

Air Transport Within An Emissions Trading Regime: A Network-based Analysis of the United States and India

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ABSTRACT

Vital to economic development, air transport is one of the fastest growing sources of greenhouse gas emissions. In this paper, the Aviation Integrated Model, currently under development at the University of Cambridge, is used to assess the impact of an open emissions trading scheme on the US and Indian air transport systems. The analysis is based on three internally consistent projections of per capita GDP, population, oil price, and carbon price until 2050. In each projection three different stabilization targets of atmospheric CO₂ concentration are examined, ranging from 450 ppm to 750 ppm. Significant reductions in air travel demand, fuel use, CO₂ emissions and required airport capacity growth before 2050 were only observed relative to a reference case in the most stringent scenario of stabilizing the atmospheric CO₂ concentration, i.e. at 450 ppm – an extremely challenging task. The air transport system response was found to increase if non-CO₂ emissions from aviation were considered in the trading scheme. This study also suggests that any given stringency level will have differing effects on short- and long-haul traffic. A comparison between the domestic aviation system impacts in the US and India suggests a generally smaller response of the Indian air traffic system to a given CO₂ emissions trading scheme due to lower price elasticities and average trip distance.

INTRODUCTION

The demand for air travel is widely projected to continue its strong historical growth of about 5% per year in worldwide revenue passenger and freight ton kilometers (RPK/RTK) over the next 20-40 years (e.g. 1, 2, 3), with some regions projected to grow much faster (e.g. India and China). While this growth carries a range of societal and economic benefits, it also creates challenges. One of the most important of these is the growing environmental impact of this sector, both on a local (e.g., noise, air quality) and global scale (e.g., climate change). The mitigation of these impacts is often proposed to occur through policy mechanisms. This paper examines the effects of one such policy mechanism: a global Emissions Trading Scheme (ETS). This type of market-based policy mechanism has gained increasing attention since the European Union (EU) has legislated that all flights taking off or landing in Europe will be included in the EU ETS from 2012 (4). An integrated aviation/environment assessment tool, currently under development in the Aviation Integrated Modelling (AIM) project, is used to simulate the impacts of a global ETS policy on passenger aircraft fuel use, greenhouse gas (GHG) emissions, airport capacity requirements, and other aviation system characteristics through 2050 in the United States and India. These two regions were selected because they have different degrees of economic development, travel demand characteristics and air transport system maturity and hence different likely responses to the policy. The components of the AIM model relevant to this study are described in the next section. The results from its application to the US and Indian systems are discussed and conclusions drawn thereafter.

THE AVIATION INTEGRATED MODEL

The Aviation Integrated Model consists of seven interacting modules as shown in Figure 1, each covering a different component of the air transport and environment system. The chosen architecture permits important feedback and data flows between the key system elements to be captured and provides natural input sites for policy measures to be imposed upon the system as shown. A detailed description of all the modules and their interactions is given in (5). The primary modules relevant to this study are the Aircraft Technology & Cost, Air Transport Demand, Airport Activity and Aircraft Movement modules. The set-up for these modules in this study is briefly summarized in the next sections.

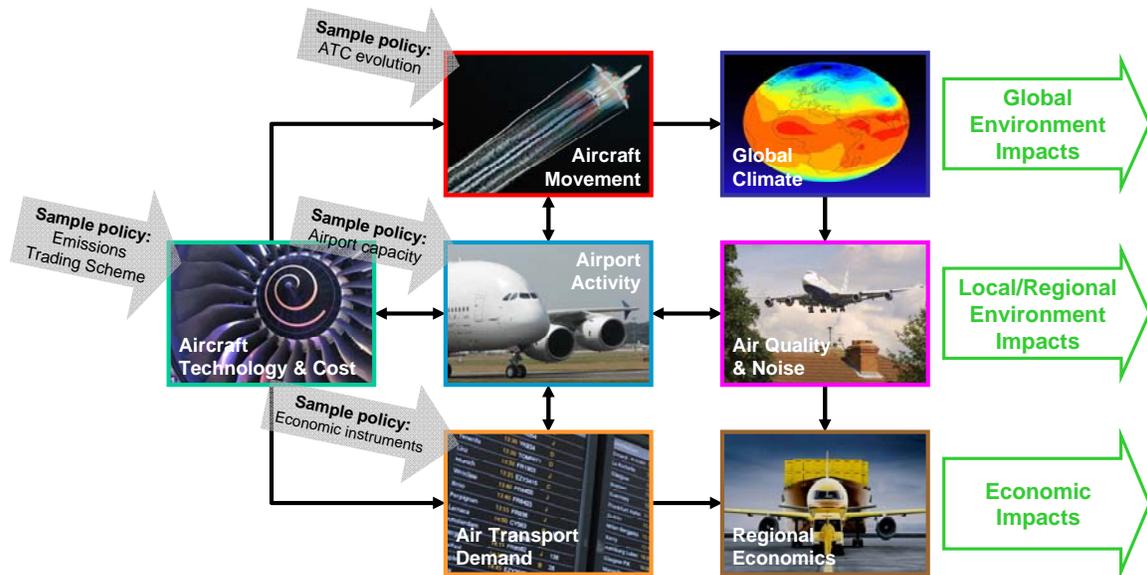


FIGURE 1 University of Cambridge Aviation Integrated Model.

Aircraft Technology & Cost Module

The Aircraft Technology & Cost Module simulates fuel burn, emissions and operating costs as a function of stage length for airframe and engine technology levels likely to have an effect within the forecast horizon. In order to obtain a more realistic representation of the spectrum of commercial aircraft technologies operating within the world's air transport network, three size classes (small with up to 189 seats, medium with 190 to 299 seats and large with 300 or more seats) and two technology classes (pre-1995 and post-1995) were considered. Performance and emissions data for the Boeing 737-300, 767-300ER and 747-400 were used for the pre-1995 size classes respectively, and Airbus A319, A330-300 and Boeing 777-300 for the post-1995 types. The fuel burn and emissions calculations for these aircraft types below 3,000 feet were based on the ICAO engine exhaust emission data (6) and the ICAO reference Landing and Take-Off (LTO) cycle (7). Taxi times account for estimated taxi-out delays, calculated by the Airport Activity Module described below. Above 3,000 feet, the performance during climb, cruise, descent, and airborne holding were modeled according to the parameters for the representative aircraft types from the Eurocontrol Base of Aircraft Data (BADA) (8). The introduction characteristics of new technology aircraft and retirement of old technology aircraft over the modeled period was considered to be similar to past fleet turnover characteristics determined from the OAG Back Aviation worldwide fleet database. Given the average lifetime

for an individual jet aircraft is about thirty years, and successful technologies may remain available for purchase 15-20 years after their initial introduction, aircraft introduced over the next decade are likely to be representative of the future fleet throughout most of the period examined from 2005 to 2050, and hence no radically new technologies (e.g. blended wing body aircraft) were considered.

The rate of technology development and improvements in fuel burn for future aircraft models is likely to be driven by future changes in fuel costs, including those from carbon trading. For this study it is assumed that fuel burn for the best available *new* aircraft technology improves by 1%, 1.5% or 2% per year respectively for scenarios where the 2030 oil price plus associated carbon trading costs is below \$100/bbl, between \$100/bbl and \$150/bbl or over \$150/bbl in year 2005 dollars. These improvement rates represent low, medium and high values with respect to historical trends.

More information on the Aircraft Technology and Cost Module can be found in (5).

Air Transport Demand Module

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

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

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

Metropolitan area population and income data were derived from individual country censuses and household income surveys (9, 10, 11). Fares were obtained from base year surveys and published fare lists (12). For the US, the 2005 base year true origin-ultimate destination passenger air trips data, used to estimate the coefficients in Equation 1, was also derived from (12). For India, such data was estimated with a model equating segmented trip data (13, 14) to the product of an assignment matrix and the true origin-ultimate destination passenger air trips (to be described in a subsequent paper).

The future demand for air trips was estimated using forecasts of the key explanatory variables. Among those, future fare trends depend on the change in operating costs (most notably the oil price) and market economics. For simplicity and transparency perfect competition is assumed between airlines on all routes. This means that fares between true origin-ultimate destination city pairs equal the marginal costs of carrying passengers between the respective cities, accounting for flights serving both direct and connecting itineraries.

In Equation 1, the cost variable includes the cost of journey duration via the value of a passenger's time. It is thus possible to include the demand-reducing effect of increased journey time as well as that of increased fares. However, as cost elasticities are typically quoted using response to airfares rather than generalized costs, Table 1 gives the parameter estimates, standard

errors, and adjusted R^2 for the US and Indian air transport systems using Equation 1 with fare substituted for generalized cost.

All parameters in Table 1 are significant at the 95% level and the R^2 obtained ranges from 0.54 to 0.76, depending upon the aircraft stage length category and region. The airfare elasticities (τ) are well within the range of that identified by literature studies (15, 16), while the income and population elasticities (2α and 2γ) for the US are similar to those estimated by (17). Parameter values and significance levels remain similar in the generalized cost case.

More information on the Air Transport Demand Module can be found in (5).

TABLE 1 Elasticity estimates, standard errors (in parentheses) and adjusted R^2 for the US and Indian air transport system.

	2α	2γ	δ	ε	τ	φ	R^2
US							
Short haul (<500 miles)	0.881 (0.041)	0.517 (0.063)	0.488 (0.054)	-0.720 (0.066)	-1.38 (0.060)	1.36 (0.266)	0.692
Medium haul (500-1000 miles)	0.939 (0.027)	0.609 (0.049)	0.418 (0.047)	-0.916 (0.035)	-1.66 (0.069)	1.68 (0.192)	0.758
Long Haul (> 1000 miles)	0.810 (0.022)	1.11 (0.046)	0.373 (0.102)	-0.764 (0.030)	-2.27 (0.072)	0.860 (0.058)	0.569
India	1.02 (0.202)	1.19 (0.243)	1.06 (0.518)	-1.91 (0.619)	-1.28 (0.365)	— ^a	0.543

^a not applicable

Airport Activity Module

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

The flight routing network was assumed to remain unchanged from the base year, with the proportion of the three different aircraft types used on the required flight segments estimated as a function of projected passenger demand, segment length and network type (hub-hub, hub-spoke, or point-to-point) according to a multi-nomial logit regression on historical data. According to this regression, aircraft size increases with passenger demand, segment length and on routes to or from hub airports. Flight frequencies were forecast by applying base year passenger load factors by segment (which were assumed to remain constant with time) to passenger demand estimated by the air transport demand module. These approaches are similar to those used in (18).

US airport capacities were based on the declared capacities for each airport within the modeled network from the ASPM database (19). Consistent capacity data is not widely available for the Indian region, and hence airport capacities for this region were based on a model adapted from (20). This model calculates the maximum theoretical single runway capacity for a mixed mode operation (arrival-departure-arrival-departure) as a function of fleet mix and separation minima. A single runway model appropriately describes the operation at the major Indian airports: even those airports with more than one runway normally operate with only one at a

time. Hence, theoretical maximum capacities across the network were calculated using Indian separation minima (of 6 or 8 nautical miles as appropriate and determined through personal communication with Airports Authority of India personnel) and fleet mix observed in the Official Airline Guide schedule (13) at each airport in 2005. The resulting maximum theoretical capacities were validated through comparison with capacity data for the few airports in India for which declared capacity data was available, e.g. from the AEDT global airport dataset (21).

Delays due to airport capacity constraints were estimated using queuing theory, applying the cumulative diagram approach and classical steady state simplifications described in (22). In this delay model, flight delays, both on the ground and in airborne holding before landing, were estimated as a function of flight frequencies and airport capacity constraints. These were added to gate departure delays (due to mechanical failures and late arrivals), which were assumed to remain at current levels (with schedule padding increasing to maintain schedule reliability). Runway departure delays were distributed between the taxiway and the gate according to a taxi-out threshold calculated for each airport from historical delay data for airports for which it was available, and according to average taxi-out thresholds for airports for which historical data was not available. Similarly, delays due to destination airport capacity constraints were 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 was assumed to be propagated upstream to the departure gate.

Flight delays resulting from airport capacity constraints impose extra costs on airlines because of increased fuel burn and other per-hour operating costs. These extra costs increase fares as modeled by perfect competition. The costs associated with flight delays were modeled according to estimated fuel burn rates from the Aircraft Technology and Cost Module and published airline cost inventories (23) where available. When such inventories were not available, costs were modeled according to US airline cost inventories, but adjusted according to regional differences in international airline operating economics (24).

More information on the Airport Activity Module can be found in (5).

Aircraft Movement Module

The air traffic by flight segment generated by the Airport Activity Module is the main input to the Aircraft Movement Module, which works in conjunction with the Aircraft Technology and Cost Module to identify the amount and location of emissions released from the required flight segments, accounting for inefficiencies introduced by the air traffic control system. These inefficiencies take the form of extra distance flown (and hence extra fuel burn and emissions produced) beyond the shortest ground track distance for any given airport pair in the schedule. These extra distances were estimated for different phases of flight by using archived flight track data, as described in (25).

More information on the Aircraft Movement Module can be found in (5).

MODEL APPLICATION

The modules described above were run iteratively within the integrated architecture shown in Figure 1 in search of the point of equilibrium between air travel demand, air traffic delay and generalized costs. For the purposes of this comparative study between US and India under an ETS, the model was run with 178 cities/337 airports in the US and 88 cities/94 airports in the Indian set with a base year of 2005 and projections to 2050.

Each assessment builds upon a reference scenario, in which no environmental policies were introduced and non-fuel related operating costs remain approximately constant. The reference scenario also assumes that airport capacity increases in an unconstrained manner to maintain delays at 2005 levels for each airport. It is widely acknowledged (e.g. 26) that air transport system capacity will need to increase to accommodate future growth. For example, the US NextGen project aims to accommodate up to three times the 2004 air traffic in the US aviation system by 2025, the required capacity increase for which is under investigation by studies such as the NASA Virtual Airspace Modeling and Simulation (VAMS) project (27). It is likely that this increase cannot be accommodated without construction of additional infrastructure at major airports (28) and increased use of secondary airports (29). Hence, the results indicate how much extra airport capacity will be required in the regions studied.

In the ETS policy scenario, the impact of an emissions trading regime on aviation system behavior was assessed. Several degrees of freedom of such policy instruments exist, such as open (including more sectors than aviation) versus closed (aviation only) and global versus national. In this study, it is assumed that aviation is included in an open global trading scheme that includes all sectors of the world economy. Such a scheme would naturally result in the lowest carbon price, as it takes advantage of the many lower-cost GHG mitigation options in other sectors and world regions.

Another policy choice is whether to target CO₂ emissions only or include all GHG emissions (i.e. including ‘non-CO₂’ effects of NO_x-induced methane and ozone changes, contrails, etc.) in the trading scheme. Industry and policy makers have attempted to account for these effects through the use of a so-called ‘uplift factor’ (UF), where the impact of aviation on the future climate is assumed to be a multiple of its CO₂ emissions. The scientific community is in agreement that problems exist with the use of UFs since the different impacts due to aircraft emissions act over many different time and length scales, so basing any calculations on just one time and length scale can produce misleading results. Commonly, UFs have been based on the radiative forcing due to aviation around the year 2000. Sausen et al. (30) recently suggested that the total radiative forcing impact due to aviation in 2000 (not including aviation induced cirrus) was 48 mW/m², similar to the total calculated in IPCC (31) for 1992. When compared with the radiative forcing impact due to CO₂ alone, 25 mW/m², this equates to an UF of 1.9, compared with 2.7 calculated from the IPCC results. Despite the lack of consensus on the use of UFs, they have recently been considered for use (at a value of 2.0) in the European Emissions Trading Scheme (32). For the purposes of this study, UF values of 1.9 and 2.7 are considered as a means of testing the sensitivity of the results, as well as a base-case where non-CO₂ effects are omitted (i.e. the UF has a value of 1.0). These values encompass the range generally under consideration.

In order to capture the uncertainties that exist in the establishment of a global emissions trading scheme, three CO₂ atmospheric stabilization targets were analyzed: 450, 550 and 750 ppm. Underlying these numbers were growth trends in population, income, oil price, and carbon price from a study for the US Climate Change Science Program (CCSP) (33). The CCSP study included runs from three integrated energy-economy-environment models to simulate the various impacts of an unconstrained reference run and various atmospheric stabilization scenarios. The models include the MIT Integrated Systems Model (IGSM), the Stanford University Model for Evaluating the Regional and Global Effects of GHG Reduction Policies (MERGE), and the Pacific Northwest Laboratory Mini Climate Change Assessment Model (MiniCAM). Runs from all three models were used here to reflect the uncertainty of the future evolution of and

adjustments by the world economy to exogenously imposed changes (i.e., global warming policies).

Table 2 summarizes the key input data to the AIM model derived from the three models underlying the CCSP report. The trends in population, GDP per capita, oil price and carbon price were relatively uniform across the three models, but the rates of growth differ significantly, due partly to the assumptions regarding the future evolution of exogenous variables and differences in model structures and parameters. As demonstrated by the 2008 developments in oil price, any single input projection comes with a high degree of uncertainty and hence it is vital to consider the full range of input scenarios.

Naturally, the tighter the stabilization level, the stronger reductions are required, and the higher the carbon price. The differences in carbon price across the three studies forming the CCSP report can be attributed to differences in model structures, assumptions regarding the available mitigation technologies, and substitution elasticities between capital and various types of energy carriers, along with other factors. In the emissions trading scenarios in this paper, these CCSP carbon prices were imposed exogenously on the price of refined oil, thus corresponding to a quasi carbon-tax.

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

		2005	2025	2050
Population, millions				
US	IGSM	296	347	391
	MERGE	295	339	345
	MiniCAM	296	334	386
India	IGSM	1082	1353	1569
	MERGE	1101	1356	1453
	MiniCAM	1093	1366	1506
GDP per capita, \$(2005)				
US	IGSM	44400	68600	115000
	MERGE	43800	56900	81600
	MiniCAM	42500	54300	72800
India	IGSM	715	1160	2010
	MERGE	733	1560	4320
	MiniCAM	705	1790	5500
World Oil Price, \$/bbl				
	IGSM	54.9	99.9	145.9
	MERGE	54.9	78.2	110.2
	MiniCAM	54.9	66.2	84.7
Carbon Price, \$/tCO₂				
	IGSM	0	17-105	18-260
	MERGE	0	1-46	2-178
	MiniCAM	0	1-40	2-143

Reference Scenarios

The reference scenario uses the input values from Table 2 for each CCSP scenario with a zero carbon price over the entire time horizon. The results for the US domestic aviation system from 2005 to 2050 are provided in Figure 2. Because perfect competition is assumed, fares are under predicted in 2005, when the airline industry made a net profit. This leads to a slight over-prediction of RPK and fuel burn when compared with observed values from 2005. These effects are seen as discontinuities in the results discussed next.

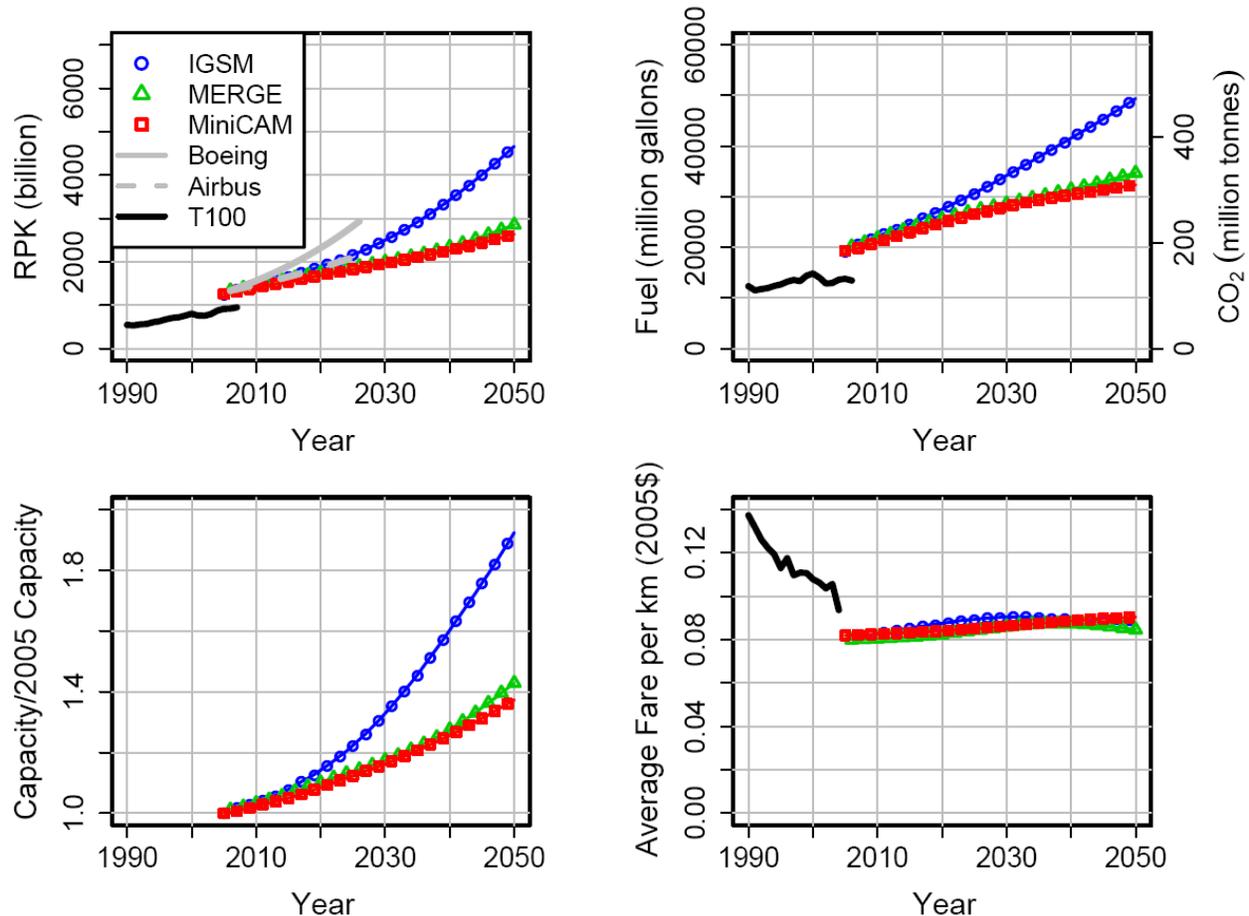


FIGURE 2 US domestic aviation system reference scenario (a) System RPK, (b) Fuel burn and CO₂ emissions, (c) Capacity increase required for 2005 delay levels, and (d) Average airfare per km.

Figure 2a shows the simulated RPK development, which grows from 1.1 trillion in 2005 to between 2.7 and 4.7 trillion in 2050, depending upon the scenario (IGSM/Merge/MiniCAM). The historical values for this airport set from BTS T100 data (12), as well as growth projections for domestic US aviation from the (scaled) Airbus Global Market Forecast (1) and for North American aviation from the (scaled) Boeing Current Market Outlook (2) show favorable comparison. Figure 2b provides the simulated fuel burn and CO₂ projections: because of the fuel burn reductions simulated in the Aircraft Technology & Cost module, aircraft fuel use and CO₂ emissions typically increase at a progressively lower rate over time. Required average capacity increases at the 33 most congested airports to maintain 2005 delay levels are shown in Figure 2c. A near doubling of average runway capacity is predicted to be required by 2050 in the IGSM

scenario, although some major hub airports have greater capacity needs, for example up to 2.7 times capacity increases at Chicago O’Hare and Atlanta. In reality, such capacity increases are unlikely to occur at major airports, many of which are 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 hub airports. There may also be a greater shift by airlines to operate larger aircraft types, reducing the relative increase in traffic required to serve the increase in demand. Such effects will be captured in future by an airline response model currently under development. Average air fare per kilometer is presented in Figure 2d: this shows a roughly level trend in airfare which can be attributed mainly to a balance between increasing oil prices and decreasing fuel burn per RPK. In this paper we do not examine the effects of increasing competition, which is behind some of the past decreasing trend in fares, or industry consolidation, both of which may affect the level of costs which can be passed on to the passenger and hence the fare trend.

Analogous results for the Indian domestic air transport system are presented in Figure 3.

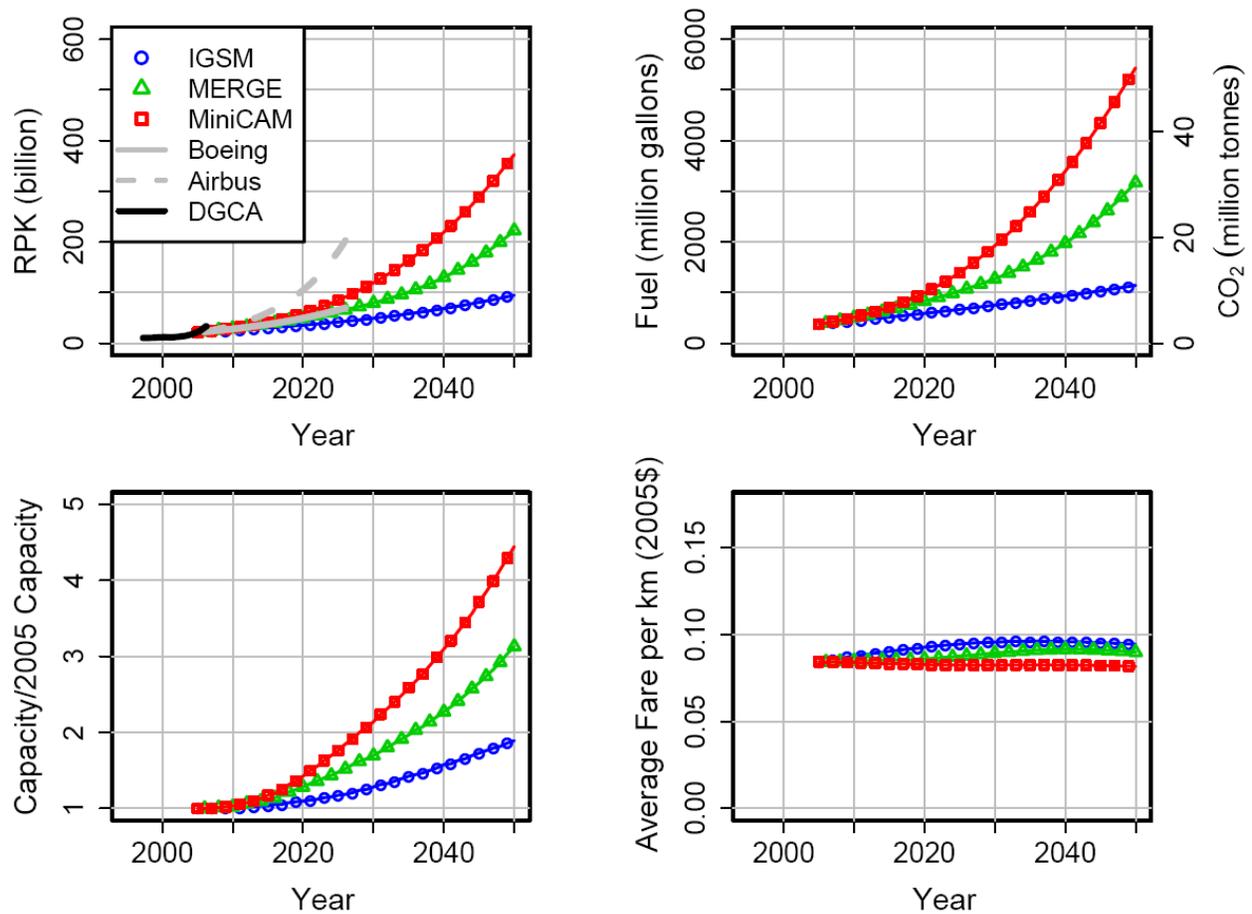


FIGURE 3 Indian aviation system reference scenario (a) System RPK, (b) Fuel burn and CO₂ emissions, (c) Capacity increase required for 2005 delay levels, and (d) Average airfare per km.

Projected domestic RPK (Figure 3a) grows from 12.8 billion in 2005 to between 95 and 373 billion in 2050, depending upon the scenario from Table 2. As with the US case, the

associated increase in fuel use and CO₂ emissions is smaller due to the introduction of increasingly fuel-efficient aircraft over time (Figure 3b). Figure 3c illustrates that the required average capacity increase for domestic air travel at major airports (Mumbai, Delhi, Kolkata, Chennai and Thiruvananthapuram) is about twice that of the US – a consequence of the strong growth in RPK. Currently, the route closest to capacity in this network is Delhi-Mumbai, which already experiences significant delays. Thus, future developments such as Mumbai's proposed second airport are 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. Airfare, shown in Figure 3d, displays a similar trend to that in the US. However, since the Indian air transport system is currently undergoing a transition from a formerly regulated air transport system to one that is increasingly liberalized and competitive, the modeled fare for 2005 is likely to be less accurate than for later years.

Emissions Trading Scenarios

The impact of the emissions trading scheme described above on the domestic US and Indian air traffic systems is presented in this section for comparison with the reference scenarios. The input values from Table 2 were used along with the indicated carbon prices. These assume a global trading scheme is introduced in 2012, aimed at stabilizing atmospheric CO₂ at a given value between 450 and 750 ppm. As stabilization at 750 ppm produces results which are nearly identical to the base case with no carbon charging, these scenarios are omitted in the following discussion.

Figure 4 shows the results for the US system. For easier readability, only the results for the 450 ppm scenario are shown in addition to the reference scenario. The differences between the 550 ppm and the reference scenario are typically about 30% of the difference between the 450 ppm and reference scenario. As can be seen, carbon trading reduces the growth in RPK in the most extreme case (450 ppm) by up to 50%, and the additional imposition of an uplift factor of 2.7 can reduce demand almost to base year levels. Fuel use, CO₂ emissions, and required extra airport capacity experience slightly smaller reductions. However, these reductions are strongly scenario-dependent. To obtain a reduction in RPK of over 20% requires a reference scenario with high carbon prices and either stabilization at 450 ppm, or 550 ppm with an uplift factor significantly greater than one.

The varied response of the air transport system arises mainly from the widely differing carbon and oil price assumptions in the input scenarios. By 2050, the IGSM scenario with stabilization at 450 ppm has an effective oil price (oil price plus carbon price) of nearly \$250/bbl (year 2005 dollars). Under the assumption of perfect competition, the analysis suggests that airlines pass an average of 30% of the extra costs due to carbon charging on to ticket prices. For the equivalent MiniCAM model this price is only \$140/bbl, and only 8% of costs are passed on.

The increases in ticket price due to emissions trading are not evenly distributed. Because short-haul routes generate lower emissions, their ticket price increases are smaller. In the IGSM scenario, total enplanements drop by 32% between the reference and 450 ppm scenarios. Because of the smaller charges and smaller price elasticities (see Table 1), short-haul enplanements decrease by 29% between the reference and 450 ppm scenarios, while long-haul enplanements drop by 37%. However, the actual change in short-haul enplanements may be greater than this, as we do not model mode substitution. Note that the difference in the price-induced demand is actually larger, since the reported decline is by segment; thus, some of the

decrease in short-haul travel results from reduced demand for long-haul hub-and-spoke itineraries.

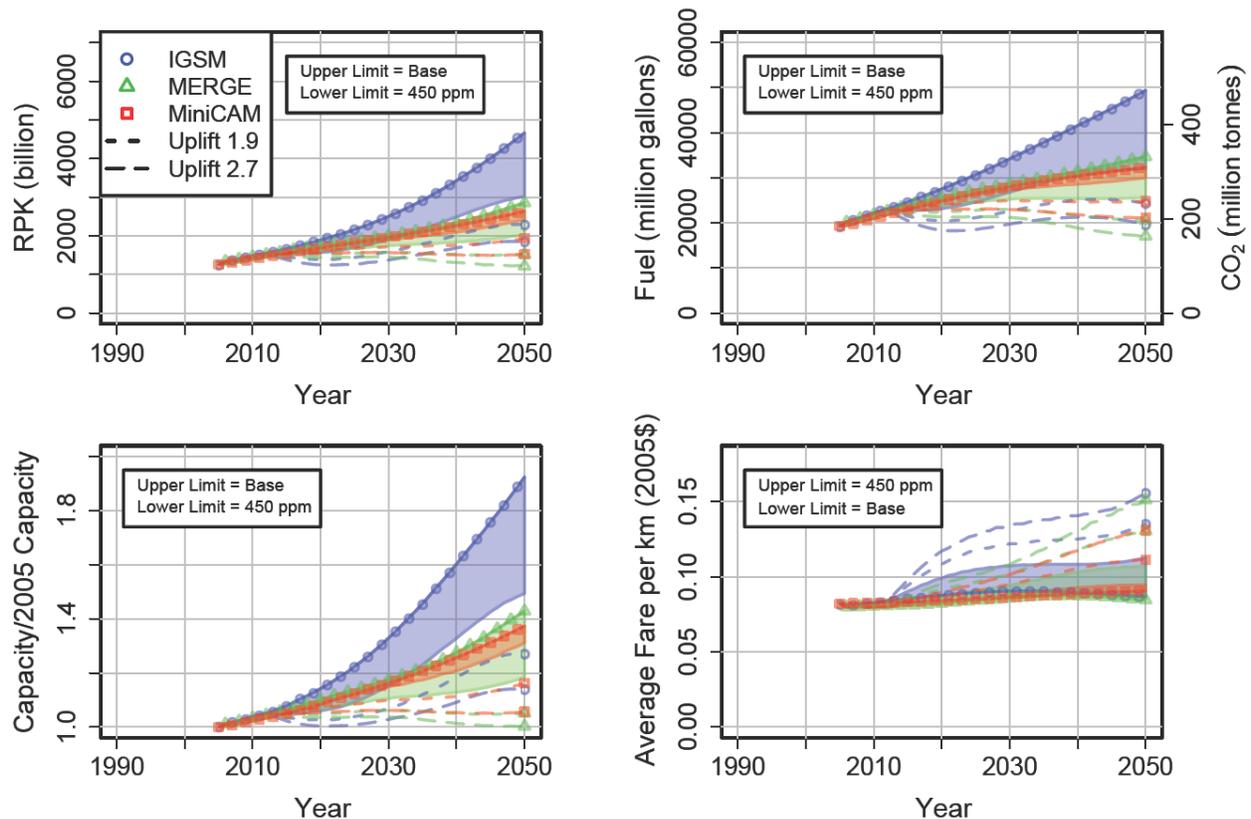


FIGURE 4 US aviation system ETS scenario (a) System RPK, (b) Fuel burn and CO₂ emissions, (c) Capacity increase required for 2005 delay levels, and (d) Average airfare per km. Results for the 550 ppm stabilization scenario are not shown; these typically have only 30% of the effect of the 450 ppm scenarios. The 750 ppm stabilization scenario is nearly identical to the base case.

The dashed lines in Figure 4 indicate the effect of including non-CO₂ greenhouse gases into the emissions trading scheme via uplift factors on the 450 ppm scenarios. Because of the extra permits that need to be purchased, a higher uplift factor leads to a higher airfare and thus a stronger decline in RPK, fuel use and CO₂ emissions, and lower required capacity growth. Using an uplift factor of 1.9, the drop in total enplanements from the reference scenario in 2050 would be 47% in the IGSM scenario.

Analogous results for the Indian air transport system are given in Figure 5. While the general development of the variables under consideration is similar to the US case, the percentage decline (relative to the reference scenario) in RPK, fuel use, and CO₂ emissions is generally smaller than that in the US under most emissions trading scenarios. For example, using the scenario inputs based upon the MERGE model in Table 2, the growth rates in RPK in the US domestic system would decline from 1.8%/yr to 1.0%/yr from the reference case to the 450 ppm stabilization case. In contrast, the corresponding decline in the Indian air traffic system is from 5.3%/yr to 4.5%/yr. The smaller relative response to extra fuel costs can be attributed to the average shorter travel distances and the smaller airfare elasticity (see Table 1).

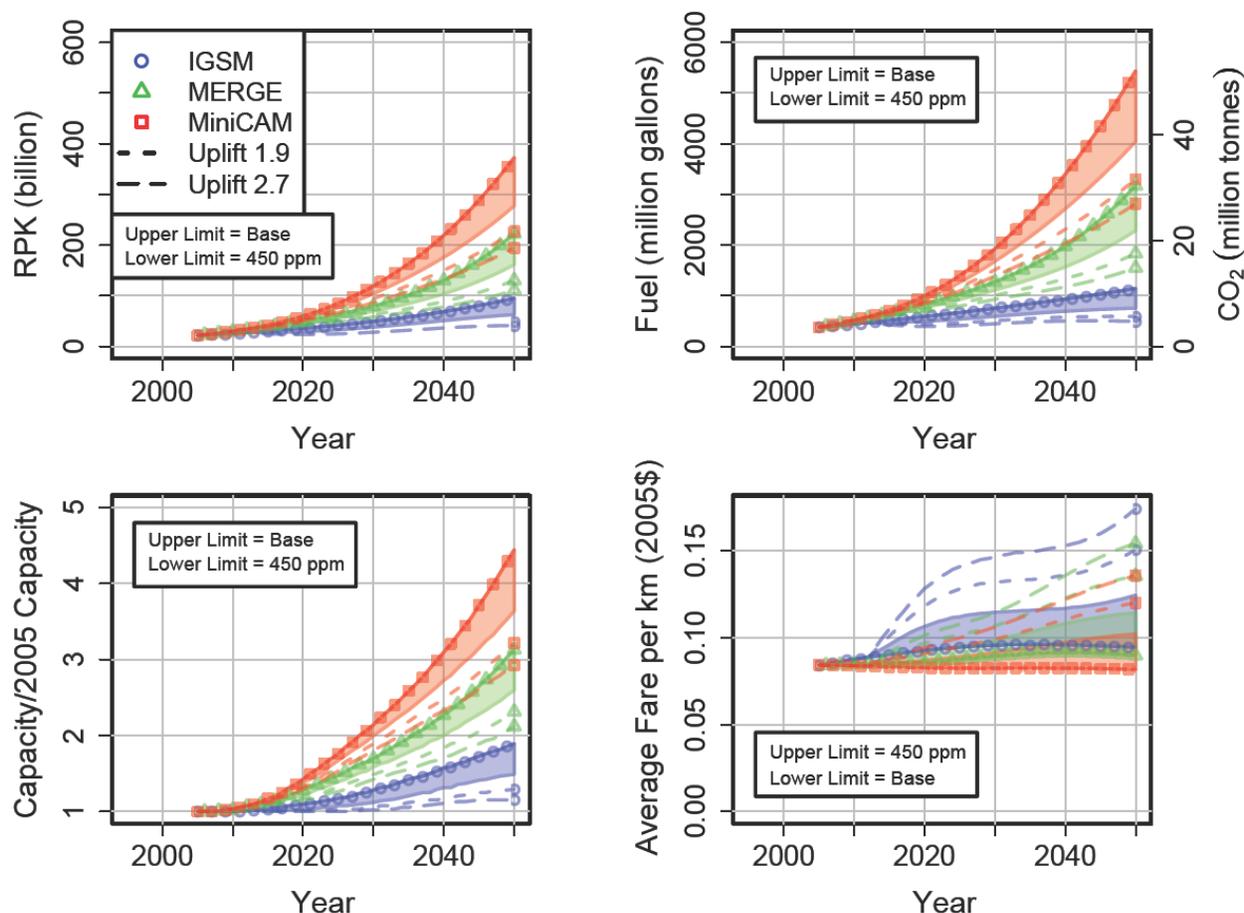


FIGURE 5 Indian aviation system ETS scenario (a) System RPK, (b) Fuel burn and CO₂ emissions, (c) Capacity increase required for 2005 delay levels, and (d) Average airfare per km. Results for the 550 ppm stabilization scenario are not shown; these typically have only 30% of the effect of the 450 ppm scenarios. The 750 ppm stabilization scenario is nearly identical to the base case.

CONCLUSIONS

This analysis of the domestic US and Indian aviation system suggests that an open global CO₂ emissions trading scheme can have a noticeable impact on aviation RPK, fuel use, CO₂ emissions, and required capacity growth. However, such impact is likely to only occur in the most stringent (and challenging) case examined here, that of an atmospheric stabilization level of 450 ppm, or if a significant uplift factor is applied in the 550 ppm case. In the most extreme case, with a 450 ppm stabilization target and an uplift factor of 2.7, RPK in 2050 would decline by up to 60% compared to the reference scenario levels – leaving it close to 2005 levels. In the other, less stringent stabilization cases, the impact on the air transport system is significantly lower. However, the carbon prices continue to rise after 2050 and the impact on the aviation sector would continue to increase. Thus, the largest aviation sector impact will likely occur after mid-century.

Under any stabilization scenario, the reductions in short-haul enplanements were found to be smaller compared to long-distance trips. Thus, the decline in the required future airport capacity is less significant than the decrease in revenue passenger kilometers (RPK). This

inhomogeneous decline would thus also lead to a rising relative importance of short distance air travel.

A comparison between the US and Indian air transport sector impacts suggests a smaller effect on the Indian air transport system. This is the combined result of a lower airfare elasticity and a shorter average travel distance. Even in the most stringent CO₂ emissions trading scenario of a stabilization target of 450 ppm, the Indian air transport system would grow by 4.5%/yr, only down from 5.3%/yr in the reference scenario. This may suggest that aviation is likely to continue to grow strongly, especially in developing regions, even under tight environmental constraints.

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REFERENCES

- 1 Airbus, "Global Market Forecast 2007-2026", http://www.airbus.com/fileadmin/documents/gmf/PDF_dl/00-all-gmf_2007.pdf, 2007 [Cited 27 June 2008]
- 2 Boeing, "Current Market Outlook 2007", http://www.boeing.com/commercial/cmo/pdf/Boeing_Current_Market_Outlook_2007.pdf [Cited 27 June 2008].
- 3 Schäfer A., 2006, Long-Term Trends in Global Passenger Mobility, invited paper in: The Bridge, The National Academies Press, Washington, D.C., Vol. 36, pp. 24-32.
- 4 BBC News, EU includes aviation in CO₂ curbs, Tuesday, 8 July 2008 14:54 UK, <http://news.bbc.co.uk/1/hi/world/europe/7495567.stm>
- 5 Reynolds T., S. Barrett, L. Dray, A. Evans, M. Köhler, M. Vera-Morales, A. Schäfer, Z. Wadud, R. Britter, H. Hallam, R. Hunsley, "Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Tool", 7th AIAA Aviation Technology, Integration and Operations Conference, Belfast, 18-20 September 2007, AIAA-2007-7751.
- 6 ICAO, "ICAO Engine Emissions Databank" http://www.caa.co.uk/docs/702/080407%20%20ICAO_Engine_Emissions_Databank-Issue_15-C.xls, [Cited 27 June 2008].
- 7 ICAO, "ICAO Annex 16, Volume II: Aircraft Engine Emissions", ICAO Publications, 2006.
- 8 EUROCONTROL, "Base of Aircraft Data (BADA)", Version 3.6, July 2004.
- 9 U.S. Census Bureau, Census 2000 and American Community Survey 2005, <http://www.census.gov> [Cited 27 June 2008].
- 10 Office of the Registrar General and Census Commissioner, "Census of India 2001", <http://www.censusindia.gov.in> [Cited 29 July 2008]
- 11 Government of Indian Ministry of Statistics and Programme Implementation, National Sample Survey Report No. 508(61/1.0/1),2006)
- 12 US Department of Transportation, Bureau of Transportation Statistics, DB1B and T100 survey, <http://www.transtats.bts.gov> [Cited 29 July 2008]
- 13 Official Airline Guide, "OAG 2005 Flight Schedule Database", OAG Worldwide Inc., 2005.
- 14 Directorate General of Civil Aviation, "India Air Transport Statistics 2004-05 and 2005-06", 2007, <http://www.dgca.nic.in/reports/stat-ind.htm> [Cited 29 July 2008]
- 15 Gillen D.W., W.G. Morrison, C. Stewart, 2007. Air Travel Demand Elasticities: Concepts, Issues and Measurement, in "Advances in Airline Economics Volume 2: The Economics of Airline Institutions, Operations and Marketing", D. Lee (Editor), Elsevier.

-
- 16 Oum T.H., W.G. Waters, J.S. Yong, 1990. A Survey of Recent Estimates of Price Elasticities of Demand for Transport, Infrastructure and Urban Development Department, The World Bank, Washington, DC.
 - 17 Jamin S., A. Schäfer, M.E. Ben-Akiva, I.A. Waitz, 2004. Aviation Emissions and Abatement Policies in the United States: A City Pair Analysis, *Transportation Research D*, 9(4): 294-314.
 - 18 Bhadra D., Gentry, J., Hogan, B. & Wells, M., "CAASD's Future Air Traffic Estimator: A Micro-Econometric Approach", 13th Annual Federal Forecasters Conference, BLS Training Center, 2003.
 - 19 Federal Aviation Administration, "Airline Service Performance Metrics Database", 2008, www.apo.data.faa.gov/aspm/entryASPM.asp [Cited 27 June 2008].
 - 20 de Neufville, R., A. Odoni, "Airport Systems Planning, Design, and Management," McGraw Hill Companies, Inc., ISBN 0-07-138477-4, 2003.
 - 21 Volpe National Transportation Systems Center, Wyle Laboratories, Inc., "AEDT Database – Airport Database," Environmental Measurement and Modeling Division, Volpe National Transportation Systems Center, Cambridge MA, 2008.
 - 22 Evans, A.D., "Rapid Modelling of Airport Delay", 12th Air Transport Research Society World Conference, Paper 202, Athens, Greece, 6-9 July 2008.
 - 23 Dept. of Transportation, Bureau of Transportation Statistics, DB1B Survey, Form 41, T100 Traffic & Financial Data, www.transtats.bts.gov [Cited 27 June 2008] .
 - 24 International Civil Aviation Organisation, "Regional Differences in International Airline Operating Economics: 2002 and 2003", Cir 310 AT/132, 2006.
 - 25 Reynolds, T. G., "Analysis of Lateral Flight Inefficiency in Global Air Traffic Management", 8th AIAA Aviation Technology, Integration and Operations Conference, Anchorage, Alaska, US, Sep. 2008, AIAA-2008-8865.
 - 26 Miller, M.E., G.A. Trott, "Effects of Future Traffic on the National Airspace System," AIAA Modeling and Simulation Technologies Conference and Exhibit, Providence, Rhode Island, US, Aug. 2004, AIAA 2004-5438.
 - 27 NASA, Virtual Airspace Modeling and Simulation (VAMS) project, <http://vams.arc.nasa.gov/> [cited 14 November, 2008].
 - 28 FAA/JPDO, "Integrated Work Plan for the Next Generation Air Transportation System", 2008, http://www.jpdo.gov/iwp/IWP_Version_02_Master_w-o_appendix.pdf [Cited 27 June 2008] .
 - 29 Bonnefoy, P.A., R.J. Hansman, "Scalability and Evolutionary Dynamics of Air Transportation Networks in the United States," 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO), Belfast, Northern Ireland, Sept. 2007, AIAA 2007-7773.
 - 30 Sausen, R. et al. (2005) Aviation Radiative Forcing in 2000: An Update on IPCC (1999), *Meteorol. Z.*, 14(4), 555-561.
 - 31 IPCC (1999) Aviation and the Global Atmosphere. A Special Report of Working Groups I and III of the Intergovernmental Panel on Climate Change, edited by J. Penner et al., Cambridge University Press, New York.
 - 32 European Parliament, "Amendment of Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community," Strasbourg, 13 November 2007, <http://www.europarl.europa.eu/sides/getDoc.do?jsessionid=1E4649C1A7AE84EAC75B7A1BE6B3BD9D.node1?pubRef=-//EP//TEXT+TA+P6-TA-2007-0505+0+DOC+XML+V0//EN#title3> [cited 11 November 2008].
 - 33 U.S. Climate Change Science Program, "Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations", 2007, <http://www.climatechange.gov/Library/sap/sap2-1/finalreport/sap2-1a-final-all.pdf> [Cited 27 June 2008].