Mitigation of Aviation Emissions of Carbon Dioxide

Analysis for Europe

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This paper investigates the interaction between economic, technological, and operational measures intended to reduce air transport-related emissions of carbon dioxide (CO_2). In particular, the introduction of aviation to the European Union Emissions Trading Scheme (ETS) in 2012 may prompt increased uptake of presently available options for emission reduction (e.g., retrofitting winglets, expanding maintenance programs) by airlines operating in Europe. Carbon prices may also determine the use of options currently under development [e.g., open-rotor engines, second-generation biofuels, and improved air traffic management (ATM)]. The results of a several studies analyzing airline costs and emission reductions that are possible from different mitigation options are applied to a systems model of European aviation. With 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), technology uptake and the resulting effect on fuel life cycle CO_2 emissions with and without an ETS are analyzed. 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. European aviation fuel life cycle emissions could be reduced below 2005 levels before 2050 if cellulosic biomass fuels are made available by 2020. However, the land use requirements in this scenario may limit its practicality at currently projected cellulosic biomass yields.

Global aviation demand, in revenue passenger-kilometers (RPK), is predicted to grow at about 5% per year over at least the next 20 years (*1, 2*), with European domestic aviation RPK growing at a rate of 2% to 4%. Because technology improvements typically deliver a 1% to 1.5% decrease in fuel burn per RPK per year (*3*), this suggests European aviation emissions are likely to continue to increase. However, the goal of emissions targets is typically envisaged as a lowering of aviation emissions. For example, the U.K. government has announced its intention to reduce U.K. aviation emissions to below 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 introduction of technology, introducing operational changes, or reducing RPK growth levels.

In Europe, aviation is to be included in the European Union Emissions Trading Scheme (ETS) from 2012 (*5*), meaning that overall emissions will be capped at a given level that declines year to year. Participants in an ETS who emit more than their "free" quota under the cap can 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 compared with many other sectors. However, a recent study (*7*) suggested that cost-effective direct mitigation options exist that 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 period considered (*8*).

Further promising mitigation options (each also with its 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 with 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 Air Traffic Management (ATM) Research (SESAR) project (*10*) could reduce the extra fuel burn that aircraft currently incur by flying nonoptimal routes due to ATM inefficiencies.

Additional potentially large savings in life-cycle carbon dioxide (CO_2) emissions may be achieved by introducing aviation-suitable biofuels. A range of biomass-derived fuels are under development, each with different life-cycle 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 that 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,

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Transportation Research Record: Journal of the Transportation Research Board, No. 2177, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 17–26.
DOI: 10.3141/2177-03

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 those actions might affect fares and passenger demand, and what the resulting effect on total CO_2 emissions is for a range of different future scenarios.

METHODOLOGY

Aviation Systems Model

An aviation systems model, the Aviation Integrated Model (*13–15*), was used to capture the interdependencies in the European aviation system. This is a program funded by the U.K. Natural Environment Research Council and Engineering and Physical Sciences Research Council, 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 U.K. Climate Change Committee (*16*) and to study the U.S. and Indian air transport systems (*14*). The Aviation Integrated Model consists of seven interacting modules, as shown in Figure 1, each covering a component of the air transport and environment system. This architecture permits important feedback and data flows between key system elements to be captured and provides natural input sites for policy measures to be imposed upon the system, as the figure shows. Detailed descriptions of the modules and their interactions are given in Reynolds et al. (*13*). In this study, the aircraft technology and cost, air transport demand, airport activity, and aircraft movement modules were used. 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 setup for these modules is summarized below.

Aircraft Technology and Cost Module

The aircraft technology and 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 (Table 1). Performance and emissions modeling for these aircraft below 3,000 ft was based on the International Civil Aviation Organization (ICAO) engine exhaust emission data (*17*) and the ICAO reference landing and takeoff cycle (*18*), adjusted for airport-specific taxi-out delay times from the airport activity module. Above 3,000 ft, performance during climb, cruise, descent, and airborne holding was modeled by using the Eurocontrol Base of Aircraft Data 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 U.S. airline cost data (*20*) adjusted for global differences in operating costs (*21*). European navigation charges were obtained from Reynolds et al. (*22*).

The improvement in fleet fuel burn resulting from the retirement of older aircraft and the introduction of new aircraft types was modeled on the basis of 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, at 0.2% per year (*23*). New models of aircraft were assumed to take advantage of incremental improve-

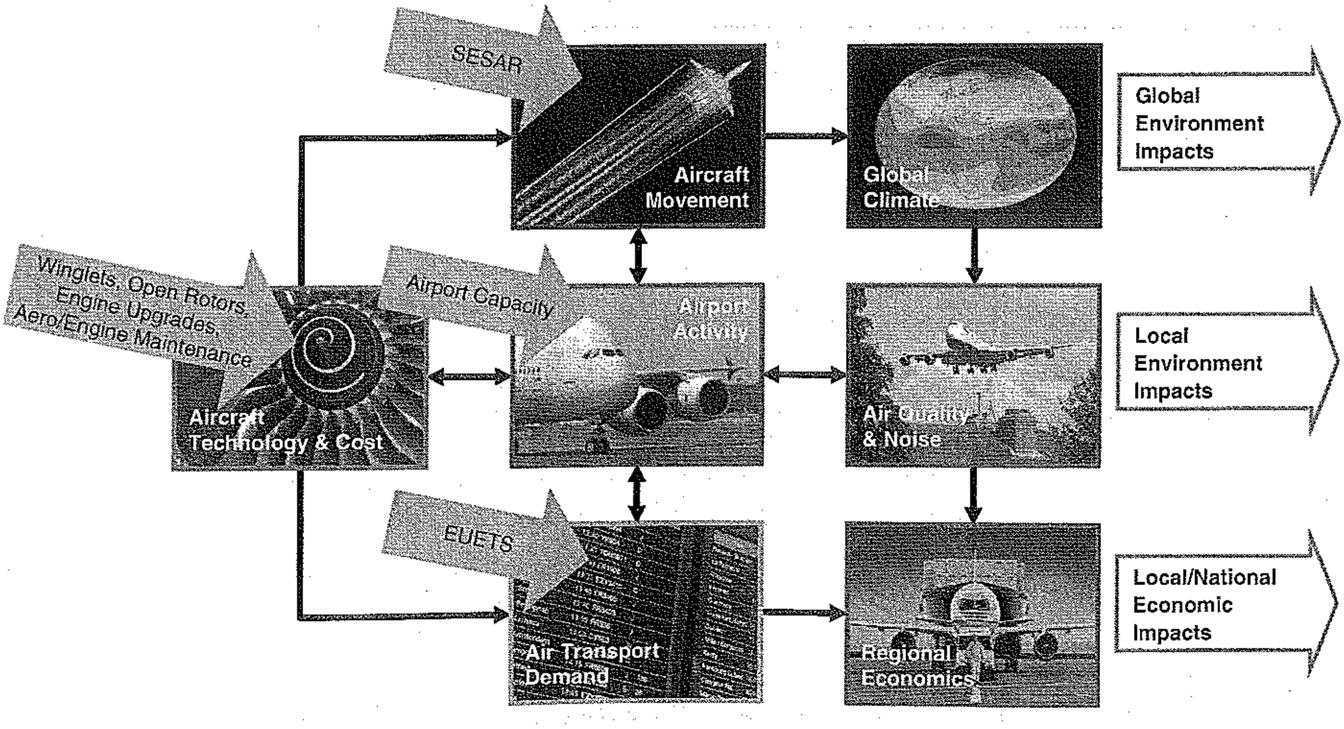


FIGURE 1 University of Cambridge Aviation Integrated Model.

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.

ments in technology and hence have lower starting fuel burn than current models. However, the option of retrofits or introduction of radical new technologies (with associated changes in airline costs) was treated separately as an airline choice, to avoid double-counting of 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 was 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 in which the 2030 oil price plus associated carbon trading costs is below \$100/bbl, between \$100/bbl and \$150/bbl, or over \$150/bbl in 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, by using a simple one-equation gravity-type model given in Equation 1.

$$D_{ij} = \left(I_i I_j\right)^{\alpha} \left(P_i P_j\right)^{\gamma} e^{\delta A_{ij}} e^{\epsilon B_{ij}} e^{\phi S_{ij}} e^{\omega \mathrm{DF}_{ij}} C_{ij}^{\tau} \qquad (1)$$

where

P = base year metropolitan area population;
I = associated income;
C = generalized travel costs consisting of fares, value of travel time, and flight delay;
A, B = binary variables indicating whether one or both cities in pair have qualities that might increase visitor numbers (for example, being a major tourist destination or capital city);
S = binary variable indicating whether road links exist between given city pair;
DF = binary variable indicating whether flight is domestic; and
$\alpha, \gamma, \delta, \epsilon, \phi, \omega, \tau$ = elasticities to be estimated.

Base year metropolitan area population and income data were obtained from individual country censuses and household income surveys (*25, 26*), with income converted to 2005 dollars by using market exchange rates. Base year fares and journey times were estimated by 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 a source of transportation statistics (*30*). As true origin–ultimate destination demand data were not available, an assignment matrix approach was used to estimate elasticities for short-, medium-, and long-haul trips (*14*). Routing was estimated through scheduled journey and available connection times (*29*) based on an analysis of U.S. routing used by Jamin et al. (*8*). All parameter estimates in Table 2 are significant at the 95% level and compare well to literature values (*31*). The R^2 obtained was .47.

The future demand for air trips was estimated with scenario-based forecasts of the key explanatory variables, with delay and airline cost values from the aircraft technology and cost and the airport activity modules. In particular, future fare trends depend on the change in operating costs (most notably oil price) and market economics. For simplicity and transparency, airline rates of return were assumed to remain constant in all markets, as modeled by Waitz et al. (*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 nonstop 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

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

	Estimated Elasticities						
	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 (500–1,000 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 (>1,000 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)

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 by means of simplified runway capacity models (*34*) and standard capacity estimation charts corresponding to different airport configurations (*35*). Delays due to airport capacity constraints were estimated by 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 with modeled European flight frequencies and airport capacities, the calculated departure delays due to capacity constraints at origin airports were distributed between the taxiway and the gate according to a taxi-out threshold estimated from historical U.S. data (*37*). Similarly, delays due to capacity constraints at destination airports were distributed between the air and ground according to an airborne-holding threshold based on U.S. data (*37*), above which the delay was assumed to be propagated upstream of the departure gate.

Projections of airport capacity tended to be short term and focused on capacity expansions that are already in the planning or construction stage. Rather than use external projections of capacity, future airport capacity expansion within the Aviation Integrated Model was simulated 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 procedure 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 that cannot be completely removed from the system). These inefficiencies manifest as extra distance flown beyond the shortest ground track distance or excess fuel burned 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 information from flight track and flight data recorders from the region, as described by Reynolds (*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 economical to adopt for most aircraft unless carbon prices significantly exceed currently projected levels. Others, for example, increased use of turboprops, have associated issues that are difficult to quantify, such as cabin noise (*40*). The combined effects on emissions of any two measures are not necessarily additive and can depend on adoption order (e.g., applying an engine upgrade kit and then reengining). For this paper, a range of abatement options was chosen from those evaluated by Morris et al. (*7*). The options studied here and listed in Table 3 are only a selection of those that may become available, and 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 operating costs of a given aircraft, and change in 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 that already have winglets or to future models of aircraft that are assumed to be already fitted with winglets if these can provide a cost-effective fuel burn advantage. Characteristics of these options in cost, applicability, and fuel burn reductions were taken from Morris et al. (*7*) and Henderson (*41*). The assumptions used here were significant simplifications, and in many cases, current information about future costs and emissions was 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 on the basis of a payback period of 7 years (i.e., an abatement option will be introduced only if the cost savings over the next 7 years are expected to be greater than the upfront and yearly costs of applying the measure over that 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.

For biofuels, it is assumed that costs under emissions trading are based on fuel life-cycle (well-to-wake) emissions rather than simply airborne emissions. The assumptions here were that 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 pro-ethanol program (*42*). Aviation biofuel prices were assumed to be at least US$0.70/L (*12*) or—following the profit-maximizing behavior of the fuels industry—equivalent to the costs of Jet A, whichever value was higher. Life-cycle emission characteristics were also derived from Schäfer et al. (*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 were gathered, and contains 1,127 airports and accounting for about 95% of global scheduled RPK. For the intraregional Europe model presented here, the corresponding European subset was used, which contains 173 cities and 337 airports. A full list is given in Dray et al. (*15*).

Underlying the projection of future aviation growth in the Aviation Integrated Model are scenario-based projections of key variables

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

Mitigation Technology	Availability (year, proportion of fleet)	Fuel Burn Reduction Potential (% per aircraft)[a]	Upfront Costs (2005$)	Yearly Costs (2005$)	Comment
Winglets	Base year, up to 25% depending on aircraft size	1.2% to 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
Cellulosic biomass fuels	2020, all (limited availability before 2040)	85 (life-cycle CO_2 emissions from 100% biofuel)	0	Biofuel costs	Mitigation potential relative to petroleum-derived jet fuel on life cycle basis. Reversible

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

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 that considers these factors simultaneously. This study used a set of external scenarios from the U.S. Climate Change Science Program (*24*). These were developed with MIT's Integrated Global Systems Model (IGSM), Stanford's Model for Evaluating the Regional and Global Effects of GHG [greenhouse gas] 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 subscenarios. A near-term carbon price of about €20 per tonne of CO_2 has been suggested by a number of studies (*43*), whether or not aviation is included (*44*). Therefore, in this study, the carbon-trading scenario chosen for each model was the one that 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 (*6*). It was assumed here that airlines pay in full for their allowances and do not receive a free allocation.

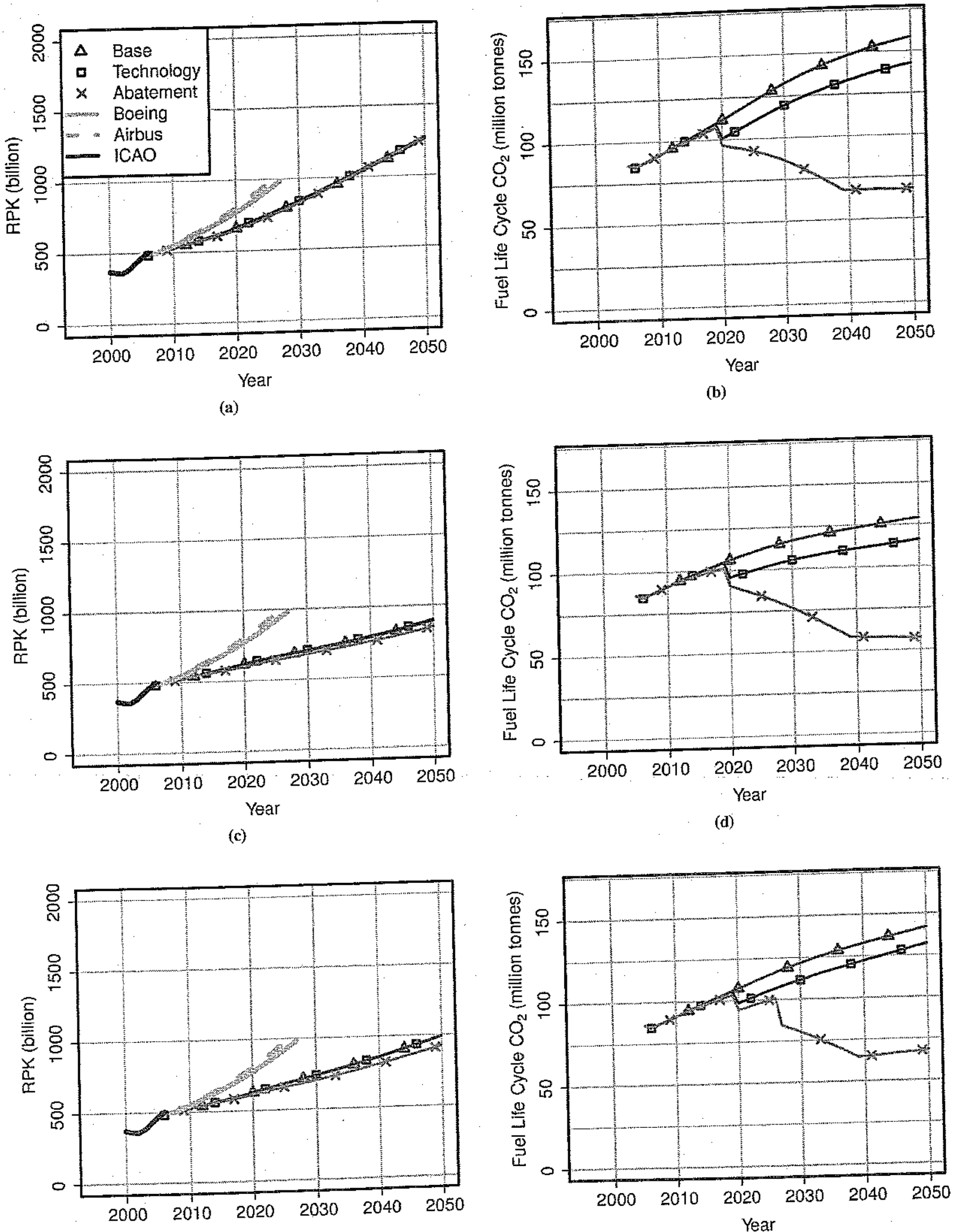
RESULTS

To assess the interaction between mitigation measures, three basic policy scenarios were run for each of the IGSM, MERGE and MiniCAM models:

- Base. In this scenario, no carbon price was applied and no abatement measures were made available for adoption by airlines. Individual aircraft fuel burn was affected only by fleet turnover and incremental improvements in the technology of new aircraft.
- Technology. In this scenario, no carbon price was applied but all technological abatement measures were made available to airlines, which will adopt them if they provide an overall cost saving over a 7-year payback period.
- Abatement. This scenario was similar to the technology scenario, but in addition, a carbon price was imposed.

Figure 2 shows the RPK and fuel life-cycle CO_2 emissions from these three scenarios. Figures 2*a* and 2*b*, 2*c* and 2*d*, and 2*e* and 2*f* show, respectively, the IGSM, MERGE, and MiniCAM background models. In addition, alternative RPK forecasts from Airbus and Boeing (*1, 2*) and historical data from ICAO (*45*) are shown in each part of Figure 2. The yearly RPK growth rates projected for European aviation are lower, at about 2%, than those from the Airbus and Boeing forecasts, although not outside the range of those predicted for the European system (*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 period studied, so RPK growth rates here are also typically lower than for models that use a declining trend in travel cost.

To help interpret Figure 2, Figure 3 shows the mitigation option uptake by scenario, in the number of aircraft in the fleet for which each measure is adopted compared with total fleet size. The base case is omitted as its technology uptake is zero by assumption. Figures 3*a*, 3*b*, and 3*c* indicate the technology case, in which a carbon price is not applied, and Figures 3*d*, 3*e*, and 3*f* show the abatement case, which includes carbon trading.



(a)

(b)

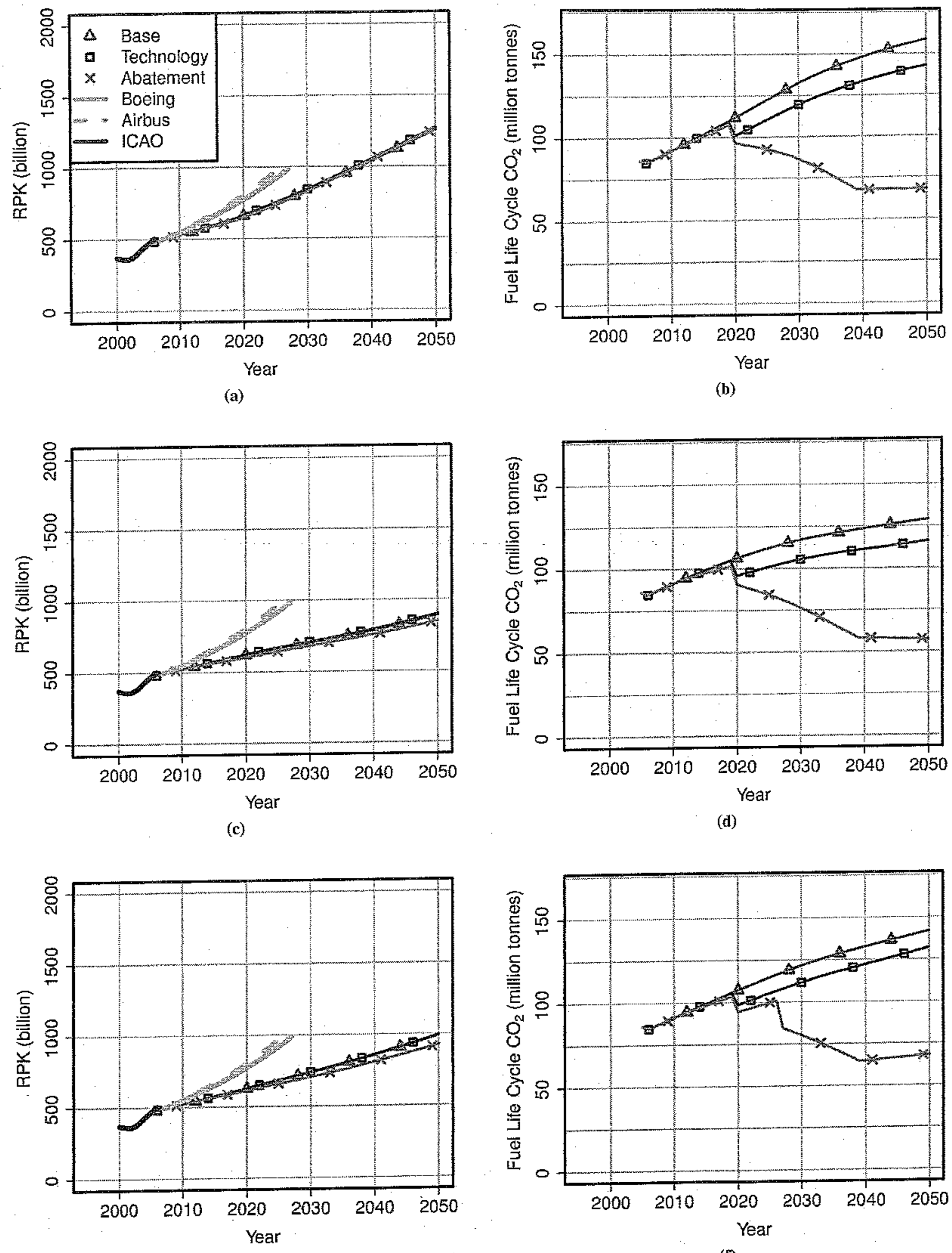
(c)

(d)

(e)

(f)

FIGURE 2 RPK flown and fuel life-cycle CO_2 emitted in the base (no abatement measures adopted), technology, and abatement scenarios: (*a*) IGSM RPK, (*b*) IGSM CO_2, (*c*) MERGE RPK, (*d*) MERGE CO_2, (*e*) MiniCAM RPK, and (*f*) MiniCAM CO_2.



(a) (b) (c) (d) (e) (f)

FIGURE 3 Number of aircraft in fleet adopting different emission mitigation measures by time and background scenario comparison with total fleet: abatement scenario for *(a)* IGSM RPK, *(b)* for MERGE RPK, and *(c)* for MiniCAM RPK, including emissions trading, and Technology scenario for *(d)* IGSM emissions, *(e)*, MERGE emissions, and *(f)* MiniCAM emissions, with no emissions 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 will slightly increase in the technology case (lines with square points in Figure 2) over the base case (lines with triangular points). However, this effect is minimal. Only low-cost, low-impact measures that do not have a strong effect on total emissions are adopted before 2020, as shown in Figures 2*a*, 2*c*, and 2*e* and Figures 3*d*, 3*e*, and 3*f*. 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, compliance is assumed to be 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 that 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 life-cycle emissions in the abatement case (when a carbon price is applied, lines with crossed points). The underlying uptake of mitigation options by scenario is shown in Figures 3*d*, 3*e*, and 3*f*. RPK traveled 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 result indicates that airlines are choosing to pass on some of the costs of emissions trading to passengers. However, airlines also take action to reduce their emissions trading costs by investing in technology. The combined fuel-plus-carbon price burden on airlines is greatest in the IGSM abatement scenario (Table 4). This makes it economical 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*d*.

Because the combined fuel-plus-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, in two cases, 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 economical for some of the fleet. The second is the IGSM abatement scenario. In this case, the savings that airlines have made from early adoption of one technology (open rotors) lowers the cost-effectiveness of adopting another (SESAR compliance).

TABLE 4 Main Scenario Data, Following U.S. Climate Change Science Program Study (*24*)

	2000	2020	2040
Population, millions			
Western Europe[a]			
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	19,437	33,554	60,457
MERGE	22,163	31,992	44,211
MiniCAM	16,598	15,607	24,387
Eastern Europe			
IGSM	2,548	5,433	11,913
MERGE	2,145	4,264	8,079
MiniCAM	2,845	5,188	11,124
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

[a] 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.

Figures 2*a*, 2*c*, and 2*e* show that, in the abatement case, fuel life-cycle 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 life-cycle CO_2 emissions significantly. By 2040, all three abatement scenarios have emissions below 2005 levels, even though RPK has increased. Most of this decrease in emissions is due to the lower life-cycle 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 United Kingdom target of reducing 2050 U.K. aviation emissions below 2005 levels is potentially achievable in an ETS-plus-biofuels scenario.

However, in the highest-growth scenario (IGSM), the biofuel usage for satisfying intra-European air travel demand alone from 2040 to 2050 is about 18 billion gal. To produce this much cellulosic biomass, a land area of about 14 million ha (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 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 that may be available to airlines before 2050 are studied, the analysis in this paper demonstrated the general interaction of different options and the emissions reductions that may potentially be achievable even when a reduced selection of measures is used. While some abatement options (in particular winglet retrofits and increased engine maintenance) are economical to adopt in the absence of an ETS, it was found that, under the assumptions made in this paper, the widespread use of open-rotor engines and biofuels occurs only 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, most airlines would be expected 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 was 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 reduction of CO_2 emissions in the fuel life cycle 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 CO_2 emissions in the fuel life-cycle from European aviation in 2040 to below 2005 levels. However, for this to be a feasible scenario for land use, a higher-yield biofuel would have to be developed.

ACKNOWLEDGMENTS

The Aviation Integrated Modelling project is funded by the U.K. Engineering and Physical Sciences Research Council and the Natural Environment Research Council. This study was funded by resources from the U.K. Omega project. These sources of support are gratefully acknowledged.

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The Environmental Impacts of Aviation Committee peer-reviewed this paper.