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Network and Environmental Impacts of Passenger and Airline Response to Cost and Delay

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The Aviation Integrated Model is a policy assessment tool designed to simulate the operation and economic/environmental effects of local and world airline networks over the next 30-50 years within a modular framework. Feedback between demand, capacity, air traffic delays and policy measures is a key part of this model. For example, unconstrained model projections of US air transportation system growth with no passenger, airline or policy response included show average arrival delays of over two hours at major US airports in 2030, a condition that is unlikely to materialize. A more likely situation is that a combination of responses act to bring the air transport system to a new equilibrium at which higher fares, extra capacity or increased operational efficiency reduces the delays to a more acceptable level. Similarly, the application of policies designed to mitigate some of the environmental impacts of air transportation will also alter the system equilibrium state. In this paper we use the Aviation Integrated Model to systematically examine these feedback effects, concentrating specifically on the passenger response to increases in travel time, airfare, and policy responses to environmental concerns. We contrast the reference case in which the main feedback effect is passenger and airline response to air traffic delay with sample policy scenarios.

I. Introduction

The demand for air travel is widely projected to continue to grow at least over the next several decades. Whilst this growth carries societal and economic benefits, it also presents challenges both in terms of response to limited system capacity and environmental effects. An important task for policy makers is to strike an acceptable balance between these positive and negative aspects. The main negative externalities of aviation are noise, reduced air quality and global impacts on the climate, for example through emissions of greenhouse gases[1]. Efforts that impact mitigation in any one of these areas will affect the others, either in a positive or negative way (e.g. Refs. 2, 3). For example, some operational changes can reduce both noise and global climate impacts, whereas some technical modifications designed to reduce noise can result in increased global climate impacts (e.g. through added fuel burn due to increased weight). A number of policy options impact air travel demand through an increase in ticket price, either directly or via an increase in airline costs. It is these that we are interested in investigating in this paper.

In this study we use our systems model to examine the network usage and environmental effects of passenger and airline response to constrained aviation growth, including constraints from limited capacity and from policies aimed at mitigating environmental effects. A brief description of the parts of the AIM model relevant to this study is given in Section II. Section III presents results for case studies of the US and Indian domestic systems, and conclusions are drawn in Section IV.

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II. Modeling

The Aviation Integrated Model consists of seven interacting modules as shown in Fig. 1, each covering a different aspect of the air transportation and environment system. For this study, we use only the Aircraft Technology and Cost, Aircraft Movement, Airport Activity and Air Transport Demand modules. Further details of all modules are given in Ref. 4; however, since significant updates have been made, a brief description of the modules included in this study is given below.

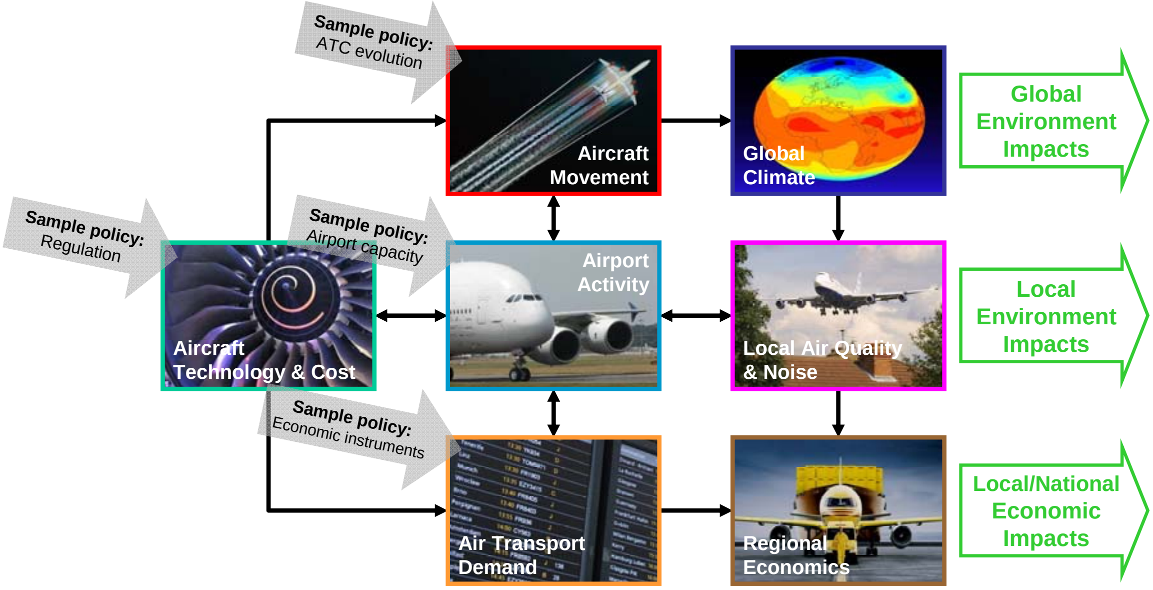

Figure 1: Aviation Integrated Modelling general architecture.

A. Aircraft Technology and Cost

The Aircraft Technology and Cost module simulates the emissions of a typical flight. The total emissions depend on flight frequency, aircraft weight, ground and airborne delays and lateral routing inefficiencies as well as on the aircraft/engine type, which are modeled through interactions with the Aircraft Movement Module discussed later. To obtain a sufficient representation of the spectrum of aircraft technologies operating within the US air traffic network, several classes of aircraft are considered covering different size and technology levels. For the work presented in this paper, only the current fleet is modelled and hence the technology division is made assuming an old (pre 1995) and a new (post 1995) technology category. To represent the 'old technology' category, data corresponding to the B737-300 was used to characterize aircraft with up to 189 passenger seats, while the B767-300ER and the B747-400 were used for aircraft with 190 to 300 and above 300 seats, respectively. For new technology, similar aircraft size groups are represented by the A319 (up to 189 seats), the A330-300 (between 190 and 300 seats) and the B777-300 (above 300 seats). For this study we assume that the introduction of new technology aircraft and retirement of old technology aircraft over the modeled period will be incremental and gradual. As the average lifetime for an individual jet aircraft is about thirty years[5], and successful technologies may remain available for purchase 15-20 years after their initial introduction[6], these aircraft types are likely to be representative of the future fleet throughout most of the period examined – from 2005 to 2030, and to 2050.

The fuel burn calculation below 3000 feet is based on the ICAO engine exhaust emission data[7] and the ICAO reference Landing and Take-Off (LTO) cycle[8], with the exception of taxi time, which is derived from estimated taxi-out times calculated by the Airport Activity Module described in Section II.C. The ICAO engine exhaust emissions data bank includes emission indices and fuel flow rates for a large number of aircraft engines. The data is provided for four engine-operating modes that are used for modeling the different phases of the LTO cycle. These phases (including engine idling while stationary on the ground, taxiing from the terminal area, taking off to 3000 ft, landing from 3000 ft and taxiing back to the terminal area) are therefore represented by a fixed thrust setting and the corresponding emission indices and fuel rates.

Above 3000 feet, the aircraft performance elements during climb, cruise, descent and airborne holding were modelled according to the EUROCONTROL Base of Aircraft Data (BADA)[9]. This is a simplified model based on an energy balance relating the rate of work done by the forces acting on the aircraft to the rate of increase in potential and kinetic energy. The database provides performance and operating procedure coefficients to solve the equation for different flight phases including climb, cruise, descent and airborne holding.

B. Air Transport Demand

The demand for true origin-ultimate destination passenger air trips is estimated by the Air Transportation Demand Module, using a simple one-equation gravity model with base year population, income, fare, travel time and air traffic delay data as the explanatory variables.

Population and income data are derived from individual country censuses and household income surveys (e.g. the US Census and American Community Survey[10]; the Indian census[11]). Fares are obtained from base year surveys and published fare lists (e.g. Ref. 12), with regressions of known fares with distance flown and region being used to estimate missing fare values. Future fare trends are modeled differently depending on the type of constraints on the air transport system. In constrained growth scenarios, future fares are assumed to change from base year values according to a competition model in which airlines compete with fare and flight frequency, as described by Ref. 13. This model allows average fares to be estimated from airline costs per passenger, flight frequencies offered by all airlines, and the passenger value of time. The model does not, however, capture some of the more complex elements of airline pricing, such as price discrimination (yield management). This model is also not valid for cities served by only one operator (monopolies) or for remote regions which have subsidized travel, but such cities tend to fall outside the city-set modeled in this paper (see section III). In the unconstrained growth scenarios, in which the cost of flight delay is not modeled, the competition model described by Ref. 13 was found to underpredict increases in fares and overpredict flight frequencies in comparison to those observed in the data - because of the model's inability to capture the more complex elements of airline competition introduced by price discrimination. Therefore for unconstrained runs we assume that fares follow past trends (see. e.g. Ref. 4). Future population and income trends are applied from the model scenario used (see section III).

C. Airport Activity

The Airport Activity Module forecasts global air traffic by flight segment as a function of the projected passenger air trips, and estimates the resulting ground delay through assigning the (limited) airport capacity. The proportion of the three different aircraft types used on each segment is estimated as a function of projected passenger demand, segment length, and traffic type (hub-hub, hub-spoke, or point-to-point) according to a multi-nomial logit regression on historical data. According to this regression, aircraft size increases with passenger demand, segment length, and on routes to or from hub airports. Flight frequencies are forecast by applying base year passenger load factors by segment (which are assumed to remain constant with time) to the passenger demand. These approaches are similar to those used in Refs. 14 and 15.

Ground delay is modeled as a function of airport capacity constraints using a rapid airport delay model, similar to that applied in Ref. 4, and described in detail in Ref. 16. In this model, flight delays, both on the ground and in airborne holding before landing, are estimated as a function of flight frequencies and airport capacity constraints, and are added to gate departure delays (due to mechanical failures and late arrivals), which are assumed to remain at current levels (assuming schedule padding increases to maintain schedule reliability). Delays due to airport capacity constraints are estimated using queuing theory, applying the cumulative diagram approach and classical steady state simplifications described by Ref. 17. Runway departure delays are distributed between the taxiway and the gate according to a taxi-out threshold calculated for each airport from historical delay data for airports for which it is available, and according to average taxi-out thresholds for airports for which historical data is not available. Similarly, delays due to destination airport capacity constraints are distributed between the air and ground according to an airborne holding threshold calculated for each airport from historical delay data or an average value, and above which delay is assumed to be propagated upstream to the departure gate.

Only existing airport capacities are modeled, as identified from the ASPM database,[18] the IATA global airport dataset,[19] and the AEDT airport database[20]. Where airport capacities are not available, airports are assumed not to be constrained by airport capacity, and flight delays are modeled as a function of gate departure delays only. This is a reasonable assumption as data is available for the majority of airports for which significant future flight delays are likely. Flight delays resulting from airport capacity constraints impose extra costs on airlines because of increased fuel burn and other per-hour operating costs. These extra costs increase fares as modeled by the airline competition model described in Section II.B above. The costs associated with flight delays are modeled according to estimated fuel burn rates from the Aircraft Technology and Cost Module (described in Section II.A) and published airline cost inventories (e.g. Ref. 12) where available. When such inventories are not available, costs are modeled according to

US airline cost inventories[12], but adjusted according to regional differences in international airline operating economics[21].

D. Aircraft Movement

The air traffic by flight segment generated by the Airport Activity Module is the main input to the Aircraft Movement Module, which works in conjunction with the Aircraft Technology and Cost Module to identify the location of emissions released from aircraft in flight accounting for inefficiencies introduced by the air traffic control system. These inefficiencies take the form of extra distance flown (and hence extra fuel burnt) beyond the shortest ground track (i.e. great circle) distance for any given airport pair in the schedule. The extra distances are estimated for different phases of flight and by world region (in order to account for differences in air traffic control characteristics) by using archived flight track data[22]. For the US portions of this study, Enhanced Traffic Management System (ETMS) data from an "average" day in 2005 were used to identify average extra distance flown in the origin and destination terminal areas (where emissions primarily affect local and regional environmental impacts) and extra distance flown as a function of route length in the enroute phase (where emissions primarily affect the global climate). The additional emissions resulting from these factors for the schedule in this case study were accounted for in the results that are presented later.

The modules described above are run as part of a feedback loop as shown in Fig. 1, with output produced only when equilibrium between demand, delay and cost has been obtained

III. Sample Case Studies

The current version of AIM uses a global set of 700 cities, containing 1,018 airports. Air traffic between these cities accounts for around 95% of world scheduled available seat-kilometers[23]. Airports are assumed to belong to the same city if they are less than 62 km apart[**], unless they are on a small island or have reduced ground accessibility for some other reason. For the purposes of this paper, we are interested in the effect that system constraints have on a developed world region, and any differences from this displayed by a developing world region. We therefore choose the US domestic aviation system (178 cities) and include for comparison the Indian domestic aviation system. Currently, many Indian cities with airports fall outside the AIM set of the 700 busiest cities for air traffic as defined above[††]. In order to more accurately study network effects in India, we expand the Indian set of cities to 88, which covers all Indian cities with current scheduled passenger services. We use a base year of 2005.

1. Reference Scenario

In the reference scenario, no environmental policies are introduced and costs remain at present-day levels, with the exception of fuel costs. We use the growth trends in population, income, and oil price from the MIT Integrated Systems Model (IGSM) reference run, as conducted for the US Climate Change Science Program[34]. According to that scenario, the US population grows from 283 million in 2000 to 387 million in 2050. During the same time period, GDP per capita rises from $39,000 to $115,000 and the oil price from $32.4/bbl to $107.1/bbl (all values in year 2005 US dollars). We scale the increase in population and GDP/capita uniformly across the 178 US cities.

The associated growth in air transportation will likely be constrained by airport capacity. Whilst some capacity increase is likely in the US system before 2050, it is uncertain how much will be provided. The FAA's Capacity Benchmarking Report[24] details only capacity improvements to be applied before 2013. The NextGen project plans to provide airspace capacity at a level to accommodate three times the 2004 demand in the US aviation system by 2025[25]. However, runway capacity, which is the currently the main capacity bottleneck for US domestic aviation, is typically difficult to increase due to space limitations and regulations. We therefore run two different reference cases for the US domestic aviation market; one in which no capacity increases are applied (constrained scenario) and one in which it is assumed that capacity will be added as required to meet passenger demand, maintaining present-day levels of delay (unconstrained scenario). System RPKM, delays and CO_2 emissions for these cases are shown in Fig. 2. Also shown are actual RPKM values for this airport set from BTS T100 data[12], and growth projections for domestic US aviation from the Airbus Global Market Forecast[26] and for North American aviation from the Boeing

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[**] This value was found to give the most satisfactory result for a test selection of world multi-airport systems.

[††] However, given that the growth of air traffic in India is more rapid than the world average, it is likely that many of these cities would be on a list of the 700 busiest if it were compiled for 2030.

Current Market Outlook[27]. The Boeing and Airbus forecasts apply to different airport sets, thus in order to display absolute values in Fig. 2 we have scaled base year values so that they match model values for the airport set we are using and then applied Boeing and Airbus growth rates. The estimated NO_x emissions by airport are presented in Fig. 3. In the constrained scenario, RPKM initially experiences a slightly higher growth than in the unconstrained scenario due to the different cost formulations modeled (Section II). However, subsequent growth in RPKM is much more rapid in the unconstrained scenario, translating into higher levels of emissions and delay. In particular, unconstrained growth produces large local emission increases at the major hub airports such as Chicago O'Hare (KORD) and Atlanta (KATL). In the constrained model, whilst emissions are still highest at these airports, the relative increase in emissions from year 2005 levels is much less.

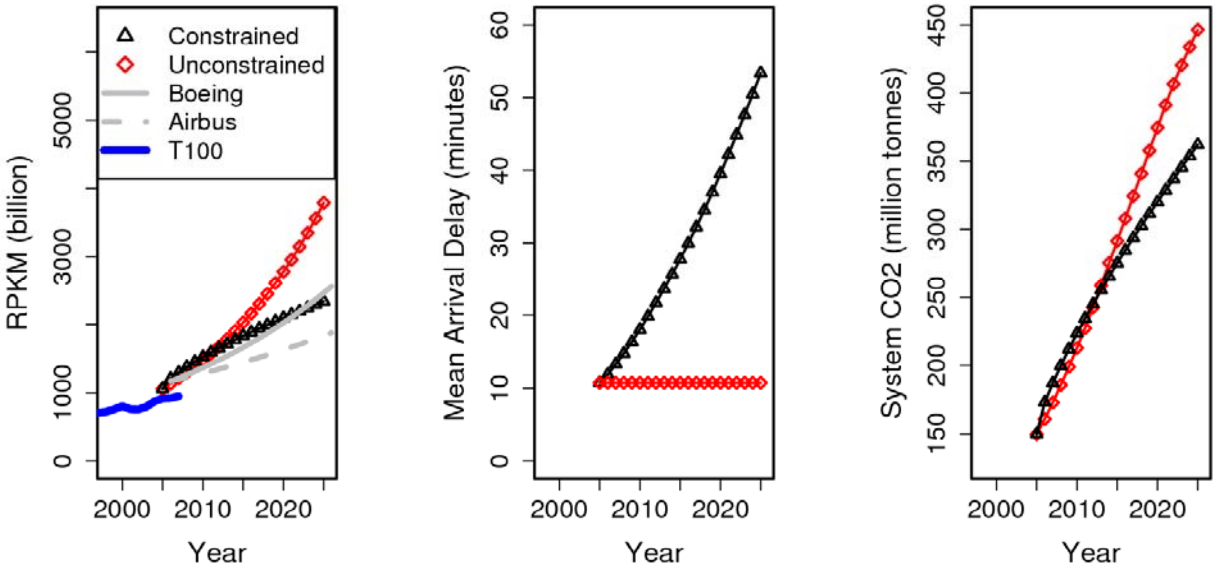

Figure 2: System RPKM, delays and emissions for US domestic flights between 2005 and 2025 for the reference scenario.

We stop the unconstrained scenario in 2025, as by this point very large runway capacity increases are already required which would in reality entail significant change from present-day network usage. For example, if enough capacity is provided for total US domestic RPKM growth to follow the unconstrained model trajectory, but it is not possible to provide extra capacity at Atlanta, the yearly number of passengers on cancelled flights at Atlanta exceeds the number of seats available at the airport to carry those passengers on later flights by 2015. A similar situation occurs at St. Louis (KSTL) in 2019 and Chicago O'Hare in 2020. For the constrained scenario, the only airport which reaches this state is Atlanta, in 2042. (Future versions of the Airport Activity Module will simulate short and long-term airline response to capacity constraints[28]).

In Fig. 4 we show average arrival delays in the constrained scenario and capacity increases required to accommodate demand at present-day levels of delay in the unconstrained scenario in 2025. A high arrival delay at an airport in the constrained scenario does not necessarily indicate a need for greater capacity, since the delay may be incurred entirely at the departure airport. For example, the high average arrival delays at airports receiving flights from Chicago O'Hare are partially a function of very high delays at Chicago O'Hare. If these delays are to be avoided (and in the absence of radical changes to operational procedures that reduce separation or runway occupancy requirements), we find that Chicago O'Hare requires an increase in runway capacity of more than 2.5 times by 2025 from 187 to 477 aircraft per hour – an increase roughly in line with the NextGen targets. In reality, such capacity increases are unlikely to occur at major airports, which are often space-constrained and unable to add new runways. It is more likely that nearby minor airports will expand to meet some of this demand, and that some hub operations will shift to less-congested airports.

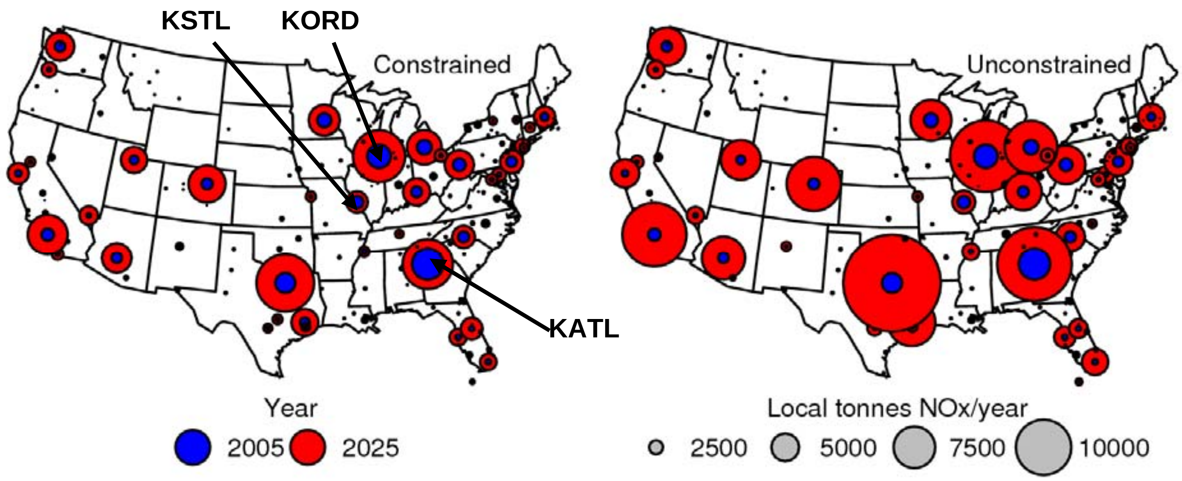

Figure 3: Local NOx emissions (excluding holding) by airport for the continental US in the constrained and unconstrained CCSP base scenarios.

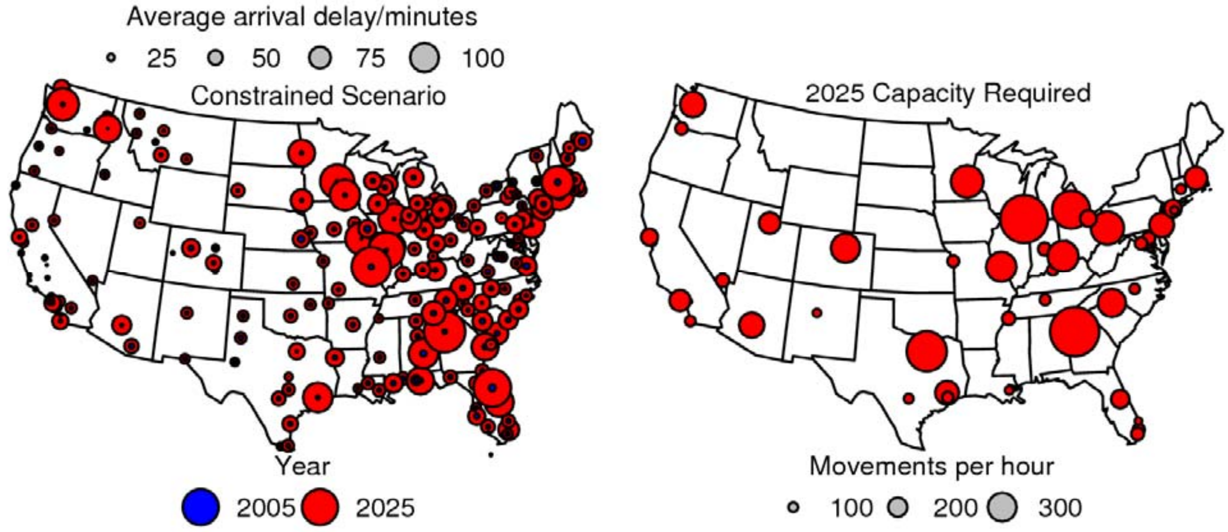

Figure 4: Average arrival delays by airport for capacity-constrained growth, and the capacity required at major US airports to accommodate that growth in 2025 whilst maintaining present-day levels of delay.

As a contrasting example to the US, we consider the Indian domestic transport system. Although the Indian system is less mature at present, it is currently experiencing rapid growth. Whilst environmental constraints may be important in future, it is likely that capacity constraints will play a significant role much before this. Currently, the route closest to capacity in this network is Delhi-Mumbai, which already has significant delays. Since these two airports are the country's biggest hubs, they are also a key link for flows on the entire network.

Past growth rates are compared with model runs and recent Airbus and Boeing forecasts in Fig. 5. As for Fig. 2, we scale growth-rate only forecasts to match model runs from their base year. Although the Airbus and Boeing forecasts are for different airport sets, the difference between their growth rates highlights the uncertainties in forecasting demand for flights in developing economies. As the CCSP base scenario as used for the US model has GDP growth rates for India which are much lower than current values, we use instead the SRES B2 scenario[5], which was used for Aviation Integrated Model runs in Ref. 4. This scenario has a current GDP per capita growth rate for India of 6.8% per year. For constrained model runs we apply capacity limits only at Mumbai and Delhi, due to the limited availability of capacity figures for other, less-constrained airports. It is apparent that current reported growth rates are higher than nearly all forecasts. Constrained model runs suggest that the air transport system is already under high stress, with capacity limits constraining growth at Mumbai and Delhi. However, growth is still able to occur at other airports. As for the US case, the different cost model formulation in the constrained model initially produces slightly higher growth than in the unconstrained case. Current growth rates in RPKM as reported by DGCA India[29] are higher than both the constrained and unconstrained scenarios.

Whilst domestic US aviation is currently growing at rates similar to constrained model runs, the domestic Indian aviation system is growing much more rapidly. This suggests that an environment in which new capacity can be added rapidly is having a real and tangible effect, and that current capacity limits as quoted by the AEDT airport database[20] for Mumbai and Delhi airports may underestimate the true capacity. However, future developments such as Mumbai's proposed second airport are still highly important if the current rapid growth across the Indian aviation network is to be sustainable over a longer term, as may be a shift to alternative hub airports. Our results also indicate that future modeling of the Indian system and its response to policy needs to take extensive capacity growth and significant network change into account.

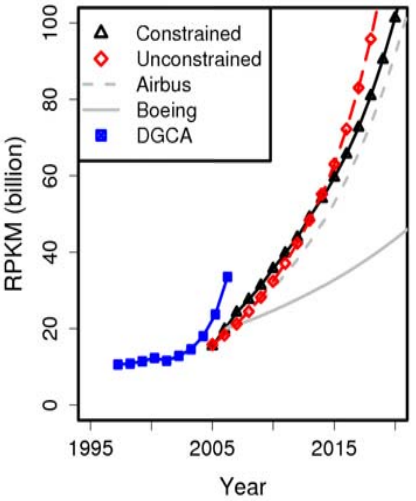

Figure 5: Past and projected RPKM growth for the Indian domestic aviation system. The Boeing growth forecast is for the Asia-Pacific region excluding China.

2. Sensitivity to Cost Increases

Increases in direct operating cost beyond those expected in the reference case may come from several sources[30]. Among those, perhaps the most likely is fuel costs being greater than expected (potentially from high oil prices or environmental taxes designed to reduce CO_2 emissions). Fuel costs scale roughly with distance flown, so any increases will affect long-haul flights more strongly than short-haul ones. Another possibility is that taxes may be applied per-takeoff in an attempt to reduce noise or local area emissions, or that landing charges at individual airports may increase to fund infrastructure improvements, as has been suggested for London Heathrow[31]. In this case the cost increase scales with number of flights. Short-haul journeys will therefore be affected more than long-haul ones. In both cases capacity may remain the major limiting factor on growth if cost increases from other sources are small. With the exception of taxes applied directly to ticket price at the point of sale, airlines also have the choice of how much of an increase in costs to pass on to passengers and in what manner to apply it.

In order to generalize the air transport system sensitivity to different types of cost increase and its interaction with delay, we model its response over a range of input values for 2005 (current delays) and 2025 (constrained scenario with high delays). We assume that cost increases are passed on fully and proportionately (e.g. a per-km cost increase translates to a per-km ticket price increase)[‡‡]. Three situations are considered: increasing cost which scales with distance flown (per aircraft-km); increasing cost which scales with the number of origin-destination passengers (per passenger); and increasing cost which scales with the number of enplanements (per segment). The resulting CO_2, local NO_x emissions below 3000 feet, air traffic delay and RPKM response are shown in Figure 6. Ticket price increases are indicated by different colors, ranging from red (zero cost increase) to blue (maximum cost increase). Identical colors across the three pricing strategies would lead to the same total tax burden for a given year. The maximum cost increase in 2005 is $34 per passenger, $22 per segment and 1.8 cents per aircraft-km. For 2025 these values are $12 per passenger, $8 per segment, and 7 cents per aircraft-km (all values in year 2005 US dollars).

To measure the relative change in NO_x emissions across the network, we set a threshold value for NO_x defined as the level of emissions which is exceeded by approximately 10% of airports in the no cost increase case. The number of airports which have emissions above this level after cost increases have been applied is then plotted.

Some effects are common to all types of cost increase. As expected, RPKM demand reduces with rising charges in all cases, and this translates into decreases in air traffic delay and emissions. However, the imposition of any form of price increase raises the proportion of short-haul flights flown. This arises from the lower price-sensitivity of business travelers, who make up a larger proportion of passengers on short-haul flights. Any shift to short-haul also affects the location of air traffic delay and emission hotspots. As was shown in Fig. 3, the reference scenario leads to high emissions at mid-continental hub airports which arise mainly from long-haul flights. If ticket

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[‡‡] This is a simplification, as the absorption of the cost-increase by passengers and airlines depends upon the slope of the supply and demand curve relative to another; we will deal with these effects in more detail in future versions of AIM.

prices increase, the relative emissions burden becomes greater at East Coast airports which serve more short-haul flights, and lower at mid-continental hubs. This is particularly the case if ticket prices increase in a per-km manner.

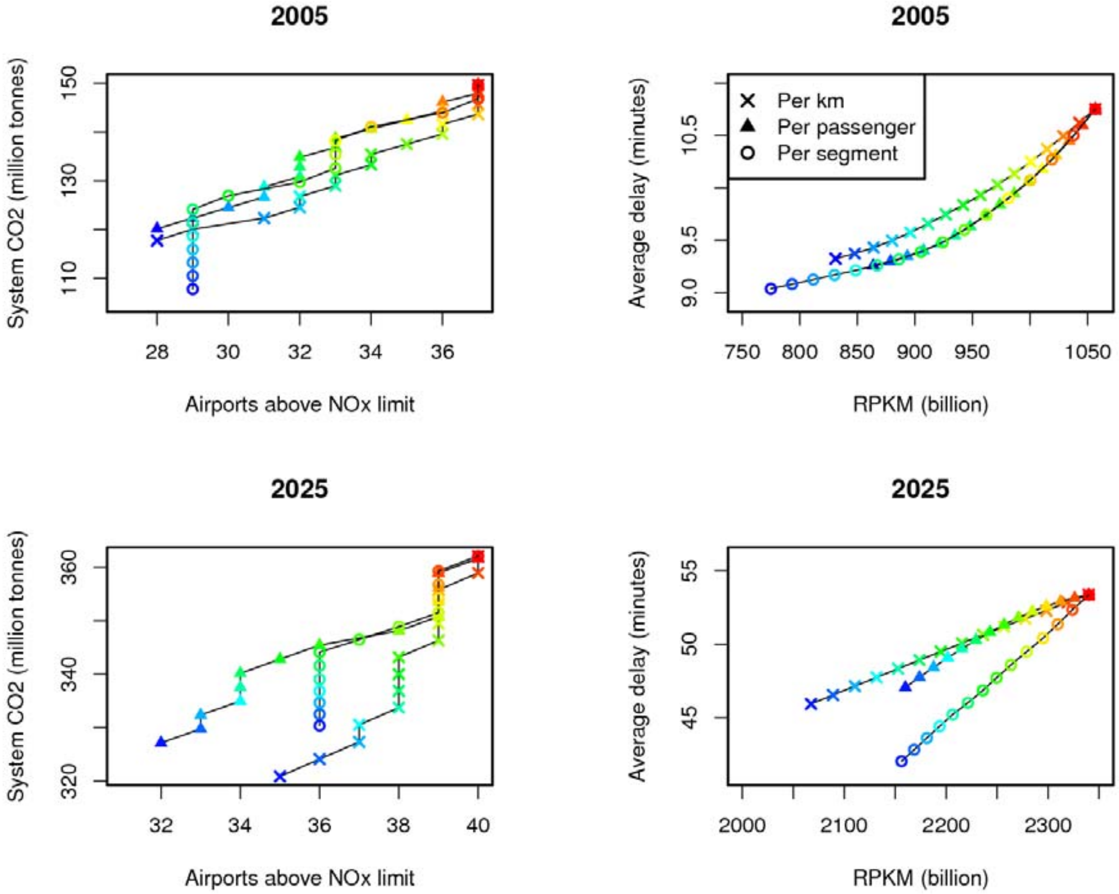

Figure 6: Sensitivity of local and airborne emissions, demand and air traffic delay to differently-formulated increases in ticket price. Points with the same color have the same total system tax burden, with red being zero. Ticket price increases at the blue (maximum) end for 2005 are 34 dollars per passenger, 22 dollars per segment and 1.8 cents per km. For 2025 these values are 12 and 8 dollars and seven cents (all values in year 2005 US dollars).

Differences between the cost formulations behave broadly as expected. For example, per aircraft-km ticket price increases typically lead to lower CO_2 emissions but greater local NO_x emissions and delays relative to per-passenger or per-segment increases for a given total tax burden. This is a consequence of the total number of enplanements being larger in the per-km case, with shorter average distance flown. Per-segment cost increases typically produce a better result in terms of reducing delays, as they discourage multi-segment journeys with multiple takeoffs and landings.

As shown in Fig. 6, the constrained 2025 system is more sensitive to cost changes than the 2005 system. This arises in part from the high delays in the reference case. A small decrease in demand can produce a large decrease in air traffic delay at an airport which is close to its capacity level. As all airborne and a portion of ground delays are incurred with the engine running, this also affects emissions. As more airports are at or above capacity in 2025 than 2005, reductions in delays are greater over the whole range of ticket price increases. However, the effect of these levels of price increase is still far less than that of overall demand growth.

3. Carbon Trading

Whilst the analysis above gives an idea of how the air transport system responds in a generalized fashion, any future tax imposed on aviation will probably be linked to the actual costs of reducing environmental impacts. We take as a policy example the addition of aviation to a carbon trading scheme. Aviation has typically been excluded from carbon trading initiatives. However, the European Union has recently proposed including all flights taking off or landing in Europe[32] in the EU Emissions Trading Scheme (ETS). As the ETS carbon price is currently small, it is unclear as to whether this will have any effect on demand or emissions in the short term[33].

To obtain internally consistent projections of carbon taxes with the goal of achieving a specific atmospheric CO_2 concentration target, we use again the IGSM carbon trading scenarios for the US Climate Change Science program[34]. These assume a global trading scheme is introduced in 2012, aimed at stabilizing atmospheric CO_2 at a given value between 450 and 750 ppmv. For consistency, we use also the population, GDP, and oil price projections which were used to obtain these carbon prices. However, the decrease in oil price predicted in these scenarios leads to an overall change in ticket price which can be very small[§§]. Therefore we run all carbon trading scenarios using the reference scenario oil price development. This assumes that OPEC would be able to prevent the reference oil price from declining because of reduced consumer demand. (Consumers and airlines would have to pay the price of refined oil plus the carbon tax, which leads to a decline in the demand for oil products and thus, potentially, in a declining fuel price). We assume that only the carbon emissions of aviation are covered by the scheme, and that there is no multiplier applied to account for the effects of other emissions.

Figure 7 shows RPKM, air traffic delay and aviation system CO_2 emissions for the CCSP base and carbon trading scenarios. It is apparent that carbon trading has only a small effect on demand or emissions before 2050. This arises from a number of effects. Firstly, although the total cost burden may be significant, it is divided between a large number of passengers. In the most stringent scenario (stabilization at 450 ppmv) the 2050 carbon price equates to $259 (year 2005 dollars) per tonne of CO_2. However, on average per passenger this equates to only $47. Secondly, the competition model used indicates that airlines are likely to attempt to absorb some portion of the costs. We find that 2050 ticket prices are up to $60 greater in the 450 ppmv scenario than in the reference scenario. However this increase does not occur on all routes, with many having much smaller ticket price increases. Demand reduction is therefore still relatively small. This suggests that capacity limitations are still a much stronger constraint on demand and global emissions growth than carbon charging.

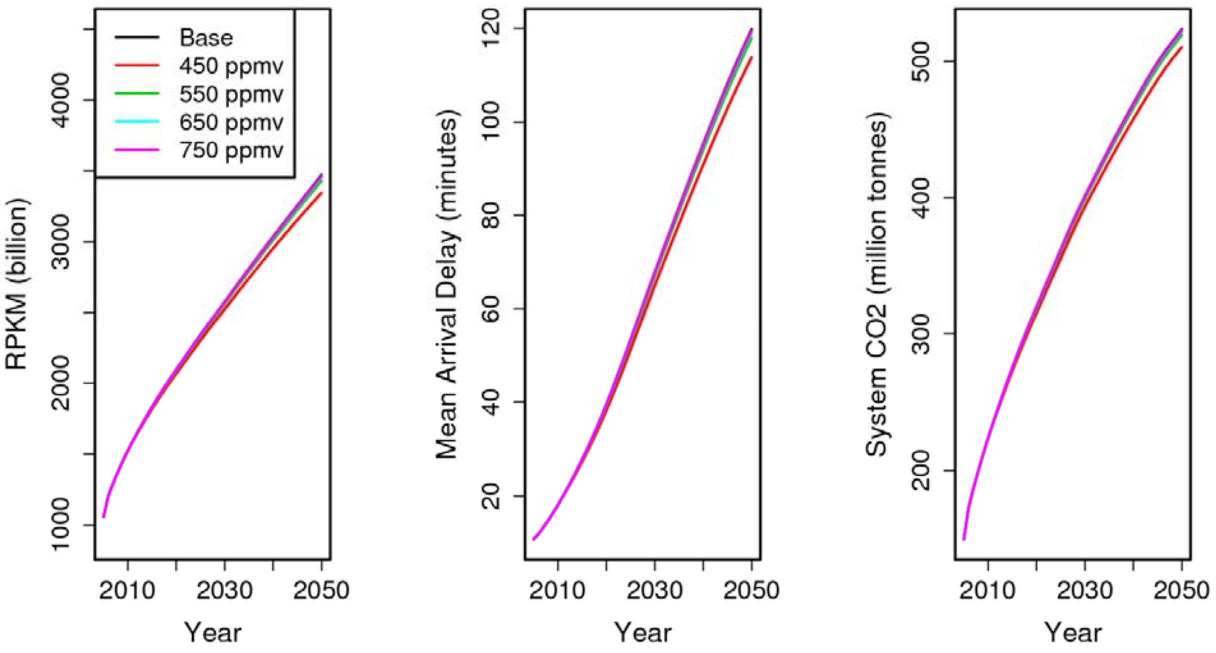

Figure 7: Effect of Carbon Trading scenarios on the RPKM, air traffic delay and emissions in the US domestic system (constrained models) between 2005 and 2050.

[§§] Year 2050 oil producer prices in the most stringent carbon trading scenario (stabilization at 450 ppmv) are roughly at year 2000 levels in real terms, whereas in the base scenario oil producer prices in 2050 are three times year 2000 levels. Therefore if we apply the scenario oil price most of the increase in ticket price from carbon charging is offset by a corresponding decrease in ticket price from lower fuel costs. The resulting differences in 2050 ticket prices are typically only $2-3. This is on the low end of the ticket price increases examined in section III.2 above, and has only a tiny effect on total emissions.

IV. Summary

Our analysis of the US domestic aviation system suggests that the strongest challenge to long-term growth is limited runway capacity. Model runs of unconstrained demand growth require significant capacity increases at major US airports which are probably only achievable with network change, new hubs and the expansion of currently minor airports. If growth is constrained by current capacity, predicted system delays and associated costs become large enough to have an appreciable dampening effect on air travel demand. In contrast, economy-wide policies aimed at manipulating aviation demand and hence emissions by cost increases may have only a small effect on demand. In particular, even relatively stringent carbon trading scenarios have minimal effect on aviation emissions before 2050. However, in other regions of the world demand growth is being accompanied by rapid capacity expansion. Our preliminary models of Indian domestic aviation suggest that current system growth is slightly more rapid than unconstrained models, possibly because of the different regulatory environment with regard to adding capacity. If these trends are maintained, this suggests that South and East Asian aviation may experience more rapid growth than expected relative to US aviation.

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