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Long-term scenarios for aviation: Demand and emissions of CO_2 and NO_x

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NOTE: At the time of publication, the author Anu Vedantham was affiliated with the Energy Defense Fund. Currently, she is a staff member of the Penn Libraries at the University of Pennsylvania.

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Abstract

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Keywords

aviation, emissions, long-term scenarios

Comments

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This study presents a dynamical systems model for long-term scenarios of demand in the aviation sector and resultant emissions of CO_2 and NO_x. We analyze the dynamics of demand growth for aviation, particularly in the emerging markets of developing nations. A model for subsonic aviation emissions is presented that reflects the consequences of industry forecasts for improvement in aviation fuel efficiency and emissions indices as well as projections of global economic and population growth over the next century. (Emissions of commercial supersonic aircraft are not modeled here.) The model incorporates a dynamical system of logistic growth towards a time-dependent capacity level. Using the long-term model, we present a set of projections of demand for aviation services, fossil fuel use, and emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x) through the year 2100; previous forecasts have not extended past 2040. We briefly discuss expectations for the distribution of NO_x emissions over altitude and latitude.

Keywords. Aviation; Emissions; Long-term scenarios

Introduction

Emissions from aviation have become a focus of increasing scientific interest in recent years. Globally, civil aviation is growing faster than nearly all other economic sectors, with the notable exception of information technology (Gould, 1996). Despite substantial progress in aircraft fuel efficiency, increased demand has led to a much higher growth rate in fossil fuel use by the aviation sector when compared to other transportation sectors or to world energy use overall. Furthermore, the energy intensity of aviation is significantly higher than that of rail or automobile travel (Gould, 1996). Given expectations of continued growth in the aviation sector over the next century, CO_2 emissions from aviation are expected to rise from their current level of 3% of the CO_2 emitted from all fossil fuel combustion.

We consider here future emissions from subsonic aircraft only. Recent proposals to expand the supersonic fleet (currently at only a handful of planes) to 500 or 1000 High Speed Civil Transport aircraft (HSCT) would have substantial effects on the amount, distribution and environmental consequences of emissions.

Aviation and the atmospheric environment

From the perspective of aviation, the atmosphere may be divided into three altitude zones: the boundary layer, the upper troposphere, and the lower stratosphere, as indicated schematically in Figure 1.

Aircraft are currently the only human-made *in situ* generators of emissions in the upper troposphere and in the stratosphere. The depletion of the stratosphere's ozone layer by chlorofluorocarbons (CFCs) and related chemicals has underscored the importance of anticipating other potential insults to the ozone layer. Some emissions from subsonic aircraft and the majority of emissions from supersonic aircraft occur directly in the lower stratosphere, where these effluents can affect the concentration of ozone by adding to it at some altitudes and latitudes, and by diminishing it at others (WMO, 1995; Thompson, 1996).

Carbon dioxide (CO_2), water vapor, nitrogen oxides (NO_x), carbon monoxide, hydrocarbons, sulfur dioxide, sulfate particles and soot are emitted by aircraft at all altitudes. The altitude of emission is not relevant to determining the influence of CO_2 from aviation on the atmosphere's greenhouse effect. In contrast, other

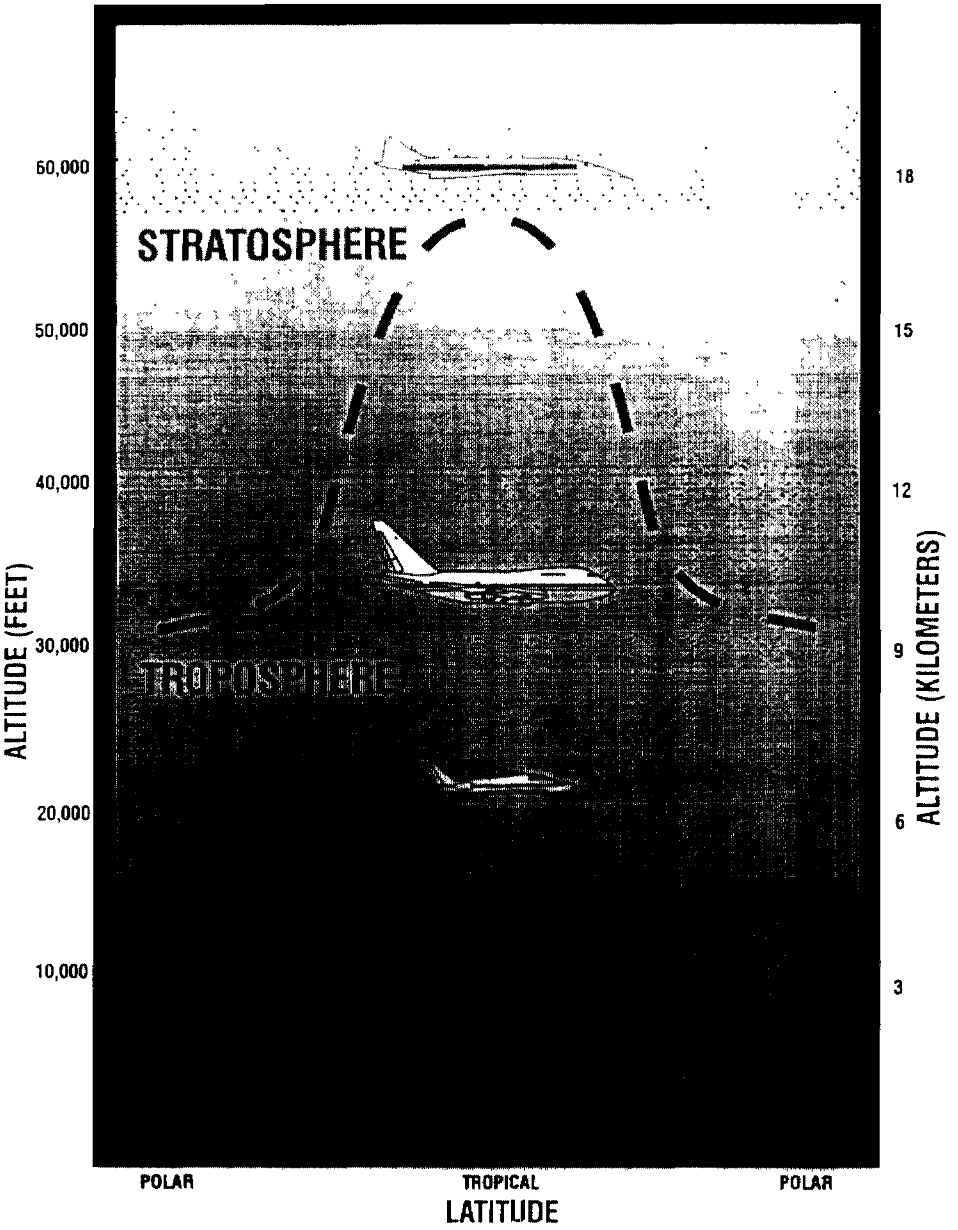

Figure 1 Aviation and the atmosphere

emissions may influence the chemistry or radiative properties of the atmosphere in different ways at different altitudes. For example, NO_x emissions react quickly with many other atmospheric constituents. The resulting distribution and environmental effects of NO_x, which include the production and destruction of ozone, are highly dependent on altitude, latitude and season (Ehhalt, 1992, WMO, 1995; Brasseur, 1996).

Boundary-layer emissions: During takeoff and landing, aircraft emit in the boundary layer, which averages about 1 km in altitude at the mid-latitudes. Under the action of sunlight, emitted gases react with other atmospheric constituents to produce ozone and a variety of other compounds that compose smog. Aircraft emissions during takeoff and landing are regulated in many nations (eg, under the Clean Air Act in the US); emissions at cruise altitudes are not regulated at present.

Upper tropospheric emissions: Almost 60% of the fuel burned by scheduled passenger and cargo flights during 1990 resulted in emissions above 9 km altitude (Stolarski, 1993a, p.124). NO_x emissions in the upper troposphere may undergo reactions with other atmospheric gases that are stimulated by sunlight to form ozone.

In the upper troposphere, ozone acts as a potent greenhouse gas, so any additional source is of interest from climatic perspective. Although a global picture of ozone has not yet emerged, the limited measurements and model results available suggest that concentrations may have doubled over much of the northern hemisphere since pre-industrial times. The apparent buildup of ozone in the upper troposphere may have added a significant increment to the anthropogenic greenhouse effect of CO_2 and other gases (Hauglustaine, 1994).

Although only about 2% of global anthropogenic NO_x emissions are due to aviation, NO_x emitted at cruise altitudes may be more efficient under some circumstances, on a per-molecule basis, as generators of ozone than NO_x emitted near the ground (Johnson, 1992). Furthermore, NO_x emitted by aircraft at northern mid-latitudes in the upper troposphere is of similar magnitude to the NO_x generated there from natural sources. Atmospheric models ascribe a 1–10% ozone increase in the upper troposphere to current emissions from aviation (WMO, 1991; Schumann, 1993; Stevenson, 1997; Brasseur, 1996).

Other emissions from aircraft in the upper troposphere may affect climate as well. Particles emitted by subsonic jets can produce visible contrails that reflect sunlight, and ice crystals from these contrails may enhance the formation of thin cirrus clouds that trap heat. Schumann (1993) estimates the long-term climate effect of changes in tropospheric ozone and changes in cirrus cloud cover due to current aviation emissions to be a few hundredths of a degree Celsius (compared to 1–2 C for the eventual equilibrium warming due to all anthropogenic greenhouse gases currently in the atmosphere).

Stratospheric emissions: The troposphere and the stratosphere are separated by the tropopause which varies roughly between 9 and 17 km altitude. The tropopause acts as an invisible barrier to the vertical movement of gases, but in the tropics, deep convection is probably effective at transporting a fraction of the insoluble gases emitted at cruise altitude (such as NO_x) into the stratosphere.

Subsonic aircraft frequently cruise in the stratosphere itself, emitting NO_x and other gases directly into that region. About 20% of the global fuel burn may occur in the stratosphere on average, but a much larger fraction occurs during wintertime flights over the North Atlantic (Schumann, 1993; Baughcum, 1996). NO_x emitted in the stratosphere may lead to increased or decreased concentrations of ozone, depending on the altitude and latitude of emission. Water vapor, sulfur dioxide and sulfate particles may also have important effects on the ozone balance of the stratosphere. Furthermore, ozone in the lower stratosphere also acts as a greenhouse gas that affects Earth's thermal-radiation balance.

Photochemical models indicate that at altitudes between 13 and 20 km, added NO_x switches from stimulating the creation of ozone to destroying it (WMO, 1991; Schumann, 1993; Hidalgo and Crutzen, 1977; Thompson *et al.* 1996). If this transition actually occurs in Earth's atmosphere, its location would be a complicated function of season and latitude. Currently, this function is not well known. Neither is there an adequate predictive model for the transport of NO_x (and its chemical products) from lower altitudes to higher altitudes within the stratosphere (Holton, 1995). If the HSCT proposal should be implemented, its greatest consequences would be in the stratosphere, where its effect would vary with altitude. On balance, a large HSCT fleet would probably reduce total ozone (Stolarski, 1995).

Current emissions

Quantifying current emissions from aviation is a crucial first step to determining the environmental impact of the sector. The International Energy Agency (IEA) places global aviation fuel use in 1990 at 174.8 Mt based on its annual data collection on a country-specific basis. However, these statistics may not reflect exactly where fuel is consumed and may also include some fuel that is used for non-aviation purposes (Baughcum, 1996a). Also, since this data is gathered at refineries and at points of sale, it does not provide information regarding the geographical and altitude distribution of emissions.

Jet fuel consumed by US Certificated Air Carriers is reported in some detail to the US Department of Transportation (USDOT), and these statistics provide some insight into the amount of fuel used by different aircraft and engine types. USDOT and IEA use fundamentally different conventions when assigning fuel use to a particular nation; therefore, data from these two sources cannot be compared easily

Bottom-up inventories aggregate a detailed simulation of flights to produce estimates of fuel use; their results typically provide emissions estimates by altitude and longitude/latitude. Aircraft/engine combinations are modeled in some detail to determine emissions characteristics. Data on typical cruise altitudes, flight corridors, changes in emissions indices with altitude, and popular combinations of engine/aircraft types are some of the other relevant factors. The final fuel use estimates are often checked for validity against the IEA's 'top-down' fuel consumption inventory described above.

McInnes and Walker conducted the first global three-dimensional inventory of aviation emissions; their study accounted for 51% of the IEA-reported fuel use for 1989 (McInnes and Walker, 1992). The inventory covered only civil passenger aviation, but provided a valuable first look at the process of conducting bottom-up analyses.

The National Aeronautics and Space Administration (NASA)'s Atmospheric Effects of Stratospheric Aircraft (AESA) program has conducted a large-scale effort using proprietary data from Boeing and McDonnell-Douglas, and flight plan details from the Official Airline Guide.[1] The NASA inventory for 1990 emissions includes a detailed analysis of military fuel usage, and a city-pair-based breakdown for civil aviation. The results have provided detailed emissions estimates on a grid of 1

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[1] See Stolarski (1993a), Stolarski (1993), Prather (1992), Baughcum (1996), Baughcum (1996a) for complete history of NASA's work

longitude by 1 latitude by 1 km, and have incorporated a sizable array of aircraft/engine combinations. The inventory has been able to account for 76% of IEA-reported fuel use. NASA has also recently provided details on seasonal variations by simulating emissions for four specific months (Baughcum, 1996a).

The European Community has conducted a similar study through the AERONOX research project. The resultant ANCAT/EC inventory is based on flight data from Air Traffic Control, and uses engine performance models (ANCAT, 1995). ANCAT/EC provides inventories for four specific months in 1992. Due to double-counting of European flights and definitional differences, this inventory overestimates fuel burn when compared to IEA-reported fuel use (CAEP, 1995).

The International Civil Aviation Organization (ICAO), the United Nations agency that regulates civil aviation, is currently undertaking a detailed comparison of the NASA and ANCAT/EC inventories to determine possibilities for improved accuracy. Preliminary analysis of the two efforts indicates significant differences in NO_x emissions estimates. (CAEP, 1995).

Forecasts of future emissions

The time-frame for emissions forecasts varies considerably, and has been the subject of much discussion. The climate change research community has produced long-term forecasts of total emissions from all sectors in order to better study environmental processes that evolve over many decades. The IPCC has produced a series of scenarios for emissions through 2100, and climate change models have focused on this time-scale as well. Such long-term approaches, while needed for policy purposes, require broad generalization and uncertain extrapolation of current trends.

In contrast, forecasts from the aviation industry have been limited to one or two decades, although ICAO is considering a 50-year time horizon currently. Advantages of shorter-term forecasts include greater accuracy as well as better estimates of technological progress and region-specific economic change.

However, compelling reasons exist to consider long-term consequences. Designing a new aircraft can take up to a decade, and each aircraft design has a lifetime of about 25 years. NASA's analysis of fleet composition shows that older aircraft remain a substantial portion of the commercial fleet over several decades. Analysis of the number of Boeing aircraft in the commercial fleet shows that the share of older designs such as 737 and 727 declines gradually over the 25 year period from 1970 to 1995, and similar patterns hold for other airplane manufacturers as well (Baughcum, 1996, pp. 43). Technological decisions regarding engine and airframe design made today may well govern emissions through 2030. Long-term forecasts of aviation emissions, despite the risks involved, also provide a framework for policy and technological discussion. International policy agreements that may affect emissions at cruise altitudes will require several years of negotiation, and after implementation, may take decades to make a significant impact on emissions.

A long-term forecast of aviation emissions requires analysis of demand growth, fuel efficiency and changes in emissions indices. We present the model's components in this order.

Demand model

Several major airplane manufacturers, airplane engine manufacturers, airline companies, industry associations and ICAO produce annual forecasts of aviation demand growth. In general, these short-term forecasts look ahead a decade or two, and depend on econometric analysis. They correlate demand with economic and demographic factors such as GNP, disposable income, and volume of international trade (examples include FAA, 1993, ICAO, 1992, McDonnell Douglas, 1992 and Boeing, 1993). The resulting econometric model is then combined with short-term forecasts of the explanatory variables to project demand growth rates, often using linear correlation among explanatory variables. Extrapolating econometric growth rates into forecasts that extend past a few decades is not defensible, since market processes cannot grow at the same rate indefinitely. The dynamics and timing of rapid expansion and eventual market saturation in individual markets need to be addressed explicitly.

The Environmental Defense Fund (EDF) model we present here uses a long-term non-linear dynamical systems approach (Vedantham and Oppenheimer, 1994) A variation on the logistic model captures the growth and eventual saturation of demand growth rates in both industrial and developing countries. Growth rates and market capacities for different regions of the world are determined by their economic history and the examination of aviation market history in industrial nations. We consider individually the underlying dynamics of different sectors including personal travel and business travel. The long-term estimates for regional gross national product (GNP) and population growth developed by the Intergovernmental Panel on Climate Change (IPCC) are incorporated, and the demand model is validated using the history of the US domestic market. We present the assumptions and structure of the model below.

Long-term dynamics of aviation demand growth

The evolution of aviation demand in a new market is affected by several factors:

Latent demand: When an airport network is built in a previously unserved region, it offers a new transport option and thus taps latent demand. This development usually results in an initial period of rapid growth; in the United States from 1950 to 1960, for example, aviation demand grew very rapidly, at an average annual rate of 14.1% (Taneja. 1976).

Continued expansion: An airport network is a dynamic infrastructure that opens up new avenues for business and personal travel. People learn to work and do business in more distant places, and the diaspora of emigration can expand. As aviation becomes incorporated into leisure and business habits, demand for travel increases enormously and the network of trading and personal ties expands geographically. This results in a rapid and continuing growth in demand. Figure 3 includes the US history of annual flight miles in revenue passenger miles (RPM), i.e. occupied seat miles; this history, and the fact that 31% of the US adult population flew in 1990 (Boeing, 1993), shows the steady incorporation of aviation into personal and business habits.

Modal shifts: Aviation transcends most geographical barriers and, for longer journeys, offers significant time savings over land- and sea-based transport: it thus provides incentives to shift from other transport options. Access to aviation also creates opportunities for new business ventures, such as the export of perishable items. In general, as the income level of an individual or a firm rises, so does the personal value placed on time. In the passenger market as well as portions of the freight market, income growth favors a modal shift from land- and sea-based transport to aviation.[2] This trend is clear in most Organization for Economic Cooperation and Development (OECD) member nations, where from 1973 to 1992 the modal structure of transportation has shifted away from buses and rail toward airplanes (Scholl *et al*, 1996).

Eventual maturity:[3]Barring unforeseen developments, it is likely that aviation demand will eventually reach maturity as it approaches market capacity and relative growth rates slow. Trends toward maturity are evident already in the US domestic market and in the markets of many industrialized nations.

The logistic differential equation is a simple dynamic model of growth in the presence of market capacity limits. Various forms of this model have been used extensively to successfully represent a wide range of processes, from the market demand for a new service, such as cable television for example, to the penetration of technologies, such as a new automobile engine design (Lakhani, 1975). In the energy-modeling literature, the logistic has been used typically with a constant capacity to represent for example the dynamics of technological and modal substitution in a single industry (Marchetti, 1980; Edmonds and Reilly, 1985).

Table 1 Sectors of aviation demand market

No.	Sector	Share of global aviation fuel usage – 1990[a] (%)
1	Civil business	14.6%
2	Civil personal	42.1%
3	Civil freight	17.8%
4	Military	22.8%
5	General aviation	2.8%

[a]Vedantham and Oppenheimer (1994, p. 20).

Continued growth of GNP and population imply a continuing, albeit slow, growth in demand, even over the very long term. We use a logistic model with a time-varying capacity that captures eventual slowdown in growth rates without imposing a zero-growth rate ceiling. This model has been used by biologists to represent population growth in an environment with a growing carrying capacity (May, 1981). The logistic model is a 'business-as-usual' look at market evolution; it provides a useful baseline for consideration of the effects of external, unpredictable factors such as energy crises and policy changes.

Sectors of aviation demand

We divide aviation demand into five sectors as listed in Table 1: the civil passenger market is split into business travel and personal travel sectors, where personal travel includes tourism and leisure visits. The civil freight sector includes the sizable fraction of freight that is transported by passenger aircraft. Demand is measured in ton-kilometers (TK), which measures both weight carried and distance flown.

The separation of passenger travel into business and personal sectors is complex, since empirical data is weak. Estimates of the global business travel share range from 33% to 40% (Boeing, 1995; and Gould, 1996); furthermore, the relative shares of business and personal travel varies widely across nations. In general, business travel's share of the total is much higher in poorer nations; China for example may have a business share as 80 90%.[4] Reasons for a high business share in developing nations include low levels of disposable income, and government restrictions on travel and foreign exchange currency. Our region-specific estimates for business share are provided in Table 4.

Definition of economic groups

The traditionally wealthy economies of the world such as the United States and most members of the OECD, have

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[2] Personal communication with James A. Edmonds, Batelle Laboratories, August 1993.

[3] We define a market as mature when the annual demand growth rate differs from the annual growth rate of market capacity by less than 5%.

[4] Personal communication with Kim Cheung, Marketing Research, Boeing (1993).

Table 2 Definition of economic groups

No.	Group name	Members
1	Industrial economies	OECD members, except Japan
2	Newly industrialized economies	Asian Newly Industrialized Countries (NICs), Japan
3	Rapidly developing economies	China and the rest of Asia
4	Slowly developing economies	Africa, Latin America, the Middle East
5	Post-Communist economies	Post-USSR states, Eastern Europe

had an extensive airport network in place for many years now, and substantial segments of their populations have become accustomed to flying often. In most developing countries, on the other hand, only a skeletal network exists, and the vast majority of the population has never flown. Many developing countries are planning large-scale investments in airport infrastructure, in anticipation of a demand boom as incomes rise. China, for example, is a unique growth area, with Shanghai planning a new airport for 60 million passengers a year, and national plans for development of 50 to 100 new airports over the next 10 years (Gould, 1996).

The model sorts the nations of the world into five economic groups described in Table 2. The lack of reliable long-term projections of country-specific economic and demographic change necessitates this level of geographic generalization. The assignment of countries to these five large groups may be of limited relevance for a few nations. Brazil, for example, falls in Group 4, but may well experience rapid expansion soon.

Sector-specific models

Within each economic group, we model three sectors of civil aviation separately: civil business passenger, civil personal passenger, and civil freight. These sectors are modeled as logistics with time-varying market capacities. The change in demand level $D_{s,g}$ in sector s for economic group g varies over time t (in years) as

$$\frac{\mathrm{d}D_{s,g}}{\mathrm{d}t} = r_{s,g}D_{s,g}\left(1 - \frac{D_{s,g}}{C_{s,g}K_{s,g}(t)}\right)$$

where $r_{s,g}$ is the intrinsic rate of expansion, and $C_{s,g}K_{s,g}(t)$ is the capacity of the market. $C_{s,g}$ is a constant capacity factor and $K_{s,g}\,(t)$ is a time-dependent variable.

Business passenger and freight demand: These two sectors depend strongly on the health of the economy. We assume that once a new market is opened up, these two sectors experience a logistic expansion toward a capacity level that is a constant fraction of the nation's GNP, setting $K_{1,g}(t) = K_{3,g}(t) = \mathrm{GNP}_g(t)$. The relation between the capacity level factor and GNP is likely to be different for individual nations. For example, an island nation like the United Kingdom will need a proportionally larger business aviation sector than a continental and well-connected nation like France. Given the sizable number of nations within each economic group, we assume however that such differences will average out across the economic groups.

Personal passenger demand: We assume that the expansion in business travel is accompanied by an expansion in personal travel, which includes tourism and leisure visits. Per-capita demand varies much more widely across nations, and thus across economic groups, than does demand per unit GNP. For example, in 1990, the average North American flew 1740 miles, while the average African flew only 45 miles (Boeing, 1993). The demand analysis in the second column of Table 4 shows the remarkably large range across economic groups in the 1990 ratio of passenger demand to population.

This disparity in levels of per-capita travel reveals a large pool of latent demand in some economic groups. Since personal travel by air has a high income elasticity,[5] demand will increase rapidly when a poor nation experiences an economic boom and per-capita income increases. However, there is great domestic income inequality within most developing countries (World Bank, 1993) and significant demand for aviation is likely even in countries with very low per-capita incomes (Atkinson, 1975).

Aviation demand is a continuously increasing function of income, with people in higher-income brackets having a much higher per-capita demand level. In the United States, 76% of the 4085 households with income over $100,000 flew in 1990 compared to 11% of the 14,085 households with incomes of less than $10,000. Growth in aviation demand depends fundamentally on penetration into lower income brackets (Boeing, 1993). This dynamic indicates the potential for high aviation demand from developing countries as incomes rise and seat prices (as well as cargo costs) fall. We assume that current differences in domestic income inequality between industrial and developing countries will decrease over time.[6] It follows that, although personal travel levels will always vary widely across income brackets, total personal travel

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[5] Personal communication with Clifford Winston, Brookings Institution, March 1993.

[6] Atkinson (1975), p. 22; World Bank (1994). The latter reference makes clear that over decadal timescales this assumption is not uniformly valid.

Table 3 Summary of IPCC Scenarios[a]

Scenario name	World population (Billions)		Average annual global GNP growth rate	
	In 2025	In 2100	1990–2025	1990–2100
IS92a, IS92b	8.4	11.3	2.9%	2.3%
IS92c	7.6	6.4	2.0%	1.2%
IS92d	7.6	6.4	2.7%	2.0%
IS92e	8.4	11.3	3.5%	3.0%
IS92f	9.4	17.6	2.9%	2.3%

[a] Leggett (1992, p. 78).

demand is likely to depend in the long term on the population of a nation.

We model personal passenger demand as a logistic with a capacity level proportional to the region's population, setting $K_{2,g}(t)$ = Population$_g(t)$. The model does not account for possible feedback relationships between GNP and population.

Military and general aviation demand: Given the end of the Cold War, no substantial arms race is currently expected. The world's primary military powers — the United States and the states that constituted the former Soviet Union — together account for half the world's military fleet (Stolarski and Wesoky, 1993a, p.135), and they are currently reducing their military expenditures. The general aviation group constitutes 3% of the total aviation market and is predominantly a leisure activity in wealthy economies. We assume that both these sectors do not experience logistic expansion, instead they grow nominally, at the same rate as global GNP. More elaborate models are possible over the short-term, but the long-term dynamics of these sectors are difficult to determine.

Thus, for these two sectors:

$$\frac{dD_{4,g}/dt}{D_{4,g}} = \frac{dD_{5,g}/dt}{D_{5,g}} = \frac{dGNP_g/dt}{GNP_g}$$

GNP and population growth assumptions

The IPCC has created six emissions scenarios (named IS92a through IS92f) built from five forecasts of GNP and population growth through the year 2100 (Leggett, 1992; Pepper, 1992). The five region-specific forecasts provide a range of plausible futures; Table 3 summarizes the global values (Leggett, 1992, pp. 69–97). The IPCC report includes analysis of expected policy changes affecting fuel prices and emissions limits. Feedback from the IPCC's policy assumptions to the GNP growth-rate projections is insignificant;[7] our model does not include the policy assumptions in projecting aviation demand.

Market dynamics

Start of expansion: The airline industry in a newly developing market will experience a sharp boom when it taps into latent demand. It is reasonable to assume that the boom in aviation demand will reflect a growing economy. Although the establishment and expansion of an airport network can follow a policy edict, a country with a booming economy is more likely to invest in an airport network than a country experiencing economic or political dislocation. Public policy decisions to build airports and define flight routes have long-lasting economic consequences. Financial investment often has greater impact in a new market; a million dollar investment in China, for example, creates more airport capacity than the same amount would, if spent in the West (Gould, 1996).

Economic Groups 1 and 2 have already begun aviation market expansion; we assume that most nations in Groups 3, 4 and 5 represent largely unserved markets. For Groups 3, 4 and 5, our assumptions regarding the start of market expansion reflect near-term economic expectations; prior to the expansion start date, demand grows nominally in proportion to GNP growth. Annual demand growth is very sensitive to business cycles and transient phenomena. Since the logistic represents a smooth long-term dynamic, these dates approximate the beginning of rapid growth, and cannot reflect near-term changes accurately.

Market capacity: Figure 2 shows the demand and GNP growth rates for the US domestic market, providing a valuable microcosmic look at the evolution of a fairly well-contained, mature aviation market. The historical graph traces the high demand growth rates during expansion in early 1950s, close correlation with economic business cycles throughout, and a steady downward trend in demand growth rates as the market approaches maturity.

Building on Figure 2, we create two sets of market capacity levels based on multiples of the 1990 demand levels for Group 1 (the OECD nations excepting Japan), since this economic group is closest to maturity today. For business passenger and freight demand, we set the base capacity level at twice the 1990 demand level for these sectors, and the high level at three times the 1990 demand level. Similarly for personal passenger demand, we set the base level at twice the 1990 personal passenger demand for Group 1, and the high level at three times the 1990 level (Vedantham and Oppenheimer, 1994). Since the economic groups span large geographic areas, we assume that any country-specific and culture-specific variations in capacity level that may exist will not result in significant differences across economic groups.

Maturation period: Figure 2 indicates approximately a 70-year period from start of market expansion to maturity for the US market. However, nations that are building their infrastructure today may well attain

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[7] Leggett *et al* (1992), p. 76; personal communication with William Pepper and Jane Leggett, principal authors of Pepper *et al* (1992).

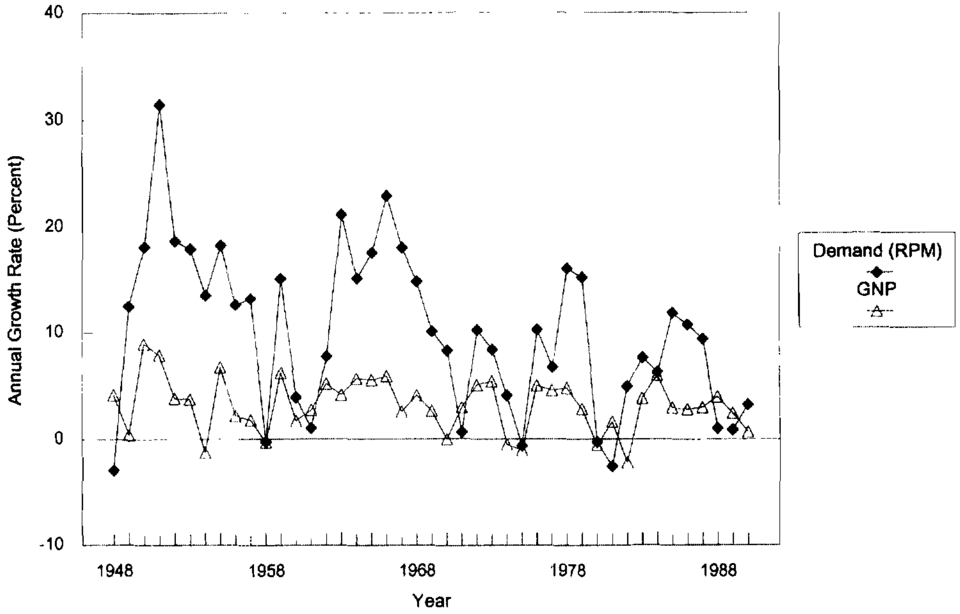

Figure 2 History of demand and GNP growth rates: US domestic passenger market

Table 4 Demand analysis and definition of demand sets

Economic group	Ratio of demand to population (ton-km per capita)	Business Share[a]	Expansion start	Base-demand maturation date	High-demand Maturation Date
1. Industrial economies	178	10%	begun	2010	2010
2. Newly industrialized economies	52	15%	begun	2050	2030
3. Rapidly developing economies	4	62%	2000	2070	2050
4. Slowly developing economies	20	62%	2010	2080	2060
5. Post-communist economies	66	50%	2010	2060	2040

[a] Detailed breakdown available in Vedantham and Oppenheimer (1994)

market maturity faster. They will benefit from technological improvements, and some fraction of their populace will be more familiar with lifestyle and business habits that incorporate aviation. For example, China's investment in aviation is aiming to achieve in a decade what many countries have taken half a century to complete (Gould, 1996). Markets in the post-Communist economies are likely to mature faster than those of developing countries (Groups 3 and 4) because they have undergone industrialization.

We create two demand sets termed as base-demand and high-demand. Each demand set includes assumptions on market capacity level, expected start date for market expansion, and maturity period length: Table 4 presents the details. These demand sets amount to implicit assumptions about diverse social factors, including travel trends in developing countries, penetration of future telecommunications technologies, and development of competing modes of transportation.

Validation of the demand model: We validate the demand by applying it to the history of the US aviation market from 1947 to 1990. Logistic expansion begins prior to 1947 and follows the base-demand set of assumptions for Group 1. Figure 3 compares historical demand and the model results. The model provides a good approximation of the overall trend; however, as expected, it cannot capture short-term fluctuations.

Demand projections

The five IPCC scenarios and the two demand sets above provide a total of 10 demand projections. Figure 4 shows our global demand projections under the six IPCC scenarios for the base-demand set. The sharp upswings when different regions start expansion are clearly visible. Under the 'middle' IS92a scenario (considered the IPCC base case), the base-demand level in 2100 is higher than the 1990 level by a factor of 22, and has an average annual demand growth rate of 2.85% over the 110 year forecast period. Table 5 provides model results for selected years for both the base-demand and high-demand sets. For both the base-demand and high-demand sets, the range for different population and GNP estimates is considerable, spanning more than a factor of three in

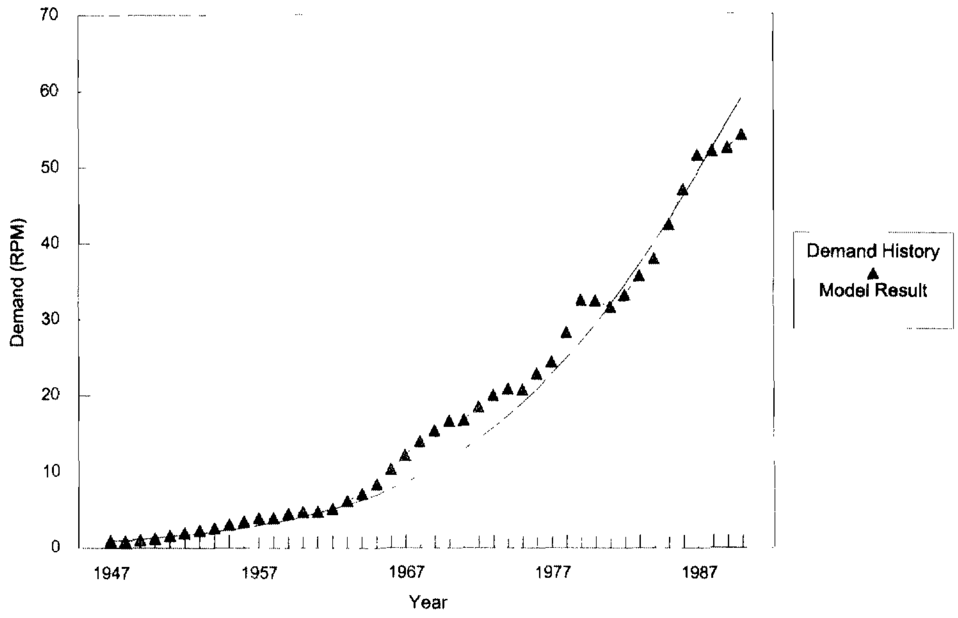

Figure 3 Validation of model: comparison to US domestic passenger market history

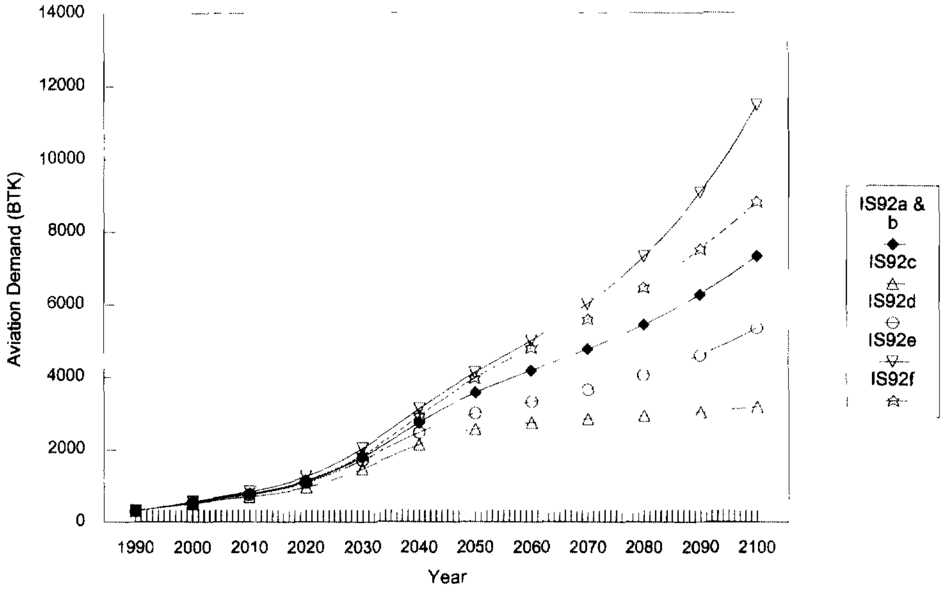

Figure 4 Demand scenarios - Base-Demand Set

2100. Clearly the evolution of population and GNP will have a large effect on aviation demand. The assumptions about rates of expansion and maturity are also important; the high-demand projection for the IS92a scenario in the year 2100 is more than 55% higher than the base-demand value.

Improvement in fuel efficiency

Fuel efficiency has increased steadily over the last few decades due to new engine and airframe technologies, as well as operational improvements that lead to higher load factors and more efficient routing. However, improvements in fuel efficiency are becoming less dramatic over time (Price, 1995).

Balashov and Smith of ICAO have calculated fuel efficiency in 1990 for global civil aviation at 510g of fuel/TK, and estimate an annual decline in fuel consumption per TK of 2–3% from 1976 to 1990 (Balashov, 1992). The study predicts an annual reduction in civil aviation's fuel consumption per TK of 3.1% from 1990 to 2000, and 2.5% from 2000 to 2010. Greene has conducted a detailed analysis of engine and airframe technologies and synthesized a range of short-term estimates. He forecasts

Table 5 Summary of All Model Results

Factor	1990
Demand (BTK)	332
Fuel Use (Mt)	179
CO_2 (GtC)	0.15
Percent of Global CO_2	2.1%
NO_x (Mt)	1.96
NO_x above 9 km (Mt)	1.15

Model Results		Base-demand level					High-demand level				
IPCC Scenario	Factor	2000	2015	2025	2050	2100	2000	2015	2025	2050	2100
IS92a	Demand (BTK)	555	935	1428	3556	7336	887	1522	2803	6329	11568
	Fuel Use (Mt)	258	374	544	1143	1484	395	610	1123	2086	2378
	CO_2 (GtC)	0.22	0.32	0.47	0.99	1.28	0.34	0.53	0.97	1.8	2.05
	Percent of Global CO_2	2.6%	NA	3.8%	6.8%	6.3%	4.1%	NA	7.9%	12.4%	10.1%
	NO_x (Mt)	2.57	3.28	4.42	7.88	7.93	3.92	5.34	9.12	14.39	12.71
	NO_x above 9 km (Mt)	1.51	2.03	2.73	4.87	4.90	2.30	3.30	5.63	8.89	7.86
IS92b	Demand (BTK)	555	935	1428	3556	7336	887	1522	2803	6329	11568
	Fuel Use (Mt)	258	372	544	1143	1484	395	610	1123	2086	2378
	CO_2 (GtC)	0.22	0.32	0.47	0.99	1.28	0.34	0.53	0.97	1.8	2.05
	Percent of Global CO_2	2.7%	NA	4.0%	7.1%	6.7%	4.1%	NA	8.2%	13.0%	10.7%
	NO_x (Mt)	2.57	3.28	4.42	7.88	7.93	3.92	5.34	9.12	14.39	12.71
	NO_x above 9 km (Mt)	1.51	2.03	2.73	4.87	4.90	2.30	3.30	5.63	8.89	7.86
IS92c	Demand (BTK)	527	816	1193	2563	3169	847	1330	2389	4577	5115
	Fuel Use (Mt)	243	325	455	837	658	375	530	961	1528	1078
	CO_2 (GtC)	0.21	0.28	0.39	0.72	0.57	0.32	0.46	0.83	1.32	0.93
	Percent of Global CO_2	2.8%	NA	4.5%	9.6%	12.3%	4.3%	NA	9.4%	17.6%	20.2%
	NO_x (Mt)	2.42	2.42	3.7	5.77	3.52	3.73	4.65	7.81	10.54	5.76
	NO_x above 9 km (Mt)	1.42	1.50	2.29	3.56	2.18	2.19	2.87	4.82	6.51	3.56
IS92d	Demand (BTK)	549	908	1375	2990	5347	876	1475	2694	5146	8219
	Fuel Use (Mt)	255	364	525	958	1075	390	592	1081	1688	1677
	CO_2 (GtC)	0.22	0.31	0.45	0.83	0.93	0.34	0.51	0.93	1.45	1.45
	Percent of Global CO_2	2.9%	NA	4.9%	9.2%	9.0%	4.5%	NA	10.0%	16.2%	14.0%
	NO_x (Mt)	2.53	3.19	4.26	6.61	5.75	3.88	5.19	8.79	11.64	8.96
	NO_x above 9 km (Mt)	1.49	1.97	2.63	4.08	3.55	2.28	3.21	5.43	7.19	5.54
IS92e	Demand (BTK)	575	1023	1605	4111	11483	912	1659	3089	7089	17389
	Fuel Use (Mt)	268	412	611	1298	2260	408	668	1234	2297	3474
	CO_2 (GtC)	0.23	0.35	0.53	1.12	1.95	0.35	0.58	1.06	1.98	2.99
	Percent of Global CO_2	2.5%	NA	3.5%	5.6%	5.4%	3.9%	NA	7.0%	9.8%	8.4%
	NO_x (Mt)	2.67	3.61	4.96	8.95	12.08	4.05	5.85	10.02	15.84	18.57
	NO_x above 9 km (Mt)	1.57	2.23	3.06	5.53	7.47	2.38	3.61	6.19	9.78	11.48
IS92f	Demand (BTK)	558	949	1459	3959	8823	894	1554	2893	7299	14388
	Fuel Use (Mt)	259	379	554	1284	1821	398	620	1158	2429	3018
	CO_2 (GtC)	0.22	0.33	0.48	1.11	1.57	0.34	0.53	1	2.09	2.6
	Percent of Global CO_2	2.5%	NA	3.3%	6.4%	5.9%	3.9%	NA	6.9%	12.2%	9.8%
	NO_x (Mt)	2.58	3.32	4.5	8.85	9.73	3.95	5.43	9.41	16.75	16.13
	NO_x above 9 km (Mt)	1.52	2.05	2.78	5.47	6.01	2.32	3.36	5.81	10.35	9.97

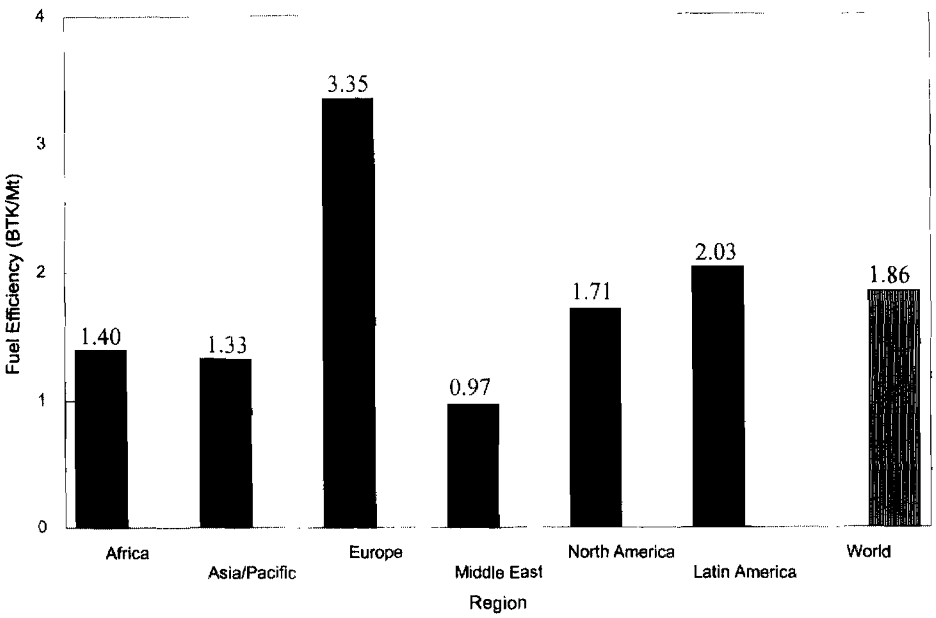

Figure 5 Civil aviation's fuel efficiency in 1990

a base-case annual increase in fuel efficiency of the commercial aircraft fleet of 1.3% over the period from 1989 to 2010 (Greene, 1992)

Although technological and operational breakthroughs are difficult to foresee, the pace of efficiency improvement is likely to decline over the long term especially in the absence of policy changes. We model fuel efficiency with a constant-capacity logistic to describe the diminishing returns, assuming a business-as-usual policy background. We recognize however that such mathematical extrapolation implicitly assumes the successful incorporation of technological breakthroughs that cannot be foreseen as extensions of today's technology. The model's parameters are chosen to match the short-term estimates from ICAO and Greene above. Future policy disincentives for energy use may increase the rate of efficiency improvement beyond our assumptions.

Figure 5 shows fuel efficiency for civil aviation in 1990 for seven geographic regions, based on ICAO, IEA and NASA statistics. An important caveat is that ICAO and IEA use different conventions for geographical allotment, with ICAO crediting passenger kilometers to the airline's country of origin, and IEA crediting fuel use to the country where fuel is loaded. Both conventions offer incomplete pictures. Nevertheless, we can conclude that there are strong differences in fuel efficiency today across regions and that there may be a tendency toward higher fuel efficiency in wealthier regions. We assume that Economic Group 1 has the highest fuel efficiency in 1990, followed in order by Groups 2, 3, 4 and 5: the military and general aviation markets have fuel efficiency levels lower than Group 1

The rate of fuel efficiency improvement is also likely to differ across economic regions, but a clear trend is difficult to discern here. A developing nation may not have the capital to invest in the state-of-the-art technologies that an industrial nation might prefer. Local environmental laws may affect engine emissions. Often developing nations give a second life to airplanes that have become too noisy and inefficient for wealthier nations. On the other hand, load factors tend to be higher in developing countries than in industrial countries, raising fuel efficiency (Barrett, 1994). Also, a newly industrializing country may buy the latest aircraft, building a more modern fleet as a result. We assume that Groups 3 and 4 have a slightly slower rate of improvement than the others.

Fuel usage projections

Figures 6 and 7 compare the efficiency and fuel use projections, respectively, for the ICAO and Greene estimates under the IS92a base scenario and the base-demand set. Clearly, the evolution of fuel efficiency will be a crucial determinant of aviation fuel use, and policy incentives that encourage appropriate research into engine and airframe technology can have significant impact here. We use the Greene efficiency estimate in all subsequent analysis.

Table 5 provides details on fuel use for all IPCC scenarios. Under some scenarios, fuel consumption by aviation becomes a substantial fraction of primary energy used in the form of liquid fuels after 2050. If commercial production of liquid biofuels or synthetic fuels does not provide additional supplies, then price changes could affect the validity of the projections in later years.

Carbon dioxide (CO_2) emissions

Calculation of CO_2 emissions from the fuel use projections is straightforward since the emission index (EI),

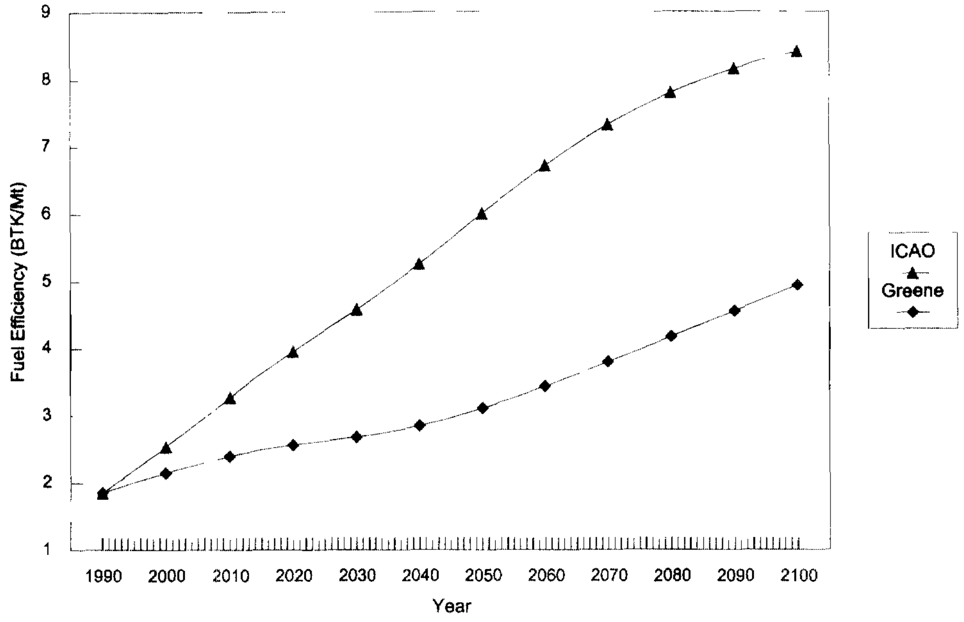

Figure 6 Fuel efficiency ICAO and Greene; estimates under IS92a, Base-Demand Set

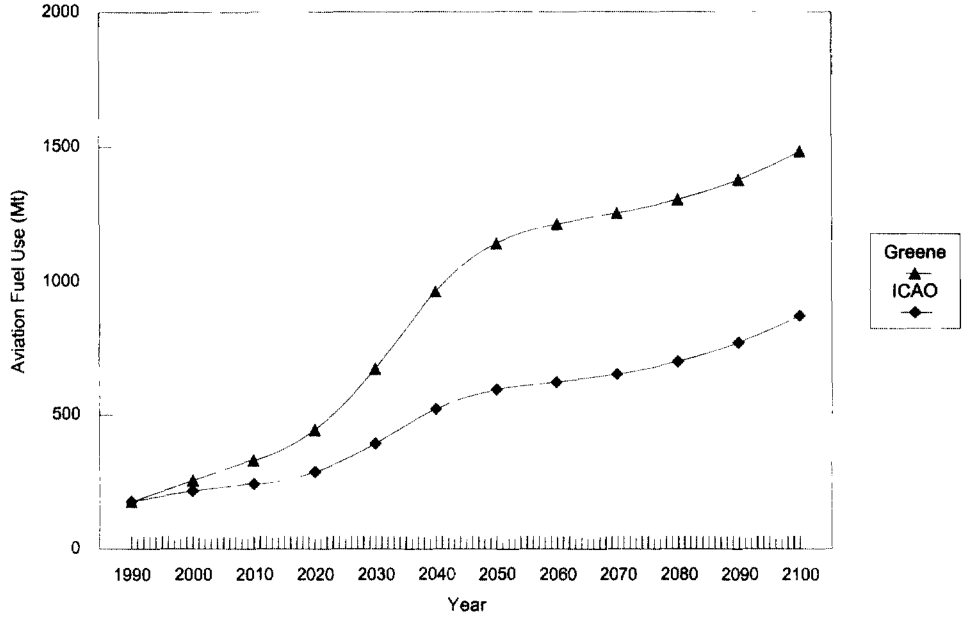

Figure 7 Fuel use projections ICAO and Greene; estimates under IS92a, Base-Demand Set

defined as the weight ratio of pollutant emitted to fuel burned in g/kg, is unlikely to change much over time from its current value of 3.16 (Prather, 1992). This assumes that aviation continues to depend largely on jet fuel as it does today (Balashov and Smith, 1992), and that the fuel's composition and purity does not change significantly.

Figure 8 shows CO_2 emissions projections for the six IPCC scenarios under the Base Demand Set. Under the Base-Demand Set and the IS92a scenario, CO_2 emissions grow at an annual rate of 1.9% over the 110 year forecast period, reaching 1.3 gigaton carbon (GtC), an increase of a factor of 8 over the 1990 level. Model results in Table 5 show that, for both the Base-Demand and High-Demand Sets, the range for different population and GNP estimates spans more than a factor of three by 2100. Of particular interest, projected CO_2 emissions rise only modestly above current levels by 2015 (the limit of current industry-government projections) but climb rapidly thereafter, reaching thrice current levels by 2025 for the base-demand IS92a scenario. For the IS92c scenario (low population and GNP growth) under both demand sets, the level of CO_2 emissions in 2100 is lower than that in 2050, reflecting a successful catch-up effect where

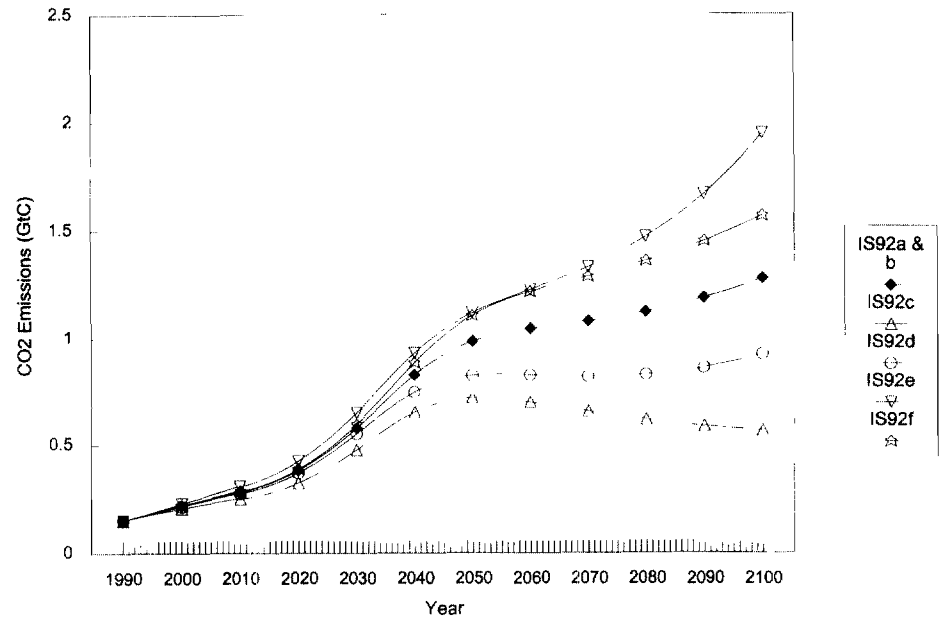

Figure 8 CO_2 emissions scenarios - Base-Demand Set

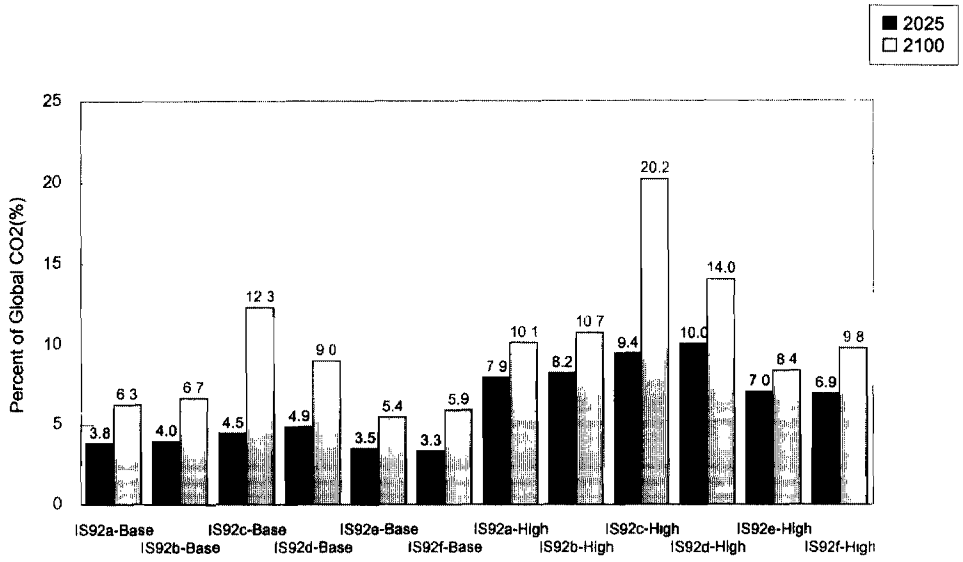

Figure 9 Fraction of global CO_2 emissions: IPCC scenarios, High and Base-Demand Sets, no policy assumptions

technological improvements have compensated for demand growth.

The CO_2 emissions projections for aviation can be compared with the IPCC's scenarios for total anthropogenic CO_2 emissions (including emissions from energy consumption and deforestation), though some caveats are needed. Many of the IPCC scenarios include policy assumptions affecting fuel prices and emissions. Our model, on the other hand, includes no policy assumptions, offering a business-as-usual viewpoint only.

Figure 9 shows the fraction of global CO_2 emissions from aviation in 2025 and 2100 for both demand sets (through a direct comparison between our model's results and the IPCC scenarios' emission estimates). We can conclude that aviation may well become a significant contributor to global CO_2 emissions.

The base IPCC IS92a scenario assumes no policy effects, so the direct comparison between our model's results and this IPCC scenario is straightforward. IS92b assumes some restrictions on CO_2 emissions from industrialized nations; at 2.1% of global CO_2 emissions, the aviation sector is unlikely to experience more than a slight decline as a result. IS92c and IS92d assume a much lower level of global fossil fuel resources, which will tend to increase fuel prices and provide incentives for fuel efficiency improvement. For these two scenarios, aviation fuel use is likely to decline, bringing down the global share of aviation emissions compared to the

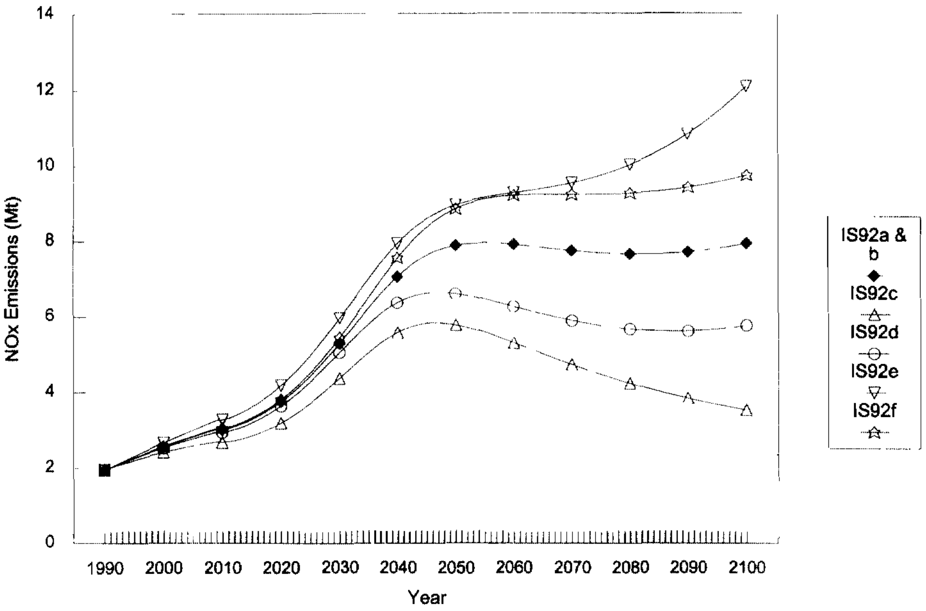

Figure 10 NO_x emissions scenarios Base-Demand Set

values in Figure 9. IS92e and IS92f assume greater fuel availability, which would decrease incentives for fuel efficiency improvement; as a result, aviation's CO_2 emissions may increase compared to the values in Figure 9.

Emissions of nitrogen oxides (NO_x)

Estimating NO_x emissions from fuel use projections is a complex task. The emissions index (EI) for NO_x varies greatly with the altitude, thrust-level, engine-design, combustor-type, aircraft frame and other factors. Estimates for specific engine-airframe combinations range from 6 to 40 g of NO_x (as nitrogen dioxide) per kg fuel (Egli, 1990). Since our model is a highly aggregated one, we use a single average emission index for NO_x. There is substantial variation in estimates of the current average index for NO_x. Egli and Schumann propose an average index of 18 while the NASA inventory determines an index of 10.9 (Stolarski, 1993a). The difference in proposed EI values has significant impact on estimates of current NO_x emissions.

Unlike CO_2, the EI for NO_x is likely to change significantly over time as new engine technology develops and is incorporated into the fleet. Despite the potential for improvements in combustor technologies that determine NO_x emissions, there are trade-offs between increasing the fuel efficiency of an aircraft engine and reducing its emitted NO_x.[8] The evolution of aggregate NO_x EI depends on the details of future engine technology, as well as changes in fleet mix. The NASA inventory assumes a reduction in the aggregate NO_x EI of approximately 20% by 2015 (Stolarski, 1993a). A consensus has been emerging however in favor of a more pessimistic estimate for NO_x EI. Recent projections by the United Kingdom's Department of Trade and Industry assume only 6.3% reduction from 1993 to 2020.[9] As in the case of fuel efficiency improvement, progress in reducing NO_x EI is likely to decline over the long term, in the absence of policy changes. The model uses a constant-capacity logistic with parameters that match the short-term NASA estimate. As in the case of the fuel efficiency projections, we recognize that specific technologies to support such evolution in NO_x EI cannot yet be defined.

Figure 10 shows the NO_x emissions projections for the base-demand set, and Table 5 provides detailed results for both demand sets. Since total NO_x emissions are reduced because of both fuel efficiency improvement and EI reduction, technological improvement can compensate for a greater fraction of demand growth than was possible in the case of CO_2 emissions. For the IS92c and IS92d scenarios (lower population and GNP growth) under both demand sets, the level of NO_x emissions in 2100 is lower than that in 2050, showing the cumulative gain of efficiency and emissions index improvements over demand growth.

NO_x emissions at cruise altitudes

Calculation of emissions at different altitudes and latitudes requires analysis of current and future flight routes

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[8] Bahr (1992); personal communication with A. J. Fiorentino, Pratt and Whitney (October 1993).

[9] Personal communication with Peter Newton, Department of Trade and Industry of the United Kingdom, London.

ideally using individual city-pairs. The NASA inventory provides a detailed distribution for the years 1990 and 2015, and determines considerable variation in aggregate NO_x EI as a function of altitude.

As indicated in Figure 1, the tropopause lies between 9 and 17 km altitude. We estimate future emissions in the upper troposphere and lower stratosphere by scaling the NO_x projections using the NASA inventory's database of emissions above 9 km. We scale the NASA projections upwards to account for 100% of the IEA estimate on total fuel consumption; this calculation indicates global NO_x emissions of 1.15 Mt above 9 km in 1990. Table 5 provides the results for different scenarios. This assumes only that aircraft will continue to burn fuel at altitudes above 9 km throughout the next century in amounts proportional to the current fraction of emissions there. Finer estimates can be made, but their long-term plausibility is unknown. We include no new policy assumptions regarding NO_x emissions; additional restrictions aimed at the landing–takeoff (LTO) cycle may affect emissions at cruise altitudes.

The environmental effects of NO_x emissions may be significantly different in the lower stratosphere as opposed to the upper troposphere. Since the altitude of the tropopause varies considerably with latitude and with season, a much closer analysis of altitude effects, as well as future flight paths and seasonal factors, will be needed to determine environmental impact on the stratosphere.

Also, the distribution of emissions in particular areas of the globe needs further study. NASA's city-pair analysis of traffic in 1990 and 2015 indicates that certain flight corridors, especially in the northern mid-latitudes, receive much higher levels of emissions than the global average. Over the next century, the growth of demand from developing countries will change this distribution significantly. Comparison of NASA's latitude distributions for the years 1990 and 2015 reveals a consistent redistribution of emissions to the equator and southern latitudes (Stolarski, 1993a). Over the next century, this trend can be expected to continue; as a result, emissions will be distributed more evenly across latitudes. Distribution across longitudes is much harder to determine, since the evolution of particular cities and flight corridor patterns cannot be analyzed across several decades.

Conclusion

The EDF model focuses on long-term dynamics in the global aviation market. The present disparities in per-capita aviation demand between rich and poor nations are very large. Significant latent demand for aviation services exists in poorer nations; vast regions in many developing countries are as yet untouched by airport networks. Increases in GNP and personal income levels are likely to result in rapid expansion and growth of aviation demand in these regions. The timing and extent of industrialization can be crucial in determining the extent of environmental impact.

Based on our assumptions regarding the evolution of aviation markets, highlights of model results include:

- Demand for aviation services is expected to grow throughout the next century. Growth rates are expected to peak around 2030 in the base case, with a corresponding increase in global demand by a factor of 10 by 2050, and a factor of 22 by 2100.

We have not considered the effects of possible positive feedback between an improved aviation infrastructure and continued economic growth, which may contribute to further demand growth. We have also not considered non-economic factors like increased tourism across greater distances, which would alter the distribution of flights among city-pair routes, or the rapid diffusion of telecommunications technology which could reduce demand growth.

- Fuel consumption, CO_2, and water vapor emissions by subsonic aircraft would jump by more than a factor of 8 by 2100 in the base case, despite substantial increases in fuel efficiency. Different GNP and population assumptions lead to growth as low as a factor of 4 or as high as a factor of 19. For the IS92a base scenario, aviation's CO_2 emissions amount to 1.3–2.1 Gtons of carbon in 2100; for comparison, all US fossil fuel use today amounts to roughly 1 Gton of carbon. Comparison with IPCC scenarios indicates that aviation contributes 3–10% of global CO_2 emissions by 2025 and 5–20% by 2100.
- NO_x emissions from subsonic aircraft would range from 3.5 Mt to 18.6 Mt by the year 2100, with a base case estimate of 7.9 Mt, despite a reduction by half in EI.
- Much of the demand and emissions growth occurs after the year 2015, the horizon of most other aviation emission projections.

As we consider the consequences of the potential growth of aviation emissions, we can draw precedents from the tremendous and continuing boom in automobile use in the United States. The current level of one automobile for every two people and 12,400 miles driven per vehicle per year could not have been foreseen when the automobile industry was young. (Davis, 1993) We make the following general recommendations:

- Proactively limiting aviation emissions now will reduce the risk to the global environment, while allowing more flexibility later in managing all sources of climatic change and ozone depletion. An efficient and fair allocation of responsibility for cruise altitude emissions from international flights needs to be determined.
- Model results indicate the potential for technological progress to reduce the emissions consequences of demand growth. Developing a 'green' airplane should

become an US national policy goal and a goal of the aircraft manufacturing industry.

- Earlier results indicate that effective technology transfer from industrial to developing nations can help reduce emissions. (Vedantham and Oppenheimer, 1994) Policies that facilitate rapid dissemination of aviation improvements will accelerate increases in engine efficiency and decreases in fleet-wide NO_x EI.

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