwater, D., Caves, R. & Budd, L., “Climate Related Air Traffic Management”, Final Report for the Omega Consortium, 2009. To be made available at http://www.omega.mmu.ac.uk/climate-related-atm.htm.
Strack, W. C., Knip, G., Weisbrich, A. L., Godston, J. and Bradley, E., 1982. “Technology and benefits of Aircraft Counter Rotation Propellers”, NASA Technical memorandum 82983.
US Department of Transportation, 1997. “Departmental Guidance for the Value of Time in Economic Analysis”. http://ostpxweb.dot.gov/policy/Data/VOT97guid.pdf [Cited 21 Feb. 2009]
Wilson, C., et al., 2009, *Sustainable Fuels for Aviation*. Final Report for the Omega Consortium, to be made available at http://www.omega.mmu.ac.uk/sustainable-fuels-for-aviation.htm.

Appendix 2 – European City and Airport Set

The city and airport sets used in this study are automatically generated from base year schedule and location data. An airport is a candidate to be a part of the set if any scheduled flights landed or took off at it during the course of the base year. We consider cities on a Greater Metropolitan Area basis. In some cases, particularly for large urbanised areas, this means that cities may have areas within more than one country. Airports are gathered into cities using a location-based algorithm with a 40-mile distance threshold for inclusion, unless the airport is located on a small island or otherwise geographically isolated. A small number of secondary airports at large distances from the cities they were advertised to serve fell outside this distance threshold (e.g. Stockholm Skavsta Airport). Classification of these airports was undertaken on a case-by-case basis based on the area served and the airport-city distance involved.

After the generation of the global city list, cities were ranked by their share of global passenger seats, flights and seat-km provided, based on base year schedules. A cut-off point for city set inclusion was chosen corresponding to a cumulative seat-km total equal to 95% of the total global seat-km offered. This resulted in a global set of 700 cities (1127 airports) of which 173 cities (337 airports) are in the Western Europe/Eastern Europe/Former Soviet Union area modelled here. Of these, we present airport-level results only for the EU-27 countries and closely associated airports. The applicable EU-27 airports in this set are listed below.

Table 6: List of Cities and Airports modelled.

City	Country	Scheduled Takeoffs in 2005	Airports
London	UK	592412	LHR,LGW,STN, LTN,LCY,CBG
Paris	France	419388	CDG,BVA,ORY
Frankfurt/Mannheim	Germany	291168	MHG,FRA
Amsterdam/Rotterdam	Netherlands	265122	RTM,AMS
Madrid	Spain	197898	MAD
Munich	Germany	191697	MUC
Milan/Lugano	Italy/ Switzerland	180313	MXP,SWK,LUG, BGY,LIN
Rome	Italy	163612	FCO,CIA
Cologne/Dusseldorf/ Dortmund	Germany	160961	DUS,DTM,CGN
Antwerp/Brussels/ Leuven/Ghent	Belgium	152738	BRU,CRL,ANR
Copenhagen/Malmo	Denmark/ Sweden	147812	CPH,MMX
Barcelona	Spain	142224	BCN

Stockholm	Sweden	133327	NRK,NYO,ARN, BMA
Bratislava/Vienna	Slovakia/Austria	125541	VIE,BTS
Blackpool/Manchester /Liverpool	UK	122734	MAN,BLK,LPL
Cannes/Monte Carlo/Nice	France/Monaco	120823	LTT,NCE,MCM
Berlin	Germany	93913	THF,SXF,TXL
Athens	Greece	80255	ATH
Helsinki	Finland	79334	HEL
Dublin	Ireland	77303	DUB
Coventry/Nottingham/ Birmingham	UK	73725	EMA,BHX,CVT
Hamburg	Germany	68468	LBC,HAM
Prague	Czech Republic	66163	PRG
Palma Mallorca	Spain	64019	PMI
Stuttgart	Germany	61187	STR
Glasgow	UK	61019	PIK,GLA
Lyon	France	60923	GNB,LYS
Chambery/Geneva/ Annecy	France/ Switzerland	59650	NCY,GVA,CMF
Lisbon	Portugal	59615	LIS
Warsaw	Poland	57497	WAW
Edinburgh/Dundee	UK	56647	DND,EDI
Budapest	Hungary	54400	BUD
Malaga	Spain	47536	AGP
Venice	Italy	40605	TSF,VCE
Marseille/Avignon	France	40504	AVN,MRS
Belfast	UK	39255	BHD,BFS
Tenerife	Spain	36711	TFS,TFN
Cardiff/Bristol	UK	36442	CWL,BRS
Alicante/Murcia	Spain	35514	MJV,ALC
Gothenburg	Sweden	35017	GSE,GOT
Toulouse	France	34458	TLS
Mulhouse/Basle	Switzerland/ France	33903	MLH,BSL
Las Palmas (Gran Canaria)	Spain	33861	LPA
Bournemouth/ Southampton	UK	33748	BOH,BBS,SOU
Hanover/Brunswick	Germany	33433	BWE,HAJ
Durham/Newcastle	UK	29568	MME,NCL
Luxembourg	Luxembourg	28830	LUX
Liege/Maastricht	Belgium/ Netherlands	28519	MST,LGG
Aberdeen	UK	28270	ABZ
Vitoria/Logrono/Bilbao	Spain	26654	RJL,VIT,BIO
Bologna	Italy	24179	BLQ

Nuremburg	Germany	23712	NUE
Bucharest	Romania	23553	BBU,OTP
Bordeaux	France	23480	BOD
Palermo/Trapani	Italy	22962	TPS,PMO
Naples	Italy	22873	NAP
Turin	Italy	22725	TRN
Ercan/Larnaca	Cyprus	22343	ECN,LCA
Strasbourg/Lahr/ Karlsruhe/Baden Baden	France/ Germany	21876	FKB,SXB,LHA
Catania	Italy	21307	CTA
Porto	Portugal	21275	OPO
Leeds/Doncaster/ Humberside	UK	20642	HUY,LBA,LHA
Thessaloniki	Greece	20403	SKG
Seville	Spain	17984	SVQ
Frankfurt Hahn	Germany	17473	HHN
Florence	Italy	17384	FLR
Billund/Esbjerg	Denmark	16684	EBJ,BLL
Ljubljana/Klagenfurt	Slovenia/Austria	16299	KLU,LJU
Bremerhaven/Bremen	Germany	15875	BRV,BRE
Santiago de la Compostela/La Coruna	Spain	15447	LCG,SCQ
Cork	Ireland	15203	ORK
Verona/Brescia	Italy	14991	VBS,VRN
Riga	Latvia	14517	RIX
Nantes	France	14511	NTE
Guernsey	UK	14261	GCI
Jersey	UK	14236	JER
Ibiza	Spain	13580	IBZ
Dresden	Germany	13158	DRS
Isle of Man	UK	13120	IOM
Fuerteventura	Spain	13034	FUE
Sofia	Bulgaria	12753	SOF
Pisa	Italy	12573	PSA
Malta	Malta	12397	MLA
Vilnius	Lithuania	12196	VNO
Lanzarote	Spain	12170	ACE
Leipzig/Altenburg	Germany	12104	LEJ,AOC
Shannon	Ireland	11849	SNN
Tallinn	Estonia	11714	TLL
Madeira	Portugal	11209	PXO,FNC
Muenster/Enschede	Germany/ Netherlands	10981	FMO,ENS
Krakow/Tarnow	Poland	10957	KRK
Faro	Portugal	10895	FAO
Clermont-Ferrand/Aulnat	France	10609	CFE

Gerona	Spain	10472	GRO
Cagliari	Italy	10346	CAG
Arad/Timisoara	Romania	10104	TSR,ARW
Salzberg	Austria	10028	SZG
Montpellier/Beziers/Nimes	France	9391	FNI,BZR,MPL
Graz/Maribor	Austria/Slovenia	9377	GRZ,MBX
Heraklion/Crete	Greece	9362	HER
Lorient/Quimper/Brest	France	9012	UIP,LRT,BES
Bari	Italy	9005	BRI
Genoa	Italy	8926	GOA
Santa Cruz de la Palma	Spain	8721	SPC
Biarritz/San Sebastian	France/Spain	8202	EAS,BIQ
Menorca	Spain	8174	MAH
Rhodes	Greece	8164	RHO
Lille	France	8119	LIL
Inverness	UK	8114	INV
Linz	Austria	8078	LNZ
Asturias	Spain	7541	OVD
Vigo/Pontevedra	Spain	7524	VGO
Olbia	Italy	7235	OLB
Rennes	France	7165	RNS
Figari/Ajaccio	France	7092	FSC,AJA
Norwich	UK	6910	NWI
Gdansk/Gydnia/Sopot	Poland	6464	GDN
Bastia/Calvi	France	6292	CLY,BIA
Paderborn	Germany	6155	PAD
Plymouth/Exeter	UK	6092	PLH,EXT
Eindhoven	Netherlands	6056	NRN,EIN
Tampere	Finland	6006	TMP
Oulu	Finland	5855	OUL
Helsingborg/Angelholm/ Halmstad	Sweden	5851	HAD,AGH
Santander	Spain	5738	SDR
Almeria	Spain	5613	LEI
Aalborg	Denmark	5612	AAL
Friedrichshafen/ Altenrhein/Hohenems	Germany/ Switzerland/ Austria	5501	ACH,FDH,HOH
Pau/Lourdes	France	5379	LDE,PUF
Aarhus	Denmark	5363	AAR
Visby	Sweden	5338	VBY
Cadiz/Jerez de la Frontera	Spain	5160	XRY