Aircraft Emissions and the Global Atmosphere

Abstract

Emissions from airplanes and their potential global effects on the atmosphere have become the subject of intensive study by scientists, and are now drawing the interest of governments. Global fuel consumption has risen much faster for aviation than for other energy-use sectors. Concerns have focused on the contribution of nitrogen oxides (NO_x), carbon dioxide ($C0_2$), water vapor (H_20) and other engine effluents to the buildup of the atmosphere's greenhouse effect. Future aircraft emissions also may affect the stratosphere's ozone layer.

This report describes an effort to develop long-term scenarios for emissions from aviation in order to provide a basis for assessing their potential environmental impact throughout the 21st century. Carbon dioxide and nitrogen oxides from the current and projected subsonic aircraft fleets are the main focus of this study. The scenarios in this report were produced by a model that builds on technological and operational assumptions made by industry and government for the period through 2015.

It is important to state from the outset what this report is not about. It is not a detailed examination of the environmental effects of aviation. It is not an assessment of the potential for technological or operational changes that could reduce emissions from expected levels. It does not set forth a comprehensive and detailed policy prescription for limiting emissions from aviation. This report does not analyze the potential emissions of a vastly expanded fleet of supersonic aircraft, such as the proposed High-Speed Civil Transport (HSCT), although its possible environmental impacts are discussed briefly.

Comments

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AIRCRAFT EMISSIONS
AND THE
GLOBAL ATMOSPHERE

Long-term Scenarios

By
Anu Vedantham
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ENVIRONMENTAL
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The Environmental Defense Fund (EDF) is a leading national, New York-based, not-for-profit research and advocacy organization with over 250,000 members nationwide. EDF's staff includes scientists, economists, engineers, and attorneys who seek practical solutions to a broad range of environmental and human-health problems.

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EXECUTIVE SUMMARY

Emissions from airplanes and their potential global effects on the atmosphere have become the subject of intensive study by scientists, and are now drawing the interest of governments. Global fuel consumption has risen much faster for aviation than for other energy-use sectors. Concerns have focused on the contribution of nitrogen oxides (NO_X), carbon dioxide (CO_2), water vapor (H_2O) and other engine effluents to the buildup of the atmosphere's greenhouse effect. Future aircraft emissions also may affect the stratosphere's ozone layer.

This report describes an effort to develop long-term scenarios for emissions from aviation in order to provide a basis for assessing their potential environmental impact throughout the 21st century. Carbon dioxide and nitrogen oxides from the current and projected subsonic aircraft fleets are the main focus of this study. The scenarios in this report were produced by a model that builds on technological and operational assumptions made by industry and government for the period through 2015.

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Carbon dioxide is a greenhouse gas, and its continued buildup is expected to lead to significant global warming. Nitrogen oxides have two potential consequences on a global scale. In the upper troposphere (i.e., approximately 6-12 km altitude at mid-latitudes), where most aviation emissions occur, NO_x emissions are likely to stimulate the production of ozone, which acts as a potent greenhouse gas at those altitudes. Water vapor emitted there may enhance cirrus cloud formation, which would also contribute to greenhouse warming.

Some emissions from subsonic aircraft and the majority of emissions from supersonic flight occur directly in the lower stratosphere (roughly 12-20 km altitude), where NO_x emissions can affect the concentration of ozone, by adding to it at some altitudes and latitudes, and by diminishing it at others. Water vapor and sulfur dioxide emitted in the stratosphere may also affect the abundance of ozone. Ozone in the lower stratosphere acts as a greenhouse gas, in addition to filtering out ultraviolet radiation from the sun. Therefore both increases and decreases in its concentration are of environmental concern. (There is no evidence that current aviation emissions add a significant increment to the measured depletion of ozone arising from chlorofluorocarbons [CFCs] and related compounds.)

Great uncertainties arise in estimating the effect of additions of nitrogen oxides, water vapor, and other emissions from aircraft on both tropospheric and stratospheric ozone. Preliminary estimates of the impact of a large future HSCT fleet depend directly on assumptions about the NO_x emission rate of engines still under development, in addition to chemical and dynamical properties of the stratosphere that are not well understood. The effects of subsonic emissions in the stratosphere have not been examined extensively. Some of this uncertainty is expected to be resolved over the next 5 to 10 years due to expansion of research efforts, but it may take longer to obtain reliable quantitative estimates of the consequences of aviation.

The emissions scenarios in this report are based on a model of future aviation demand (passenger, business, freight, and military transport) and changes in aviation technologies and operations. The simulation of aviation demand attempts to capture the dynamics of growth and saturation expected by the aircraft industry to occur in both industrial and developing countries. Economic and population growth rates for groups of countries, classified by expected near-term behavior of aviation demand, are important parameters in projecting long-term demand.

Due to the large uncertainties inherent in modeling future demand and technological change, our projections should be considered to be scenarios that indicate sensitivities to underlying assumptions, rather than forecasts. In addition, the model assumes in all cases that demand by the end of the 21st century will be largely determined by the gradual changes expected in gross national product (GNP) and population, rather than rapid changes in travel habits and lifestyles that dominate in new markets.

This assumption could lead to substantial error if, at one extreme, telecommunications obviates the need for vastly expanded travel in developing countries; or, at the other, if the trend toward market saturation apparent for the U.S. does not develop elsewhere. Furthermore, our assumptions with regard to changes in emissions characteristics of aircraft, and in fuel economy of engines and operations, are based on overall expectations of engine manufacturers and of the U.N.'s International Civil Aviation Organization (ICAO) for the next two decades and on a logistic model for the period thereafter, rather than on examination of particular technologies.

Nevertheless these scenarios indicate the magnitude of potential emissions growth under a wide variety of reasonable assumptions. Best estimates of future demand and emissions are represented by a base case developed from population and GNP assumptions of the Intergovernmental Panel on Climate Change (IPCC). Technological and operational developments are projected assuming no substantial changes in governmental policies that may affect aviation. We assume a continuing reliance on carbon-based liquid fuels. The demand model is validated by comparison with the historic growth of air travel in the U.S.

Highlights of our results include the following:

- Demand for aviation services will continue to grow throughout the next century, but growth rates are expected to peak around 2030 in the base case, leading to an increase in global demand by a factor of 10 by 2050, and a factor of 20 by 2100. Most of the increase in demand arises from developing countries. Demand in the base case falls within the range of projections by industry and government through 2010.

- Fuel consumption, carbon dioxide, and water vapor emissions by subsonic aircraft jump by more than a factor of 6 by 2100 in the base case, despite more than a tripling of estimated fuel efficiency (defined as ton-km carried per kg fuel consumed). Different assumptions lead to increases as low as a factor of 3 or as high as a factor of 13. For the base case, we find that global CO_2 emissions from aviation amount to 1.0 to 1.4 gigatons of carbon in 2100, roughly the amount currently emitted by all U.S. sources of fossil fuel combustion. After 2050, consumption by aviation becomes a significant fraction of global liquid-fuel use in some scenarios, but we do not account for feedback of resulting fuel price changes on demand.

- The current contribution of aviation to global anthropogenic CO_2 emissions is more than 2%, and it is nearly 3% of emissions related to energy consumption. Estimates of aviation's share of future global anthropogenic CO_2 emissions are fraught with uncertainty due to the difficulties inherent in comparing projections based on different methodologies. For the base case, we find that aviation will contribute 4.2% to 7.0% of global CO_2 emissions by the year 2050 and 4.7% to 6.9% by the year 2100. This contribution is a larger proportion than that made by the entire economy of Japan today. The relative growth in aviation's share occurs despite an increase in CO_2 emissions from all anthropogenic sources of a factor of 2.7 by 2100 in the IPCC base-case scenario (IS92a). Comparison with other IPCC scenarios indicates that aviation could contribute 3% to 10% of global CO_2 emissions by 2050 and 4% to 14% by 2100, depending on the sensitivity of aviation demand and fuel use to changes in energy prices and policy.

- The increase for NO_X emissions from subsonic aircraft ranges from a factor of 1.4 to 6.3 over the course of the century, with a best-estimate increase of more than a factor of 3, despite a reduction by half in emissions per kilogram of fuel burned. However, the assumptions in these scenarios may be optimistic with regard to future progress in combustor technology, which would lower emissions.

- Our base-case estimates for fuel-consumption, CO_2, and NO_X emissions cover a range of values that is consistent with recent NASA projections for 2015.

- The potential contribution to global warming from aviation due to the combined effect of carbon dioxide, water vapor, and NO_X emissions cannot be accurately assessed. Based on the scenarios in this report, a substantial contribution to human-caused greenhouse warming (on the order of 10% of the total by 2050) is possible from the effect of carbon dioxide and nitrogen oxides emitted by subsonic aircraft.

The main contribution of this study is to show that, even with large improvements in technology and operations, the projected explosion in demand will create an inexorable upward pressure on emissions, unless policies are specifically aimed at limiting them. Much of this emissions growth occurs just after the year 2015, the horizon of most other aviation emission scenarios.

The ICAO is considering limitations on emissions at cruise altitude for the first time, based on the potential environmental consequences noted above. In developing policies for aviation emissions, several issues need to be taken into account, including the large scientific uncertainty in assessing environmental impact, and the likelihood that these uncertainties will be reduced slowly over time; the depleted state of the stratospheric ozone layer due to the action of non-aviation emissions, such as CFCs; the continuing buildup of the human-made greenhouse effect largely due to fossil fuel use by other sources; and the long residence time of anthropogenic carbon dioxide in the atmosphere.

Furthermore, designing a new aircraft can take up to a decade, and each aircraft design has a lifetime of about 25 years. Decisions make today may govern emissions through 2030.

This report does not address policy measures in detail. However, we make the following general recommendations aimed at reducing the risk from aviation emissions and at integrating aviation into the existing national and international frameworks for dealing with ozone depletion and climatic change:

- The potential growth in aviation's CO_2 emissions alone could eventually make this sector a significant contributor to total CO_2 emissions and projected global warming. Therefore implementation of incentives and regulations to speed the increase in efficiency for engines and operations is merited. Such changes would lower the potential climatic impact of water vapor-emissions, which also increase with fuel use.

- Substantial increases in NO_X emissions seem likely by the middle of the next century, including at altitudes where effects on climate are largest. We recommend that fleet-wide NO_X emissions from aviation be limited at cruise altitude. Current ICAO regulations deal only with the landing-takeoff cycle.

- Expansion in demand in developing countries in response to national economic growth is likely to be a key factor in determining emissions increases. (We do not examine possible effects of changes in income distribution within countries.) We recommend that technology transfer from industrial to developing nations be facilitated to enable rapid dissemination of aviation improvements, as opposed to adoption of aging technology, in order to accelerate increases in engine efficiency and decreases in NO_X emission indices.

- In collaboration with the ICAO, the parties to the Montreal Protocol on Substances That Deplete the Ozone Layer should establish a framework for limiting fleet-wide stratospheric emissions that affect the ozone layer from both subsonic and supersonic aircraft.

- The growth of CO_2 emissions should be restrained as part of the process of developing national plans under the United Nations Framework Convention on Climate Change. Flexible policies should be used, such as offset and trading programs, which turn advances in emissions reduction into an asset. The ICAO could play an important role in investigating technological and operational options which would inform the development of these plans. Additional NO_X limitations should also be a target of the national climate plans. But issues related to allocation of responsibility for emissions from international flights need to be resolved.

- Developing a "green" airplane should become a U.S. national policy goal and a goal of the aircraft manufacturing industry. Implementing this goal would be facilitated by adopting the flexible policies on CO_2 emissions noted above.
- Scientific research on the environmental effects of aviation emissions must be accelerated.

We make our recommendation for steps to limit emissions in full recognition that the ultimate desirable level of cruise altitude emissions cannot yet be determined. Not only must the environmental impacts be better elucidated, but the costs and technological opportunities and the contribution of non-aviation sources need to be evaluated. Opportunities for operational changes by the airlines and shifts to other modes of transportation, such as high-speed rail for continental, inter-city routes, need to be considered as well, because reducing NO_X emissions while simultaneously increasing engine efficiency involves trade-offs that may be difficult and costly.

Nevertheless, 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.

1. INTRODUCTION

The advent of concern over ozone depletion and global warming has led to international agreements to limit gaseous emissions to the atmosphere. Implementation of these accords will have a powerful effect on technological development in a number of industries, including automotive manufacturing, electric power generation, refrigeration, plastics, electronics, and, potentially, aviation.

Aviation played a historically significant role in the genesis of scientific and political interest in the global atmosphere.[1] Fears that engine emissions from the first generation of civil supersonic aircraft would damage the ozone layer contributed to withdrawal of support for their development by the U.S. in 1971. Consequently the international supersonic fleet, now composed of 13 British-French Concordes, has remained too small to be of concern.

Aside from some scientific research, interest in the atmospheric impact of aviation during the past two decades was largely related to the contribution to local air pollution by emissions from airplanes during taxi, takeoff, and landing.

Now the global effects of aviation, which are dominated by cruise altitude emissions of aircraft, have once again become the focus of intensive study by scientists and governments. There are three reasons for this interest. First, fuel use in aviation, and also emissions from aviation, are growing faster than those from other energy sectors. For example, world energy use grew 2.8% per year on average from 1983 to 1989. By comparison, global use of aviation fuel rose by an average of 3.9% per year during the same period. The comparable values for the 1973-1989 period are 0.69% and 2.43% for total world energy and aviation fuel, respectively.[2] The growth in consumption of aviation fuel was caused by a rapid increase in demand for aviation services and occurred despite substantial improvements in efficiency of engines and operations.

Any existing environmental effects of aviation emissions can be expected to increase rapidly in the future. In particular, carbon dioxide (CO_2) emissions from aircraft could become a significant contributor to the buildup of greenhouse gases in the atmosphere.

Secondly, concentrations of ozone in the lower part of the atmosphere, the troposphere, appear to be growing due to human influence, including at altitudes where ozone is known to act as a strong greenhouse gas. Aviation emissions have recently been shown to be highly efficient at producing ozone in that part of the atmosphere, and may be playing an important role in this ozone buildup.[3]

Finally, 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 layer. Some emissions from subsonic aircraft and the majority of emissions from supersonic flight occur directly in the lower stratosphere (roughly 12-20 km altitude), where these effluents can affect the concentration of ozone by adding to it at some altitudes and latitudes, and by diminishing it at others. In addition to filtering out ultraviolet radiation from the sun, ozone in the lower stratosphere also acts as a greenhouse gas and influences the temperature of both the upper atmosphere and Earth's surface; thus increases and decreases in its concentration bear environmental consequences.

There is no evidence that current aviation emissions add a significant increment to the measured depletion of ozone resulting from CFCs and related compounds. But subsonic traffic is increasing, and a proposal to vastly expand supersonic flight has been put forward.

The objective of this report is to provide a basis for assessing the potential long-term impact of subsonic aviation on the global atmosphere by projecting emissions from aircraft over the course of the next century. We focus primarily on emissions of two gases from subsonic aircraft, carbon dioxide and nitrogen oxides (NO_X). The environmental effects of these emissions are discussed below, but only in brief. We underscore that this report is aimed neither at examining the potential environmental consequences of aviation in detail, nor at recommending specific policies for avoiding or abating those impacts.

The method of this study differs greatly from the econometric models used by the aircraft manufacturers and by the International Civil Aviation Organization (ICAO) when projecting emissions over the near term, e.g., through 2015. Barrett[4] considers an array of parameters related to trends in travel in order to project emissions through 2031, in a non-econometric approach. We present a long-term dynamical systems model for aviation demand that uses a variation on the logistic model to capture eventual slowdown in demand growth rates. Growth rates and market capacities are determined by examination of aviation market history in industrial nations.

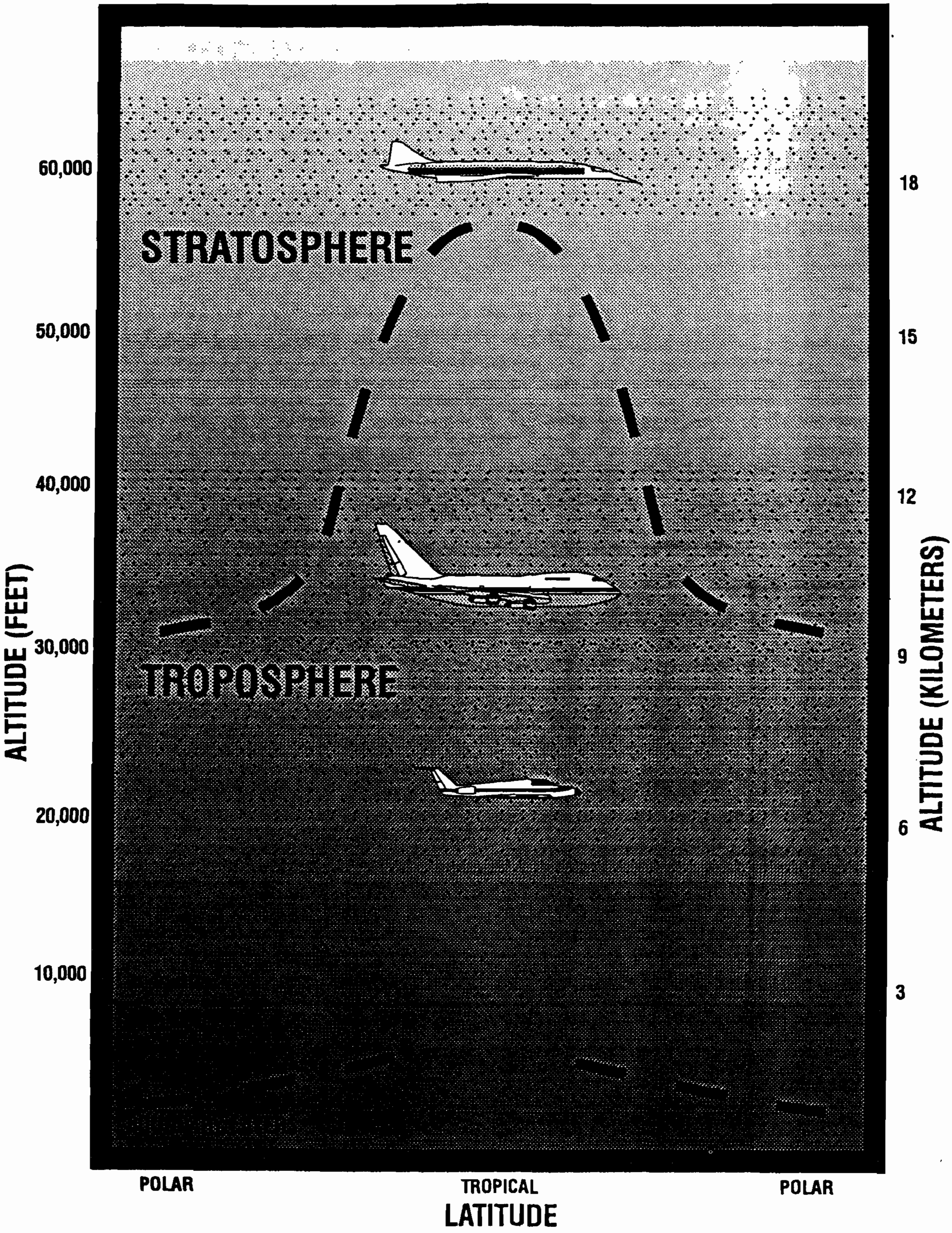
This model is considerably more complex than those used by other investigators who have considered aviation emissions through the year 2100.[5] Here we consider individually the underlying dynamics of the personal travel, business travel, and military sectors that determine overall demand growth rates.

Next we determine a relation between demand and fuel use. A logistic approach is once again adopted in order to model the rate of technological and operational changes that determine fuel efficiency. Here we rely in part on the expectations of several of the manufacturers for estimates of efficiency improvements over the next few decades. Emissions of carbon dioxide flow directly from this model. Finally, emissions of NO_X are determined, again with some reliance on manufacturers' projections of technological change in engine design. We also study cursorily the distribution of NO_X emissions with height, since its environmental effects are altitude dependent.

This report examines emissions from subsonic aircraft only. The National Aeronautics and Space Administration (NASA) is examining technology which could provide a basis for developing a fleet of 500 advanced supersonic aircraft, called High-Speed Civil Transports (HSCTs), whose emissions would not, in theory, present a threat to the ozone layer. Whether such aircraft can actually be developed in commercially viable form remains in question. Our scenarios assume no displacement of subsonic flight by the HSCT. If an HSCT did fly during the next century, it would change both the amount and the altitude of emissions, particularly nitrogen oxides, compared to the scenarios presented here.

1.1 Aviation and the Global Atmosphere

From the perspective of aviation, the atmosphere may be divided into three altitude zones: the boundary layer, the upper troposphere, and the lower stratosphere. The locations of these zones are indicated schematically in Figure 1. Carbon dioxide, water vapor, nitrogen oxides, carbon monoxide, hydrocarbons, sulfur dioxide, and soot are emitted by aircraft at all altitudes, but, with the exception of carbon dioxide, their environmental significance varies depending on the zone of emission.



AVIATION AND THE ATMOSPHERE

Carbon dioxide is the most important anthropogenic greenhouse gas. It is almost uniformly mixed throughout the atmosphere; its altitude of emission, whether during takeoff, climb-out, cruise, or descent, is not relevant to determining its environmental effect. Currently the global aviation sector accounts for nearly 3% of CO_2 emissions from energy consumption and more than 2% of total anthropogenic CO_2 emissions (including emissions from energy consumption, deforestation, and minor sources),[6] a small but significant contribution to the buildup of the greenhouse effect.

Unlike carbon dioxide, NO_X emissions react quickly with many other atmospheric constituents. Therefore the distribution and environmental effects of nitrogen oxides, which include the production and destruction of ozone, are highly dependent on altitude, season, and location. Considerable research has been carried out since the early 1970s on the effects of NO_X emissions into the stratosphere. However, new understanding of stratospheric processes since the discovery of the ozone hole has not yet been entirely incorporated into models of aviation effects.[3] Understanding of the upper troposphere is even more primitive because it is a very difficult region to model, and it has not previously been the subject of intensive attention.[3,7] As a result, with the exception of the boundary layer, we can only outline the potential range of effects of aviation emissions of nitrogen oxides.

Water-vapor emissions from aircraft, which are, like carbon dioxide, an inevitable by-product of fossil fuel combustion, may influence both the chemistry of the ozone layer and the greenhouse properties of the upper troposphere. Reliable quantitative estimates of environmental impacts in both the stratosphere and the upper troposphere for nitrogen oxides and water vapor remain a decade or more in the future.

1.1.1 Boundary-Layer Emissions

During takeoff and landing, aircraft emit at or near the ground in the boundary layer. In this region, which averages about 1 km (3,281 feet) in altitude and is well defined outside the tropics, pollutants emitted at any height swirl close to the ground within an hour or so.

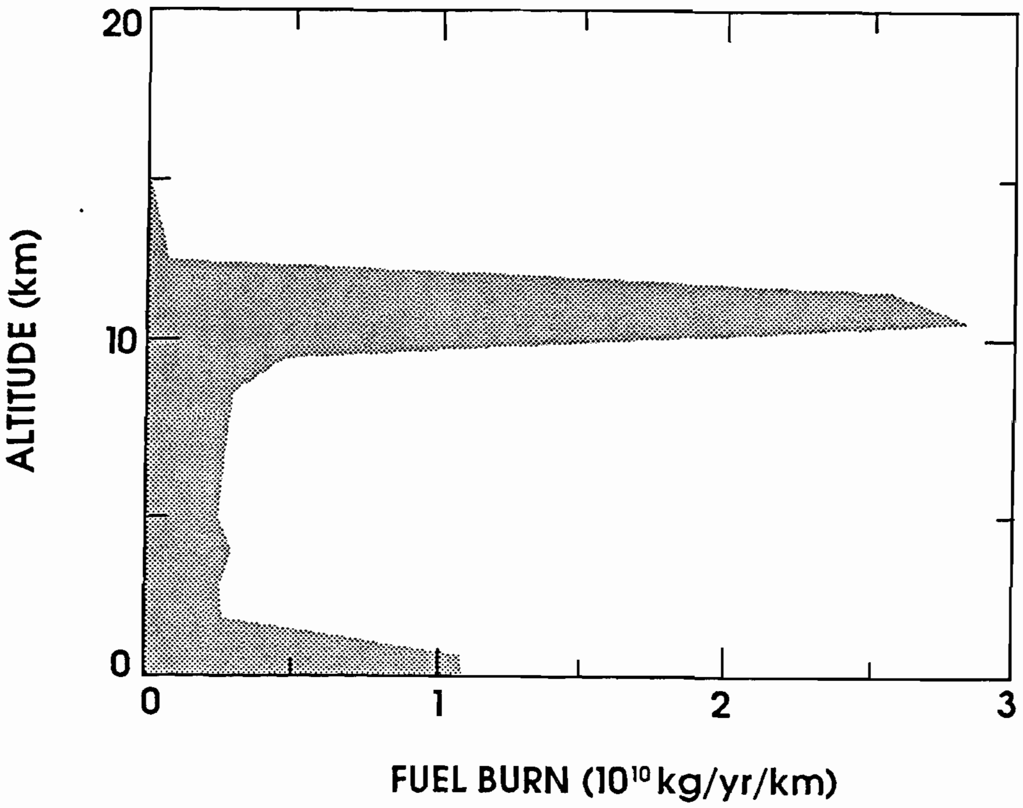
Under the action of sunlight, emitted gases, including nitrogen oxides, carbon monoxide, and hydrocarbons, are converted to ozone and a variety of other compounds that compose smog. Aircraft, as well as cars, power plants, factories, and homes, all emit these gases (as well as particles of soot), albeit in different quantities. Aircraft contribute to air pollution at the ground, particularly in the vicinity of airports. Consequently their emissions during takeoff and landing are currently regulated (e.g., under the Clean Air Act in the U.S.). We will not discuss boundary-layer processes any further since global effects are the subject of this report.

1.1.2 Upper Tropospheric Emissions

Commercial aircraft log most of their cruise miles, and contribute most of their emissions, at altitudes well above the boundary layer in the upper troposphere. The high proportion of fuel burn above 9 kms is illustrated in Figure 2 for scheduled passenger and cargo flights during 1990. NO_X emissions here may undergo reactions with other atmospheric gases that are stimulated by sunlight to form ozone. With the exception of unreactive compounds like carbon dioxide, emitted gases and their by-products are removed from the troposphere within about 10 days by washing out in precipitation, or being removed by dry deposition, chemical reaction, or photolysis.

Figure 2: Fuel Burn vs. Altitude

(scheduled passenger and cargo flights, 1990)



Reference: Stolarski and Wesosky (1993a), p124, Figure 3-2.9 (a).

The consequences of these emissions are a matter of lively interest in the scientific community at the current time. In the upper troposphere, ozone acts as a potent greenhouse gas, so any additional source is of concern. Observations have been too limited to provide a global picture of ozone in the upper troposphere. However, 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 carbon dioxide and other gases.[8]

The contribution of aviation to this change is very uncertain, but aircraft produce the only human-made emissions occurring directly at those altitudes. Other sources of nitrogen oxides exist at Earth's surface. Although only about 2% of global anthropogenic NO_X emissions are due to aviation, nitrogen oxides emitted at cruise altitudes are much more efficient, on a per-molecule basis, as generators of ozone than nitrogen oxides emitted near the ground.[9]

Furthermore, the emission of nitrogen oxides from aviation at northern mid-latitudes in the upper troposphere appears to be of similar magnitude to the nitrogen oxides arriving there from all other sources, including natural ones.[3] But it is unknown how much of the excess ozone in the upper troposphere is produced locally as opposed to how much is produced elsewhere from ground-based sources and transported there. Models, which are as yet crude, ascribe a 4-15% ozone increase in the upper troposphere to current emissions from aviation.[3]

Other emissions from aircraft may affect climate. For instance, under some conditons, water vapor from subsonic jets can form visible contrails that reflect sunlight. The ice cystals that compose the contrails may enhance the formation of thin cirrus clouds that trap heat and act in the same manner as greenhouse gases.

1.1.3 Stratospheric Emissions

Above the troposphere lies the stratosphere. The two regions are separated by a boundary called the tropopause. The tropopause, lying between 10 and 17 kms (33,000 to 56,000 feet), acts as an invisible barrier to the vertical movement of gases because temperatures begin to increase above it; this temperature inversion inhibits the upward movement of air. Generally it takes many months for gases to move across the tropopause. Almost all nitrogen oxides emitted in the troposphere, as well as their by-products, are removed from the atmosphere long before they can cross to the stratosphere.

However, subsonic aircraft frequently cruise in the stratosphere itself, emitting nitrogen oxides and other gases directly into that region. (About 20% of the global fuel burn may occur in the stratosphere[3] on average, but a much larger fraction occurs during wintertime flights over the North Atlantic.) Nitrogen oxides emitted in the stratosphere may lead to increased or decreased concentrations of ozone, depending on the altitude and latitude of emission. Water vapor and sulfur dioxide (which is converted to sulfate aerosol particles after emission) may also have important effects on the ozone balance of the stratosphere. Furthermore, the ozone and the climate issues are related since ozone in the lower stratosphere also acts as a greenhouse gas that affects Earth's thermal-radiation balance.

An effort to clarify the influence of these gases with regard to both ozone and climate was stimulated by the HSCT proposal. However, HSCTs would fly near 20 kms (66,000 feet) altitude, while commercial subsonic flights are generally restricted to altitudes below 12.5 kms (41,000 feet). Photochemical models indicate that at altitudes in between, added nitrogen oxides may switch from stimulating the creation of ozone to destroying it.[3,7]

If this transition actually occurs in Earth's atmosphere, its location would be a complicated function of season and latitude. Currently, these properties are not known with any degree of certainty. Neither is there an adequate predictive model for the transport of nitrogen oxides (and their chemical products) from the lower altitudes where subsonic jets emit them and where little is known about their effect on ozone, to the higher altitudes, where they are likely to destroy ozone. The influence of nitrogen oxides (and their chemical products) reaching the high latitudes is particularly uncertain due to low temperatures, unusual dynamics, and the potential for the formation of polar stratospheric clouds. Interactions between chlorine and NO_x chemical cycles in polar regions particularly muddy the picture.

Preliminary estimates of the impact of a large future HSCT fleet are highly dependent on assumptions about the NO_x emission rate of engines still under development, in addition to chemical and dynamical properties of the atmosphere that are not well understood. The effects of subsonic emissions in the stratosphere have hardly been examined at all. In recognition of these complexities, and in order to understand the role of subsonic emissions in the troposphere as well as the stratosphere, a subsonic assessment program was established by NASA in 1994. However, definitive findings may not be available until early in the next century.

1.2 Environmental Risks of Aviation

The foregoing discussion presents a typology of environmental risks but provides little in the way of quantitative assessment. This shortcoming reflects the primitive nature of current understanding. At 2% of global emissions,[6] carbon dioxide from aviation is already large enough to merit attention in the global warming context, and faster-than-average expansion of this sector of fossil fuel use is anticipated.

Schumann[3] estimates the long-term climate effect of changes in tropospheric ozone and changes in cirrus cloud cover (from water-vapor emissions) 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).

Quantitative estimates of potential ozone depletion in the stratosphere due to aviation are not yet possible; it is not even certain whether ozone will increase or decrease. Furthermore the nature of the ozone depletion issue and, to a lesser extent, the climate issue, would change if an HSCT fleet was actually commissioned. Nevertheless, any potential additional source of ozone depletion must be recognized as a substantial risk, given the current depleted status of the ozone layer.[3]

In other words, current aviation emissions are sufficiently large to bear watching. This study should help determine whether expected future growth makes them a special target for regulation (see Conclusions, Section 7, and Recommendations, Section 8). At the present time, standards for nitrogen oxides and certain other pollutants recommended by the International Civil Aviation Organization (ICAO), a specialized agency of the U.N., apply only to the landing-takeoff cycle, not to cruise, and do not constrain total emissions. CO_2 emissions and fuel use are not subject to any specific international regulatory limits.

1.3 Methodology for Long-term Scenarios

We project emissions levels from aviation over the long term using a series of models. We begin with a region-based assessment of future aviation demand. We adopt assumptions for demand in maturing markets such as the United States, as well in emerging markets such as China. We incorporate long-term estimates for regional gross national product (GNP) and population growth that were developed by the Intergovernmental Panel on Climate Change (IPCC), which functions under U.N. auspices. The demand model is validated using the history of the U.S. domestic market.

We then project changes in fuel efficiency and emissions indices due to technological and operational improvement. Combining the two sets of projections yields scenarios for aviation fuel usage and emissions levels over the course of the next century.

2. THE DYNAMICS OF AVIATION DEMAND

2.1 Long-term Dynamics of Aviation Demand Growth

The first step in developing long-term emissions scenarios is an analysis of the market demand for aviation services. The evolution of aviation demand is affected by several factors.

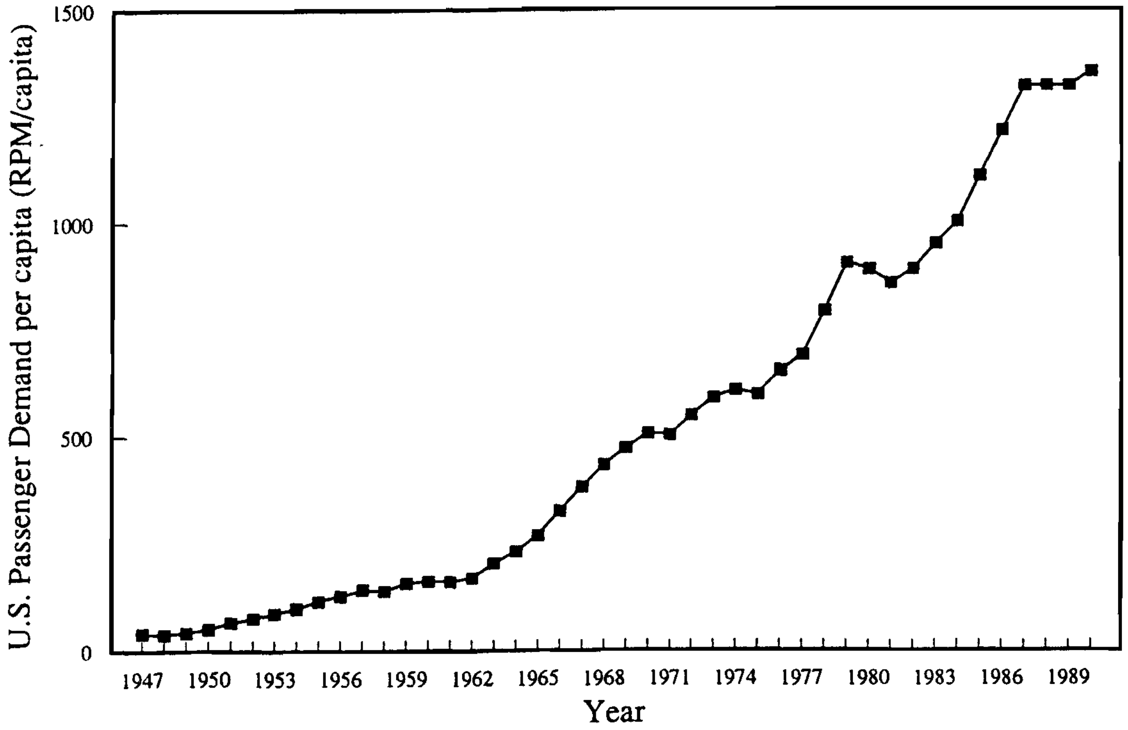
Latent Demand: When an airport network is built in a previously unserved region, it offers a new transport option and thus taps latent demand. This development usually results in an initial period of rapid growth; in the United States from 1950 to 1960, for example, aviation demand grew very rapidly, at an average annual rate of 14.1%.[10]

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 as the network of trading and personal ties expands geographically. This results in a rapid and continuing growth in demand.

Figure 3 shows the U.S. history of annual per-capita flight miles in revenue passenger miles (RPM; essentially, occupied seat miles); these data, along with the fact that 31% of the U.S. adult population flew in 1990,[11] show the steady incorporation of aviation into personal and business habits.

Figure 3 : History of Per-capita Passenger Demand in the U.S.

Revenue-Passenger-Miles (RPM)



References: Taneja (1978), FAA (1993), US (1993).

One 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 at the start of the automobile industry.[12] But the policy choices and economic forces that created a highway infrastructure started powerful trends that are difficult to modify today.

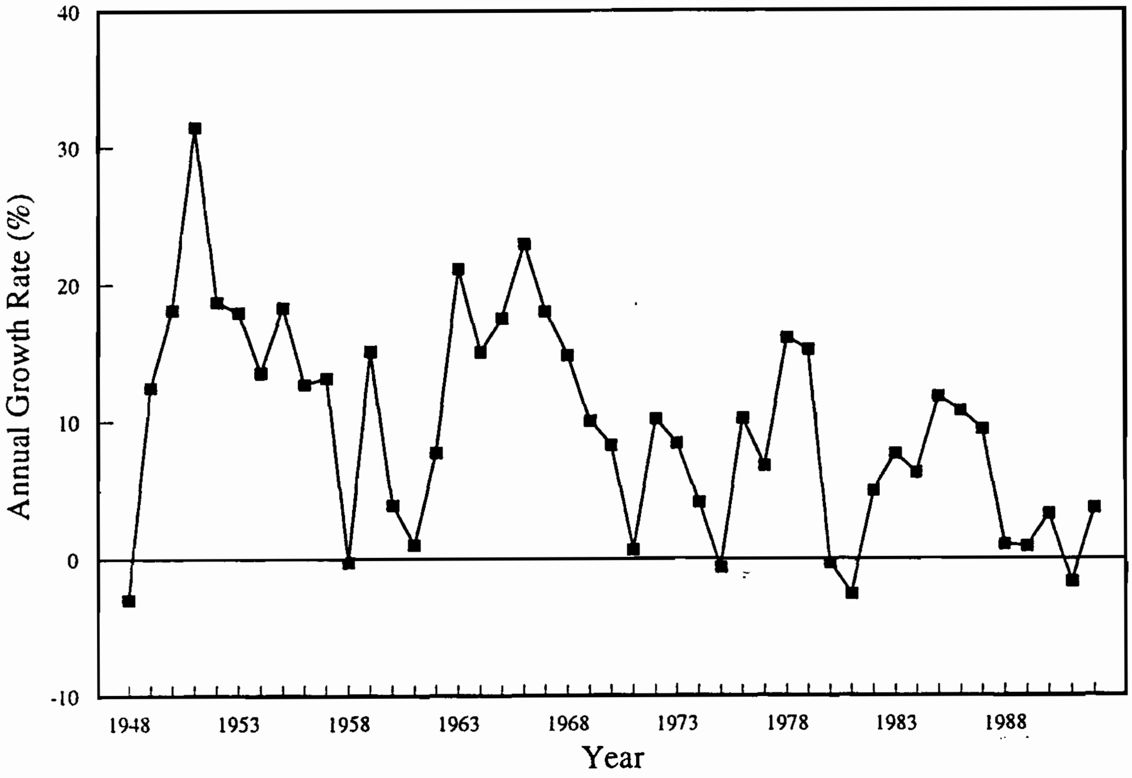
Modal Shifts: Aviation transcends most geographical barriers and, for longer journeys, offers significant time savings over land- and sea-based transport; it thus provides incentives to shift from other transport options.

Access to aviation also creates opportunities for new business ventures, such as the export of perishable items.

Income Effects: In general, as the income level of an individual or a firm rises, so does the personal value placed on time. Thus, in the personal and business travel markets, as well as portions of the freight market, income growth favors a modal shift from land- and sea-based transport to aviation.[13]

Eventual Maturity:[14] Barring unforeseen developments, it is likely that aviation demand will eventually reach maturity. As Figure 4 shows, the U.S. passenger market is already showing a decrease in relative demand growth.

Figure 4 : U.S. History of Annual Passenger Demand Growth Rates

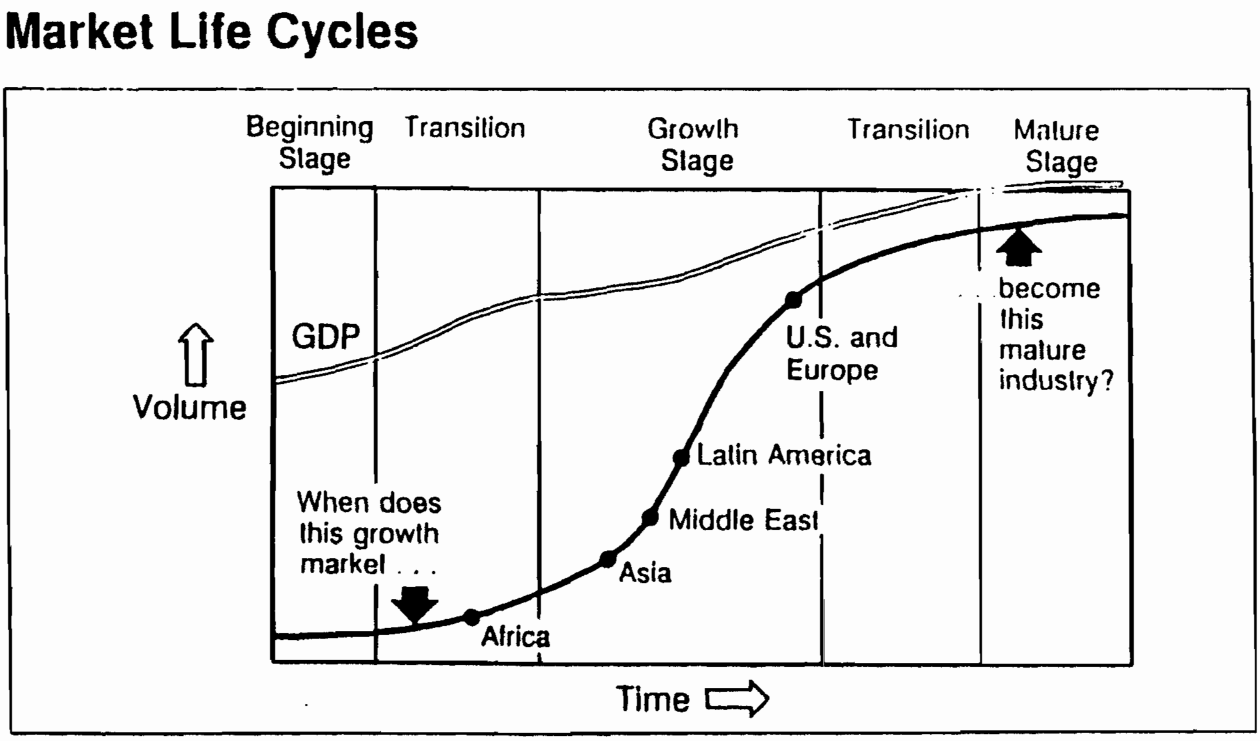


References: Taneja (1978), FAA (1993)

As demand matures and approaches market capacity, relative growth rates slow considerably. The impact of latent demand, continued expansion, and modal shifts will have been largely absorbed.

The aviation industry in some countries is very young; in others, the market appears to be approaching maturity. Figure 5 presents a qualitative picture of the dynamic market evolution of different regions of the world from Boeing's 1993 Current Market Outlook, suggesting that long-term behavior remains uncertain.

Figure 5: Market Life Cycles



Reference: Boeing (1992), p.5.2.

2.2 Forecasting Demand

Short-term projections, which look ahead as far as 10 or 20 years, generally use econometric methods. They correlate demand with economic and demographic factors such as GNP, disposable income, and volume of international trade.[15] Such correlation is combined with estimates of the explanatory variables to project demand growth rates.

Extrapolating these growth rates into longer-term forecasts is not defensible, since market processes cannot grow at the same rate indefinitely. The dynamics and timing of rapid expansion and eventual market saturation need to be addressed explicitly. We present a simple dynamic model for aviation demand. Since prices in the aviation industry fluctuate considerably, we do not incorporate changes in prices and price elasticities. Implicitly we adopt a business-as-usual assumption that energy prices and policies will affect aviation in the future as they have in the past.

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 to the penetration of a new technology.[16] In the energy-modeling literature, the logistic has been used only with a *constant* capacity, usually to represent the dynamics of technological and modal substitution in a single industry.[17]

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 limit. This model has been used by biologists to represent population growth in an environment with a growing carrying capacity.[18]

We divide aviation demand into sectors that are separately modeled as variations on a basic logistic model with a time-varying market capacity. This model projects the change in demand level N_i in sector i over time t (in years) as:

$$\frac{dN_i}{dt} = r_i N_i \left(1 - \frac{N_i}{C_i K_i(t)}\right) \tag{1}$$

where r_i is an intrinsic rate of expansion, and $C_i K_i(t)$ is the capacity of the market. C_i represents a constant capacity factor, and $K_i(t)$ is a time-dependent variable, either GNP or population.

The assumptions for each sector are discussed in subsequent sections; mathematical details are provided in Appendix A.

The logistic model is a "business-as-usual" look at market evolution; it provides a useful baseline for comparison with external factors such as energy crises, policy changes, and new communications and travel technologies.

2.3 Sectors of Aviation Demand

We consider demand for aviation services including freight, mail, military usage, and general aviation, as well as scheduled passenger travel. We further divide the civil passenger market into business travel and personal travel sectors, where personal travel includes tourism and visitation trips. The sectors of the market respond very differently to economic and policy changes.

We analyze demand in the common unit of the ton-kilometer (TK), which measures both weight carried and distance flown. This unit facilitates comparison of fuel usage across sectors, and is directly meaningful for all sectors except the military.

The five sectors of the aviation demand market are as follows:

Table 1: Sectors of the Aviation Demand Market

#	Sector	Share of Global Aviation Fuel Usage -- 1990[6]
1.	Civil Business	14.6%
2.	Civil Personal	42.1%
3.	Civil Freight	17.8%
4.	Military	22.8%
5.	General Aviation	2.8%

The Civil Freight sector includes freight transported by passenger aircraft as well as the freight transported by cargo aircraft. A sizeable fraction of total freight is transported by passenger aircraft.

The separation of passenger travel into business and personal sectors is a complex task. The world average level of international business travel is 15% of the total passenger demand; however, for different countries the relative shares of business and personal travel vary widely.[19] Empirical data is very weak; but, in general, business travel's share of the total is much higher in the poorer nations and may be as high as 80 to 90% in China.[20] Leisure travel is limited by low levels of disposable income and by strict government restrictions on travel or on foreign exchange currency. Appendix A documents the division of business and personal travel for each region; Section 6 analyzes the sensitivity of our results in this regard.

2.4 Development Status and Aviation Demand

Demand for civil aviation services is closely linked to the past and present economic health of a nation. The traditionally wealthy economies of the world such as the United States and many members of the Organization for Economic Cooperation and Development (OECD), have had an extensive airport network in place for many years now, and large segments of their populations have become accustomed to flying often. In most developing countries, however, only a skeletal network exists, and the vast majority of the population has never flown. To reflect historical economic disparity among nations, we sort the world's nations into five economic categories in Table 2.

Table 2: Definition of Economic Categories

#	Category Name	Members
1.	Industrial economies	OECD, except Japan
2.	Newly industrialized economies (NICs)	Asian NICs (e.g., Korea, Taiwan), plus 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

Japan falls in Category 2 rather than Category 1 because its aviation industry is young relative to the other OECD nations, and its market appears to be far from maturity.

The assignment of countries to particular categories is somewhat arbitrary and may be of limited relevance to the trajectories of expanded demand experienced by particular nations. Brazil, for example, falls in Category 4, but may well experience rapid expansion soon; Afghanistan falls in Category 3, but recent conflict there may delay growth even further. Section 6 includes a sensitivity analysis for such outlier nations.

The lack of reliable long-term projections of country-specific economic and demographic change necessitates this level of generalization. Section 3.3 describes the assumptions regarding the timing of economic expansion.

Within each economic category, we model three sectors of civil aviation:

- Business Passenger
- Personal Passenger
- Freight

2.5 Business Passenger and Freight Demand

Business passenger and freight demand depends closely on the health of the economy. We assume that these two sectors follow a logistic expansion toward a capacity level that is a constant fraction of the nation's GNP. In reality, the relation between the capacity level factor and GNP may be different for different 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.

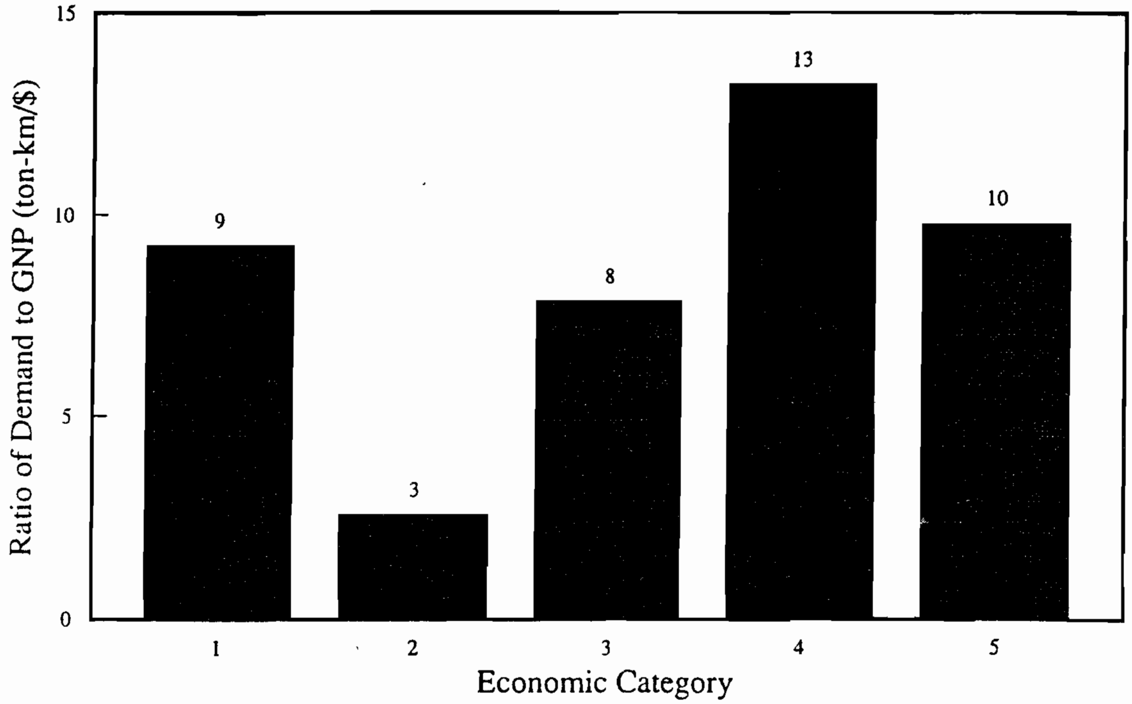
For both business passenger and freight demand, we set a generic capacity level (C in Equation 1) for all regions. In this logistic model, the relative rate of growth in demand equals that of GNP once the ratio of demand to GNP reaches the capacity level. As mentioned earlier, the mathematical details are given in Appendix A.

2.6 Personal Passenger Demand

We assume that the expansion in business travel is accompanied by an expansion in personal travel. But per-capita demand varies much more widely across economic categories than does demand per unit GNP. For example, in 1990, the average North American flew 1,740 miles, while the average African flew only 45 miles.[21] For each of the five economic categories, figures 6a and 6b show the 1990 ratios of passenger demand to GNP and population, respectively.

Figure 6a: 1990 Ratio of Demand to GNP

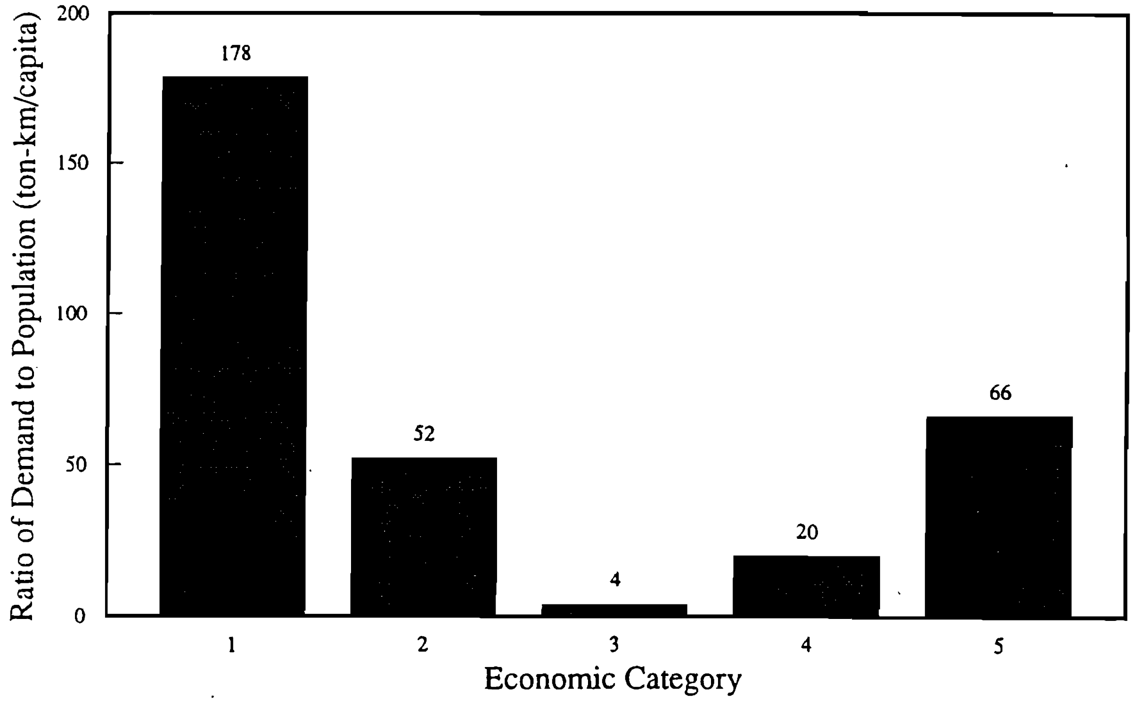
Five economic categories (ton-km/$)



1 - Industrial Economies, 2 - Newly Industrialized Economies, 3 - Rapidly Developing Economies, 4 - Slowly Developing Economies, 5 - Post-communist Economies

Figure 6b: 1990 Ratio of Demand to Population

Five economic categories (ton-km/capita)



1 - Industrial Economies, 2 - Newly Industrialized Economies, 3 - Rapidly Developing Economies,
4 - Slowly Developing Economies, 5 - Post-communist Economies

The disparity in levels of per-capita travel reveals a large pool of latent demand in some economic categories. Since personal travel by air has a high income elasticity,[22] demand will increase rapidly when a poor nation experiences an economic boom and per-capita income increases. However, since there are great income inequalities within countries,[23] significant demand for flying exists even in countries with very low per-capita incomes.[24]

The existence of significant factors other than per-capita income is suggested for the U.S. by Figure 7, which presents the ratio of per-capita demand to per-capita income. The steady increase in this ratio reveals that growth in demand is not proportional to income growth.

Figure 7: U.S. History of Ratio of Demand to GNP

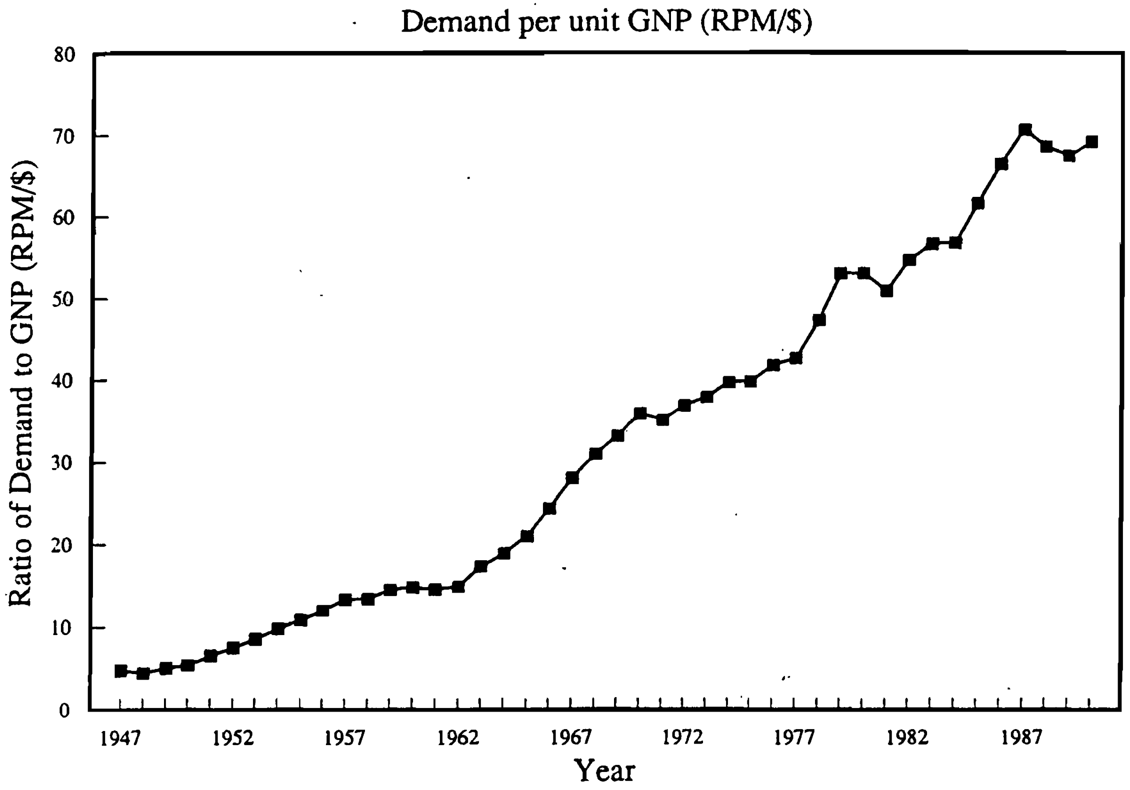


Figure 8, from Boeing's <u>Current Market Outlook 1993</u>, shows the income distribution and flying patterns for U.S. households in 1990. Aviation demand is a continuously increasing function of income, with people in higher-income brackets having a higher per-capita demand level.

population reaches the capacity level. Details are given in Appendix A. This simple model does not account for relationships between GNP and population.

2.7 Military and General Aviation Demand

Given the end of the Cold War, and no substantial arms race expected, we assume that the world's military aviation demand grows at the same proportional rate as global GNP; it does not experience a rapid expansion. Since global GNP growth is nominal compared to recent trends in overall demand growth, this represents a slow expansion of military demand. This may result in a small overestimation since the world's two primary military powers, the United States and the former Soviet Union, who together account for half the world's military fleet,[27] are currently reducing their military expenditures.

The general aviation category constitutes only 3% of the total aviation market and is predominantly a leisure activity in the mature, wealthy economies. We assume that general aviation demand also grows in proportion to global GNP.

3. ECONOMIC AND DEMOGRAPHIC ASSUMPTIONS AND VALIDATION

3.1 Economic Scenarios

We have specified the logistic models of demand growth based on long-term scenarios of GNP and population growth. The available forecasts span a wide range of futures. We have chosen the set given by the IPCC in Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.[28]

This IPCC report presents six emissions scenarios (named IS92a through IS92f), which are created from five category-based scenarios of GNP and population growth through the year 2100. The five scenarios provide a range of plausible futures, and incorporate the published forecasts of major international organizations and expert analyses. Table 3 provides a summary.[29]

The IPCC report includes analysis of expected policy changes affecting fuel prices and emissions limits. We do not include any of these factors; we use only the five GNP and population scenarios. Feedback from the IPCC's policy and pricing assumptions to the GNP growth-rate projections is insignificant;[30] therefore the projections are valid independent of their other assumptions. We recognize the limitations of the IPCC study; policy and price changes probably will affect GNP and possibly population as well.

Table 3: Summary of IPCC Scenarios[31]

Scenario Name	World Population (Billions)		Average Annual Global GNP Growth Rate	
	In 2025	In 2100	1990-2025	1990-2100
IS92**a**, IS92**b**	8.4	11.3	2.9%	2.3%
IS92**c**	7.6	6.4	2.0%	1.2%
IS92**d**	7.6	6.4	2.7%	2.0%
IS92**e**	8.4	11.3	3.5%	3.0%
IS92**f**	9.4	17.6	2.9%	2.3%

The model and the IPCC scenarios provide a skeleton that can be fleshed out with different estimates of market maturation rates and capacity levels. These estimates 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.

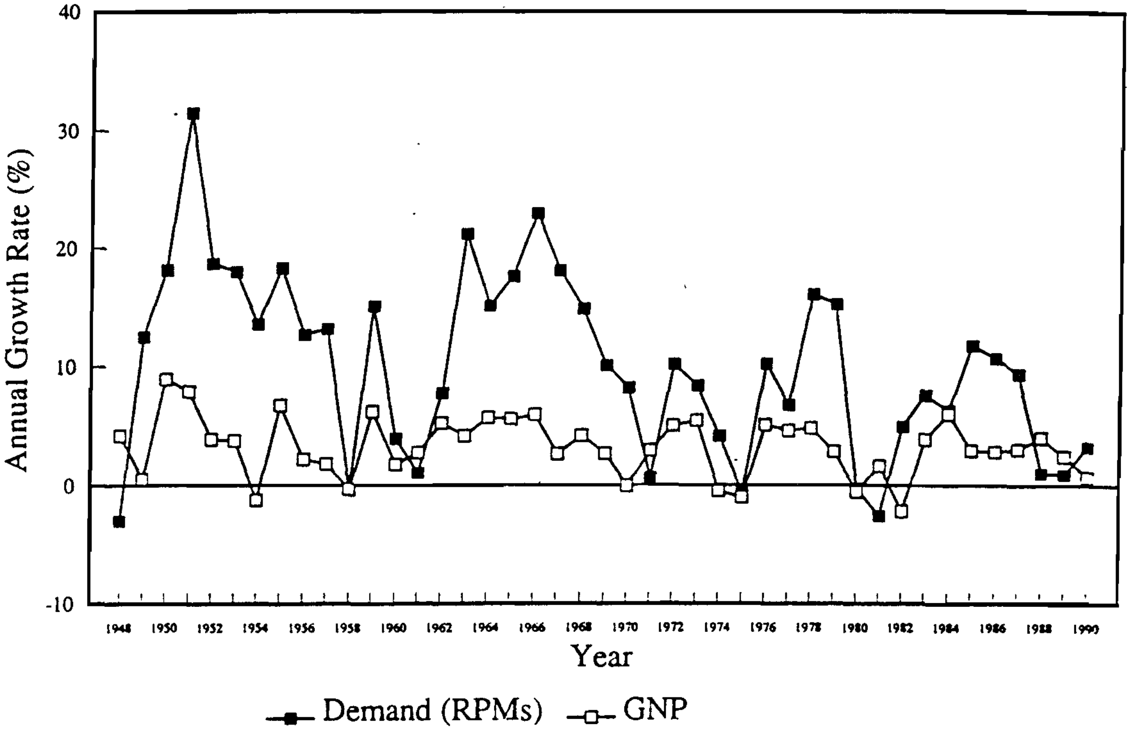
3.2 Market Capacity

Industry has defined maturity in the aviation market as being achieved when the ratio of aggregate demand to national GNP remains constant. By this criterion, the market has not yet reached maturity in any nation. Demand in industrial countries continues to grow faster than GNP growth, and it is not clear when maturity will be reached.

Figure 9 compares the histories of growth rates in aviation demand and GNP for the U.S. domestic market. The downward trend in demand growth is clear, but demand continues to grow faster than GNP. Figure 10 shows the U.S. history of growth rates in RPM per capita for the United States. This reveals continued growth in the ratio of demand to population, as well as trend toward maturation.

Figure 9 : U.S. History of Passenger Demand and GNP

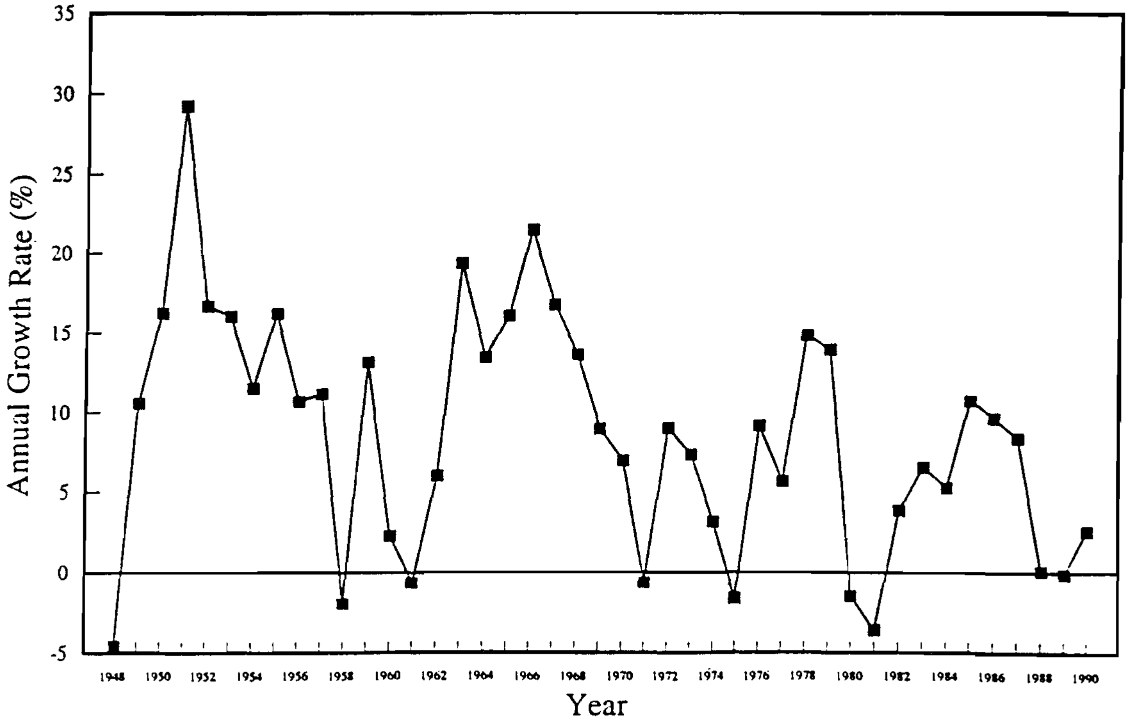
Annual growth rates



References: US (1993), Pres (1990), FAA (1993), Taneja (1978).

Figure 10 : U.S. History of Annual Growth rates

Per-capita passenger demand (RPM/capita)



References: Taneja (1978), FAA (1993), US (1993), Pres (1990).

Building on Figures 9 and 10, we create two sets of capacity levels using multiples of the 1990 demand levels for the maturing markets: Category 1 (the OECD nations excepting Japan). For business passenger and freight demand, we set the base level at twice the 1990 demand level for these sectors, and the high level at three times the 1990 level. Similarly, for personal passenger demand, we set the base level at twice the 1990 personal passenger demand for Category 1, and the high level at three times the 1990 level. Details are given in Appendix A. Section 3.5 discusses validation of the base capacity level.

Since the economic categories span large geographic areas, we assume that country-specific differences in capacity level will average out. We also assume that, given the same GNP and population, demand in the various economic categories will respond in the same way; that is, that there are no inherent tendencies for residents in a particular region to travel more or less.

3.3 Expectations of Expansion

The airline industry in a largely unserved category will experience a sharp boom when it taps into latent demand. Public policy decisions that result in the construction of airports and the creation of routes have long-lasting consequences. 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.

Categories 1 and 2 have already begun market expansion. For Categories 3 through 5, we set the start of market expansion in Table 4. Annual demand growth is very sensitive to business cycles and transient phenomena. Since the logistic provides a smooth long-term dynamic, these dates approximate the beginning of rapid growth; they cannot reflect near-term changes accurately. Section 6 provides a sensitivity analysis for the choice of start dates.

Table 4: Start of Market Expansion

#	Category Name	Date of Expansion Start
3.	Rapidly developing economies	2000
4.	Slowly developing economies	2010
5.	Post-Communist economies	2010

For Categories 3 through 5, the logistic model begins at the expansion date; prior to this date, demand in all sectors grows in proportion to GNP growth.

3.4 Maturation Period

Conservatively, the history of RPM and GNP growth rates for the United States (shown in Figure 9) indicates approximately a 70-year period from start to maturity. However, nations that are building their infrastructure today are likely to attain market maturity faster. They will benefit from technological improvements, and some fraction of their populace will also be familiar with lifestyle and business habits that incorporate aviation.

The post-Communist economies (Category 5) have an advantage over the developing economies (Categories 3 and 4) because they have undergone industrialization; they are likely to adapt sooner once their economies recuperate.

We summarize the assumptions about capacity levels and start and maturity dates by defining two demand sets in Table 5.

Table 5: Definition of Demand Sets

#	Category Name	Start Date	Base-Demand Maturation	High-Demand Maturation
1.	Industrial	begun	2010	2010
2.	Newly industrialized	begun	2050	2030
3.	Rapidly developing	2000	2070	2050
4.	Slowly developing	2010	2080	2060
5.	Post-Communist	2010	2060	2040
	Capacity Level		2 x Category 1 value in 1990	3 x Category 1 value in 1990

The base-demand set assumes no shortening of the maturity period for late entrants, while the high-demand set assumes a 20-year reduction in maturation period. In both cases, Category 5 achieves maturity 20 years faster than Category 4 economies due to its industrialized economy.

3.5 Validation of the Demand Model

We validate the model for aviation demand by applying it to the history of the U.S. aviation market from 1947 to 1990. We assume that logistic expansion begins before 1947, and we use the base capacity level of twice the 1990 U.S. demand level, with the maturity date set at 2010, as previously discussed. We then run the model using historical GNP and population growth rates from 1947 to 1990. Details are provided in Appendix A.

Figure 11 compares historical demand and the model results. The model provides a very good approximation of the overall trend; however, as expected, it cannot capture short-term fluctuations.

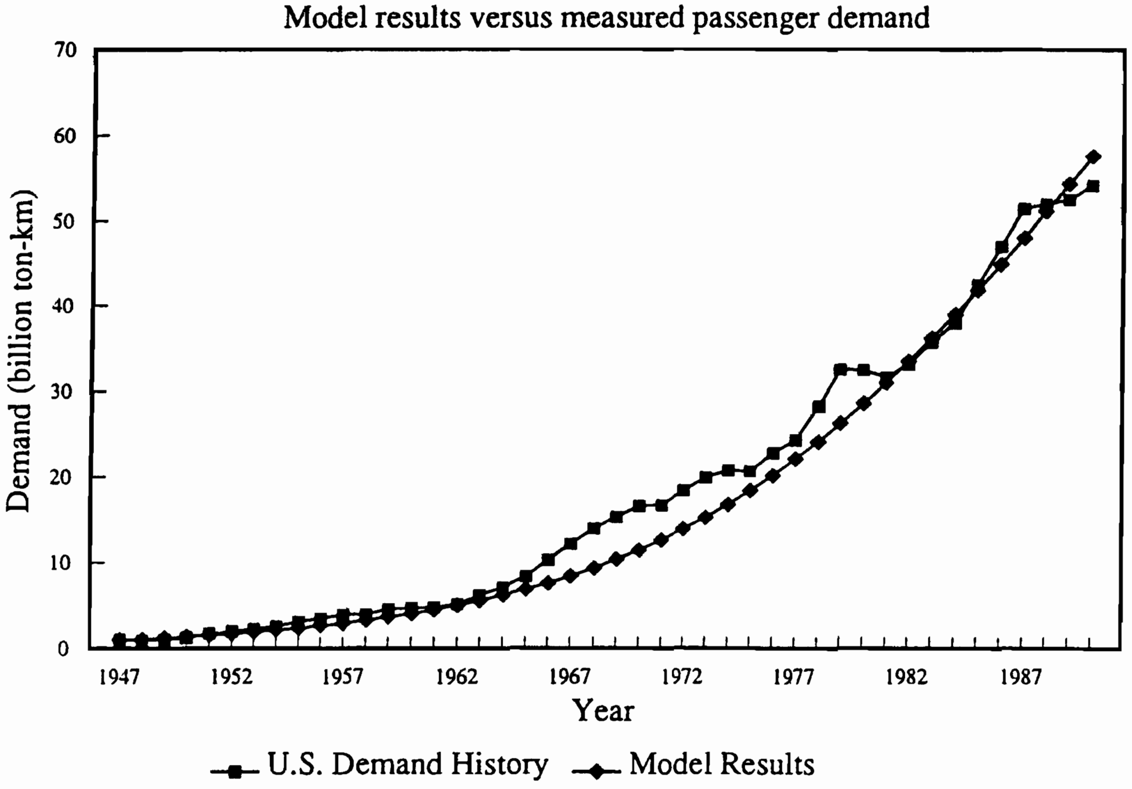


Figure 11: Validation of Model using U.S. History

Model results versus measured passenger demand

4. MODELING FUEL USAGE AND EMISSIONS

4.1 Fuel-Efficiency Improvement

To calculate emissions from aviation, we must first translate demand into fuel usage. The fuel-usage estimates can then be converted into emissions of particular chemical species through emission-index analysis.

Fuel efficiency has increased steadily due to new engine and airframe technologies, as well as operational improvements. A recent ICAO study calculated fuel efficiency in 1990 for the global civil airline industry at 510 g of fuel/TK, and estimated a decline in fuel consumption per TK in the range of 2 to 3% per annum between 1976 and 1990.[32]

The study predicts further reduction of 3.1% per year in civil aviation's fuel consumption per TK from 1990 to 2000, and 2.5% per year reduction from 2000 to 2010. These estimates of improvement in fuel efficiency account for improved engine and airframe technology, as well as operational improvements resulting in higher load factors or more efficient routing. Using a more detailed analysis of engine technologies, Greene predicts a slower pace, forecasting that annual fuel-efficiency improvement during 1989 to 2010 will range from 1.3% to 2.5%.[33]

Although technological and operational breakthroughs are difficult to foresee, the pace of efficiency improvement is likely to decline over the long term, in the absence of policy changes. We use a constant-capacity logistic to describe the diminishing returns. We choose the rate of expansion of the logistic to match the two ICAO projections of average fuel-efficiency improvement mentioned above. This procedure determines the assymptotic fuel efficiency. Appendix A provides the details.

This estimate for fuel-efficiency improvement assumes a business-as-usual policy background; any future disincentives for energy use are likely to increase the rate of efficiency improvement.

4.2 Varied Rates of Fuel-Efficiency Improvement

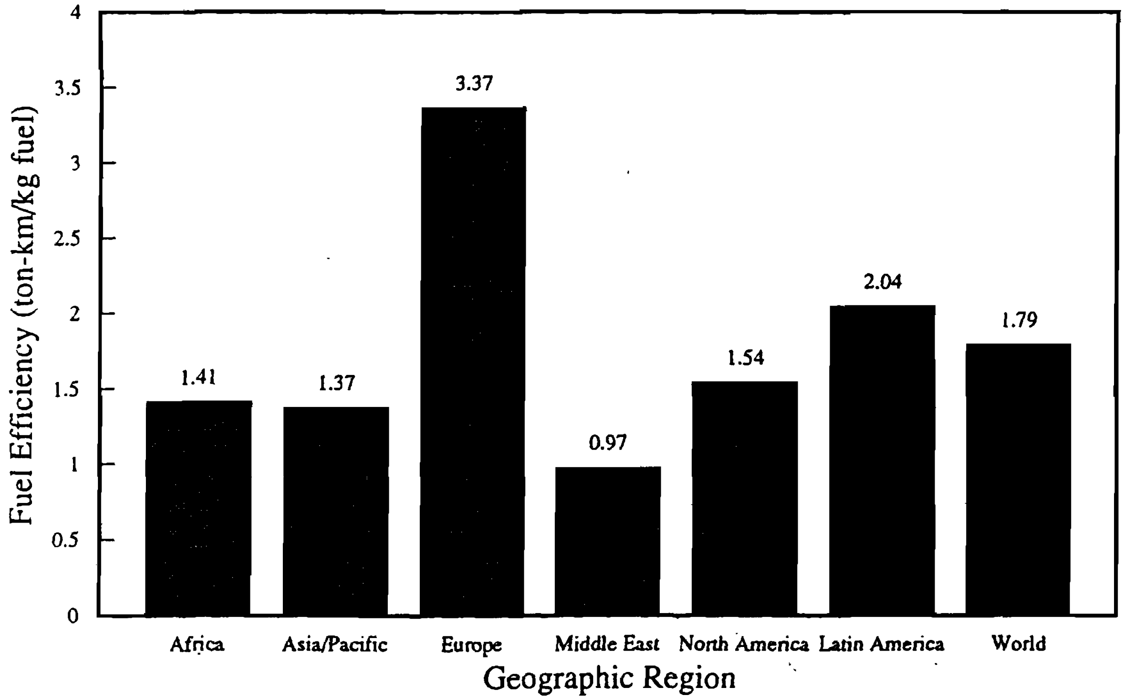
One important issue is that the rate of efficiency improvement is likely to differ across economic regions. A developing nation will hesitate to invest in the state-of-the-art technologies that an industrial nation might prefer. Often developing nations give a second life to airplanes that have become too noisy and inefficient for wealthier nations. On the other hand, load factors tend to be higher in developing countries than in industrial countries.[34] Also, a newly industrializing country may buy the latest aircraft.

Figure 12 shows fuel efficiency for civil aviation in 1990 for seven geographic regions. These efficiency values are calculated from ICAO and International Energy Agency (IEA) statistics; an important caveat is that these values were calculated by adjusting each region's total fuel use with a global correction factor representing military fuel usage. This procedure does not account for the high military fuel consumption by the U.S. and states of the former Soviet Union.

In addition, the ICAO and the IEA use very different conventions for geographical allotment. The ICAO credits passenger kilometers to the airline's country of origin, and the IEA credits fuel use to the country in which the fuel is loaded onto the aircraft. Both conventions offer incomplete pictures. Since the fuel-efficiency calculation combines the two data sets, only limited generalizations can be made. Nevertheless, Figure 12 indicates that there are strong differences in fuel efficiency across regions and that there may be a tendency toward higher fuel efficiency in wealthier regions.

Figure 12: Civil Aviation's Fuel Efficiency

Six Geographic Regions, and World Average (ton-km/kg fuel)



Calculated from: Balashov (1992), ICAO (1992), IEA (1992).

Does not include relative differences in regional military fuel usage.

Given the variation in fuel efficiency, we examine the effect of "technology delay" where less efficient categories are in the process of catching up to more efficient ones. We compare two efficiency cases. The first assumes that all categories follow the logistic defined in Section 4.1. The second assumes differences in initial efficiency as described in Table 6. It assumes varying rates of improvement across categories, but the same ultimate capacity. Parameters for the efficiency model are chosen so that the ICAO's 1990 estimate and short-term projections are matched. Table 6 summarizes the efficiency-improvement assumptions.

Table 6: Efficiency-Improvement Cases

Case	1990 Efficiency (grams of fuel/TK)	Rate	Capacity
Equal Rates	0.539	0.05	6
Varied Rates -			
Category 1	0.415	0.048	6
Category 2	0.539	0.048	6
Category 3	0.719	0.042	6
Category 4	0.770	0.042	6
Category 5	0.829	0.048	6
Military/Gen.Av.	0.539	0.048	6

Category 1 has the highest initial efficiency, followed in order by Categories 2, 3, 4, and 5. Since fuel efficiency is not the main priority for the military or general aviation markets, both have fuel efficiency levels that are lower than Category 1. Categories 1, 2, 5, and Military/Gen.Av. have a higher rate of improvement than Categories 3 and 4, reflecting their industrial base. The values in Table 6 are not a unique set; they have been chosen so that there is at most a 20- to 25-year lag before Categories 3, 4, and 5 catch up with Category 1.[35]

4.3 Modeling Emissions Indices

Fuel usage can be translated into emissions of chemical species through the analysis of emission index (EI) values. The EI for a species is defined as the weight emitted of that species per thousand-weight of fuel burned (g/kg).

4.3.1 Carbon Dioxide (CO_2)

Calculation of CO_2 emissions is straightforward since the EI for carbon dioxide is unlikely to change much over time. We use EI = 3.16 g of carbon dioxide per gram of fuel.[36] This assumes that aviation continues to depend largely on jet fuel as it does today,[37] and that the fuel's composition and purity does not change significantly.

4.3.2 Nitrogen Oxides (NO_X)

Unlike carbon dioxide, the EI for nitrogen oxides is likely to decrease significantly as new technology develops. Also, the EI for nitrogen oxides varies greatly with the altitude, thrust-level, engine-design, and combustor-type. Estimates for specific combinations range from 6 to 40 g of nitrogen oxides (as nitrogen dioxide) per kg fuel.[38] Since our model is a highly aggregated one, we use a single emission index for nitrogen oxides that serves as an average value.

There is substantial variation in estimates of an average index for nitrogen oxides. Egli (1990) and Schumann (1993) propose an average index of 18. A recent analysis by NASA's Atmospheric Effects of Stratospheric Aircraft (AESA) project determines an index of 10.9 averaged over all fuel use.[39]

The discrepancy in EI results in substantially different estimates of total NO_x emissions. The AESA project includes city-pair simulation as well as an extensive altitude-based analysis of aircraft types; it is also the most recent. Therefore we adopt the AESA EI of 10.9 g of nitrogen oxides (as nitrogen dioxide) per kg fuel in 1990, recognizing that it may correspond to a lower bound.

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.[40] The aggregate NO_x EI depends on the details of future engine technology, as well as changes in fleet mix; it is unclear, given the continuing improvements in efficiency that are anticipated, whether the aggregate NO_x EI will decline over time in the absence of new policy requirements.

The AESA project assumes a reduction in the aggregate NO_x EI of approximately 20% by the year 2015.[41] We create a logistic model of gradual decline in NO_x EI through 2100 that matches the AESA projection through 2015. Details of the model are given in Appendix A. The AESA assumption may well be too optimistic for a base case without policy.

5. RESULTS

5.1 Demand Scenarios

The five IPCC scenarios and the two demand sets above provide a total of 10 demand scenarios. Figure 13 shows total global demand for the "middle" IS92a scenario with base-demand and high-demand sets. The sharp upswings when different regions start expansion are clearly visible.

Figure 13: Global Aviation Demand for IPCC IS92a Scenario
"Middle" Case for projected population and GNP growth

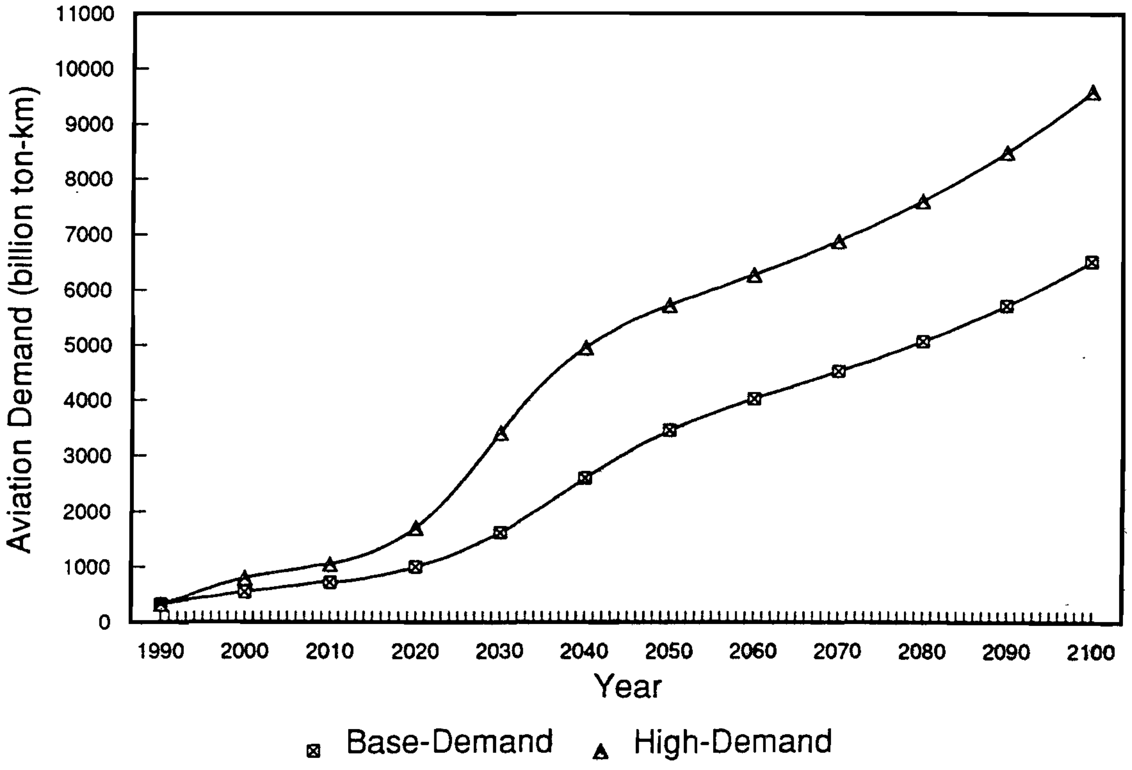
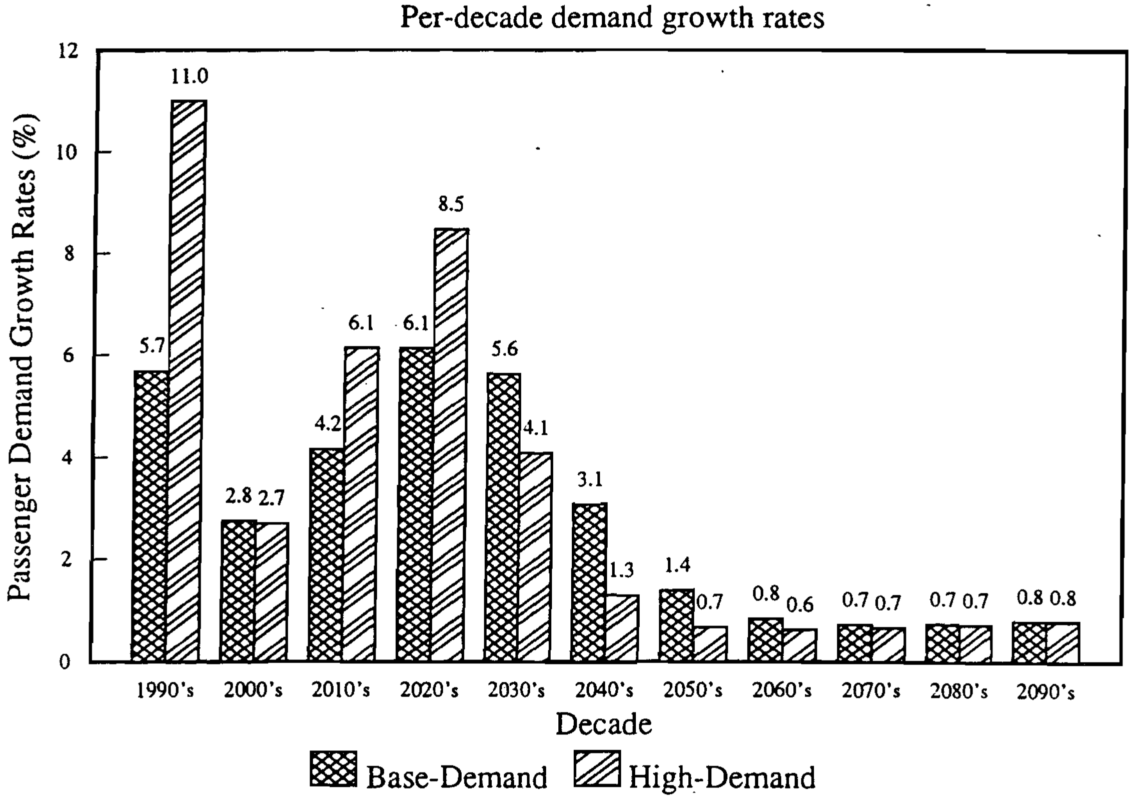


Figure 14 shows the growth-rates projections for global passenger travel; these can be compared to current shorter-term projections. For example, the ICAO predicts annual passenger travel growth rate of 5.0% from 1990 to 2001;[42] Boeing predicts 5.9% from 1992 to 2000;[43] and McDonnell Douglas predicts 6.7% from 1991 to 2011.[44] The base-demand set falls within the range of current projections with a predicted rate of 5.7%, while the high-Demand set presents a higher level.

Figure 14: Global Passenger Demand Growth Rates for IPCC IS92a



However, comparison with short-term forecasts is of limited use since this model is inherently long-term. Logistical expansion models a smooth evolution of start-up, expansion, and maturity; this cannot capture the inevitably "noisy" behavior of short-term business cycles and policy decisions. Short-term forecasts, on the other hand, focus on current business-cycle and trade prospects.

Figures 15 and 16 show demand for the five IPCC scenarios and the base-demand and high-demand sets, respectively. The range of aviation demand for different population and GNP estimates is considerable; in both figures, the range of demand levels in the year 2100 encompasses more than a factor of three. Thus the evolution of population and GNP will have a large effect on aviation demand. The current level of uncertainty in these estimates affects demand scenarios greatly.

Figure 15: Global Aviation Demand - Base-Demand Set

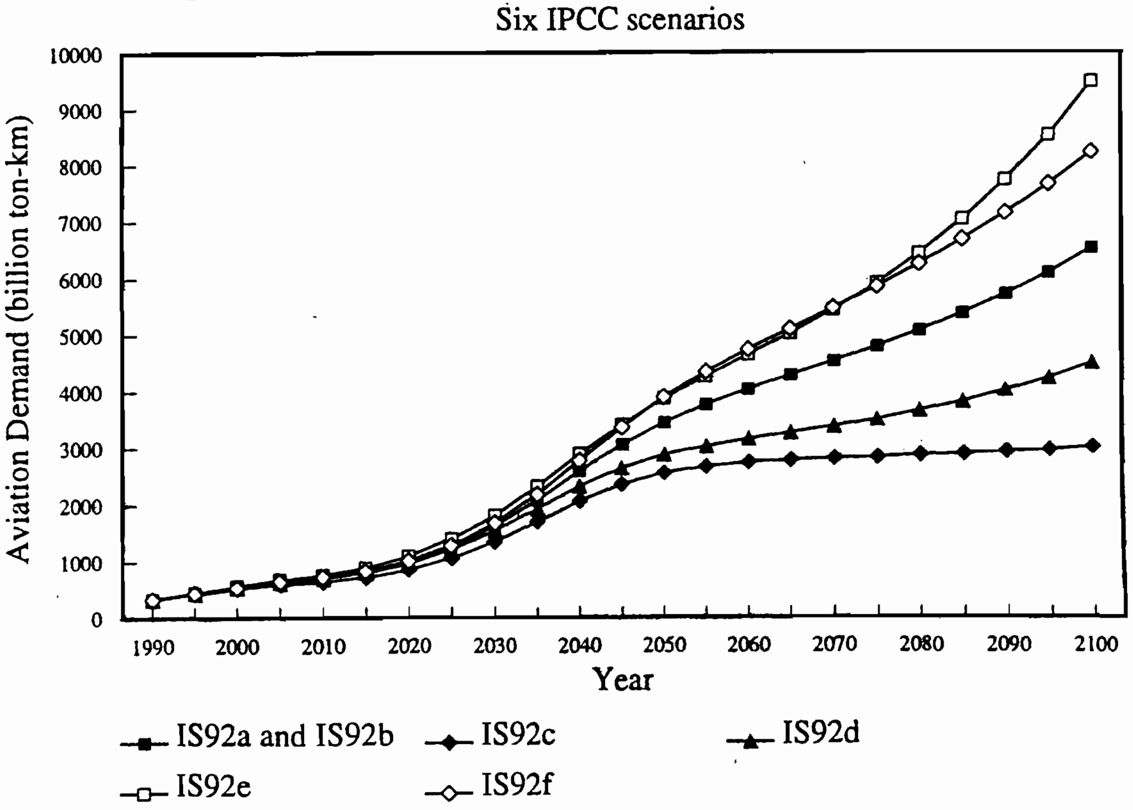
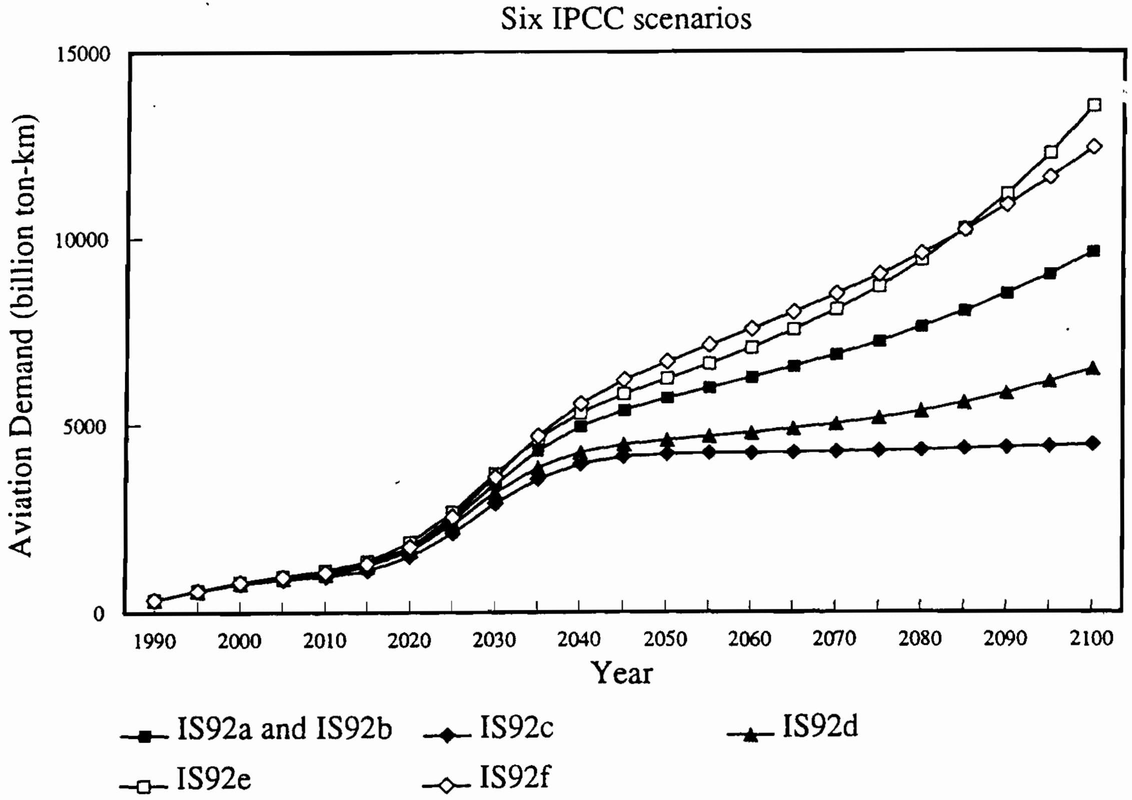


Figure 16: Global Aviation Demand - High-Demand Set



Under the base-demand set and the IS92a scenario, the demand level in 2100 is higher than the 1990 level by a factor of 20. The difference between the base- and high-demand sets is also significant; it affects the scenario for the year 2100 by more than 45%.

Figure 17: Fuel Efficiency Projection

Equal Rates for all economic categories

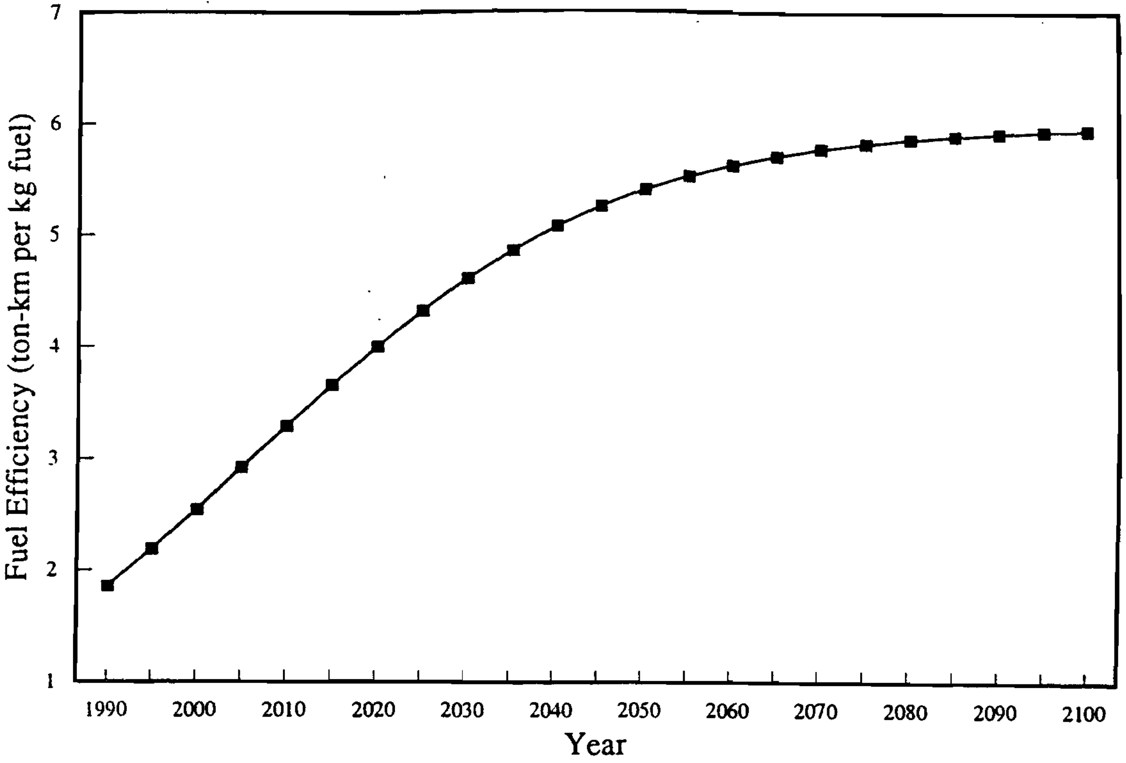
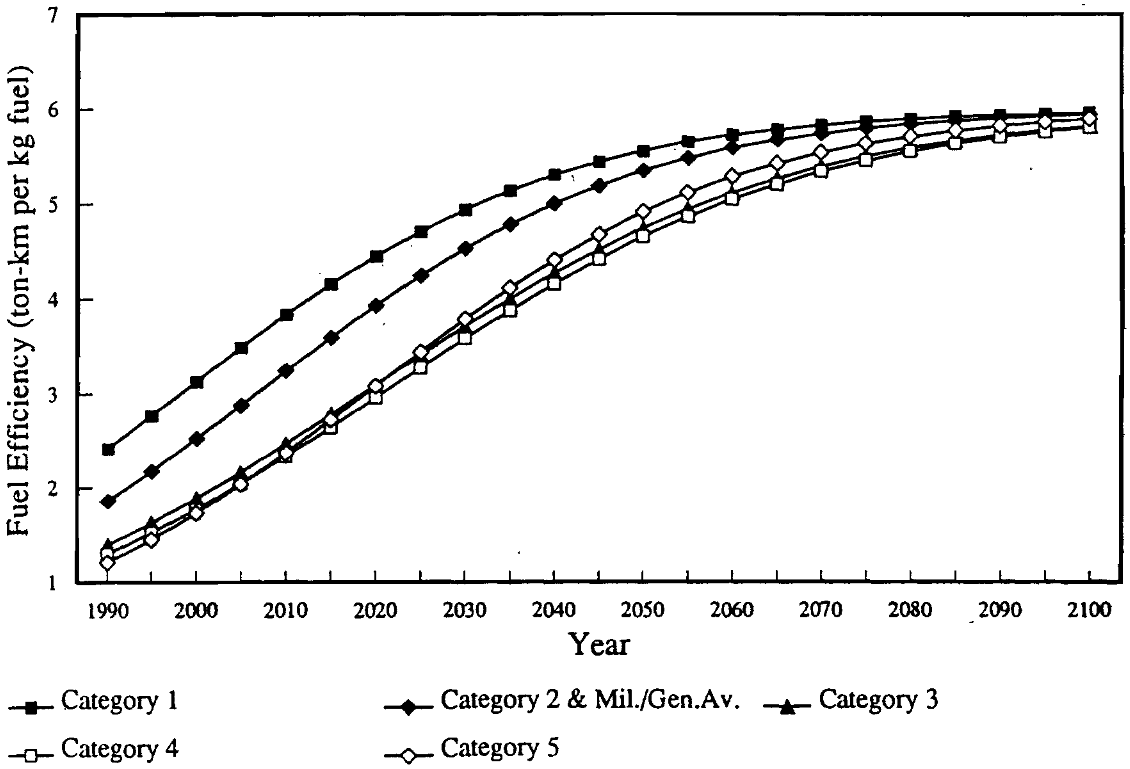


Figure 18: Fuel Efficiency Projection

Varied Rates across economic categories



5.2 Fuel Usage Scenarios

Figures 17 and 18 show the fuel efficiency improvement projections for equal-rates and varied-rates cases, respectively. Figure 19 shows the resulting fuel usage for the two efficiency cases under the base-demand assumption and IS92a. Accounting for the variable abilities of different categories to invest in fuel-efficient technologies does add modestly to total fuel use in the middle term. We use the varied-rates case in all subsequent analysis.

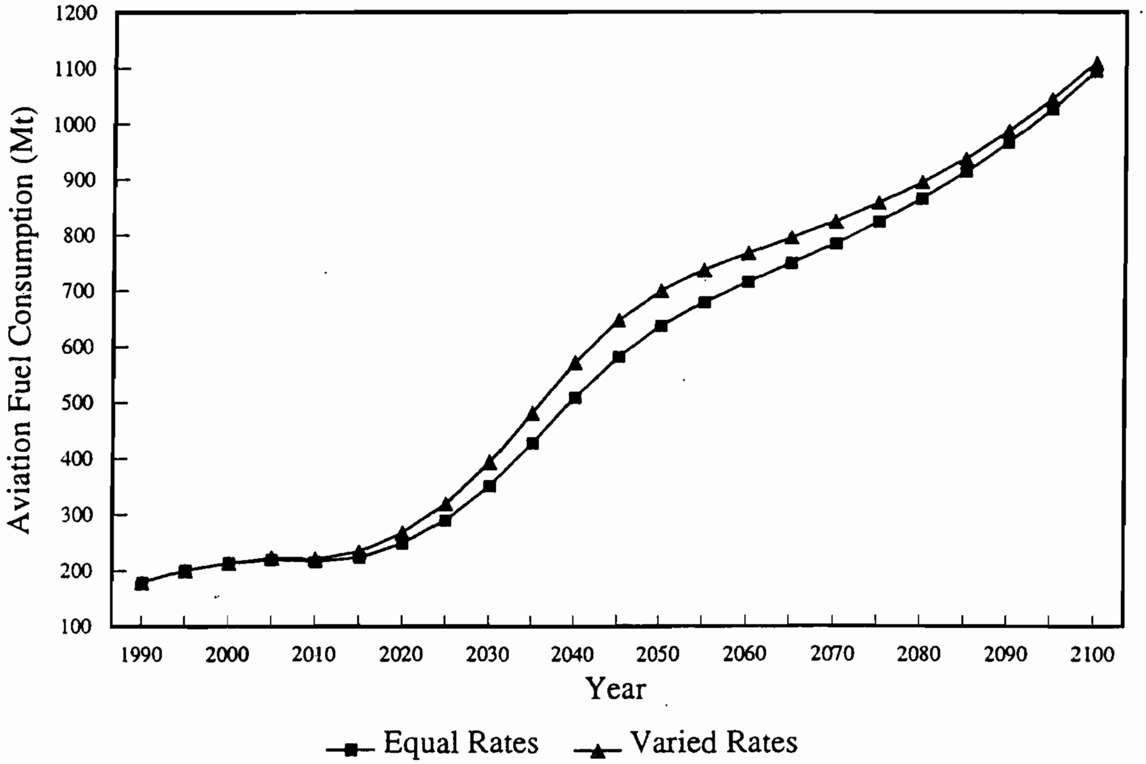


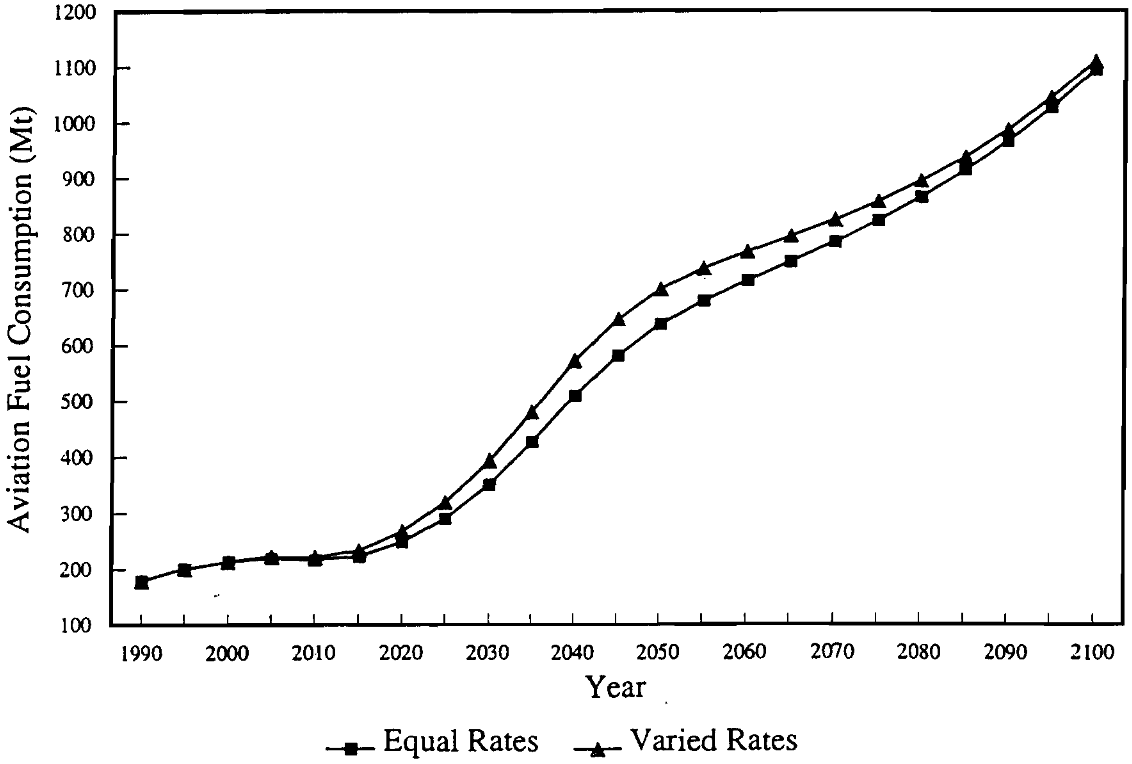
Figure 19: Global Aviation Fuel Usage: Equal and Varied Rates
IPCC IS92a, Base-Demand Set

5.2 Fuel Usage Scenarios

Figures 17 and 18 show the fuel efficiency improvement projections for equal-rates and varied-rates cases, respectively. Figure 19 shows the resulting fuel usage for the two efficiency cases under the base-demand assumption and IS92a. Accounting for the variable abilities of different categories to invest in fuel-efficient technologies does add modestly to total fuel use in the middle term. We use the varied-rates case in all subsequent analysis.

Figure 19: Global Aviation Fuel Usage: Equal and Varied Rates

IPCC IS92a, Base-Demand Set



Under the base-demand set and the IS92a scenario, the fuel-usage level in 2100 is higher than the 1990 level by a factor of 6. For the IS92a scenario, the fuel consumption in 2015 is 234 Mt (million metric tons) for the base-demand set and 365 Mt for the High demand set. This range is consistent with the 304 Mt estimate for fuel use in 2015 from the results of the NASA AESA project.

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 does not provide additional supplies, then price changes could render our scenarios unrealistic in the later years.[28]

5.3 CO_2 Emissions Scenarios

Figures 20 and 21 show the CO_2 emissions levels for the six IPCC scenarios for the base-demand and high-demand, respectively. Under the base-demand set and the IS92a scenario, the CO_2 emissions level in 2100 is 1.0 gigaton carbon (GtC), higher than the 1990 level by a factor of 6. The range of outcomes is very wide; the CO_2 emissions levels for the year 2100 vary by more than a factor of 4. 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 2040 for the base-demand IS92a scenario.

For the IS92c scenario (low population and GNP growth), both figures show that the level of CO_2 emissions in 2100 is lower than that in 2050. This reflects the catch-up effect where, in certain cases, efficiency improvements can eventually compensate for demand growth.

Figure 20: Global Aviation CO2 emissions - Base-Demand Set

IPCC scenarios, Varied Efficiency rates

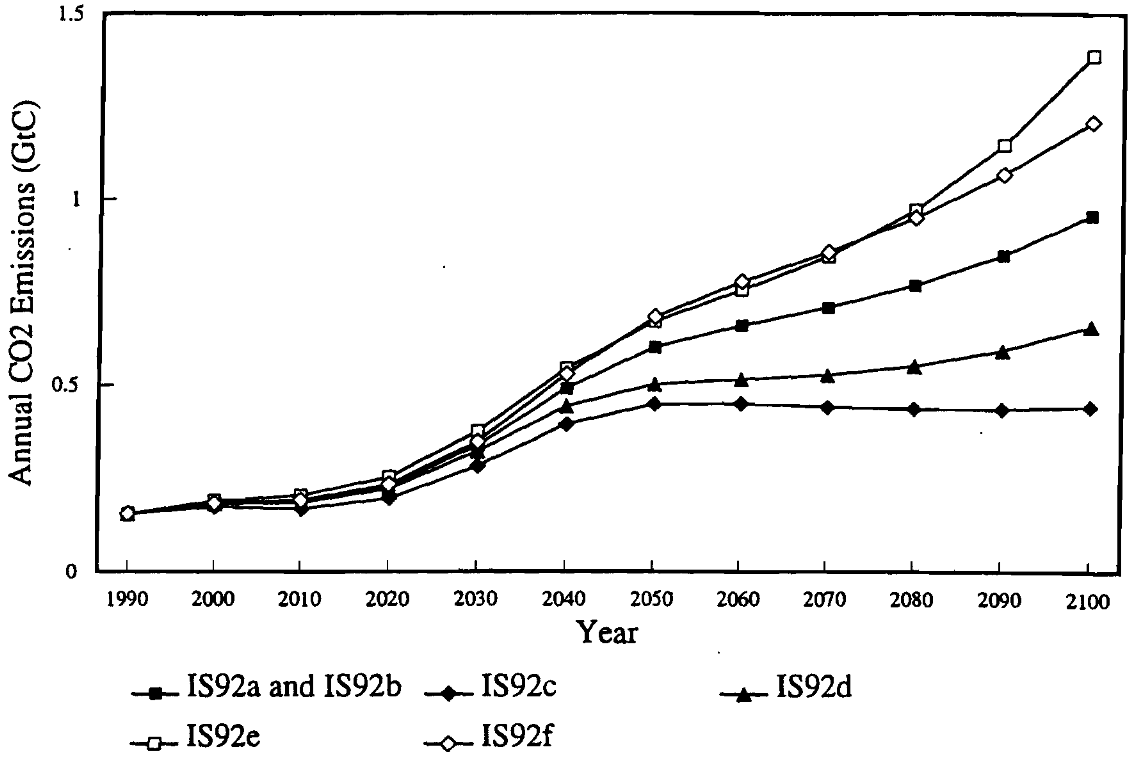
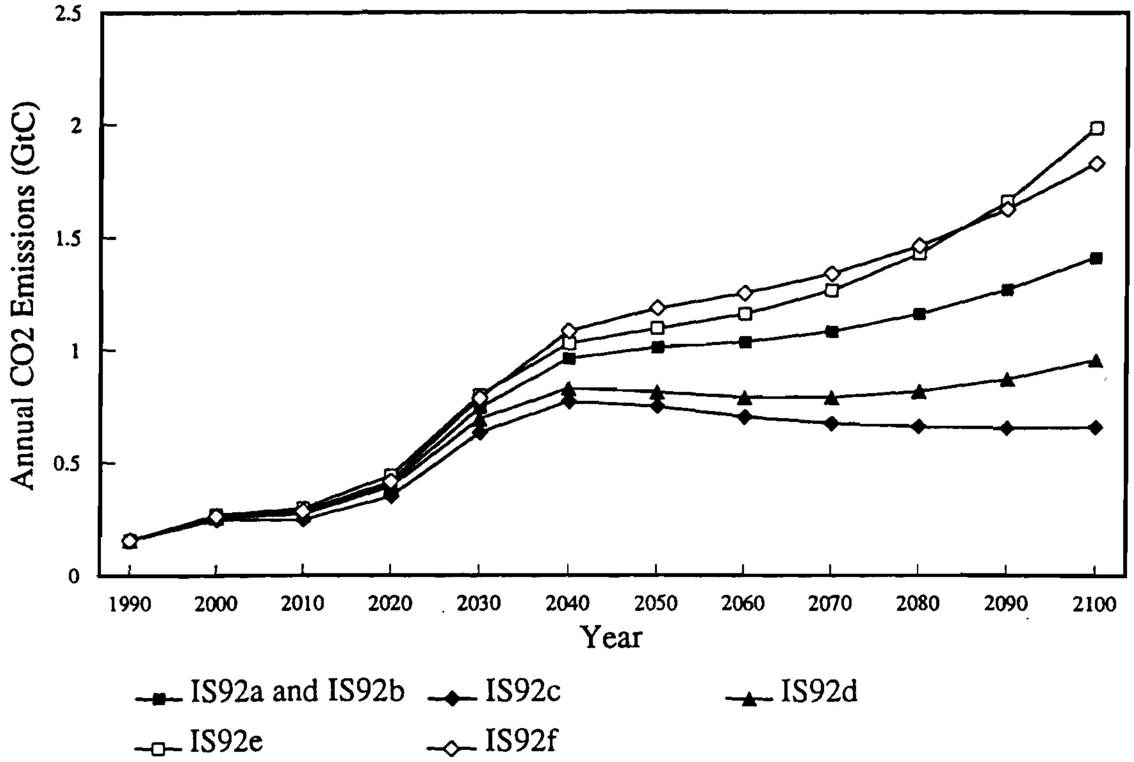


Figure 21: Global Aviation CO2 emissions - High-Demand Set

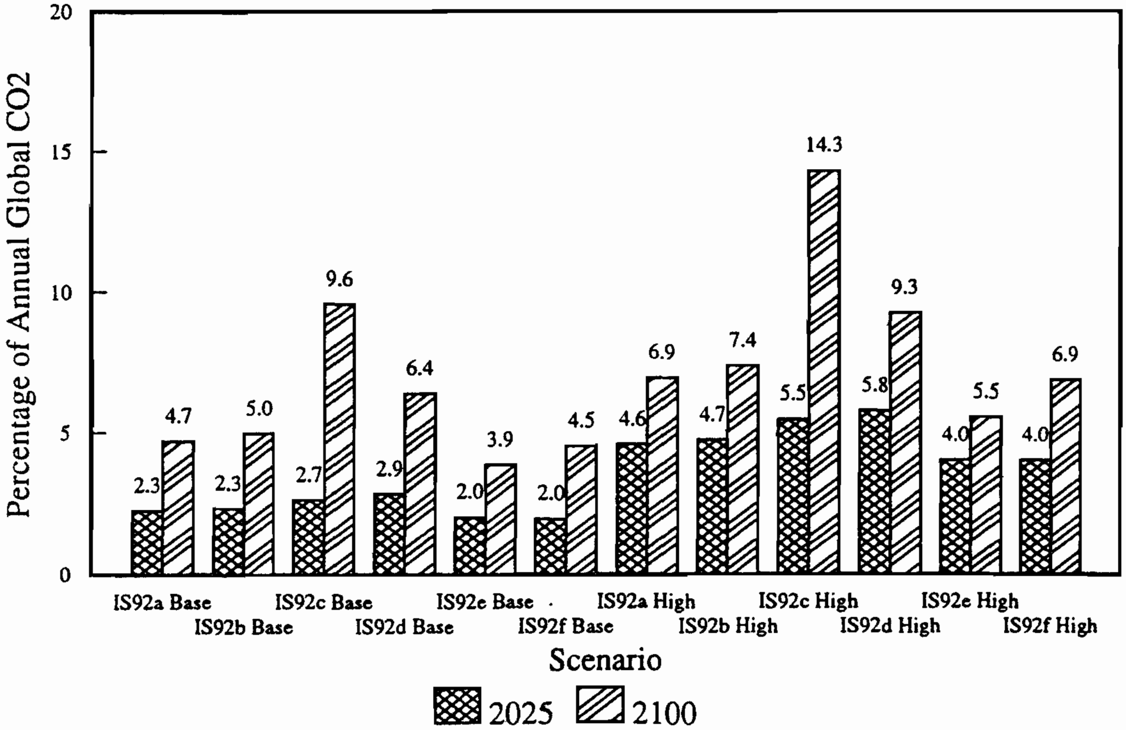
IPCC scenarios, Varied Efficiency rates



The CO_2 emissions scenarios for aviation can be compared with the IPCC's scenarios for total anthropogenic CO_2 emissions (including emissions from energy consumption, deforestation, and minor sources). The IPCC scenarios include policy assumptions affecting fuel prices and emissions. Our model includes no policy assumptions; it offers a business-as-usual viewpoint regarding aviation. Thus only limited conclusions can be drawn from comparison with the IPCC forecast. The likely feedback from policy changes and energy price increases to improved aviation fuel efficiency is recognized but not incorporated here. The omission of policy effects will create an overestimate of aviation's role, especially in the IS92e scenario, which assumes a 30% increase in fossil fuel costs. However, the policy assumptions in the IPCC base case (IS92a) do not differ markedly from expectations that underlie our aviation projections.

Figure 22: Aviation's Percentage of Total CO2 Emissions

IPCC Scenarios, High and Base Demand sets



Aviation's Share in 1990 = 2.01%

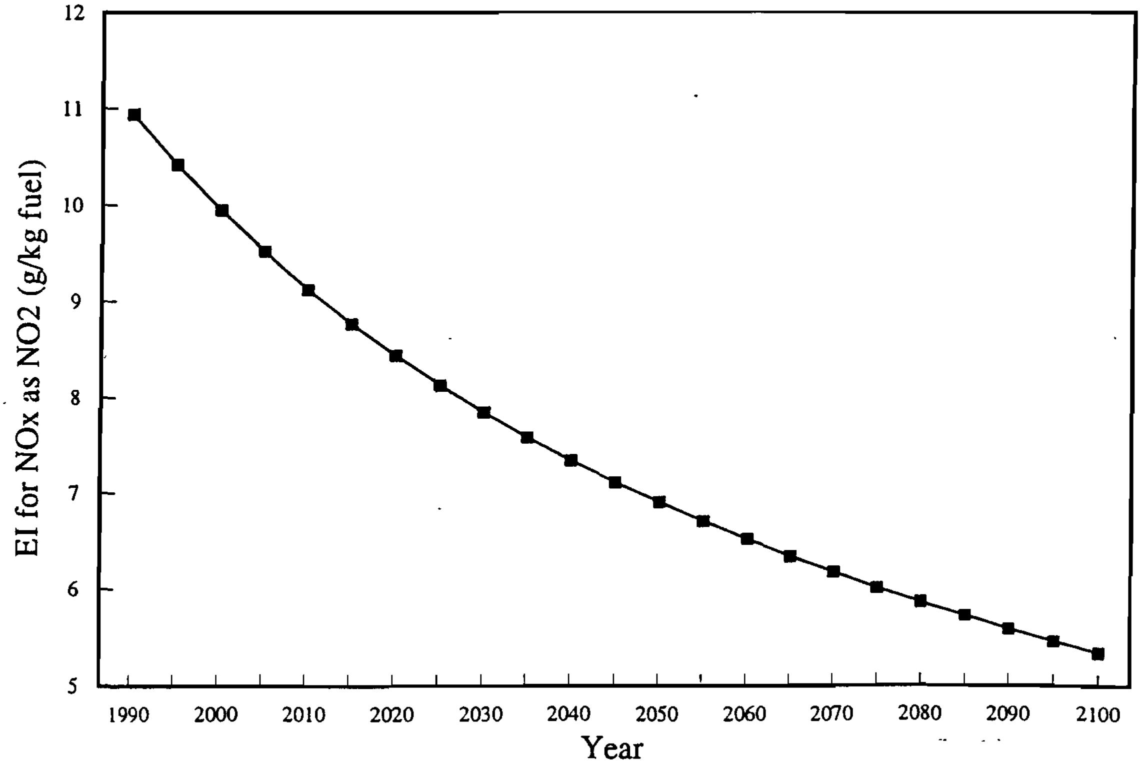
For each of the six scenarios and both demand levels, Figure 22 shows the fraction of global CO_2 emissions from aviation in 2025 and 2100. Aviation's share of global CO_2 emissions changes from its current 2.1%, becoming between 2.0 and 5.8% in 2025, and between 3.9 and 14.3% in 2100. Values for 2050, not shown in the figure, range from 3.3% to 10%. For the IS92a scenario under the base-demand set, aviation's share rises to 2.3% in 2025 and 4.7% in 2100. In general, it is clear that aviation could become a significant contributor to global CO_2 emissions.

5.4 NO_X Emissions Scenarios

Figure 23 shows the projected emissions index for NO_X and Figures 24 and 25 show the resulting global NO_X emissions for the six IPCC scenarios for base-demand and high-demand, respectively.

Figure 23: NOx Emission Index Projection

20% reduction in EI by 2015



Since total NO_X emissions are reduced because of both fuel efficiency improvement and EI reduction, in theory technological improvement can compensate for more demand growth than 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. As we noted earlier, however, our projection of NO_X EI may be too optimistic. An earlier analysis projected higher emissions for the period through 2025, based on slower declines in EI.[45]

Figure 24: Global NOx Emissions - Base-Demand Set

IPCC scenarios, Varied Efficiency rates

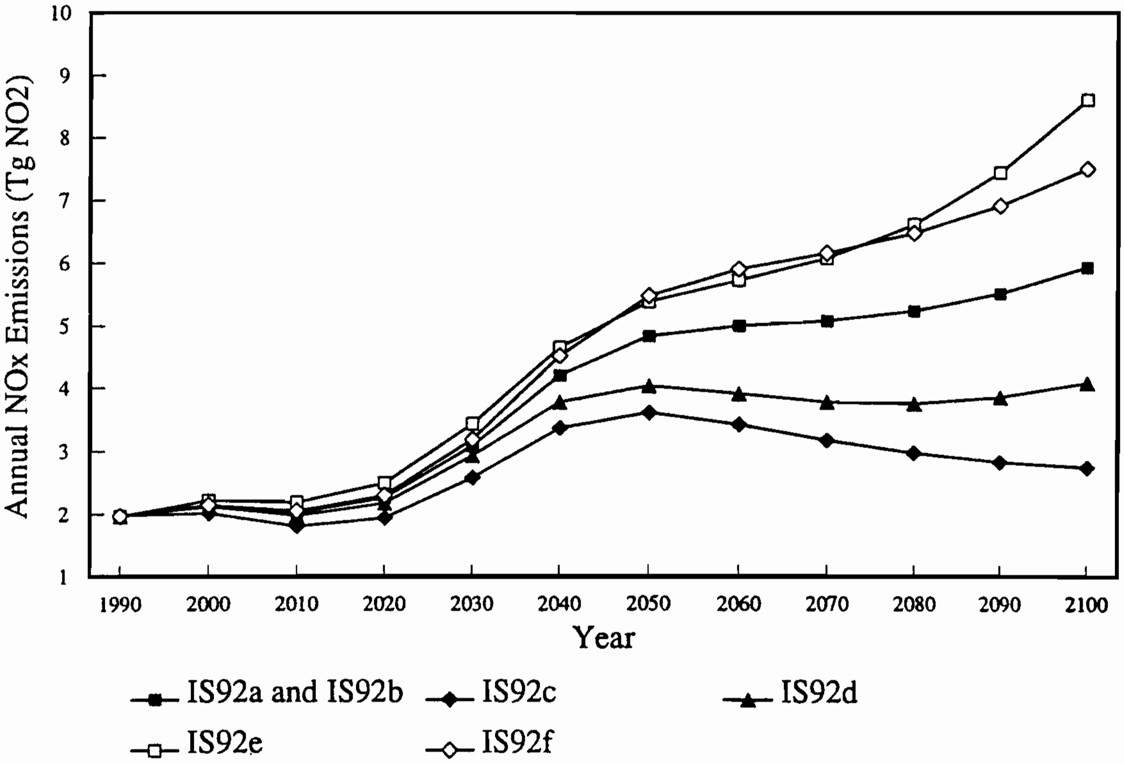
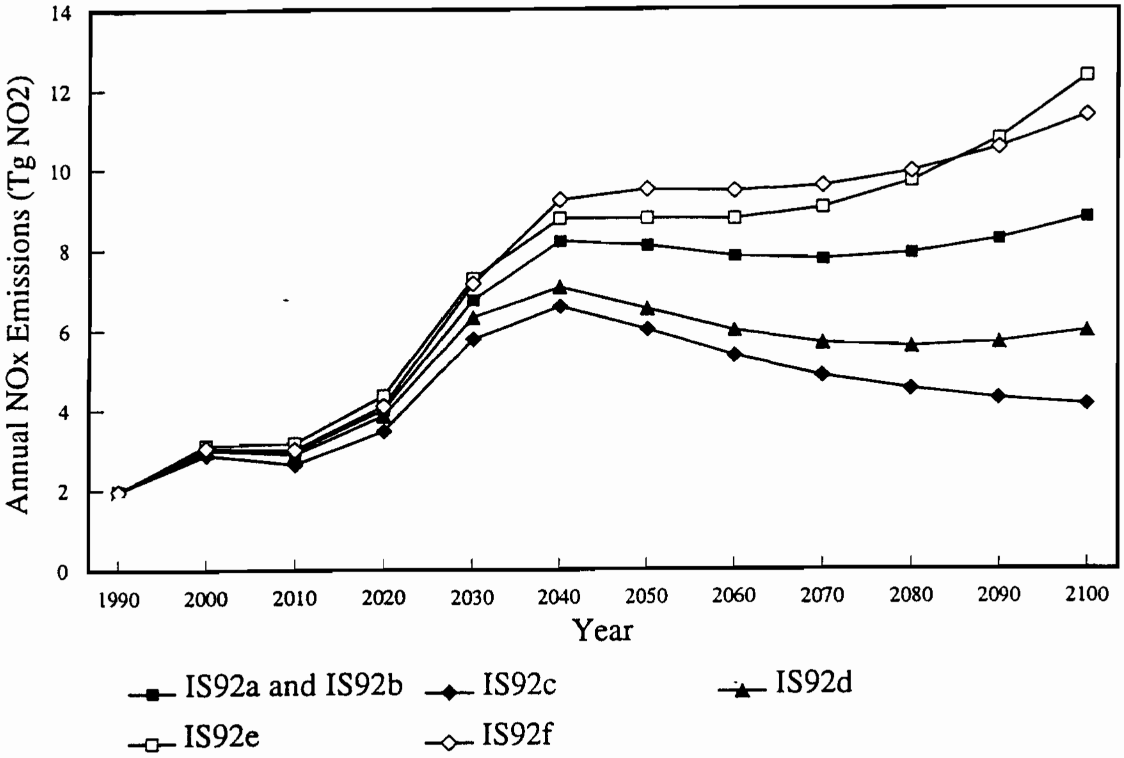


Figure 25: Global NOx Emissions - High-Demand Set

IPCC scenarios, Varied Efficiency rates



For the IS92a scenario under the base-demand set, NO_X emissions rise sharply from 2.0 Mt (NO_2) in 1990 to 4.8 Mt (1 Mt = 1 Tg) in 2050, but growth slows, reaching a level of 5.9 Mt in 2100; the NO_X emissions level in 2100 is higher than the 1990 level by a factor of 3. Appendix B presents a tabular summary of demand, fuel usage, and emissions levels for selected years. As with CO_2 emissions, projected NO_X emissions in the base case change only modestly before 2015 but rise rapidly thereafter, increasing by a factor of 2.5 by 2050 for the base-demand IS92a scenario. In 2015, NO_X for this scenario is 2.1 Mt for the base-demand set and 3.2 Mt for the high-demand set. This range is consistent with the 2.7 Mt estimate for 2015 given by the NASA AESA study.

5.5 NO_X Emissions at High Altitudes

Unlike CO_2 emissions, NO_X emissions have very different environmental effects at different altitudes. Calculation of emissions at different altitudes and latitudes requires analysis of individual city-pair routes. The 1993 NASA AESA database provides this type of detailed distribution for the year 2015.

Figure 2 shows NASA's results on the altitude distribution of fuel burn for scheduled passenger and cargo flights (which account for about one half of total aviation fuel consumption) during 1990. The sharp increase in fuel burn at and above 9 kms indicates the separation between the cruise and non-cruise segments of a flight.

We scale our long-term scenario of NO_X emissions using the 1993 NASA AESA database to estimate emissions above and below 9 kms; this assumes only that aircraft will continue to cruise at altitudes above 9 kms throughout the next century. Finer estimates can be made, but their long-term plausibility is unknown.

According to the AESA database, more than 60% of fuel usage is expended at altitudes above 9 kms, and the NO_X EI varies considerably as a function of altitude. The AESA calculations use detailed analysis of city-pair routes and engine types to calculate fuel usage; their results account for only 76% of total worldwide jet fuel consumption.[46] Scaling the AESA projections to reflect the total fuel consumption used in our model indicates that 1.15 Mt of nitrogen oxides are emitted above 9 kms in 1990. For the base IS92a scenario, NO_X emissions above 9 kms rise to 1.28 Mt in the year 2015, 2.83

Mt in the year 2050, and 3.47 Mt in the year 2100. Appendix C summarizes the altitude-based emissions projections for all six IPCC scenarios and both demand sets.

It must be emphasized that the environmental effects of NO_x emissions are significantly different in the stratosphere as opposed to the troposphere. Since the boundary between the two regions generally lies above 9 kms at mid-latitudes and varies in altitude at different latitudes, a much closer analysis of altitude effects, as well as future flight patterns, will be needed to determine environmental impact.

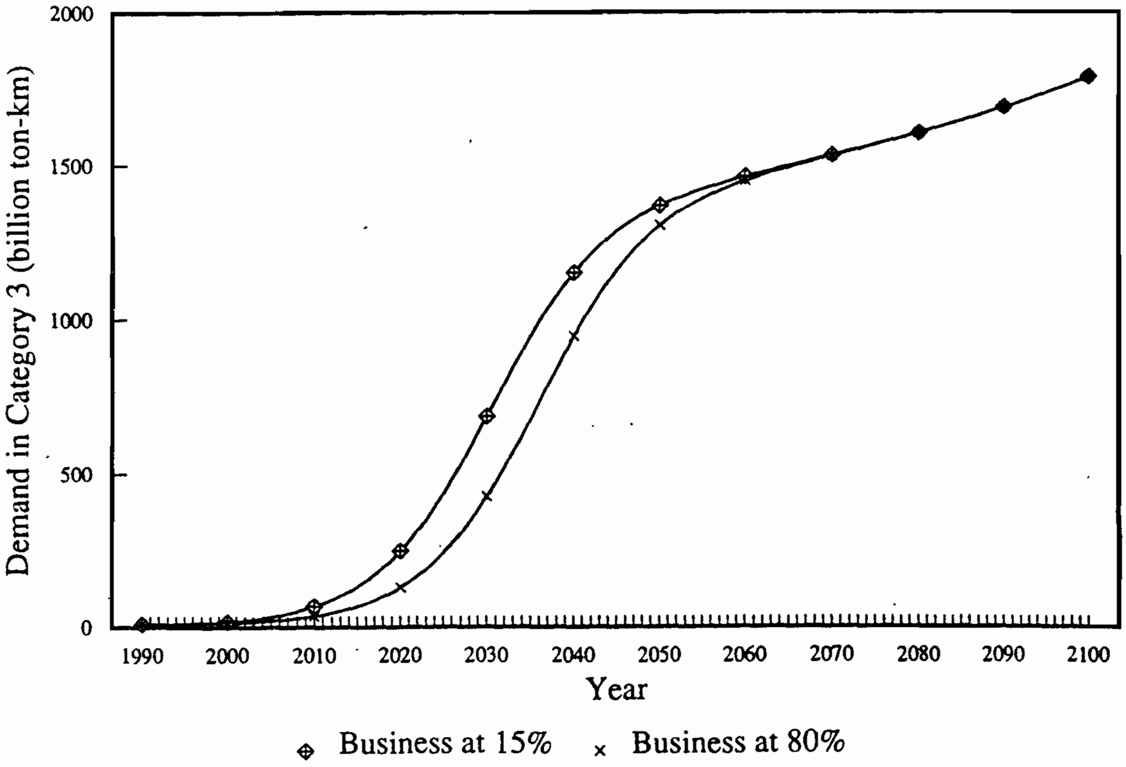
6. SENSITIVITY ANALYSIS

We now review briefly the impact of some of our most uncertain assumptions on the scenarios.

- Division of passenger travel into business and personal sectors: Since data on personal and business travel is very weak, we assumed different levels for each economic category, based on an empirical finding that wealthier nations have a smaller fraction of business travel. Personal international travel is often restricted greatly by governments in developing countries since it uses valuable foreign exchange. In the cases of both Japan and South Korea, such restrictions were lifted after per-capita income rose considerably; this resulted in a sharp rise in demand. The relaxation of restrictions by large nations such as China is likely to create sharp spikes in demand; their timing is hard to foresee.

Figure 26: Sensitivity Analysis - Demand in Category 3

Comparison: Business share at 15% and 80% of the total



Since we have set a high level of business share for Category 3, we compare our demand scenario for Category 3 with an allotment of the global average of 15% for business share. Figure 26 shows that the change in business share has a modest effect on demand in the medium term; demand levels in 2100 are unaffected.

- Assignment of countries into economic categories:

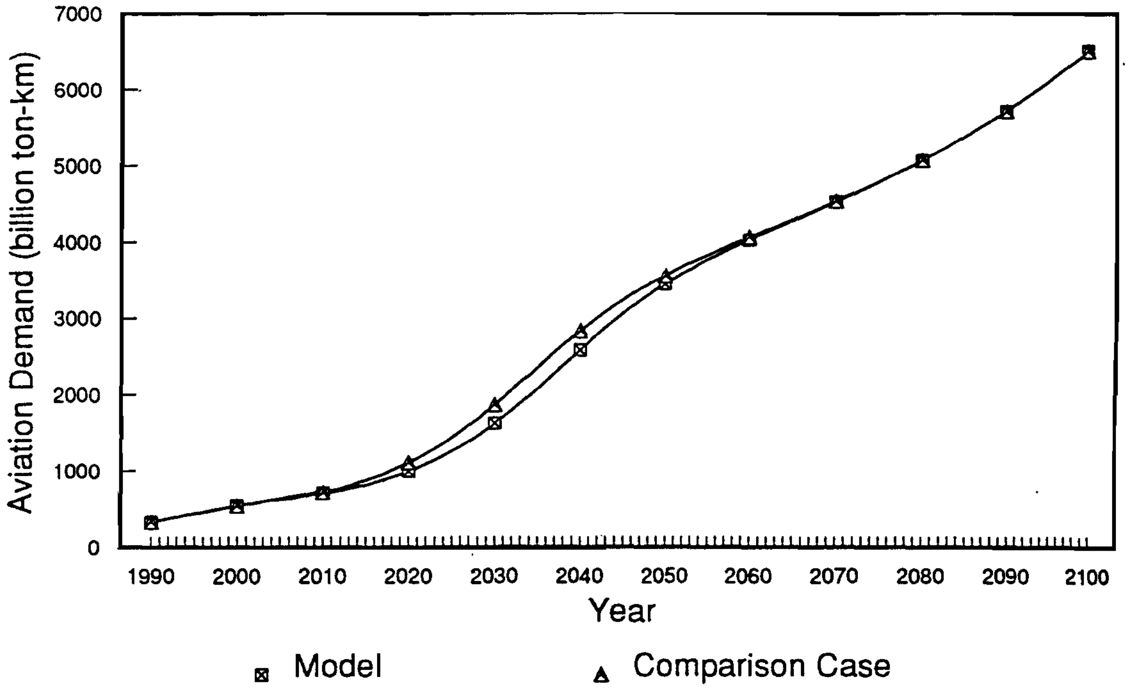
We created broad categories, each incorporating a diverse set of countries. Category 4 contains Brazil, Argentina, Nigeria, and South Africa. To examine the consequences if these four large economies begin to grow more rapidly, we can consider their contribution to the aviation demand of Category 4. One indicator is that these four countries constituted 17% of the category's aviation fuel usage in 1989.[47] Similarly, to examine the consequences of slow growth in India and Bangladesh, which fall in Category 3, we can consider the fact that these two countries account for 15% of Category 3 fuel usage. Shifting these countries across Categories 3 and 4 has a negligible effect on total demand in 2100.

- Assumptions regarding date of market expansion:

We compare the set of market expansion dates with a comparison case in which the three developing categories (3, 4, and 5) begin expansion five years earlier. Figure 27 shows that earlier expansion has a minor short-term impact and no long-term impact on demand levels. Thus our results are insensitive to this set of assumptions.

Figure 27: Sensitivity to Expansion Start Date - IS92a

Comparison: Categories 3,4 and 5 start expansion 5 years early



Comparison Case: Category 3 starts in 1995, Categories 4 and 5 in 2005

Basic model: Category 3 starts in 2000, Categories 4 and 5 in 2010

7. CONCLUSIONS

This analysis has focused on the long-term dynamics underlying markets for aviation. It reveals potential trends in the growth of aviation demand, and resultant fuel usage and emissions. We conclude that:

- 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.

- In these scenarios, developing countries supply most of the growth in demand over the next century. The timing and extent of their industrialization can be crucial in determining the extent of environmental impact. Timing and government choices regarding restrictions on international travel are also important.

Based on the U.S. experience, we assume that small increases in per-capita income for developing countries will create disproportionately large increases in aviation demand due to the high levels of income inequality within developing countries. This effect is reflected in our demand logistic model.

We have not considered the effects of many possible positive feedbacks between an improved aviation infrastructure and continued economic growth; this may further contribute to 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. Barrett incorporates some of these factors and presents a much higher business-as-usual estimate for long-term aviation demand, expecting an increase in demand by 2031 of a factor of about 9,[48] compared to the slightly less than five-fold increase estimated by 2030 for the base case by our model. On the other hand, rapid diffusion of telecommunications technology could alter lifestyles in a manner that would reduce demand growth.

- The aviation market in developing countries is likely to grow rapidly and approach maturity faster than the historical experience of industrial nations. Developing countries will benefit from the experience in industrialized countries with regard to technology and the incorporation of aviation into business and leisure.

- Future improvements in fuel efficiency will be essential to mitigate the effects of increased fuel usage due to demand growth. The issue of technology transfer must be taken into account; technological brakes to the demand acceleration will be more effective if poor nations are able to afford the new methods.

- In the absence of policy limits on fossil fuel consumption or on aircraft emissions, the contribution of aircraft becomes a significant fraction of total CO_2 emissions. Depending on population and GNP growth rates and on demand levels, aircraft emissions may comprise between 4% and 14% of global anthropogenic CO_2 emissions by 2100.

- Both current and expected levels of NO_X emissions from aircraft constitute a considerable perturbation of natural conditions. More than 60% of aviation's NO_X emissions occur at altitudes above 9 kms, where the relative importance of aviation's contribution is much greater than at lower altitudes. Introduction of new technologies that reduce NO_X emission indices beyond those currently envisioned by the aviation industry would be necessary in order to prevent substantial emissions growth.

- The combined effect of aviation emissions of carbon dioxide, nitrogen oxides, and water vapor on global warming now or in the 21st century cannot be accurately assessed at this time. The large range of estimates[3] for the current climate forcing due to nitrogen oxides (through ozone production), combined with the range of projected emissions from this report for nitrogen oxides and carbon dioxide, indicates that the total contribution to global warming from aviation could be quite significant (on the order of 10% of total warming) by the middle of the 21st century.

8. RECOMMENDATIONS

In order to determine the general implications of our findings for policy, it is important to understand the following characteristics of aviation emissions and their effects on the environment. First, very large uncertainties attach to both projected emissions and their potential consequences. The clearest understanding is of the intersection of aviation with the carbon dioxide problem: CO_2 emissions from aviation are likely to become a significant contributor to the global buildup of that gas, and carbon dioxide, once emitted, remains in the atmosphere for decades to centuries.

The effects of nitrogen oxides with regard to both climate and ozone are much more uncertain, and nitrogen oxides have a short atmospheric lifetime; they are removed from the troposphere within about a week and the stratosphere within a year or two of emission. On the other hand, scientific uncertainties surrounding nitrogen oxides may not be reduced enough to allow reliable quantitative estimates of their effects, in the upper troposphere in particular, for a decade or more. Furthermore, designing a new aircraft can take up to a decade, and each aircraft design has a lifetime of about 25 years.[49] Decisions made today may govern emissions through 2030. This characteris-tic places a premium on anticipating potential problems and being proactive in design.

Current ICAO emissions limitations apply only to the landing-takeoff cycle. There are no international limitations on fuel use or CO_2 emissions. Based on our findings, we conclude that it is an appropriate time to develop and implement regulations and incentives that will result in lower emissions of both nitrogen oxides and carbon dioxide from aviation than those anticipated in our base case. In spite of large uncertainties with regard to both emissions and their consequences, the following characteristics of this problem stand out:

- the likelihood of substantial growth of emissions unless measures are taken to limit them;
- the long lead times in developing new technologies and their long lifetimes in the fleet, once developed;
- the significance of carbon dioxide from aviation compared to total global emissions of that gas;
- the potential for disproportionate leverage on climate from emissions of nitrogen oxides and water vapor occurring directly at cruise altitudes;
- the current depleted state of the ozone layer;
- the continuing buildup of greenhouse gases from other sources;
- the expected gradual rate of progress toward reliable and stable quantitative estimates of the impacts of aviation.

We recommend development of approaches to limit emissions, recognizing the technological and economic complexities that will surely arise. In particular, the simultaneous improvement in engine efficiency and technology-based limitation of NO_x emissions would involve certain trade-offs. Consequently opportunities for operational changes which would reduce emissions should be explored by the aviation industry. A diverse transportation system would allow intermodal shifting of some demand, for instance to high-speed rail for many continental trips. Ultimately the desirable level of emissions from aviation must be determined in the context of a fuller understanding of environmental consequences of all sources of emissions, technological opportunities, and costs of improvements in the aviation sector. But a proactive approach now would both reduce environmental risk and provide more flexibility later.

The primary responsibility for regulating aviation emissions lies with the ICAO. But it has been argued that the Parties to the Montreal Protocol on Substances That Deplete the Ozone Layer and individual nations, in developing national plans under the Framework Convention on Climate Change, also may exercise regulatory responsibility. In collaboration with the ICAO, the parties to the Montreal Protocol on Substances That Deplete the Ozone Layer should establish a framework for limiting fleet-wide stratospheric emissions that affect the ozone layer from both subsonic and supersonic aircraft.

In contrast, the equivalence of CO_2 emissions, regardless of source, makes them a natural target for management under global and national emissions caps rather than technology-based regulations. The ICAO should investigate technological and operational options for aviation that would inform the development of national climate plans. Issues related to allocation of responsibility for emissions from international flights also need to be resolved.

Finally, the U.S. and other governments, and the aircraft manufacturing industry, should establish environmentally driven improvements in aviation technology (building a "green" airplane) as a key goal, much as interest in creating clean and efficient automobiles has achieved the status of a national goal. From the U.S. perspective, development prospects for a "green" airplane would be enhanced by implementation of flexible policies like a CO_2 offset and trading system to meet the national obligation under the climate accord.

Appendix A: Documentation of the Model

A.1 The Demand Model:

We model four sectors of aviation demand:

1. Civil Business Passenger
2. Civil Freight
3. Civil Personal Passenger
4. Military and General Aviation

Sectors 1, 2 and 3 are separately modeled as variations on a basic logistic model with a time-varying market capacity. This model projects the change in demand level D_i in sector i over time t (in years) as:

$$\frac{dD_i}{dt} = r_i D_i \left(1 - \frac{D_i}{C_i K_i(t)}\right) \tag{1}$$

where r_i is the "intrinsic" speed of expansion, and $C_i K_i(t)$ is the capacity of the market. C_i represents a constant capacity factor, and $K_i(t)$ is either GNP or population.

Thus, we model Business Passenger Demand D_b as:

$$\frac{dD_b}{dt} = r_b D_b \left(1 - \frac{D_b}{F_b\ GNP(t)}\right) \tag{2}$$

and Freight Demand D_f as:

$$\frac{dD_f}{dt} = r_f D_f \left(1 - \frac{D_f}{F_f\ GNP(t)}\right) \tag{3}$$

We model Personal Passenger Demand D_p as:

$$\frac{dD_p}{dt} = r_p D_p \left(1 - \frac{D_p}{F_p\ Pop(t)}\right) \tag{4}$$

We assume that the demand for Military D_m and General Aviation D_g grow at the same percentage growth rate as GNP:

$$\frac{\frac{dD_m}{dt}}{D_m} = \frac{\frac{dGNP}{dt}}{GNP} \tag{5}$$

$$\frac{\frac{dD_g}{dt}}{D_g} = \frac{\frac{dGNP}{dt}}{GNP} \tag{6}$$

A.2 Separation of Civil Passenger into Business and Personal:

Empirical data on this division is very weak. Regular statistics are collected only on incoming international passengers, and domestic travel is completely unmonitored. Boeing's estimate for the world average in 15% business[50], but this may be an underestimate since domestic travel, which is primarily business travel, is unaccounted for. Empirical data indicates that poor countries have a much higher business share, partly because of government restrictions on leisure travel; China's international traffic, for example, is estimated to be as high as 90% business[51].

We set the following assignments:

Table A.1: Business shares for Geographic Regions

Region Name	Business Share
OECD except Japan	10%
Former USSR and Eastern Europe	50%
China and Centrally-Planned Asia	80%
Middle East	40%
Africa	80%
Latin America	80%
Southeast Asia	60%
Japan and East Asian NICs	15%

A.3 Capacity Levels and Maturity:

We create two sets of capacity levels C_i as follows:-

1. **Base Capacity**:

$$\begin{aligned} F_b &= 2\,\frac{D_{b_1}}{GNP_1} \quad : \mathit{Econ.\ Category}\ 1,\ 1990. \\ F_p &= 2\,\frac{D_{p_1}}{Pop_1} \quad : \mathit{Econ.\ Category}\ 1,\ 1990. \\ F_f &= 2\,\frac{D_{f_1}}{GNP_1} \quad : \mathit{Econ.\ Category}\ 1,\ 1990. \end{aligned} \tag{7}$$

2. **High Capacity**:

$$\begin{aligned} F_b &= 3\,\frac{D_{b_1}}{GNP_1} \quad : \mathit{Region}\ 1,\ 1990. \\ F_p &= 3\,\frac{D_{p_1}}{Pop_1} \quad : \mathit{Region}\ 1,\ 1990. \\ F_f &= 3\,\frac{D_{f_1}}{GNP_1} \quad : \mathit{Region}\ 1,\ 1990. \end{aligned} \tag{8}$$

For Economic Categories 3, 4, and 5, we set up the logistic demand models described above to begin at the expansion start dates given in Table 4. Prior to these dates, demand grows at the same relative rate than GNP does.

The rate factors r_i are chosen to ensure that each individual logistic reaches maturity at the appropriate maturation dates given in Table 5.

A.4 Fuel-Efficiency Model:

We model the improvement of fuel efficiency E as a constant-capacity logistic:

$$\frac{dE}{dt} = r_e E \left(1 - \frac{E}{k_e}\right) \tag{9}$$

where r_e and K_e are chosen to fit the two short-term ICAO projections of a 3.1% per year reduction in fuel consumption per TKP from 1990 to 2000, and 2.5% per year reduction from 2000 to 2010[52].

A.5 Nitrogen Oxides (NO_x) Emissions Index Model:

We model the NO_x EI N as a constant-capacity logistic:

$$\frac{dN}{dt} = r_n N \left(1 - \frac{N}{k_n}\right) \tag{10}$$

where r_n and K_n are chosen to fit the short-term AESA result of a 20% reduction in EI by the year 2015.[53]

Appendix B: Summary of Results

Scenario and Year		Demand (BTK)	Fuel (Mt)	CO_2 (GtC)	Percent of Total	NO_x (Mt NO_2)
	1990	332	180	0.155	2.1%	1.96
Base-Demand Set:						
IS92a	2015	817	234	0.202		2.05
	2050	3445	700	0.603		4.83
	2100	6510	1109	0.956	4.7%	5.93
IS92b	2015	817	234	0.202		2.05
	2050	3445	700	0.603		4.83
	2100	6510	1109	0.956	5.0%	5.93
IS92c	2015	716	204	0.176		1.79
	2050	2553	521	0.449		3.60
	2100	2999	512	0.441	9.6%	2.74
IS92d	2015	790	226	0.195		1.98
	2050	2872	583	0.502		4.02
	2100	4489	764	0.659	6.4%	4.08
IS92e	2015	888	255	0.220		2.24
	2050	3862	780	0.672		5.38
	2100	9474	1610	1.388	3.9%	8.61
IS92f	2015	832	238	0.205		2.08
	2050	3891	793	0.683		5.47
	2100	8214	1402	1.208	4.5%	7.49
High-Demand Set:						
IS92a	2015	1266	365	0.315		3.20
	2050	5716	1170	1.009		8.07
	2100	9596	1637	1.411	6.9%	8.75
IS92b	2015	1266	365	0.315		3.20
	2050	5716	1170	1.009		8.07
	2100	9596	1637	1.411	7.4%	8.75
IS92c	2015	1113	320	0.276		2.81
	2050	4215	867	0.747		5.98
	2100	4470	764	0.658	14.3%	4.08
IS92d	2015	1223	354	0.305		3.10
	2050	4601	941	0.811		6.49
	2100	6498	1107	0.954	9.3%	5.92
IS92e	2015	1370	397	0.342		3.48
	2050	6238	1270	1.094		8.76
	2100	13533	2302	1.984	5.5%	12.30
IS92f	2015	1297	373	0.322		3.27
	2050	6685	1373	1.183		9.47
	2100	12416	2121	1.828	6.9%	11.33

Appendix C: NO_x Emissions by Altitude Range

Demand Set	Base-Demand		High-Demand	
Scenario and Year	Below 9 km NO_x (Mt)	Above 9 km NO_x (Mt)	Below 9 km NO_x (Mt)	Above 9 km NO_x (Mt)
1990	0.81	1.15	0.81	1.15
IS92a and IS92b				
2015	0.78	1.27	1.22	1.98
2050	1.99	2.83	3.33	4.74
2100	2.45	3.48	3.61	5.14
IS92c 2015	0.68	1.10	1.07	1.73
2050	1.48	2.11	2.47	3.51
2100	1.13	1.60	1.69	2.40
IS92d 2015	0.76	1.23	1.18	1.92
2050	1.66	2.36	2.68	3.81
2100	1.69	2.40	2.44	3.47
IS92e 2015	0.85	1.38	1.33	2.15
2050	2.22	3.16	3.62	5.14
2100	3.55	5.05	5.08	7.22
IS92f 2015	0.80	1.29	1.25	2.02
2050	2.26	3.21	3.91	5.56
2100	3.09	4.40	4.68	6.65

Endnotes

1. Dotto and Schiff (1978).

2. IEA (1992); (1992a).

3. WMO (1991); Schumann (1993).

4. Barrett (in press 1994).

5. Wuebbles et al. (1984).

6. Calculated from:
    Appendix A, Table A.1.
    Balashov and Smith (1992), p. 19.
    IEA (1992a).
    Leggett et al. (1992).
    Prather et al. (1992).
    Author's estimate for China's traffic.

7. Hildalgo and Crutzen (1977).

8. Hauglustaine et al. (1994).

9. Johnson et al. (1992).

10. Taneja (1976), p. 18.

11. Boeing (1993), p. 2.3, Figure 2.3a.

12. Davis and Strang (1993), pp. 1-6, 4-29.

13. Personal communication with James A. Edmonds, Batelle Laboratories, August 1993.

14. We define demand as mature when the difference between its growth rate and the growth rate of market capacity is less than 5%.

15. Examples of econometric forecasts include FAA (1993), ICAO (1992), McDonnell Douglas (1992), Boeing (1993).

16. Discussion and citations for a variety of applications given in Lakhani (1975), p. 201.

17. Marchetti (1980) gives a full description and supporting data for substitution of energy sources. Edmonds and Reilly (1985) use a logistic model to describe production of a resource-constrained renewable resource.

18. May (1981), p. 24.

19. Boeing (1993), p. 2.4, Figure 2.4b.

20. Personal communication with Kim Cheung, Marketing Research, Boeing, 1993.

21. Boeing (1993), p. 2.3.

22. Personal communication with Clifford Winston, Brookings Institution, March 1993.

23. World Bank (1993).

24. Relative buying power across countries is given in Atkinson (1975), p. 246.

25. Paraphrased from Boeing (1993), p. 2.2, Figure 2.2a.

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

27. Prather et al. (1992); "Emissions Scenarios Development: Scenario Development at McDonnell Douglas Corporation" in Stolarski and Wesoky (1993a), p. 135.

28. Leggett et al. (1992); Pepper et al. (1992).

29. Details and regional rates in Leggett et al. (1992), pp. 69-97.

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

31. Leggett et al. (1992), p. 78.

32. Balashov and Smith (1992), p. 18-19.

33. Greene (1992), p. 566.

34. Barrett (in press 1994).

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36. Prather et al. (1992), p. 118.

37. Balashov and Smith (1992), p. 18.

38. Egli (1990), p. 370.

39. Stolarski and Wesoky (1993a).

40. Bahr (1992); personal communication with A. J. Fiorentino, Pratt & Whitney (October 1993).

41. Baughcum et al., "Emissions Scenarios Development: Completed Scenarios Database," in Stolarksi and Wesoky (1993), pp. 193-194.

42. ICAO (1992), p. 3.

43. Boeing (1993), p. 1.5.

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