

The Impact of Economic Emissions Mitigation Measures on Global Aircraft Emissions

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In this paper, we examine the effects of globally-applied economic emissions mitigation measures on global air passenger demand and emissions, concentrating in particular on the effects of a worldwide emissions trading scheme. Using the Aviation Integrated Model (AIM), we investigate the relationship between the stringency of such a scheme, in terms of target atmospheric CO₂ concentration levels, and its effect on global and regional aviation systems. Our simulations suggest that a carbon trading scheme targeted at 450 ppm CO₂ could produce reductions in the carbon intensity of aviation across a wide range of future scenarios. For this target level, reductions in aviation fuel lifecycle CO₂ of up to 60% were observed in comparison to the same scenario without emissions trading. Around one-third of this decline was due to demand reductions, and the rest was the result of increased rates of technology adoption, including biofuels. Carbon trading schemes targeted at 550-750 ppm atmospheric CO₂ were effective at reducing aviation CO₂ emissions compared to a no-emissions trading case in some scenarios, but only when oil prices were high enough that the cost of Jet A was comparable to that of biomass-derived aviation fuel. However, total aviation demand and emissions increased over present-day levels in all scenarios.

I. Introduction

THE global aviation system contributes to around 4.5% of global GDP¹ and nearly 3% of global energy-use related CO₂ emissions². In addition, global demand for air passenger travel is projected to grow rapidly over the next 20 years^{3,4}, with revenue passenger kilometers (RPK) flown increasing at a rate of around 5% per year. Much of this growth is forecast to come from developing regions of the world. For example, China is currently undertaking an extensive airport-building programme⁵ aimed at accommodating increases in passenger traffic of over 10% per year. Similar growth is expected in other regions, such as India. The result is likely to be a significant increase in global aviation emissions. The prospect of increased emissions may in turn lead to regional or global economic policy measures intended to mitigate these emissions, either by accelerating the adoption of operational and technological emission-reduction measures, or by reducing demand for air travel. Such policy measures may have complex and wide-ranging effects on the aviation sector.

Economic measures targeting global aviation emissions can take several forms. One option is to include aviation within a larger global carbon trading scheme, provided international agreement could be reached on establishing such a scheme. In the absence of a global scheme, local schemes covering individual world regions might be introduced. In particular, the EU Emissions Trading Scheme is set to incorporate aviation from 2012⁶. Under this scheme, the vast majority of EU flights, including those entering or leaving the EU, will be allocated a number of allowances up to an emissions cap based on year 2004-2006 emissions. If aviation emissions continue to grow above this cap, airlines will be required to purchase allowances from other sectors which are more readily able to reduce their emissions. Assessments of the impact of this scheme on EU aviation have suggested that aviation will be a net purchaser of allowances, due to the relative difficulty of reducing aviation emissions⁷. Proposals for a US-based emissions trading (or cap-and-trade) scheme also indirectly include aviation via the cost of aviation fuel⁸. These precedents increase the likelihood that aviation would be included in a global trading scheme, if one were established. Global emissions trading schemes have been suggested and modeled by several organizations⁹. One major advantage of a global scope for emissions trading is the ability to associate the emissions target with a specific

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(if uncertain) level of global temperature rise. As discussed in Ref. 10, stabilization of atmospheric CO₂ equivalent (CO₂e) levels at 550 ppm (440-500 ppm in terms of CO₂ alone) would result in a 30-70% chance of global temperature rises exceeding a ‘very damaging’ level of 3°C. According to Ref. 9, stabilization at this level would entail carbon prices of between 2.5 and 23 US\$(2005) per tonne of CO₂ in 2020, rising to between 11 and 76 US\$ in 2050. For a typical long-haul flight, this amounts to up to around 5% of current ticket prices, with stabilization at 450ppm requiring up to a potential 17% increase. However it is uncertain as to whether the full costs of carbon trading would be passed on to ticket prices¹¹.

Given global variations in airline costs and ticket prices¹², it is likely that a global emissions trading scheme incorporating aviation would have different effects in different world regions. The demand impacts will depend on ticket price increases relative to local income, the price-sensitivity of passengers, and the extent to which airlines are able to reduce per-passenger emissions in response to emissions trading rather than purchasing additional allowances¹³. In turn, demand changes may affect airport capacity requirements, flight delays, and the demand for passengers connecting through these regions. The behavior of this large and complex system in response to changes in inputs reflects the many interactions between the interests and behavior of passengers, airlines and policymakers; a policy intervention in any one component of the system may have effects on many other components. In this paper, we model the effect of global emissions trading on global aviation demand and emissions using the Aviation Integrated Model (AIM)¹⁴, a UK Research Council-funded project aimed at developing a series of interlinked modules to describe the local and global effects of aviation. In particular, we concentrate on the interaction between the global CO₂ atmospheric stabilization level target and the resulting effect on aviation emissions, RPK flown and the adoption of new technologies.

This paper is structured as follows. Section II describes the individual components of AIM relevant to this study and the input scenario set. In section III, results are presented for global aviation under a range of stabilization targets. Finally, Section IV summarizes the paper and presents conclusions.

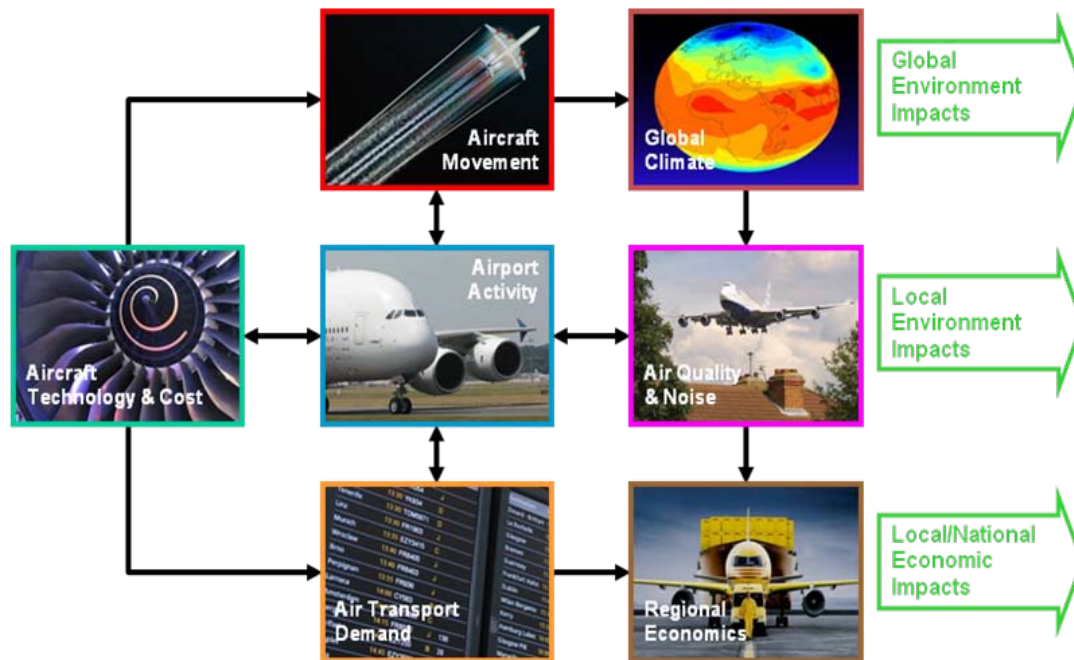


Figure 1. AIM Structure.

II. Modeling

The basic structure of AIM is shown in Figure 1. AIM consists of seven interconnected modules, programmed in Java and Matlab. The Air Transport Demand Module projects true origin-ultimate destination demand for air travel

for a set of 700 global cities, served by 1,127 airports, which accounts for around 95% of global scheduled RPK. The Airport Activity Module assigns passenger routing, a flight schedule, and aircraft types by flight segment, calculates the resulting flight delay and airport capacity requirements to maintain future flight delays close to existing levels. The Aircraft Technology and Cost Module computes costs and emissions by aircraft type, and fleet turnover rates, including airline decisions to invest in new technology. The Aircraft Movement Module calculates the location of emissions, accounting for en-route inefficiencies. Airline costs are used to estimate average airfares, which are input to the Air Transport Demand Module for the estimation of passenger demand. The modules listed above are therefore run iteratively until equilibrium between demand and supply is reached. The output is then passed to the Global Climate Module, which calculates a range of climate metrics; the Air Quality and Noise Module, which calculates local impacts for selected airports; and the Regional Economics Module, which calculates the economic impact of the obtained system equilibrium. The modules that are relevant for the analysis carried out in this paper, and the scenario set used for future population, GDP, oil and carbon prices, are described in more detail in the sections below.

A. Aircraft Technology and Cost Module

The Aircraft Technology and Cost Module simulates fuel burn, key emissions and operating costs by stage length and load factor, for airframe and engine technologies to 2050. The global fleet is represented by a set of six sample aircraft types by size and technology age, as detailed in Ref. 13. Performance and emissions modeling for these aircraft below 3,000 feet is based on ICAO reference data^{15,16}, adjusted for airport-specific taxi-out delay times estimated by the Airport Activity Module. Above 3,000 feet, performance during climb, cruise, descent, and airborne holding is modeled using the Eurocontrol Base of Aircraft Data model¹⁷, adjusted for route-specific airborne delay and inefficiency from the Aircraft Movement Module. Operating costs are taken from published US airline cost data¹⁸ and adjusted for global differences¹². Fleet turnover is modeled based on the historical behavior of the global fleet¹⁹, with aircraft fuel burn deteriorating by 0.2% per year of aircraft age.

The Aircraft Technology and Cost Module also includes the option for airlines to invest in current or future new technologies, assuming that those technologies are cost-effective over a payback period of 7 years. The technology options assumed available and their assumed costs and benefits are discussed in detail in Ref. 13; they include retrofits, increased maintenance, biofuels, open rotor engines for narrowbody aircraft and improved Air Traffic Management (ATM). For this paper we use the same set of available options. A synthetic jet fuel from cellulosic biomass is assumed to become available in 2020, at a price of at least 70 US cents per litre²⁰ or — following the profit-maximizing behavior of the fuels industry — equivalent to the costs of Jet A, whichever value is higher. However, to reflect biomass supply concerns, we limit biofuel use to a 20% blend with Jet A and limit production rate increases per year to historically-observed rates from the Brazilian proEthanol program²¹. Drop-in biofuels have direct CO₂ emissions similar to Jet A, but significantly lower lifecycle emissions. It is assumed that carbon costs will reflect the reduced lifecycle CO₂ emissions from biofuel, rather than being applied to direct emissions only. We also assume that all aviation allowances are allocated by auctioning, i.e. no free allowances based on existing emissions are provided. It is also assumed that ATM improvements in the US, European and Asian regions will be fully applied over the period 2015-2025, will be non-optional, and will supply a 4% global decrease in total fuel burn through more direct routing²². Some improvements in technology will also be non-optional, i.e. they will apply to all new aircraft models. Therefore we also assume the fuel burn per RPK of new aircraft models, not including the technology options discussed above, will improve by 1% per year, a rate which is consistent with historical trends²³.

For simplicity and transparency, airline rates of return are assumed to remain constant in all markets, as modeled by Ref. 24. 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.

B. Air Transport Demand Module

The AIM Air Transport Demand module generates true origin-ultimate destination passenger demand between a set of cities, given socioeconomic characteristics of those cities and journey times and costs from the Technology and Cost and Airport Activity Modules. The demand D_{ij} between cities i and j is calculated using a simple one-equation gravity model of the basic form:

$$D_{ij} = K(I_i I_j)^{\alpha} (P_i P_j)^{\gamma} e^{\delta A_{ij}} e^{\epsilon B_{ij}} e^{\varphi S_{ij}} e^{\omega DF_{ij}} e^{\mu R_{ij}} C_{ij}^{-\tau}, \quad (1)$$

where I_i and P_i and the per capita income and population of city i , C_{ij} is the generalised cost of getting from i to j by air, including delay, and dummy variables A_{ij} and B_{ij} indicate whether one or both cities in the pair are major tourism

or business destinations; S_{ij} and R_{ij} whether a short-haul road or high-speed rail link exists between i and j ; and DF_{ij} whether the route is a domestic one. K , α , γ , δ , ε , φ , ω , μ and τ are parameters to be estimated. We estimate separate elasticities for different world region-pairs and distance groups, depending on the data available. The major factors which change over the course of the study are population, income and generalised cost, although new high-speed rail links in Europe are also modelled. Parameters are estimated as described in Ref. 11 using true origin-ultimate destination passenger numbers when available¹⁸. Otherwise, segment passenger numbers²⁵ or scheduled seats multiplied by load factors adjusted for world region and flight length^{12,18,26} are used, combined with an assignment matrix approach. In the latter case, routing behaviour is estimated from an analysis of US routing data¹⁸. Similarly, fares, where unavailable, are estimated using yields by world region¹². Values of time for air travel are taken from US estimated values²⁷ (US DoT 1997) and adjusted for different world regions by PPP GDP per capita as in Ref. 28. Although income elasticities are estimated in this study, the values obtained are typically on the low end of those available from the literature. As discussed in Ref. 29, there are several reasons why this may be the case. In particular, the use of average incomes for cities in developing regions may be unrepresentative of air travellers in those regions, who are more likely to be business travellers at the top of the regional income range. We therefore use the income elasticities by world region and length of haul recommended by Ref. 29 instead, which are typically in the range of 1-2. This means that a doubling in income results in a 2-4 times increase in demand.

C. Airport Activity Module

The Airport Activity Module forecasts the global air traffic required to satisfy the passenger demand projected by the Air Transport Demand Module, estimates the resulting flight delay given airport capacity constraints, and calculates the airport capacity expansion required to maintain future flight delays close to existing levels. We assume a flight network and passenger routing that remain unchanged from the base year. The proportion of different aircraft types used on each flight segment is estimated according to segment demand, segment length and network type (hub-hub, hub-spoke, or point-to-point) using a multinomial logit regression on historical data²⁶. Flight frequencies are assigned to serve the given demand at base year passenger load factors (e.g. Ref. 12, Ref. 18).

Ground and airborne holding delays are estimated based on flight frequencies and airport capacity constraints using queuing theory³⁰. Where published airport capacities are not available, they are estimated using simplified runway capacity models³¹ and standard capacity estimation charts corresponding to different airport configurations (e.g. Ref. 32). Gate departure delays due to mechanical failures and late arrivals are assumed to remain at current levels. The distribution of the delay between the gate, taxiway and airborne holding is modeled using taxi-out and airborne holding thresholds estimated from historical US data³³.

Data on airport capacity expansion to 2050 is scarce and highly uncertain. We assume instead that capacity will be increased as required to serve forecast demand such that delays remain close to present-day levels. As discussed in Ref. 13, this assumption typically has an effect only on major hub airports. For these airports it is likely that capacity expansion will come from more intensive use of runways and increased use of secondary airports for true origin-ultimate destination traffic, as well as possible infrastructure expansion.

D. Aircraft Movement Module

Air traffic by flight segment from the Airport Activity Module and emissions data by aircraft type from the Technology and Cost Module are inputs to the Aircraft Movement Module, which calculates the amount and location of aircraft emissions, 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 are estimated for different phases of flight by using archived flight track data, as described by Ref. 34.

E. Emissions Trading Scenarios

Modeling the long-term effects of emissions trading on aviation at different stabilization levels requires projections of future carbon prices which are also consistent with the projections of population, GDP and oil price used by the Demand and Technology and Cost Modules. For these projections we use the scenarios developed by Ref. 9 for the period to 2050. These consist of three basic economic scenarios covering a range of possible futures, 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. For each economic scenario, five different carbon trading stabilisation scenarios are modelled by Ref. 9, corresponding to no carbon trading and to stabilisation at 750, 650, 550 and 450 ppm of atmospheric CO₂. The 450 ppm value corresponds roughly to an 11-69% risk of exceeding a 3°C global temperature rise¹⁰, whereas the 650 ppm level corresponds roughly to a 60-99% risk of exceeding 3°C and a 29-82% risk of exceeding 4°C. It is

assumed in all cases that global carbon trading begins in 2012. Table 1 lists population and GDP per capita growth rates, and oil and carbon prices, by scenario.

The IGSM, MERGE and MiniCAM scenarios are specified for the period 2000-2050. However, significant developments in scenario variables have taken place over the time period 2000-2009, most notably in the GDP of Asian countries. To make the models more consistent with these developments we use historical growth rates from Ref. 35 for GDP, population and oil prices for 2000-2008, and then switch to scenario-based growth rates.

Table 1. Summary of scenario input data by world region.

	Scenario	US	Western Europe ^{††}	Eastern Europe/ Former Soviet Union	China	India	Japan	Africa/ Latin America/ Rest of World
Population	IGSM	0.6	-0.2	-0.3	0.3	0.9	-0.2	1.3
Growth Rate, %/year ^{†††}	MERGE	0.4	0.0	-0.1	0.3	0.7	0.0	1.1
	MiniCAM	0.6	0.0	-0.1	0.2	0.8	-0.2	1.2
GDP/capita	IGSM	2.2	2.9	4.0	4.0	2.5	3.1	1.9
Growth Rate, %/year ^{†††}	MERGE	1.4	1.7	3.4	4.5	4.3	1.3	2.5
	MiniCAM	1.3	1.0	3.3	5.1	4.8	1.2	1.9
Oil Price, \$2005 per bbl	IGSM				88.8 (2020), 125.5 (2040)			
	MERGE				71.7 (2020), 98.0 (2040)			
	MiniCAM				62.3 (2020), 77.8 (2040)			
Carbon Price, \$2005 per tonne CO ₂	IGSM				5.6 - 80.1 (2020), 13.0 - 189.5 (2040) ^{§§}			
	MERGE				0.3 - 34.0 (2020), 1.2 - 118.3 (2040)			
	MiniCAM				0.3 - 28.8 (2020), 1.1 - 98.3 (2040)			

^{††} Note that each scenario uses different country sets for different regions, so these figures should be compared with caution. Country lists are given in Ref. 9 and references therein. GDP figures quoted here are without carbon trading; GDP growth is lowered slightly when carbon trading is included⁹.

^{†††} Mean scenario values for the period 2000-2050, not adjusted for 2000-2009 growth rates.

^{§§} Lower and upper ends of the range correspond to 750 ppm and 450 ppm stabilisation levels respectively.

III. Results

Simulations were run for each combination of scenario (IGSM, MERGE, MiniCAM) and stringency level (none, 750ppm, 650ppm, 550ppm, 450ppm). The primary differences between these scenarios are in terms of the global distribution of GDP per capita growth, and in oil and carbon prices (Table 1). These in turn determine the differences in the scenario results. The IGSM scenario set has high oil prices and high rates of economic growth in the US and Western Europe, coupled with relatively low economic growth rates in the developing world. For relatively stringent carbon trading scenarios (450 and 550 ppm) IGSM carbon prices are also high. This leads to a set of outcomes for aviation that have high demand growth (particularly in the US and Western Europe). Adoption of mitigation technologies is relatively high, and is driven by increasing fuel and carbon prices. The MERGE scenario set has lower GDP per capita growth rates than IGSM in the developed world and higher growth rates in the developing world. Oil and carbon price increases are moderate. The resulting aviation outcomes display RPK growth which is lower than IGSM for intra-US and intra-European flights, but higher for intra-Asian and intercontinental flights. Adoption of mitigation technologies is lower and/or later than for the IGSM case, because fuel and carbon costs are typically lower. The MiniCAM scenario set has the highest Asian GDP per capita growth rates of the three, and the lowest GDP per capita growth rates in the US and Europe. Oil and carbon prices are also relatively low; for low-stringency carbon trading scenarios (e.g. 750 and 650 ppm) the effect of carbon trading on ticket prices is small in both the MERGE and MiniCAM cases.

Figure 2 shows a summary of simulation results in terms of global fuel lifecycle[§] CO₂ emissions for aviation from 1970 to 2050 for each of the scenarios described above, under two cases: (i) with no emissions trading (panels (a), (b) and (c)), and (ii) with a global emissions trading scheme with the most stringent stabilisation target of 450 ppm of atmospheric CO₂ (panels (d), (e) and (f)). For each panel the distribution of emissions by world region is also plotted, as a proportion of the total. Global historical emissions from 1970 to 2005, input from Ref. 36, are included in order to show the growth from 2005 to 2050 in comparison to historical trends.

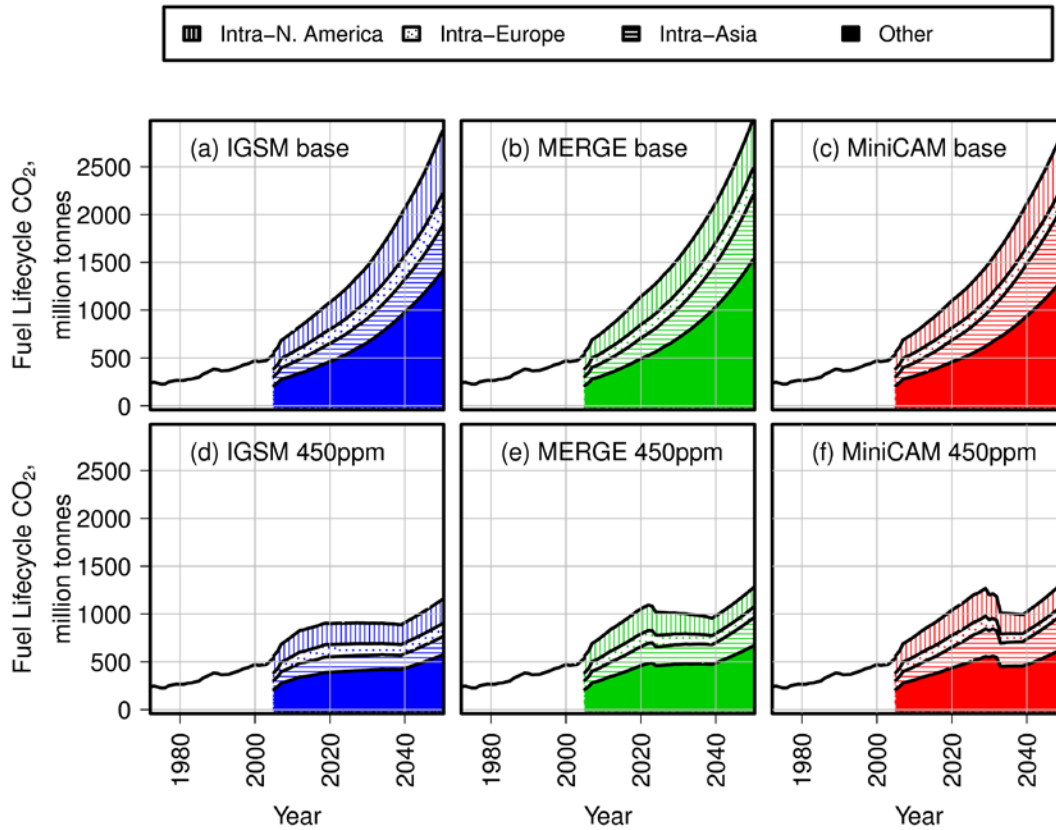


Figure 2. Fuel Lifecycle CO₂ by scenario and region from 2005, and past data for global emissions only for 1970-2005³⁶.

Comparing Figure 2(a), (b) and (c), it is clear that in the no-emissions trading case, under the assumptions and scenario set used here, global fuel lifecycle CO₂ emissions for aviation may grow by as much as 5 times 2005 levels. This result is consistent across all scenarios modelled. As discussed above, the distribution of this growth across world regions differs by scenario. Of the three scenario sets, the highest US and Western European RPK growth rates are seen in the IGSM scenarios. The highest Asian growth rates are seen in the MiniCAM scenarios. All scenarios show strong growth in intercontinental traffic, although the global distribution of that growth differs between scenarios. Comparing these results to those shown in Figure 2(d), (e), and (f), it is clear that, in these scenarios, emissions trading can significantly reduce global fuel lifecycle CO₂ emissions for aviation when a stringent emissions target is applied. However, even under this most stringent case, lifecycle CO₂ emissions may still at least double from 2005 levels by 2050. As described below, the reductions in lifecycle CO₂ in comparison to the cases without emissions trading result mainly from the adoption of fuel- and emission-saving technology, mainly biofuels and open rotor engine aircraft. Although there is a demand reduction effect (in part because of increased ticket prices and in part because GDP growth rates are lower in higher-stringency scenarios), it accounts for only around a third of the emissions reduction. The differences between the three scenarios in Figure 2(d), (e) and (f) are primarily because of different rates of technology and alternative fuel uptake in the different scenarios, in different

[§] We have assumed that fuel lifecycle CO₂ emissions from Jet A are on average 15% higher than direct emissions alone. These extra emissions arise from the fuel extraction, refining and distribution processes.

world regions. As in the no-emissions trading cases, the IGSM scenario predicts higher RPK growth rates in North America and Europe than MERGE and MiniCAM, while the MERGE and MiniCAM scenarios predict higher RPK growth rates in Asia than IGSM. By 2050, the majority of the emissions growth in all 450 ppm scenarios comes from long-haul intercontinental flights, with intra-US and intra-European emissions roughly stable.

Figure 3 shows the sensitivity of global RPK and fuel lifecycle CO₂ emissions for aviation to global emissions trading schemes with different stabilisation targets for atmospheric CO₂. Panels (a), (b) and (c) depict RPK flown in 2005, 2020, 2030, 2040 and 2050 by scenario set and stringency. Panels (d), (e) and (f) show the corresponding fuel lifecycle CO₂ emissions. RPK growth rates in the absence of carbon trading average around 3-4% per year for North America and Europe, and around 5-5.5% for Asia and other world regions. Growth rates in lifecycle emissions without carbon trading similarly average around 2.5-3% per year for North America, 2.2-3.2% per year for Europe, 3.6-4.7% for Asia and 4.2-4.5% for other routes. These results compare well to other forecasts (e.g. Refs. 3, 4, 37). The growth rates represent a combination of changes in passenger numbers, routes taken, aircraft size and aircraft technology. When the most stringent carbon trading (450 ppm) is applied, RPK growth rates per year are reduced by up to 0.4%, whereas lifecycle emissions growth rates may be significantly reduced, in some cases and regions (e.g. the MERGE 450ppm scenario for the US) almost to zero.

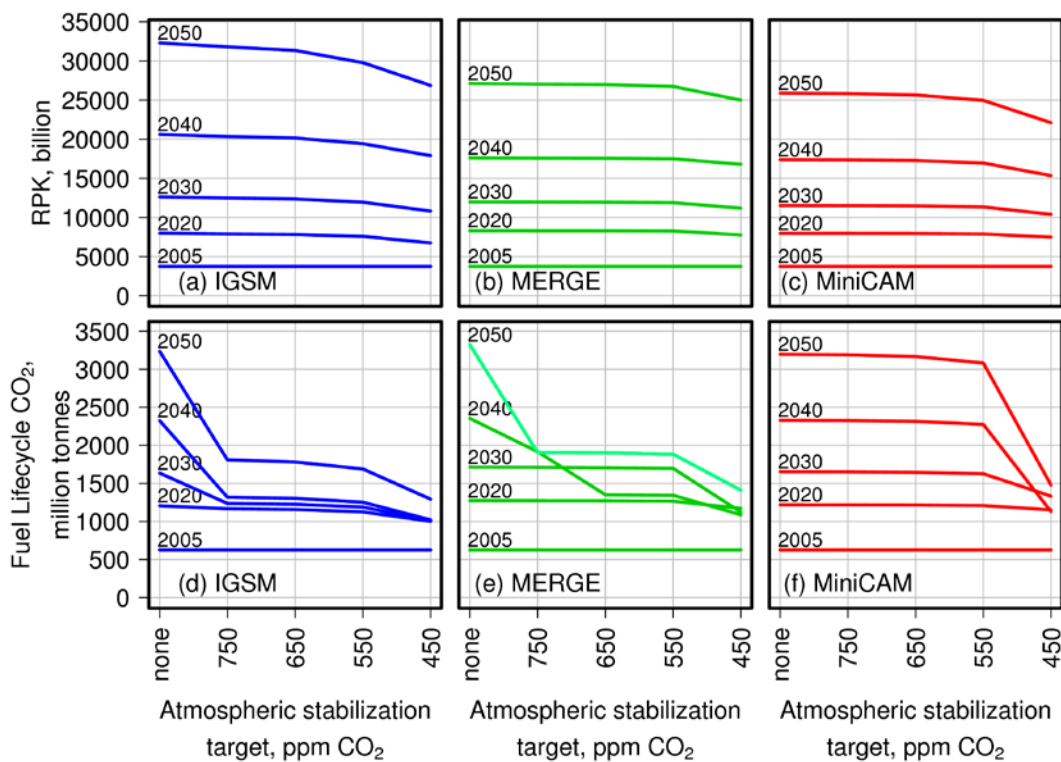


Figure 3. RPK and fuel lifecycle CO₂ dependence on stringency level, by scenario and year.

Comparison of Figure 3(a), (b) and (c) show that, while global CO₂ emissions do not differ significantly between the no-emissions trading scenarios, global RPK by 2050 is 20% lower under the MiniCAM no-emissions trading scenario than under the IGSM no-emissions trading scenario, with the MERGE results falling in between. As noted above, global RPK are not as significantly impacted by the atmospheric CO₂ stabilisation target as fuel lifecycle CO₂ emissions. By 2050 total global RPK may be between 7% and 19% lower under a 450ppm stabilisation target than with no emissions trading, while fuel lifecycle CO₂ emissions may be between 50% and 60% lower (Figure 3(d), (e) and (f)). This indicates that significant changes in aviation carbon intensity are taking place. The decline in CO₂ emissions with increasing stringency is the combined effect of technology change and reductions in demand. As discussed above, the decline in year-2050 demand with no emissions trading is comparatively small even in the 450 ppm case, although it is important. Under the IGSM scenario and the 450 ppm stringency level, this decline in demand contributes to a 20% reduction in the year-2050 CO₂ emissions relative to the no-emissions trading case. In comparison, technology induced reductions in CO₂ emissions per RPK account for the remaining 40% of the total 60% decline. This means that around one-third of the total emissions reduction from the most stringent carbon

trading scenarios arises from demand reductions, and the other two-thirds come from the adoption of new technologies in response to increased carbon costs.

The reduction in passenger demand arises from two sources. First, the emissions trading scenarios have lower GDP per capita growth rates. For most scenarios this effect is small; it has the greatest effect in the IGSM 450ppm scenario, which has a global year-2050 GDP which is 5.4% below the IGSM year-2050 no-emissions trading scenario. Secondly, ticket prices have increased. In the IGSM 550 ppm and 450ppm scenarios, the average ticket prices per RPK in 2050 are 5.2% and 9.5% higher than in the no-emissions trading scenario, respectively. Because of the associated demand reduction, we would expect aviation’s contribution to global GDP to be smaller in an emissions trading scenario than without emissions trading. The differences in aviation carbon intensity between the different scenarios are primarily due to different technological paths, as discussed below.

The results in Figure 3 also indicate that stringency levels of 550-750 ppm have a variable impact on fuel lifecycle CO₂ emissions, dependent on scenario. In contrast, a stringency level of 450 ppm has a significant impact in all scenarios, and emissions are roughly stable after 2020. This is because carbon prices are significantly higher in the 450 ppm target case than for 750-550 ppm: for example, in 2050 450 ppm-target carbon prices are over three times greater than 550ppm-target carbon prices, in all scenarios. For stringency levels between 550 ppm and 750 ppm, increases in fuel costs due to carbon trading are relatively small, and demand growth is reduced by 0-0.2% per year relative to the case with no emissions trading. However, fuel lifecycle emissions are still reduced significantly relative to the no-emissions trading case in scenarios which also have a high oil price. This is due to different adoption rates of biomass-derived synthetic jet fuel, as discussed below.

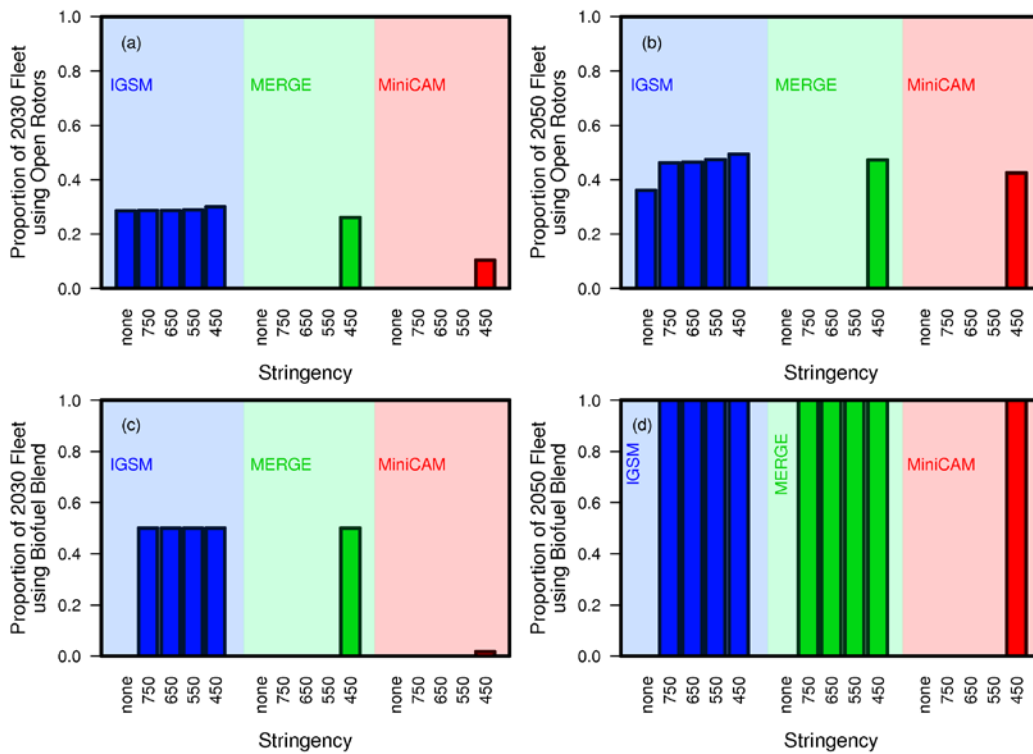


Figure 4. Technology adoption in 2030 and 2050 by scenario and stringency level.

In general, differences in carbon intensity between the modeled scenarios are mainly due to the different technologies in use in the global aircraft fleet. In Figure 4, we show the proportions of the year-2030 and year-2050 fleets using open rotor engines and biomass-derived synthetic jet fuel (in a 20% blend with Jet A). Although other mitigation measures are modelled, they are either assumed to be non-optional (hence having a similar effect in all scenarios, e.g. improved ATM), their total effect on global emissions is small (e.g. retrofitting winglets onto aircraft without them), or adoption rates are low (e.g. engine upgrade kits). Narrowbody open rotor engine aircraft are assumed to start entering the fleet in 2020; the full cost and benefit assumptions underlying the open rotor aircraft

model are given in Ref. 13. Aviation fuels from cellulosic biomass are also assumed to become available in 2020 in a 20% blend with Jet A. Uptake is limited by assumed increases in yearly production rates, as described in Section IIA. Panels (a) and (b) of Figure 4 show the proportion of the global aircraft fleet in 2030 and 2050 which use open rotor engines by scenario set and stringency level. Panels (c) and (d) show the corresponding comparison for the adoption of a 20% biofuel blend fuel.

Aircraft using open rotor engines have lower total fuel burn than aircraft using conventional jet engines for the same operations. Therefore the use of these aircraft is expected to reduce total fuel+carbon costs. In contrast, biofuels are assumed to be priced at a similar or higher level to Jet A. Therefore airlines using biofuels will not save on fuel costs, but may save on carbon costs. This means that open rotor engines are preferentially adopted in scenarios with high total costs, and biofuels in scenarios with particularly high carbon costs. It also means that in scenarios where the costs of Jet A and biomass-derived aviation fuels are similar in the absence of carbon trading, even a relatively low carbon price can result in increased adoption of biofuels.

As open rotor adoption is dependent on total costs, it is highest under the IGSM scenario, in which oil prices are high. On the other hand, biofuel adoption (Figure 4(c) and (d)) is greatest at higher stringency levels with greater carbon costs, and in scenarios where oil prices are comparable to biofuel prices in the absence of carbon trading. This is reflected in the proportions of the fleet using each technology by scenario. In the IGSM scenario set, open rotor engine aircraft are widely adopted for short- and medium-haul flights, even in low-stringency scenarios^{**}. In contrast, only the high-stringency MERGE and MiniCAM scenarios feature widespread adoption of open rotor technology. For the biofuel model used here, biofuels are adopted by aviation in two broad cases. The first is when a high-stringency CO₂ target is applied, leading to high carbon costs, as in the MiniCAM 450 ppm stringency case. As with previous studies (e.g., Ref. 13) we find that in theory biofuel blends are cost-effective for the whole fleet to adopt by 2050 in these cases. However, this depends on the construction of a suitable and sustainable infrastructure for producing and distributing aviation biofuels. The second situation in which biofuels are widely used is when oil and biofuel prices are comparable in the absence of emissions trading. In this case, a small carbon price is enough to promote widespread adoption of biofuels under the assumptions used in this paper. This occurs in the IGSM scenario with a 750 ppm target.

The differences in adoption rates of open rotors and biofuels in different scenarios are the primary reason that the scenarios differ from each other in terms of aviation carbon intensity. However, it is notable that, even with differing levels of demand and different growth rates by region, the overall behaviour of the models with increasing carbon stringency is relatively consistent. As aviation forms part of a carbon trading scheme in these scenarios, increases in aviation emissions will be met by decreases in emissions in other sectors, paid for by the emissions allowances purchased by airlines. This means that a 550 ppm scenario with high aviation CO₂ emissions has the same CO₂-only climate impact as one with low aviation CO₂ emissions. However, the modelled emissions trading scheme concentrates on CO₂ only and neglects the non-CO₂ climate effects of aviation, and noise and local air quality impacts. These impacts will typically be more severe in scenarios with high demand for aviation. Similarly, the economic impact of carbon trading on airlines, airports and airport regions will typically be more severe in higher-stringency scenarios with lower RPK growth.

IV. Conclusions

In this paper, we have presented the results of a scenario-based set of simulations looking at the global impact of a worldwide carbon trading scheme on aviation at different levels of stringency. Our simulations suggest that global passenger aviation related fuel lifecycle CO₂ emissions will continue to increase, under a variety of growth scenarios and under a range of economic policy cases, including a global emissions trading scheme with a stringent atmospheric CO₂ stabilization target of 450 ppm. This also suggests that aviation would be a net purchaser of emission allowances in such a scheme.

By 2050, aviation related CO₂ emissions may range from double the 2005 levels (under the most stringent atmospheric CO₂ stabilization target of 450 ppm) to five times the 2005 levels (with no emissions trading). In the highest stringency cases emissions are roughly stable after 2020. At lower atmospheric CO₂ stabilisation targets,

^{**} It should be noted that Figure 4 shows the proportion of the total fleet which adopt each measure. Because open rotor engines are assumed to be primarily applicable to short- and medium-haul narrowbody aircraft, the proportion of RPK flown by open rotor engine aircraft will be much lower. This is reflected in the emissions totals.

carbon trading has only a minimal effect on aviation RPK, but may have an appreciable effect on CO₂ emissions if the oil price is also high.

The decline in CO₂ emissions is the combined effect of technology change and reductions in demand growth. The decline in demand between no-carbon trading and high-stringency cases is comparatively small but important, contributing to as much as a 20% reduction in CO₂ emissions compared to the no-carbon trading case. In contrast, technology induced reductions in CO₂ emissions account for the remaining 40% of a total of up to 60% decline from the no-carbon trading case. Of the technology induced reductions modelled here, the largest contributions are from open rotor engines and biofuels. Different adoption rates for these technologies in different scenarios are also the greatest contributors to differences between the scenario results. Under the assumptions used here, open rotor adoption is primarily dependent on total costs, and so is highest in scenarios with high oil prices. Biofuel adoption is more dependent on carbon price, and so is greatest in high-stringency scenarios and where Jet A and biofuel prices are comparable in the absence of emissions trading.

The conclusions described are stable across all families of scenarios simulated, and apply to a wide range of potential future outcomes. The results suggest that both technology change and reduction in demand will be required to reduce global aviation's future contribution to CO₂ emissions significantly. However, in a functional carbon trading scheme the increase in aviation CO₂ will be offset by reductions in emissions in other sectors. Our simulations also suggest that global demand for aviation will continue to grow even in high-stringency scenarios.

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