Mitigating Aviation Carbon Dioxide Emissions: An Analysis for Europe

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ABSTRACT

This paper investigates the interaction between economic, technological and operational measures intended to reduce air transport-related CO_2 emissions. In particular, the introduction of aviation to the European Emissions Trading Scheme (ETS) in 2012 may prompt increased uptake of presently-available emission reduction options (e.g. retrofitting winglets, expanding maintenance programs) by airlines operating in Europe. In the future, carbon prices may also determine the usage of new options currently under development (e.g. open rotor engines, second-generation biofuels and improved air traffic management (ATM)). We apply the results of a number of studies analyzing the airline costs and emission reductions possible from different mitigation options to a systems model of European aviation. Using a set of nine scenarios (three internally-consistent projections for future population, gross domestic product, oil and carbon prices, each run with three policy cases), we analyze technology uptake and the resulting effect on fuel lifecycle CO_2 emissions with and without an ETS. We find that some options are rapidly taken up under all scenarios (e.g. improved ATM), others are taken up more slowly by specific aircraft classes depending on the scenario (e.g. biofuels) and others have negligible impact in the cases studied. High uptake of one mitigation option may also reduce the uptake of other options. Finally, it is observed that European aviation fuel lifecycle emissions could be reduced below 2005 levels before 2050 if cellulosic biomass fuels are made available from 2020. However, the land use requirements in this scenario may limit its practicality at currently-projected cellulosic biomass yields.

INTRODUCTION

Global aviation demand, in terms of revenue passenger-kilometers (RPK), is predicted to grow at a rate of around 5% per year over at least the next 20 years (e.g. *1*, *2*), with European domestic aviation RPK growing at a rate of 2-4%. Since technology improvements typically deliver a 1-1.5% decrease in fuel burn per RPK per year (e.g. *3*), this suggests European aviation emissions are likely to continue to increase. However, emissions targets typically envisage a lowering of aviation emissions. For example, the UK Government has announced its intention to reduce UK aviation emissions to below year-2005 levels by 2050 *(4)*. Therefore, a number of policy options have been proposed or are in the planning stage to lower emissions by speeding up technology introduction, introducing operational changes or reducing RPK growth levels.

In Europe, aviation is to be included in the EU Emissions Trading Scheme (ETS) from 2012 *(5)* meaning that overall emissions will be capped at a given level that reduces year-on-year. Participants in an ETS who emit more than their "free" quota under the cap can either purchase permits from other sectors, reduce their emissions until they get back within their quota, or accomplish a combination of the two. It is expected that aviation will primarily follow the first course *(6)*, as it is currently relatively expensive to reduce emissions from aviation in comparison to many other sectors. However, a recent study *(7)* suggested that there do exist cost-effective direct mitigation options which airlines can apply at present-day 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. The interaction between emissions trading and airline responses (and passenger responses if airline costs are passed on to ticket prices) is potentially complex and depends on airline costs and demand levels. These in turn depend on the underlying trends in European population, gross domestic product (GDP) and fuel prices over the time period considered (e.g. *8*).

Further promising mitigation options (each also with their own associated benefits, costs and difficulties) are likely to become available over the next 20 years. Geared turbofan engines are currently at the testing stage, and potentially offer a 10-15% improvement in fuel economy *(7)*. Open rotor engines are expected to offer an even more significant decrease in fuel burn compared to conventional turbofans, but may be unsuitable for long-haul flights because of the slower cruise speeds at which they operate *(9)* and may require modifications to airport infrastructure to ensure ground personnel safety. The introduction of improved European air traffic management from the Single European Sky ATM Research (SESAR) project *(10)* could reduce the extra fuel burn aircraft currently incur by flying non-optimal routes due to ATM inefficiencies.

Additional potentially large savings in lifecycle carbon dioxide emissions may be achieved by introducing aviation-suitable biofuels. A range of biomass-derived fuels are currently under development, each with different lifecycle emission, cost and yield characteristics. Present-day aviation-suitable biofuels have been produced from feedstocks such as canola, soybean and palm-kernel oils *(11)*. Cellulosic biomass fuels which do not compete for land use with food crops (using feedstocks such as switchgrass) are also under development. In the longer term, microalgae-based fuels may offer a higher-yield solution *(12)*.

These mitigation options may also interact with each other. For example, adopting biofuels may lower carbon costs significantly, reducing the incentive for an airline to adopt open rotor engines at a given carbon price. It is for this reason that a fully integrated model capable of capturing the combined effects of different policies and mitigation options is desirable. This

paper applies such a model to examine how different mitigation options combine, what actions they prompt by airlines and how this might affect fares and passenger demand, and what the resulting effect on total carbon dioxide emissions is for a range of different future scenarios.

METHODOLOGY

Aviation Systems Model

An aviation systems model, the Aviation Integrated Model *(13,14,15),* was used to capture the interdependencies in the European aviation system. This is a UK NERC and EPSRC-funded program, written in Java and Matlab, which has been in active development since 2006. It has been used in analyses of the European air transport system for Omega *(15)* and the UK Climate Change Committee *(16)*, and to study the US and Indian air transport systems *(14)*. The Aviation Integrated Model consists of seven interacting modules as shown in Figure 1, each covering a different component of the air transport and environment system. This architecture permits important feedback and data flows between the key system elements to be captured and provides natural input sites for policy measures to be imposed upon the system as shown. Detailed descriptions of the modules and their interactions are given in *(13)*. In this study the Aircraft Technology & Cost, Air Transport Demand, Airport Activity and Aircraft Movement modules were utilized. These modules are run iteratively to find an equilibrium solution for aviation system demand, emission and technology characteristics for the given year, scenario and policy variables. The set-up for these modules is briefly summarized below.

Aircraft Technology & Cost Module

The Aircraft Technology & Cost Module simulates fuel burn, key emissions and operating costs as a function of stage length and load factor for airframe and engine technologies within the forecast time horizon. The global fleet was represented by a set of six sample aircraft types by size and technology age, shown in Table 1. Performance and emissions modeling for these aircraft below 3,000 feet was based on the ICAO engine exhaust emission data *(17)* and the ICAO reference Landing and Take-Off cycle *(18)*, adjusted for airport-specific taxi-out delay times from the Airport Activity Module. Above 3,000 feet, performance during climb, cruise, descent, and airborne holding was modeled using the Eurocontrol Base of Aircraft Data (BADA) model *(19)*, adjusted for route-specific airborne delay and inefficiency from the Aircraft Movement Module. The costs associated with owning and operating these aircraft were taken from published US airline cost data *(20)*, adjusted for global differences in operating costs *(21)*. European navigation charges were obtained from *(22)*.

The improvement in fleet fuel burn resulting from the retirement of older aircraft and the introduction of new aircraft types was modeled based on historical fleet turnover behavior *(23)*. Existing aircraft were assumed to suffer an increase in fuel burn per RPK with age due to airframe/engine deterioration, with a rate of 0.2% per year *(23)*. New models of aircraft were assumed to take advantage of incremental improvements in technology and hence have lower starting fuel burn than current models. However, the option of retrofits or introducing radical new technologies (with associated changes in airline costs) is treated separately as an airline choice, to avoid double-counting technological improvements. The rate of technology development for future aircraft models is likely to be driven by future changes in fuel and carbon

costs. For this study it is assumed that fuel burn for the best available *new* aircraft technology, excluding radical new technologies such as blended wing bodies or open rotor engines, 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/barrel (bbl), between $100/bbl and $150/bbl or over $150/bbl in year 2005 dollars. These improvement rates and price thresholds represent, respectively, low, medium and high values with respect to historical trends in fuel burn *(3)* and projected oil and carbon prices *(24)*.

Air Transport Demand Module

The demand (*D*) for true origin-ultimate destination passenger air trips between cities *i* and *j* was estimated by the Air Transportation Demand Module, using a simple one-equation gravity-type model given in Equation 1.

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

The explanatory variables include base year metropolitan area population (*P*), associated 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), the binary variable *S* indicates whether road links exist between a given city pair, and the binary variable *DF* indicates whether the flight is domestic.

Base year metropolitan area population and income data were obtained from individual country censuses and household income surveys (e.g. *25, 26*), with income converted to year 2005 dollars using market exchange rates. Base year fares and journey times were estimated using published data on airline delays, yields with flight distance and business model *(27, 28)*, and schedules *(29)*. Base year segmented passenger demand was obtained from *(30)*. As true origin-ultimate destination demand data was not available, we used an assignment matrix approach to estimate elasticities for short-, medium- and long-haul trips *(14)*. Routing was estimated using scheduled journey and available connection times *(29)* based on an analysis of US routing used by *(8)*. Parameter estimates are given in Table 2; all parameter estimates are significant at the 95% level and compare well to literature values (e.g. *31*). The R^2 obtained is 0.47.

The future demand for air trips was estimated using scenario-based forecasts of the key explanatory variables, with delay and airline cost values from the Aircraft Technology & Cost and Airport Activity Modules. In particular, future fare trends depend on the change in operating costs (most notably the oil price) and market economics. For simplicity and transparency, airline rates of return are assumed to remain constant in all markets, as modeled by *(32)*. This means that future fares between true origin-ultimate destination city pairs scale relative to base year fares in the same way as average costs of carrying passengers between the respective cities, accounting for flights serving both non-stop and connecting itineraries.

Airport Activity Module

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

The flight routing network was assumed to remain unchanged from the base year, with the proportion of 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 multinomial logit regression on historical data. Flight frequencies were forecast by applying base year passenger load factors by segment to passenger demand estimated by the Air Transport Demand Module *(33)*, given average aircraft sizes calculated by the multinomial logit model.

Flight delays, both on the ground and in airborne holding, were estimated as a function of flight frequencies and airport capacity constraints. Published European airport capacities were used where available. Where airport capacities were not available, they were estimated using simplified runway capacity models *(34)* and standard capacity estimation charts corresponding to different airport configurations *(35)*. Delays due to airport capacity constraints were estimated using queuing theory, applying the cumulative diagram approach and classical steady state simplifications *(36)*.These were added to gate departure delays (due to mechanical failures and late arrivals), which were assumed to remain at current levels. While actual delay values were calculated using modeled European flight frequencies and airport capacities, the calculated departure delays due to origin airport capacity constraints were distributed between the taxiway and the gate according to a taxi-out threshold estimated from historical US data *(37)*. Similarly, delays due to destination airport capacity constraints were distributed between the air and ground according to a US data-based airborne holding threshold *(37)*, above which delay was assumed to be propagated upstream to the departure gate.

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 simulate future airport capacity expansion within the Aviation Integrated Model by assuming that capacity will be increased as required to serve forecast demand such that delays remain close to present-day levels. The majority of airports in the scenarios explored in this paper do not reach their current capacity limits by 2050. However, a small number of major hub airports do. For these airports it is likely that capacity expansion would in reality come from more intensive use of runways and increased use of secondary airports, as well as possible infrastructure expansion.

Aircraft Movement Module

The air traffic by flight segment generated by the Airport Activity Module was input to the Aircraft Movement Module. This identified the amount and location of emissions released in flight, accounting for inefficiencies introduced by the air traffic control system (some of which will be addressed through SESAR) and constraints imposed by safety procedures (such as separation requirements which cannot be completely removed from the system). These inefficiencies manifest as extra distance flown beyond the shortest ground track distance or excess fuel burnt above the theoretical optimum for different routes and aircraft types. These extra distances and excess fuel burn in different flight phases were quantified for Europe by using archived flight track and flight data recorder information from the region, as described in *(38,39)*.

Abatement Options

This study is intended to model airline and passenger responses to increasing costs (such as those imposed by an ETS). A wide range of possible options to lower fuel use and emissions are available to airlines, now and in the future. These include maintenance, operational changes and retrofits in the short term and radical new technologies in the longer term. However, many of these measures are not economic to adopt for most aircraft unless carbon prices significantly exceed currently-projected levels. Others, for example increased use of turboprops, have associated issues which are difficult to quantify, such as cabin noise *(40)*. The combined effects on emissions of any given two measures are not necessarily additive and can depend on adoption order (e.g. applying an engine upgrade kit and then re-engining). For this paper, a range of abatement options was chosen from those evaluated by *(7)*. It should be emphasized that the options studied here and listed in Table 3 are only a selection of those which may become available, and that a full assessment of every abatement option available to airlines before 2050 would be significantly more complex.

Each option has an associated upfront cost, change in the operating costs of a given aircraft and change in the fuel burn of that aircraft (all of which may be a function of the aircraft age, size or typical route). In addition, some measures are not applicable to the whole fleet. For example, it is assumed that winglet retrofits are not applicable to aircraft types which already have winglets, or to future models of aircraft which are assumed to be already fitted with winglets if these can provide a cost-effective fuel burn advantage. Characteristics of these options in terms of cost, applicability and fuel burn reductions are taken from *(7)* and *(41)*. The assumptions used here are significant simplifications and in many cases current information about future costs and emissions is extremely uncertain (e.g. open rotor engines). However, the general behavior of the interaction between options is unlikely to change significantly with more accurate information.

Airlines are assumed to adopt measures based on a payback period of seven years, i.e., an abatement option will be introduced only if the cost savings over the next seven years are expected to be greater than the upfront and yearly costs of applying the measure over that time period. Once a measure is adopted, the costs and fuel burn of the applicable cohort of aircraft are adjusted accordingly. This then affects the choice of any further measures.

In the case of biofuels, it is assumed that costs under emissions trading are based on fuel lifecycle ("well-to-wake") emissions rather than simply airborne emissions. We assume drop-in cellulosic biomass biofuel is made available from 2020 in a 50/50 blend with Jet A, and that the introduction of biofuels is gradual, with yearly production increases limited to historically-observed rates from the Brazilian proEthanol program *(42)*. Aviation biofuel prices were assumed to be at least 70 US cents per liter *(12)* or — following the profit-maximizing behavior of the fuels industry — equivalent to the costs of Jet A, whichever value is higher. Lifecycle emission characteristics are also derived from *(12)*.

City Set and Scenarios

The global Aviation Integrated 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 RPK. For the intraregional Europe model

presented here we use the corresponding European subset, which contains 173 cities and 337 airports. A full list is given in *(15)*.

Underlying the projection of future aviation growth in the Aviation Integrated Model are scenario-based projections of key variables such as population, GDP per capita and oil prices. These factors are interdependent, with (for example) high oil or carbon prices affecting GDP. Therefore any scenarios used need to incorporate integrated economic modeling which considers these factors simultaneously. In this study we use a set of external scenarios from the US Climate Change Science Program *(24)*. These were developed using MIT's Integrated Global Systems Model (IGSM), Stanford's Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE) and the Joint Global Change Research Institute's MiniCAM model. Scenario data for Western and Eastern European growth is summarized in Table 3.

The IGSM, MERGE and MiniCAM models each include a range of carbon trading sub-scenarios. A near-term carbon price of around €20 per tonne of CO_2 has been suggested by a number of studies (e.g. *43*), whether or not aviation is included (*44*). Therefore, in this study the carbon trading scenario for each model was chosen which most closely reproduced these prices over the period to 2030. Although airlines will initially receive some free allowances in the EU ETS *(5)*, a move to full auctioning has been suggested (e.g. *6*). It is assumed here that airlines pay in full for their allowances and do not receive a free allocation.

RESULTS

In order to assess the interaction between different mitigation measures, we ran three basic policy scenarios for each of the IGSM, MERGE and MiniCAM models:

Base: In this scenario, no carbon price is applied and no abatement measures are made available for adoption by airlines. Individual aircraft fuel burn is affected only by fleet turnover and incremental improvements in the technology of new aircraft.

Technology: In this scenario, no carbon price is applied but all technological abatement measures are made available to airlines, who will adopt them if they provide an overall cost saving over a seven-year payback period.

Abatement: This scenario is similar to the Technology scenario, but in addition a carbon price is imposed.

In Figure 2, the RPK and fuel lifecycle CO_2 emissions from these three scenarios are shown. The top, centre and bottom panels depict the IGSM, MERGE and MiniCAM background models respectively. In addition, alternative RPK forecasts from Boeing and Airbus *(1,2)* and historical data from ICAO *(45)* are shown. The yearly RPK growth rates we project for European aviation are lower, at around 2%, than those from the Airbus and Boeing forecasts, although not outside the range of those predicted for the European system (e.g. *46*). A number of reasons may be behind this difference, including the elasticities and background scenarios used in this study (e.g. Eastern European GDP per capita growth rates are consistently below those used by Boeing and Airbus). The airline rate of return assumptions used result in base case fares remaining broadly constant over the time period studied, so RPK growth rates here will also typically be lower than for models which use a declining trend in travel cost.

To help interpret Figure 2, Figure 3 shows the mitigation option uptake by scenario, in terms of the number of aircraft in the fleet which adopt each measure compared to the total fleet size. The Base case is omitted as its technology uptake is zero by assumption. The left-hand panels indicate the Technology case in which a carbon price is not applied and the right-hand panels the Abatement case, which includes carbon trading.

In the Technology case, as airlines are able to make fuel cost savings by adopting abatement measures, they can lower fares slightly. Therefore demand is slightly increased in the Technology case (blue lines in Figure 2) over the Base case (red lines). However, this effect is minimal. Only low cost, low impact measures which do not have a strong effect on total emissions are adopted before 2020, as shown in the right-hand panels of Figure 2 and the left-hand panels of Figure 3. Increased engine maintenance is adopted by some of the fleet in all applicable scenarios, with uptake increased by emissions trading. Improved air traffic control (SESAR) is assumed to be introduced in 2020. For the purposes of this paper, we assume compliance is optional, with complying aircraft gaining improved fuel burn if they pay adaptation costs and increased navigation charges. In reality it is likely that SESAR compliance will become mandatory either initially or after some threshold year. However, the adaptations needed to take advantage of SESAR are economic for all or most of the fleet in all scenarios, suggesting rapid adoption is likely. After 2020, therefore, the Technology scenarios have approximately 10% lower emissions than the corresponding Base scenarios, which do not include SESAR. However, without emissions trading neither open rotors nor biofuels are adopted in any scenario.

Figure 2 also shows the corresponding RPK and fuel lifecycle emissions in the Abatement case (when a carbon price is applied, green lines). The underlying uptake of mitigation options by scenario is shown in the right-hand panels of Figure 3. RPK travelled is consistently lower in the Abatement case than in the Base case (in 2020, 1.3% lower for IGSM, 2.6% lower for MERGE and 2.1% lower for MiniCAM). This indicates that airlines are choosing to pass some of the costs of emissions trading on to passengers. However, airlines also take action to reduce their emissions trading costs by investing in technology. The combined fuel+carbon price burden on airlines is greatest in the IGSM Abatement scenario (see Table 4). This makes it economic to purchase open rotor aircraft from soon after their assumed initial availability in 2020, and adoption of biofuels occurs at a rate limited only by the assumed production rate increases, as shown in Figure 3(b).

Because the combined fuel+carbon price development in the MERGE and MiniCAM models is lower than for IGSM, open rotors are not cost-effective. However, the uptake of other measures is increased over the Technology (no carbon price) case, and biofuels are used across the fleet from 2020. Additional runs in which the biofuel option is not made available indicate that, in the absence of biofuels, open rotors would be adopted in the MERGE small aircraft class from 2030. This kind of interdependency is observed elsewhere in the simulations. For example, there are two cases in which SESAR compliance is less than 100%. The first is the MiniCAM Technology scenario, in which airline costs are low enough that SESAR compliance is not economic for some of the fleet. The second is the IGSM Abatement scenario. In this case the savings airlines have made from early adoption of one technology (open rotors) lower the cost-effectiveness of adopting another (SESAR compliance).

The right-hand panels of Figure 2 show that, in the Abatement case, fuel lifecycle emissions differ little from the Base case before 2020. After this point, the introduction of SESAR and biofuels, and (for IGSM) open rotors reduces fuel lifecycle CO_2 emissions

significantly. By 2040 all three Abatement scenarios have emissions below year-2005 levels, even though RPK has increased. Most of this decrease in emissions is due to the lower lifecycle emissions of biofuels. All three Abatement scenarios use biofuel (in a 50/50 blend with Jet A) across the entire European fleet in 2050. This suggests that the UK's target of reducing 2050 UK aviation emissions below 2005 levels is potentially achievable in an ETS+biofuels scenario.

However, in the highest-growth scenario (IGSM) the biofuel usage for satisfying intra-European air travel demand alone in 2040-2050 is around 18 billion gallons. To produce this much cellulosic biomass, a land area of about 14 million hectares (roughly the size of England), would be required. It is likely that such an extensive use of biofuels is not realizable unless a higher-yield biofuel is developed.

CONCLUSIONS

This paper has explored the interaction between airline uptake of current and future CO_2 emission mitigation measures and emissions trading, by applying the results of studies on marginal abatement costs to an aviation systems model of the European air transport system. Although not all abatement options which may be available to airlines before 2050 are studied, the analysis in this paper demonstrates the general interaction of different options and the emissions reductions which may potentially be achievable even when using a reduced selection of measures. Whilst some abatement options (in particular winglet retrofits and increased engine maintenance) are economic to adopt in the absence of an ETS, it is found that, under the assumptions made in this paper, the widespread use of open rotor engines and biofuels only occurs at higher oil and carbon prices within an ETS. In practical terms, this means that in a future scenario with no ETS and low oil prices we would expect most airlines to opt to order aircraft with traditional engine types and to use Jet A fuel even when an open rotor aircraft is available to order and an aviation-suitable biofuel is widely available. It is also found that, even when adaptation to take advantage of improved air traffic control is optional, its uptake by airlines is at or near 100% in all applicable scenarios modeled here.

The interaction between different mitigation measures is potentially complex and depends on the cost-effectiveness, availability and introduction order of each measure. The most promising scenario for fuel lifecycle CO_2 emissions reduction is one in which an ETS is applied and cellulosic biomass fuels are made available. In this case, the results suggest that it could be possible to reduce fuel lifecycle CO_2 emissions from European aviation in 2040 to below 2005 levels. However, for this to be a feasible scenario in terms of land use, a higher-yield biofuel would need to be developed.

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TABLE TITLES AND FIGURE CAPTIONS

TABLE 1 Reference Aircraft Types

TABLE 2 Elasticity Estimates and Standard Errors (in parentheses) for European Air Passenger Demand

TABLE 3 Characteristics of Mitigation Options Considered, from *(7, 12, 41)*

TABLE 4 Main Scenario Data Used in this Study, Following the US Climate Change Science Program Study *(24)*

FIGURE 1 University of Cambridge Aviation Integrated Model.

FIGURE 2 RPK flown and fuel lifecycle CO_2 emitted in the Base (no abatement measures adopted), Technology and Abatement scenarios. Panels (a) and (b) depict RPK and CO_2 for IGSM, (c) and (d) for MERGE and (e) and (f) for the MiniCAM background model.

FIGURE 3 Number of aircraft in the fleet adopting different emission mitigation measures by time and background scenario in comparison to the total fleet. Panels (b), (d) and (f) show the Technology scenario with no emissions trading; panels (a), (c) and (e) show the Abatement scenario including emissions trading.
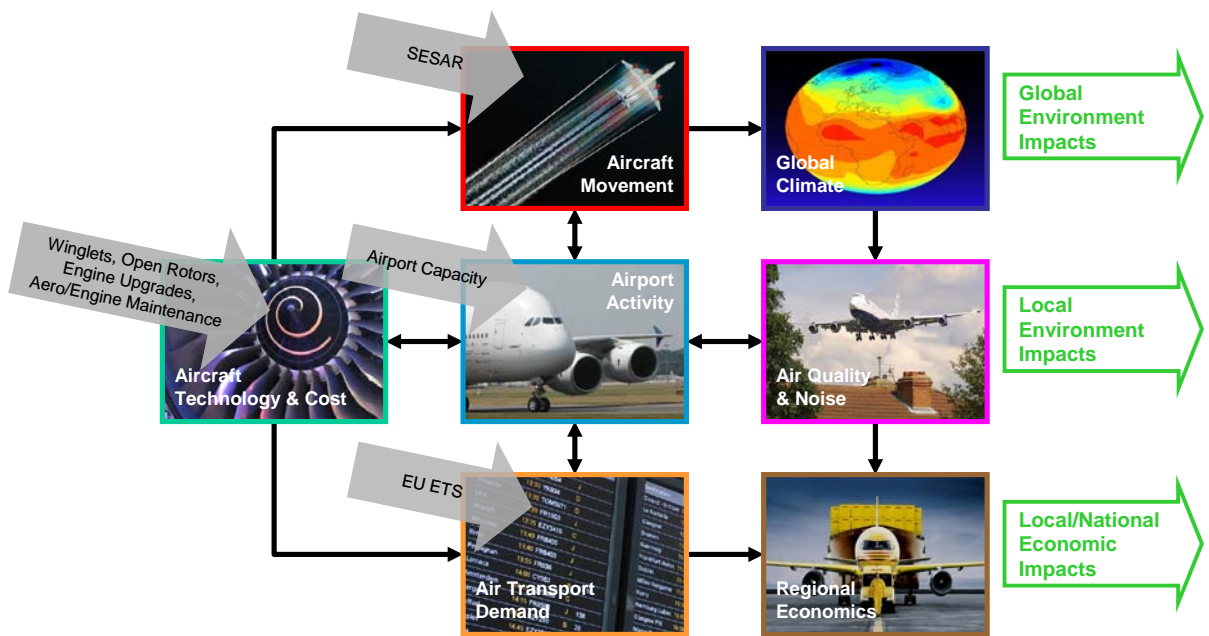
FIGURE 1 University of Cambridge Aviation Integrated Model.

TABLE 1 Reference Aircraft Types

Size Class	Age Class[a]	Airframe	Engine
<190 Seats	pre-1995	Boeing 737-300	CFM56-3-B1
	post-1995	Airbus A319-131	V2511
190-299 Seats	pre-1995	Boeing 767-300ER	PW4060
	post-1995	Airbus A330-300	CF6 80E1 A2
>299 Seats	pre-1995	Boeing 747-400	PW4056
	post-1995	Boeing 777-300	Trent 895

[a] The 1995 threshold is chosen to be 10 years before the 2005 model base year, based on date of first entry into the fleet.

TABLE 2 Elasticity Estimates and Standard Errors (in parentheses) for European Air Passenger Demand

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

TABLE 3 Characteristics of Mitigation Options Considered, from *(7, 12, 41)*

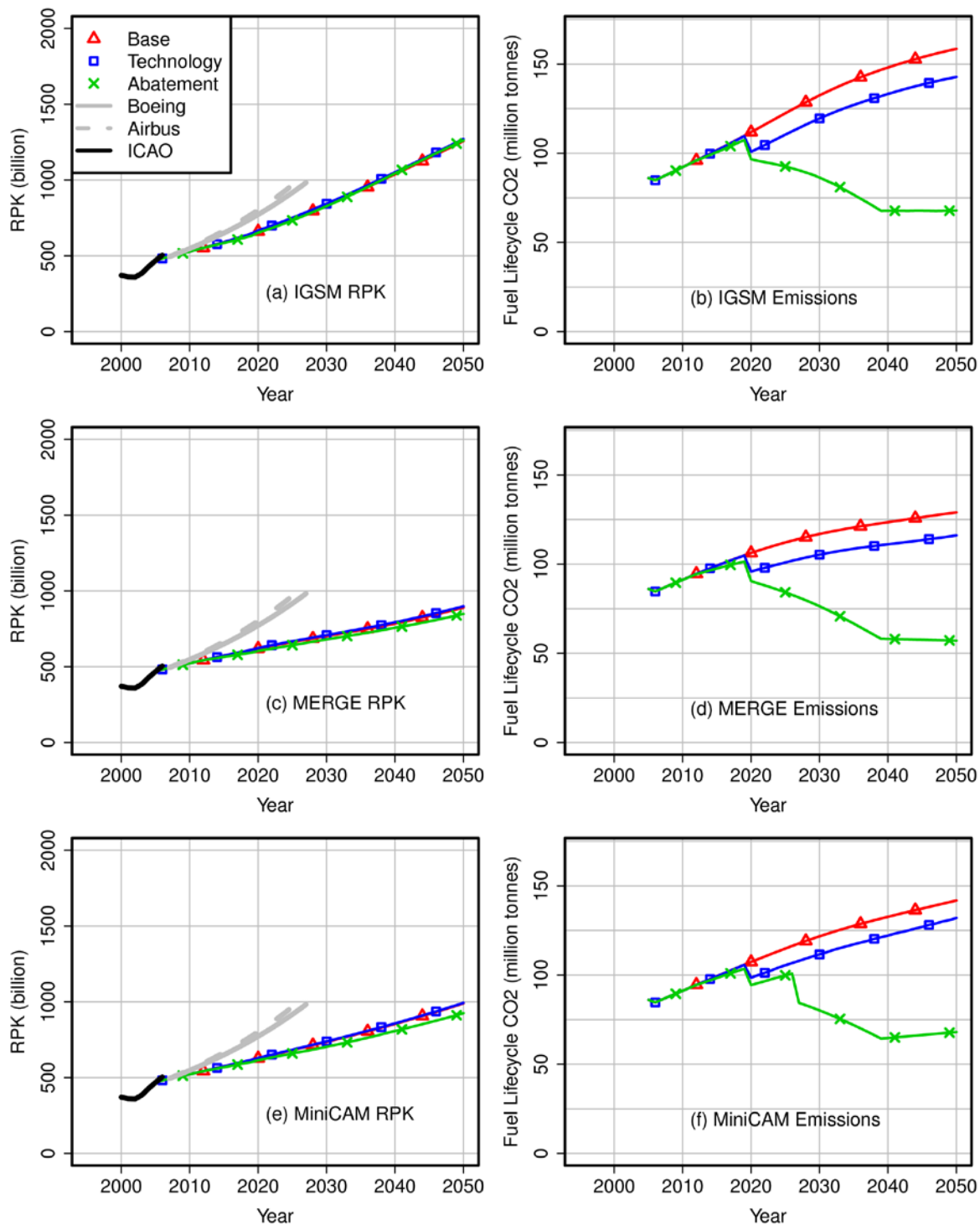| Mitigation Technology	Availability (year, proportion of fleet)	Fuel Burn Reduction Potential (% per aircraft)[b]	Upfront Costs (2005$)	Yearly Costs (2005$)	Comment
Winglets	Base year, up to 25% depending on aircraft size	1.2 - 2.4% depending on route flown	$740,000	$14,800 extra maintenance costs	
More frequent engine maintenance	Base year, all	Up to 2.5%	$0	85% increase in engine maintenance costs	Depends on aircraft age
More frequent airframe maintenance	Base year, all	Up to 1%	$0	Function of MTOW and fuel saving achievable	Depends on aircraft age
Engine upgrades	Base year, up to 37.5% depending on size	1%	15% of new engine costs	5% reduction in engine maintenance costs	
Open rotor engines	2020, all new <190-seat aircraft	30% (relative to conventional aircraft with the same year of manufacture)	$7,400,000 extra on purchase price	Engine maintenance cost increase of $740,000	Journey time increase assumed small
Improved air traffic management	2020, all	10.5%	$463,000 for avionics upgrade	$83,300 for equipment and training, 30% increase in navigation costs	Assumed reduction potential is about half of the total fuel-based inefficiencies observed in *(39)*.
Cellulosic biomass fuels	2020, all (limited availability before 2040)	85% (lifecycle CO_2 emissions from 100% biofuel)	$0	Biofuel costs	Mit. pot. relative to petroleum-derived jet fuel on lifecycle basis. Reversible

[b] Where not otherwise noted, the fuel burn reduction quoted is relative to aircraft of the same age, type and route network which do not adopt the measure.

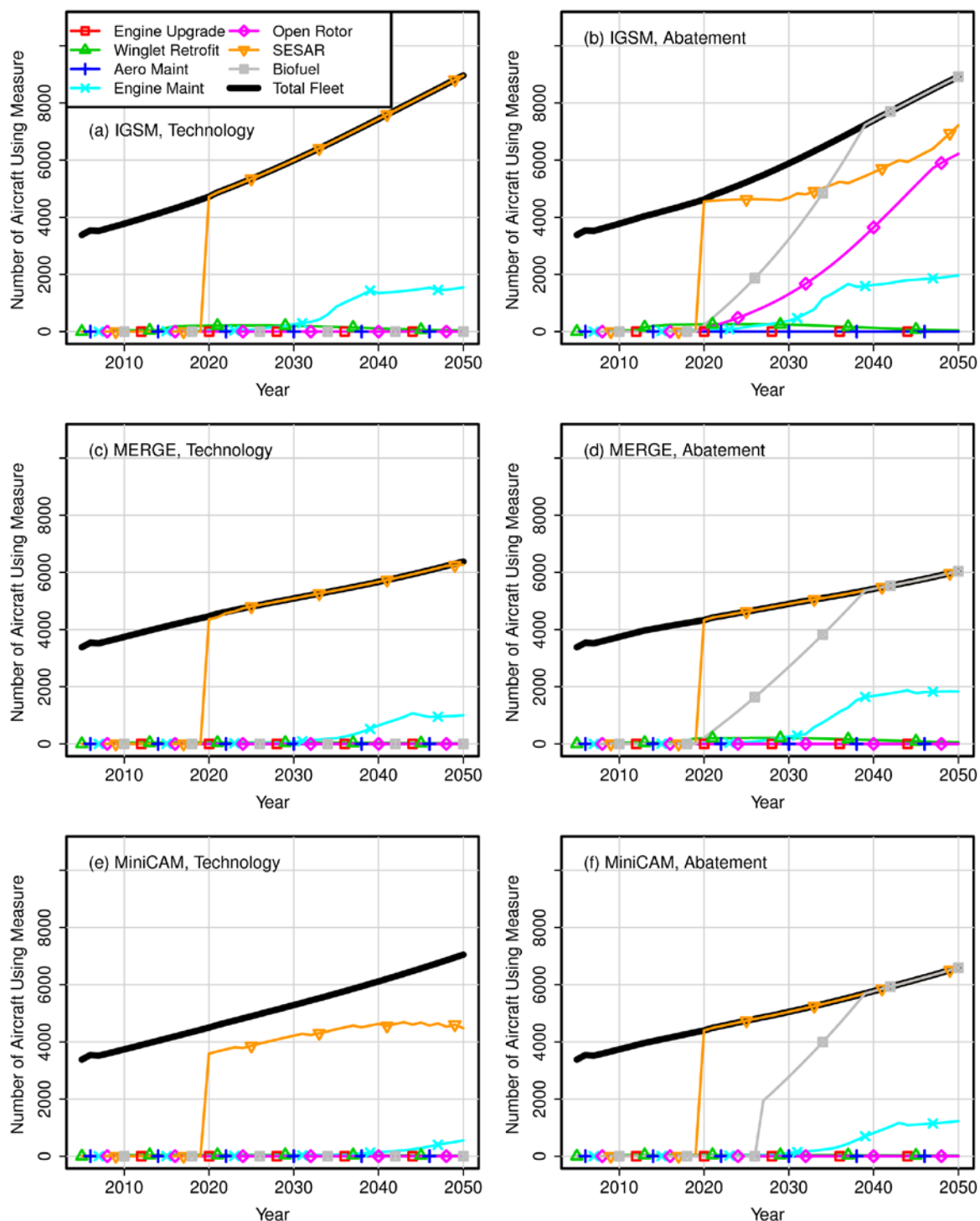**TABLE 4 Main Scenario Data Used in this Study, Following the US Climate Change Science Program Study** *(24)*

		2000	2020	2040
Population, millions				
Western Europe[c]	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, $/tCO$_2$				
	IGSM	0	23.0	46.0
	MERGE	0	33.7	112.5
	MiniCAM	0	28.5	94.3

[c] Country lists for Western and Eastern Europe are given in *(24)* and references therein. Note that the different scenarios use different country sets for Western and Eastern Europe.

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