Environmental Impacts of Aviation

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1. ABSTRACT

As the aviation industry experiences continuously increasing growths, a heightened sense of exigency necessitates that the environmental impacts related to aircraft be dealt with promptly and effectively. While the ozone depleting effects of high altitude aviation have largely been eradicating owing to technological developments and policy measures, the imperative concerns posed by climate change and global warming demand prompt responses from the aviation industry as a result of the mounting significance that aircraft and their emissions exert on present and future environmental scenarios. Although technological solutions to the problems posed by the climate change effects of aviation alone are not robust enough to mitigate emissions impacts to a satisfactory degree, comprehensive policy initiatives like emissions trading can move toward a reconciliation between the demand for aviation technologies and the need to satisfy environmental sustainability standards.

2. INTRODUCTION

Aviation established its pivotal role in the global society beginning with the Wright brothers' first powered heavier-than-air flight in 1903 and since this time has continually exerted increasingly stronger impacts on the infrastructure of the modern world, becoming an instrumental impetus of globalization. Effecting both the global economy (through commercial and private air travel and freight) and the world geopolitical arena (through military applications), aviation's scope extends into the ken of the lives of all individuals, regardless of whether or not they ever board an airplane.

Although a significant source of growth in many areas and representative of economic and cultural exchange across the modern world, aviation and air transport also have been bounded by larger societal interests and economic features. Among the most pertinent of issues in the public interest relating to aviation are matters associated with public safety and the environment, as these two interrelated concerns are fundamentally imperative in the sense that they address the well-being of all constituents across the societal spectrum in correlation with the condition of the milieu in which global discourse occurs. Recent decades have witnessed two principal problems regarding aviation impacts on the environment emerge to the forefront of both scientific and public attention: ozone depletion and global warming.

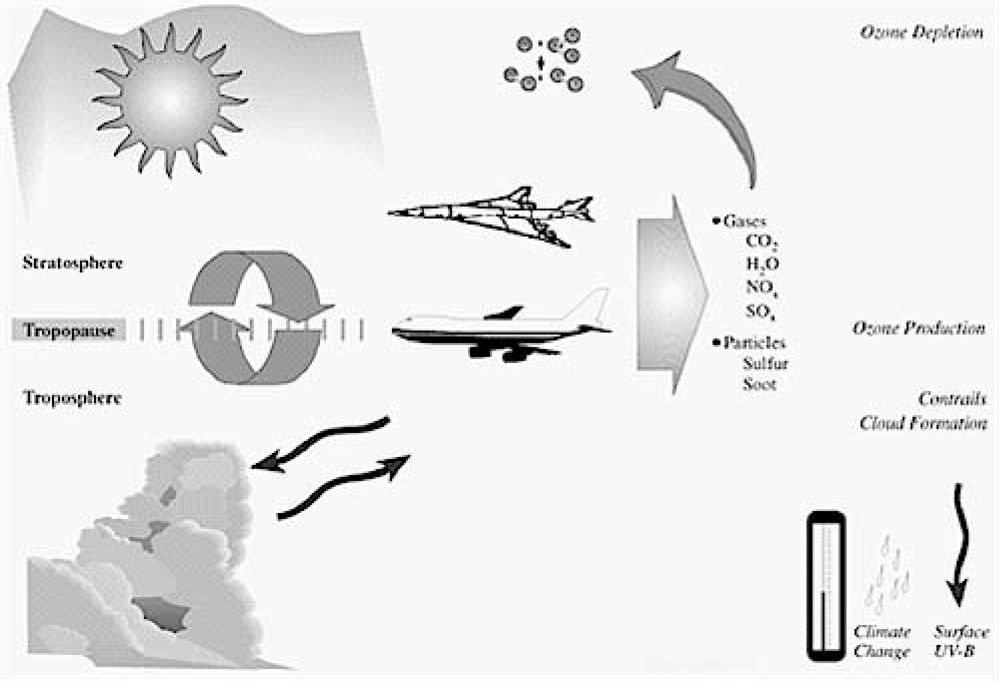

Figure 1: *This diagram summarizes the impacts of aviation on the atmosphere (2006 Penner).*

While these two environmental dilemmas challenge the structure of the global society by demanding concern from all areas of study and concentrated attention from all sectors to address these problems in an adequate manner, the exponential growth of air travel signifies that aviation must exert increasingly more substantial efforts to mitigate the detrimental effects of its operation. Although technology historically has been able to diminish the environmental effects caused by aviation to a certain extent, projected growths suggest that technological solutions alone will not be able to offset the impacts of aviation and that more extensive restructuring will have to occur.

This paper investigates the environmental impacts caused by aviation and specifically addresses the fundamental scientific mechanisms that underlie ozone depletion and global warming. After framing aviation's effects within the larger whole of the environmental science, concerns specific to the design of aviation systems and their unique emissions characteristics are discussed and analyzed in context with their governing engineering parameters. While proposed technological solutions to the aforementioned concerns will be assessed, policy initiatives also will be analyzed in correlation with the broader investigation of optimal methods to reconcile forecasted growths with the imperatives of mitigating detrimental environmental effects and promoting sustainable aviation systems.

3. OZONE

3.1. Introduction to the problem of ozone depletion

Ozone depletion represents one of the first globally pertinent environmental concerns to be correlated with aviation. Divided into several layers, the Earth's atmosphere contains the largest concentration of ozone (nearly 90% of atmospheric ozone) in the stratospheric region, which extends approximately from 32,808 to 164,042 feet (ten to fifty kilometers) above the Earth's surface (2006 EPA). Although ozone (O_3), a triatomic molecule comprised of three oxygen atoms, exists in the atmosphere in relatively small amounts in comparison to other atmospheric gases, even minute amounts of ozone play a significant role in the atmosphere. The Earth's ozone layer both prevents a fraction of the Sun's radiation from reaching the Earth's surface and most significantly absorbs the damaging UVB wavelengths of ultraviolet light, which have been associated with skin cancer, eye problems, damage to crops, and other harmful effects (2006 EPA).

Although ozone molecules are continuously being created and destroyed while atmospheric concentrations fluctuate naturally due to seasonal changes, sunspots, and geographical location, scientific studies conducted during the last few decades of the twentieth century indicated that the catalytic destruction of the ozone layer far exceeds these natural variations. While photodissociation of anthropogenic chlorofluorocarbon compounds (CFCs) is the principal source of halogen atoms in the stratosphere, other compounds collectively known as ozone depleting substances either have long enough lifetimes to allow them to be transported by winds into the stratosphere or are discharged directly into the stratosphere and release chlorine or bromine as they break down and erode the ozone layer.

In their 1985 expedition, the British Antarctic Survey revealed both the exigency of the immediate problems involving the ozone and the global connectivity of the environment through their studies of ozone depletion over Antarctica (2004 Maslin). In order to combat the reduction of the ozone layer in the lower stratosphere, the international community instituted large-scale abatement and remediation initiatives during the late 1980s. These efforts culminated in the drafting and signing of the Montreal Protocol, which aimed to protect the Earth's ozone layer by phasing out the substances closely linked to ozone depletion. As a result of the treaty's widespread espousal and implementation, concentrations of the most potent chlorofluorocarbons in the atmosphere have either leveled off or decreased, while rate of increase in atmospheric concentrations of halons has gradually decreased since 1990 (2006 Wikipedia). Current estimates predict that natural ozone production cycles will completely restore the ozone layer within fifty years (2006 EPA). Owing to the positive impacts that have resulted from the Montreal Protocol on both local and global scales, the international response to the dilemmas posed by ozone depletion ranks among the most significant environmental initiatives to date.

3.2. Aviation effects on ozone depletion

In addition to the use of chlorofluorocarbons in industrial applications acting as a primary source of ozone depletion, supersonic aircraft have been identified as a contributing cause to the destruction of the ozone layer. Since the advent of commercial supersonic flight in the middle of the 1970s, supersonic transport aircraft have been employed principally as a mechanism for extremely fast business travel across the Atlantic Ocean, as cruising speeds of approximately Mach 2 allow such aircraft to traverse large distances in relatively short periods of time. Despite the convenience of this mode of transportation, supersonic aircraft are environmentally problematic owing in part to their higher than average cruising altitudes. Unlike most planes that fly in the upper region of the troposphere, supersonic transport aircraft typically travel at cruise altitudes that cause infusion of exhaust gases in the lower stratosphere, which is one of the most sensitive atmospheric regions to “catalytic ozone-destroying chemistry” (2000 Reid). The lowermost region of the stratosphere, at altitudes that are characteristic of supersonic flight, exhibits larger rates of ozone depletion a few kilometers above the thermal barrier at the bottommost layer of the stratosphere in a region known as the tropopause. As a result of the dramatically different chemistry in the stratosphere, where ozone concentration reaches a maximum, nitrogen oxides involved in catalytic cycles deplete the protective ozone layer in this atmospheric region and allow harmful ultraviolet radiation to access the Earth’s surface (2001 Colvile). Owing to the particularly slow vertical movement and circulation in this atmospheric region, exhaust gases released from aircraft take much longer to disperse than such emissions would in the troposphere. Taking into account an anticipated size of a supersonic aircraft fleet to be approximately five-hundred in number and a typical cruising time of five hours per day per plane in the stratosphere, studies have estimated that a fully operational supersonic transport program would expel as much NO_x into the stratospheric region as the Earth’s surface transmits due to natural processes (2000 Reid).

The primary components of aircraft exhaust responsible for ozone depletion are the nitrogen oxides that are produced during combustion. Known collectively as the oxides of nitrogen (NO_x), these oxygen compounds are emitted from aircraft engines in the forms of nitrogen oxide (NO), nitrogen dioxide (NO_2), and dinitrogen pentoxide (N_2O_5). Although the presence of nitrogen oxides actually produces ozone at the tropospheric altitudes at which subsonic airplanes typically fly, the oxides of nitrogen emitted in the exhaust gases of supersonic aircraft contribute to ozone destruction in stratospheric altitudes where the atmospheric chemistry differs greatly from lower altitudes (2000 Reid). Professor Paul Crutzen, a joint Nobel laureate in chemistry, made the discovery in 1969 that NO_x functions as an efficient catalyst for the depletion of stratospheric ozone (2000 Reid). According to Crutzen's studies, the depletion of stratospheric ozone occurs according to the following reaction:

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

$$\text{With the net effect of: } O_3 + O \rightarrow 2O_2$$

Consequently, Crutzen's research demonstrates that one molecule of ozone can be deconstructed into two molecules of oxygen on the condition that a free atom of oxygen is liberated from a present source of nitrogen, like the oxides of nitrogen released in supersonic aircraft exhaust in the stratospheric region (2000 Reid).

While the chemical reaction above contributes to the depletion of stratospheric ozone, design modifications to second generation supersonic transport aircraft and limited deployment of supersonic fleets are expected to lessen the possibility of supersonic transport representing a significant contributor to the problem of ozone destruction. According to estimates, the latest improvements in the design of supersonic aircraft have already reduced the overall impact on stratospheric ozone destruction, causing a depletion of the ozone layer of less than 1% (2000 Reid). However, although the NO_x emission index (a value that relates the number of grams of NO_x per kilogram of fuel consumed) for most subsonic aircraft system is approximately 10 g/kg, the NO_x emission index for advanced supersonic engines with a double annular system is approximately three times this value (2006 Penner). In order to combat this intolerably high value, a proliferation of research projects has appeared in recent years that aims to develop systems with ultra low NO_x emission indexes. While the task of reducing the NO_x emission index for supersonic aircraft to levels of approximately 5 g/kg with high temperatures at the compressor outlet may seem an insurmountable undertaking, recent findings have indicated that the combination at high altitudes and low absolute pressures where supersonic aircraft typically travel are conducive to the control of mixing processes involved with combustion, which indicates that NO_x emissions targets may not be as impossible to implement as was previously imagined (2006 Penner). Increases in thermal efficiency, propulsive efficiency, and the bypass ratio over the past two decades also have allowed engineers to make great strides toward developing less polluting and more economical supersonic aircraft designs.

However innovative and efficient new supersonic transport advances may be, such breakthroughs are meaningless unless the proper initiatives are established that can guarantee that these new technologies are promptly implemented in the aviation industry. For instance, while the environmental influence of emissions produced by the Olympus engines on current Concorde supersonic aircraft is much more significant than is possible with current technologies, the most recent supersonic aircraft in use employ engines with exhaust emissions that are comparable to those produced in the 1960s when the technologies were first introduced (2006 Penner). Thus, incentives must be offered to reward innovation and exploration of breakthrough technologies instead of opting to renovate and employ outdated equipment simply due to the short term expenditure gains brought about by slovenly research and business practices. Furthermore, while recent advances in aircraft materials, structural technologies, and systems tools may permit companies to produce and maintain second generation supersonic transport aircraft at a lower cost, such savings should not correspond to a decline in passenger fares until the costs of the long term impacts resulting from such environmentally harmful have been internalized in the operations of the aviation industry, as will be discussed in greater detail later in this paper.

While the employment of a second generation of supersonic aircraft does not seem to pose as much of a significant environmental concern as initial supersonic designs in terms of their contribution to ozone depletion, the environmentally detrimental effects of employing a bigger fleet of supersonic transport that is larger than the exceedingly limited size and utilization currently in place greatly alters mix scenarios and would require further design modifications in order to make such a form of transportation viable in long term economic and ecological schemas. Additionally, to enable any flight routes over populated regions would require a significantly more environmentally benign flight configuration that nearly eliminates disrupting sonic booms while minimizing the inefficiencies associated with lower altitude flights. In order to reduce the losses and inefficiencies caused by shock waves, ongoing design advances have focused on lowering the lift to drag ratio of supersonic aircraft; however, this ratio is still substantially lower than that of subsonic aircraft (2006 Penner). Moreover, if supersonic air transport is to comply with LTO cycle and potential climb and cruise emissions rules like all other aircraft, substantial efforts must be placed into the development of a combustion system that is optimized for subsonic climb and cruise conditions in addition to supersonic cruise situations (2006 Penner). Thus, technical challenges involving supersonic aircraft design would have to be overcome if productivity gains resulting from briefer block times are to counteract the significantly higher fuel burn per passenger mile that prevent supersonic transport aircraft from being competitive with their subsonic counterparts (2006 Penner). Furthermore, supersonic aircraft also contribute to climate change, which constitutes a problem with a much larger degree of exigency than the deterioration of the ozone layer at present. The climate change and global warming impacts of supersonic and other forms of air transport will be discussed in much greater detail later in this paper.

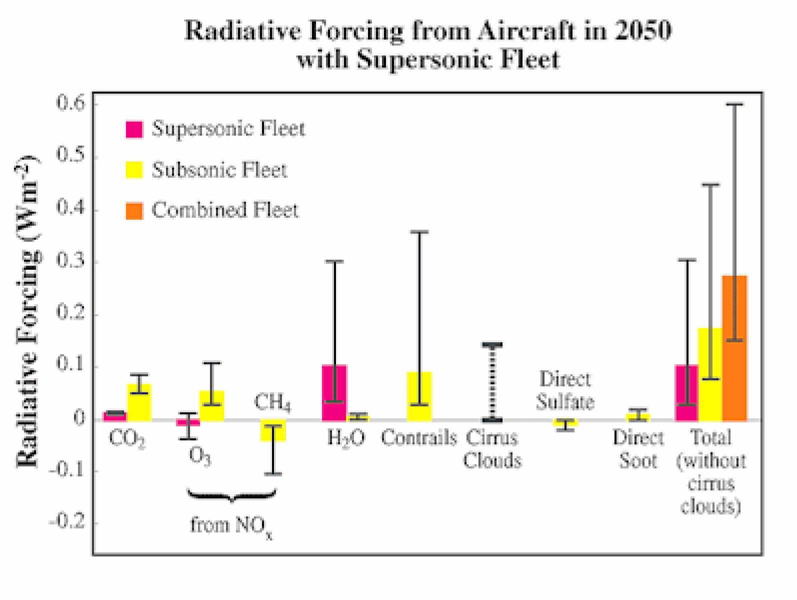

Figure 2: *Estimates of the globally averaged radiative forcing annually from the emissions of a combined fleet of subsonic and supersonic aircraft in 1992 and in 2050 are pictured above. While the solid bars indicate the best known estimates for forcing values, uncertainty bars represent the uncertainty range for these forcing quantities (2006 Penner).*

Despite recent and ongoing design improvements aimed at reducing the overall environmental impact of supersonic aircraft, other possible sources of ozone depletion still exist in the subsonic aviation sector. The average cruising altitude of subsonic propeller driven aircraft has increased steadily in recent decades and has been accompanied by a small increase in the average cruising altitude of jet and turbofan powered aircraft (2006 Penner). The particularly harmful effects of aircraft exhaust in the vulnerable stratospheric region becomes exceptionally problematic when one considers that as much as 75% of the total fuel burned during a typical flight is done so in the lower stratosphere (2001 Colvile).

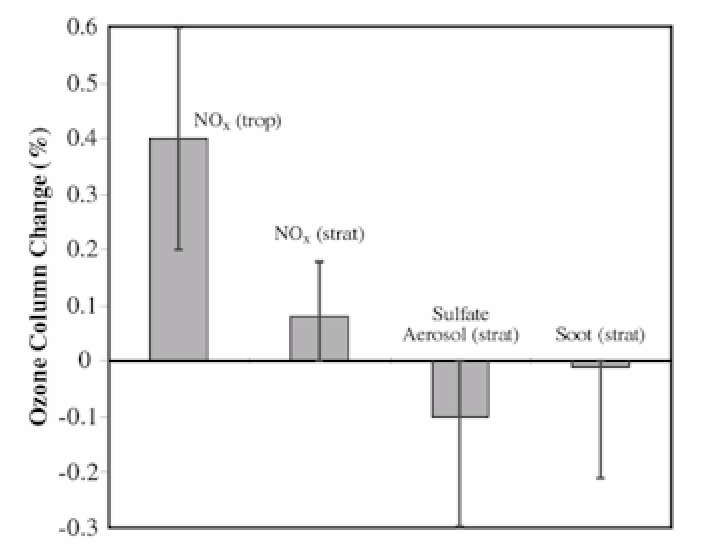

Figure 3: *Displayed in this graph are current estimates of northern mid-latitudinal percentages of total ozone column changes caused by nitrogen oxide emissions in both the troposphere and the stratosphere in addition to aerosol emissions in the stratosphere from subsonic aviation. While the heights of the solid bars represent mid-range estimates, the error bars indicate an estimate of the two-thirds uncertainty range for the data (2006 Penner).*

Encouraged to fly at these higher altitudes in the lower region of the stratosphere by the pecuniary incentive of significantly decreased fuel burn, subsonic aircraft can induce ozone depletion through the introduction of NO_x-filled emissions into the stratospheric region in addition to the use of other ozone destructing substances on civilian aircraft. Although the International Civil Aviation Organization has recognized the problematic nature of the continued use of such materials (2006 Gillespie), airframes continue to be designed and created with halons used as fire extinguishers as a result of antiquated regulatory requirements.

3.3. Case Study: The American SST Program

The history of the American Supersonic Transport Program provides an excellent illustration of the complex interactions between science, technology, and policy and of the competing claims of industry, government, and academia and the manner in which such disputes are typically resolved in real world scenarios.

Although smaller-scale supersonic transport studies were conducted in America as early as 1952, the technological innovation necessary to make sustained supersonic flights possible did not occur until 1956. After the 1962 announcement of the syndicate effort between Britain and France to build the supersonic Concorde, President Kennedy spearheaded efforts in the United States to build commercial supersonic transport aircraft in order to maintain a technological advantage that he viewed as an essential contributor to the nation's economic wellbeing. Citing "social, economic, political, and military reasons" that were allegedly critical for the nation to "maintain its leadership in the design, production, and utilization of all categories of aircraft," Kennedy sponsored direct government funding for the National Supersonic Transport program with an initial projected federal expenditure of $750 million (1981 Rosenbloom). By 1966, adverse public reactions to the project began to appear more prominently, as individuals voiced their concerns about the particularly loud sonic booms that are produced by supersonic aircraft when pressure waves build up and compress to form shock waves as the plane's velocity exceeds the speed of sound and considered the time gains caused by the quicker flights to be subordinate to the undesirable consequences brought about by supersonic transport. As airlines and passengers became increasingly unresponsive to the project, questions arose as to whether it would be optimally beneficial for the aviation industry to concentrate its efforts to improve the reliability and safety of its present subsonic aircraft or to disregard these prospects by rushing headlong into the SST project, which entailed an enormous gamble with the possibility of considerable losses.

Although a 1966 design competition saw Boeing and General Electric secure the government contract to begin work on the supersonic transport program, criticism from political, economic, and social fronts accompanied numerous design revisions over the subsequent five year period. The initial Boeing supersonic airplane designs, which had been drafted for a project years earlier, featured a swing wing model with one of the earliest wide-body designs (2006 Wikipedia). However, engineers altered this configuration repeatedly due to technical troubles first by adding canards behind the nose of the wing and eventually by abandoning a variable wing geometry for a much simpler tailed delta wing configuration with a smaller cabin in a design that became known as the Boeing 2707.

Although work on a mockup and two prototypes of the Boeing supersonic aircraft was to begin in 1969, mounting censure from sources ranging from the congressional appropriations committee to the media began to cast strong doubts upon the future of the project. While the Federal Aviation Administration continued its defense of the program on the grounds that supersonic air travel allied with the nation's best interests in terms of its economy and its leadership in the aviation sector, the House committee considered the large expenditures on the project, which had already far exceeded the initial projections, to be inexcusable in their own right owing to studies that found proponents' claims regarding time gains and new jobs produced by supersonic transport to be exaggerated (1981 Rosenbloom). Furthermore, the SST project became the epitome of negligent and unnecessary government spending, as many politicians considered intolerable the government endeavor to subsidize the inefficient and problem-laden development of a technology used for private enterprise when funding for education and sewage treatment, among other services, was being reduced (1981 Rosenbloom).

In addition to concerns about the economic viability of supersonic transport, the environmental concerns that surfaced in the late 1960s in regard to aviation's impact on stratospheric ozone depletion signaled increasingly vociferous opposition to the project from both environmentalists and the public at large. Increasing costs, ambiguous marketability, and questionable need aside, concerns about the environmental costs of supersonic transport aircraft (citing reasons similar to the aforementioned analysis in Section 3.2) coupled with unease about continually slackened contract requirements that surrendered environmental sustainability for better short term economic gains led the President's Science Advisory Committee to recommend that the SST program support from the government be terminated. As President Nixon renewed program funding under the pretext that foreign policy features of the project superseded the possibilities of economic and environmental disasters, doubts about the SST program shifted from the arena of the questionable governmental role in funding the essentially private venture and environmental impacts of the project to the domain of fiscal desirability and technical viability (1981 Rosenbloom).

Nevertheless, with a swell of environmental interest and activism signaled by the ratification of the Environmental Protection Act and the creation of Earth Day in 1970, the possibility of significant environmental ramifications caused by supersonic transport aircraft, as described by expert witnesses at publicized congressional hearings, exerted a great deal of influence on the general public. During these inquiries, Russell Train (who was the Chairman of the Council on Environmental Quality at that time) gave testimony confirming anxiety that a fleet of supersonic aircraft may cause substantial effects on the atmospheric composition of the upper atmosphere, allowing an increased amount of harmful ultraviolet radiation to reach the Earth's surface. Coupled with discontent over Boeing's inability to lessen considerably the noise levels of the plane's operation (some sources claimed that a single supersonic plane would generate as much noise as fifty Boeing 747s taking off), this testimony shifted public opinion so drastically away from the continuation of the SST program that important factions within Congress found it no longer in their best interests to support the project, which led to the termination of the SST program in March of 1971 (1981 Rosenbloom).

Although the halting of the program had severe fiscal repercussions for Boeing that nearly led the company to bankruptcy, the most important consequences of the termination of the American supersonic transport program resulted from the policy paradigms established through this case. Owing to the lack of critical examination by Congress into the fundamental assumptions of the SST program and unwillingness and negligence to confront directly the evidence presented about the technologies involved in the project, this case suggests that political motivations instead of directly scientific ones impelled the decisions that were made in regard to the future of the SST project. While a cursory evaluation of this conclusion may appear disheartening, that a grassroots public opposition to the SST program, which remained responsive to fundamental environmental and technological concerns of this project, motivated politicians to oppose the continuation of a highly questionable technological program serves as an encouraging testimonial to the powerful influence of public involvement in bottom-up policy initiatives. Additionally, the case of the American SST program illustrates that expert testimony regarding technological issues may not be a completely rational process "resulting in only one possible conclusion" (1981 Rosenbloom). As such, the debates instigated by the program contributed to escalating trends of public doubt of bureaucratic assessments of technological debates and of the inclination to examine critically the political biases of all allegedly scientific testimonials and ultimately demonstrated the exigency of working toward an equilibrium between political, economic, and scientific claims that contribute to the discourse of policy formation.

4. CLIMATE CHANGE

4.1. Introduction to the problems of climate change and global warming

Climate change and global warming constitute one of the most pressing challenges confronting modern society. Not just a scientific concern, the issue of global climate change includes areas ranging from geopolitics, local politics, economics, sociology, and individual lifestyle choices. At its most fundamental level, global warming consists of the increase of greenhouse gases like carbon dioxide in the atmosphere resulting from activities like the burning of fossil fuels and deforestation. A broad scientific consensus has concluded that changes in carbon dioxide concentrations and recent global warming trends result from human activities, as detailed figures and reports have been analyzed, compiled, and summarized in the assessment reports issued by the Intergovernmental Panel on Climate Change. Since the industrial revolution, carbon dioxide concentrations in the atmosphere have increased nearly 30% (2004 Morgan) to the highest levels in at least a half million years (2004 Maslin). Over the past hundred years, average global temperatures have increased by 1.1 ºF (0.6 ºC), while global sea levels have risen 1.6 to 5.5 in (4 to 14 cm) (2005 EU). Owing in part to the global exigency and gravity of the possible consequences of this problem, global warming challenges the very structure of our international society by posing fundamental questions that attempt to synthesize the antithesis between conventional ideas of the nation-state versus global responsibility and between shortsighted thinking that favors immediate gains versus forward-looking acumen that esteems long term sustainability.

In order to understand the implications of global warming, it is essential to maintain at least a familiarity with the mechanisms that underlie climate change. The temperature of the Earth is controlled by the balance of the incoming energy from the Sun and of the outgoing energy flux into space. While approximately one-third of the shortwave radiation that enters the Earth’s atmosphere is reflected back into space, greenhouse gases in the atmosphere trap and re-emit longwave radiation back to the Earth’s surface, consequently warming the atmosphere. Without greenhouse gases like carbon dioxide, water vapor, ozone, methane, and nitrous oxides, the Earth’s temperature would be approximately 36 ºF (20 ºC) cooler (2004 Maslin). Factors including the planet’s mass, distance from the Sun, temperature gradients, and the composition of the atmosphere (an aspect heavily influenced by greenhouse gases) each play a formative role in determining the climate of the Earth, or the average weather pattern. Although the carbon dioxide concentrations in the atmosphere are directly associated to worldwide temperatures, certain global climate models suggest that climate change follows a nonlinear course, though the climatic response to forcing factors remains the most difficult aspect of global warming to analyze and thus has become the primary facet of climate change most under debate (2004 Maslin). Concentrations of greenhouse gases are increased through activities including the burning of fossil fuels that produces carbon dioxide and land use changes that largely result from deforestation associated with urbanization. According to a 2001 IPCC report: "In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely [60-90% confidence] to be due to the increase in greenhouse gas concentration" (2004 Maslin). With carbon dioxide emissions comprising the largest source of greenhouse pollution, the continents of North America, Europe, and Asia produce over 90% of the industrially produced carbon dioxide, with the United States at the top of the list, producing nearly ten times as such carbon dioxide per capita than China (2004 Maslin).

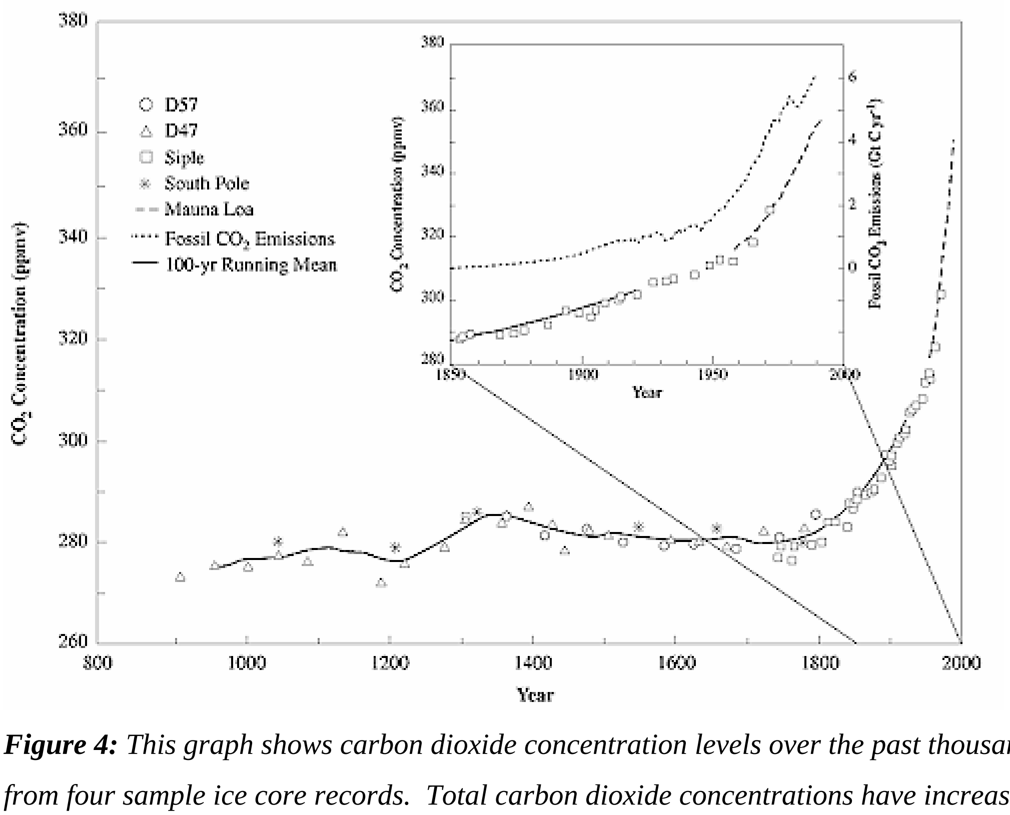

__Figure 4:__ This graph shows carbon dioxide concentration levels over the past thousand years from four sample ice core records. Total carbon dioxide concentrations have increased from approximately 280 to 360 ppmv between the years of 1850 and 1990 alone (2006 Penner).

Taking into account natural and anthropogenic forcing mechanisms (both internal and external) that drive climate change, a majority of climate models predict that anthropogenic-enhanced greenhouse effects will cause increasingly detrimental warming outcomes in the near future. Using the most sophisticated general circulation models to predict future climate trends, estimates forecast that Earth's average temperature will warm between 2.5 and 10.4 ºF (1.4 to 5.8 ºC) over the next century as compared with current temperatures with an average sea level of 7.9 to 34.6 in (20 to 88 cm) due to thermal expansion (2004 Maslin). However, if large ice sheets and glaciers melt, sea level increases may be much larger, as the melting of half of Greenland and half of the West Antarctic ice sheet would cause global sea levels to rise large enough that the areas flooded in Asia alone would cause the number of displaced refugees to be on the order of a hundred million people (2006 Gore). Although uncertain factors like economic growth, population growth, consumption of fossil fuels, developments in alternative energy technologies, and possible international emissions agreements give a certain degree of variability to predictions of future concentrations of carbon dioxide, the best case scenario predicts carbon dioxide concentrations to rise approximately 75% by 2100 (2004 Maslin). While the greatest uncertainties in climate predictions involve the role of cloud formations and their interaction with radiation, global climate models are accurate within approximately 75%, but indications have shown that such future predictions are often conservative (2004 Maslin).

In terms of possible impacts of future global warming scenarios, the influences of greenhouse emissions on the global climate will likely exert widespread effects on the natural environment as well as on global societies and their economies. While the scope of this survey does not permit any degree of detailing in regard to the superfluity of likely consequences of warming scenarios, the changes brought about by global warming can be summarized by indicating that coastlines will be greatly affected, storm and flood patterns are expected to become more erratic and increase in number and intensity, possible changes to El Niño-Southern Oscillation will occur, human health threats will be increased (including a greater stress on resources, an increased threat of transmission of infectious diseases, and a scarcity of fresh water resources), many ecosystems will be unable to respond to climate change leading to a severe threat to biodiversity, and food production rates may be unable to sustain a larger global population owing to an inability of agricultural regions to adapt to warmer climate (2004 Maslin).

Although examples abound of civilizations that collapsed under the external pressures of abrupt climate changes, the transformations brought about by climate change function as an external mechanism only, and it is the internal structure of a society that ultimately determines the degree to which climate changes affect the fabric of a particular civilization. As a result of scientific predictions regarding the likely environmental impacts of climate change if no effort is made to address the problem, the IPCC launched an investigation to study the "potential sensitivity, adaptability, and vulnerability of each national environment and socio-economic system" (2004 Maslin) with the hope of developing an effective strategy to mitigate the effects of global warming. Noting the inevitability of certain components of climate change, the IPCC report recommends that anticipatory adaptation proves more efficient and fiscally responsible than emergency resolutions and suggests that such measures will bring immediate gains and opportunities to society while guarding against the major threat of unpredictability. However, owing to the fact that many greenhouse gases have long residence times in the atmosphere, current reductions in greenhouse gas emissions may not exclude the possibility of inevitable continuation of warming trends in the future. Even if complete and instantaneous abatement of greenhouse emissions were possible, such reduction would nevertheless result in almost constantly increasing rates of atmospheric concentrations of greenhouse gases for at least two centuries (2006 Penner).

In addition to abatement procedures aimed to slow or stop emissions of greenhouse gases, a number of techofixes have also been proposed. These proposed technological solutions are typically classified into four general methods: 1. eliminating carbon dioxide from industrial processes, 2. using less energy or increasing energy efficiency, consequently emitting less carbon dioxide, 3. employing alternative or renewable sources of energy, such that a net amount of carbon dioxide is not introduced into the atmosphere, and 4. growing more forests or promoting increased ocean intake of carbon dioxide from the atmosphere. While each of the aforementioned technofixes exhibits technical limitations and safety drawbacks, all of these approaches and technologies have the capacity to make a contribution toward a resolution to the climate change dilemma, as an amalgamation of improved energy efficiency and sustainable energy sources ultimately will be the most pragmatic and efficient method of solving problems concerning energy dependence and climate change.

4.2. The contribution of aviation to climate change and global warming problems

4.2.1. Overview

Although representative of economic and cultural exchange across modern global society and an important source of growth in many constituencies, aviation and air transport contribute to climate change problems in a number of significant ways. In recent years, carbon dioxide emissions from the aviation sector have accounted for approximately 3% of total carbon dioxide released; however, the total impacts of air transport on climate change are appreciably larger than this solitary statistic suggests (2005 EU). In addition to the principle greenhouse gas emissions of carbon dioxide generated by aircraft themselves and also the production of the energy used in ancillary applications (e.g., in airport buildings, in manufacturing processes, among other sources), other emissions including nitrogen oxides, water vapor, and particulates contribute to the total warming effect.

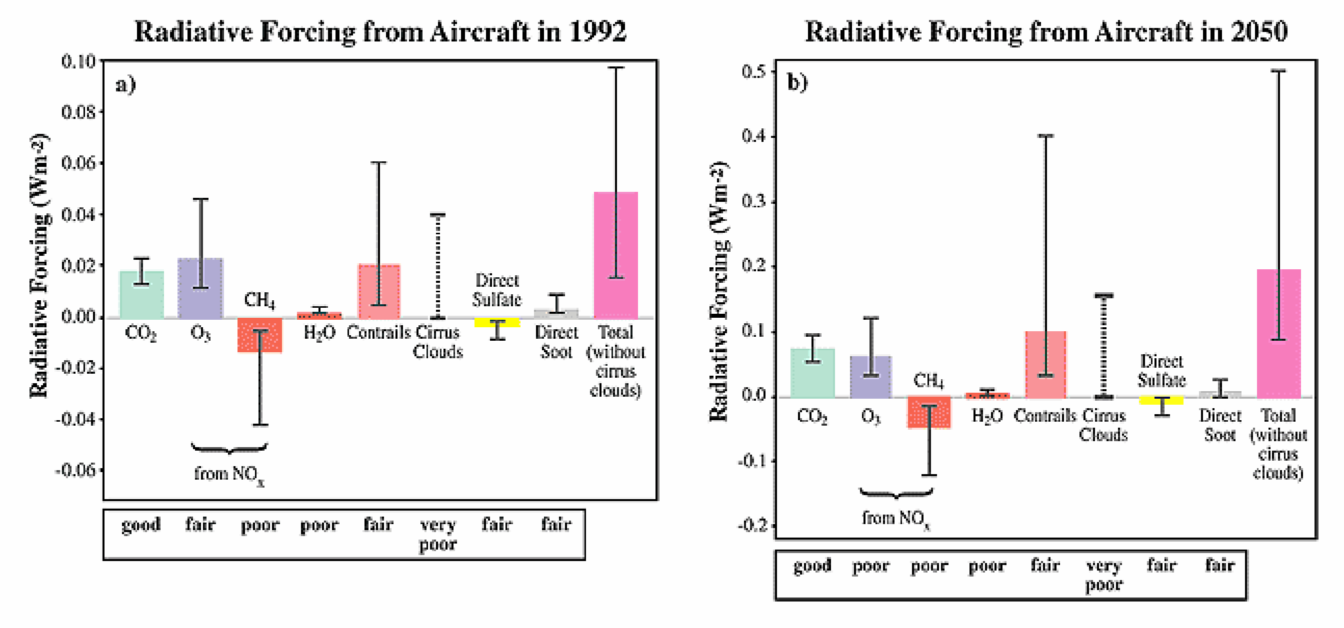

Figure 5: *These diagrams show estimates of the globally averaged radiative forcing annually from subsonic aviation emissions in 1992 and in 2050. While the solid bars indicate the best known estimates for forcing values, uncertainty bars represent the uncertainty range for these forcing quantities (2006 Penner).*

Bearing in mind the IPCC's assessment that the overall climate change effect of aviation is two to four times greater than the effects induced by carbon dioxide emissions alone (even this estimate airs on the conservative end of the prediction spectrum, as it does not take into account the potential effects of cirrus cloud forcing), the exigency of devoting further investigation to the impacts of aviation on the environment cannot be overstated. The foregoing problem is coupled with the exponential growth of the aviation industry and disproportionate deficiency in emissions regulations and efficiency improvements. As a result, this pressing concern calls for examination from scientific, engineering, and political perspectives.

4.2.2. Carbon dioxide effects induced by aviation

Of the many environmental effects of aviation, the emission of carbon dioxide resulting from combustion signifies the most considerable source of greenhouse gas emissions and is the most understood aviation-related contribution to climate change. In total, aircraft emissions of carbon dioxide amounted to nearly 514 million tons in 1992 (2001 McClarty). Furthermore, carbon dioxide emissions from international aviation sources have increased nearly 48% between 1990 and 2002 (2005 EU). A chemical analysis of atmospheric reactions with aircraft emissions prescribes that every 3.15 units of carbon dioxide are emitted for each unit of fuel burned. As a result of the total amount of carbon dioxide emitted being proportional to the quantity of fuel consumed, the predicted increases of 2% to 3% in the rate of carbon dioxide emissions in the future, which takes into account projected advancements in aircraft fuel efficiency, proves extremely problematic from both environmental and economic perspectives (2001 McClarty).

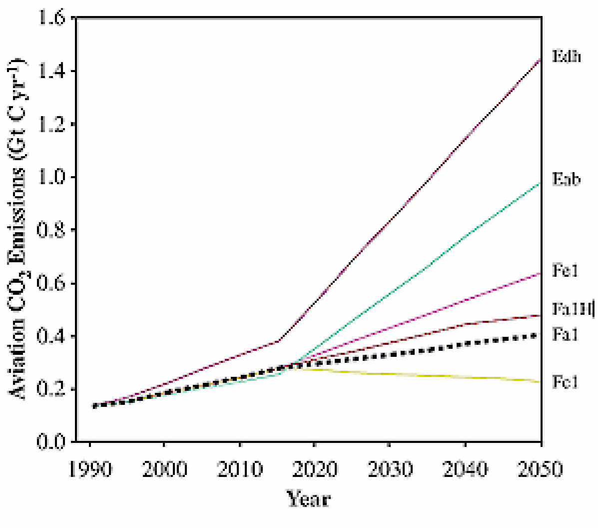

Figure 6: *The graph above shows predicted aviation emissions of carbon dioxide between 1990 and 2050. Six different scenarios for emissions are shown in order of increased fuel consumption (2006 Penner).*

Owing to the particularly long residence time of carbon dioxide in the atmosphere (which is approximately 100 years), the emitted carbon dioxide from aircraft usually combines thoroughly in the atmosphere, making aviation produced carbon dioxide indistinguishable from carbon dioxide emitted from other sources (2006 Penner). Consequently, the globally mixed emissions of carbon dioxide are believed to exert constant warming effects regardless of the altitude at which they are emitted (2006 Wikipedia). However, flights at lower cruising altitudes inherently expend more fuel and accordingly would increase emissions of carbon dioxide into the atmosphere (2003 Schumann).

While the contributions of the aviation industry to current worldwide carbon dioxide emissions levels ostensibly appear minute in comparison with the larger carbon dioxide production by volume from other sectors, a closer investigation of the total radiative forcing that aviation contributes to climate change appears significantly more alarming when the disproportionate total constituent role of the aviation sector and large magnitude of distances traveled in comparably short time periods are evaluated against other sources of carbon dioxide emissions. According to the Royal Commission on Environmental Pollution, the total carbon dioxide emissions per passenger mile for a completely filled airliner at cruising altitude is analogous to that of a car transporting three or four individuals (2006 Monbiot). While the assumption that all flights are booked to capacity is profoundly Panglossian, this statement nevertheless suggests that even flights over a relatively short duration emit a quantity of carbon dioxide that is comparable to the emissions produced by other modes of transportation over much longer periods of time. For instance, each passenger aboard a one-way flight from New York to London produces approximately the same amount of carbon dioxide (1.2 tons) that each individual would be permitted to release over an entire year if emissions regulations were established (2006 Monbiot).

4.2.3. Nitrogen oxide effects induced by aviation

While the carbon dioxide induced effects of aviation exert substantial effects on the environment and constitute the largest source of climate change caused by aircraft, the effects of the oxides of nitrogen produced by aircraft combustion additionally wield an influence in causing global warming at lower altitudes. Although the emissions of nitrogen oxides in the lower stratosphere contribute to the depletion of ozone owing to the particular nature of the chemistry in this atmospheric region, the emissions of this same substance in upper regions of the troposphere has the opposite effect of forming ozone, a gas that contributes to the greenhouse effect. Moreover, nitrogen oxides have shorter residence times in the atmosphere than carbon dioxide emissions, resulting in high concentrations of this particular gas near busy flight routes primarily in middle latitudes in the northern hemisphere (2006 Penner). Thus, the warming effects caused by aircraft nitrogen oxide emissions exert principle influences on the regions over which the gasses are introduced into the atmosphere.

A significant problem with the nitrogen oxide emissions produced by the combustion process of aircraft engines results from the greater concentrations of ozone that result from high altitude (between 26,000 and 43,000 feet) production of ozone, which makes aviation emissions in this region more potent in their warming effect than emissions of nitrogen oxides at the Earth's surface (2006 Wikipedia). Recent studies also have indicated that the production of ozone in the upper level of the troposphere has a larger influence on climate change than initial calculations of the radiative forcing value for this component of aviation emission indicated (2003 Schumann). Additionally, the emissions of nitrogen oxides in the atmosphere reduce ambient levels of methane, another gas that contributes to the greenhouse effect. Although this interaction contributes to a climate cooling effect, this magnitude of this result is not large enough to offset the warming effect induced by the radiative forcing of ozone formation (2001 Colvile) though precise quantifications of this effect remain to some extent elusive (2003 Schumann). Unlike emissions of carbon dioxide and water vapor, which both are emitted in proportion to the fuel consumed by the aircraft engine, the combustion technology employed by aircraft determines the emissions of nitrogen oxides; thus, engine technologies that are capable of operating at lower temperatures and pressures can reduce the levels of nitrogen oxide production (2001 McClarty).

4.2.4. Water vapor and contrail effects induced by aviation

Although both carbon dioxide and nitrogen oxide emissions from aircraft both contribute to climate change, the global warming and environmental impacts of aviation are not limited to these two sources. When piston and jet engines used in aviation consume fuel composed predominantly of hydrocarbons, hydrogen merges with oxygen during the combustion process to produce water that emerges from the engine as steam or water vapor. Just as carbon dioxide formation necessary results from such a combustion process, the consumption of jet fuel also proportionately entails the emission of water vapor. For each unit of fuel expending, the combustion process produces one unit of water (2006 Wikipedia).

When the water vapor concentration in the exhaust of an aircraft increases the amount of air moisture, the water content in the air can pass the saturation point, leading to vapor condensation and the formation of contrails. While the likelihood of condensation occurring is heavily dependent on a number of environmental and technological factors, high temperature differences between the extremely hot and wet exhaust emitted from an aircraft and the much colder air of the upper troposphere generally provide ideal conditions for contrail formation. Condensation trails are most likely to develop at higher altitudes during daily or seasonal periods with the lowest temperatures (e.g., during night or winter flights), as colder atmospheric conditions are most conducive to contrail formation. The amount of time that contrails subsist in the atmosphere is largely dependent on the humidity of the air, and longer residence times in the upper atmosphere are correlated with greater impacts on regional climate (2006 ScienceDaily). Regardless of subsistence times in the atmosphere, the effects of contrails encompass a region approximately within a 100 mile radius of the initial developing location (2003 Minnis).

Figure 7: *As photographed on May 4, 1995, this picture shows contrails over central Europe (2006 Penner).*

Furthermore, contrail formation additionally can give rise to the formation of cirrus clouds, the type of cloud composed of ice crystals that appear as wisplike filaments from the Earth's surface, and increases in the coverage of cirrus clouds and in the thickening of existing cirrus clouds have been strongly correlated with high altitude air traffic (2003 Minnis). While the majority of cloud formation results from water concentrations from the air surrounding an aircraft, the supercooled water vapor requires the triggering of the aircraft's exhaust to convert the trapped water content into ice crystals in a rapid manner (2006 Wikipedia).

In addition to contrail formation resulting directly from aircraft engine exhaust, contrails also can form as a result of condensation induced by wingtip pressure effects. Owing to pressure variations around the contour of an airplane wing, areas with extreme pressure drops (particularly those on the tips of the wing) lead to corresponding drops in the temperature of the air surrounding the wing, which can cause moisture in the air to condense and lead to the formation of contrails at higher altitudes.

Although the contrails associated with aviation traffic are known to influence climate change via radiative forcing mechanisms, the precise quantitative modeling of the impacts of contrails and cirrus clouds on global warming exhibits more uncertainties than do the assessment of carbon dioxide impacts. While contrails and cirrus clouds reflect a certain amount of incoming solar radiation back into space, they additionally confine heat in the atmosphere and in doing so contribute to global warming effects, which constitutes a larger overall environmental impact than the cooling component. Although the warming effects of cirrus cloud formations resulting from aircraft contrails are higher that than of contrail formation by itself, many estimates of the radiative forcing values for the contrail induced effects of aviation do not include the effects of cirrus cloud enhancement. Since these predictions are highly variable, this aspect of the environmental impacts of aviation is largely unaccounted for in climate change scenarios.

According to the IPCC, the contribution of the contrail radiative forcing effect exerts an overall warming result that is approximately 2.7 times larger than carbon dioxide (2006 Monbiot). However, the precise radiative forcing values present a wide range of uncertainty, with some studies indicating the radiative forcing value from both linear contrails and the resulting cirrus cloud generation to be anywhere from 15.3 mW/m^2 (2003 Minnis) to much more substantial estimates between 60 and 100 mW/m^2 (2003 Schumann). Despite the variability involved in future predictions of contrail induced climate effects, NASA studies have indicated that the cirrus cloud formations produced by contrails of aircraft exhaust can account for the average increases in surface temperature of about 0.5 ºF (0.28 ºC) in the United States from 1975 to 1994 (2006 ScienceDaily). From a qualitative standpoint, contrails analyses performed with meteorology computed climate circulation models indicate that, assuming constant levels of air traffic in the future, linear contrail cover would be slightly smaller, as the upper regions of the troposphere would be warmer than at present due to increased global warming effects (2003 Schumann). However, this analysis does not account for such factors as changes in aerosol concentrations, other air traffic effects, or geographical scattering of cloud formations and as a result contains a large degree of uncertainty. In addition to studies that calculate aviation increases of regional cirrus cover currently on the order of a few percent (2003 Schumann), future predications indicate that contrails will cover roughly 10% of the United States and Europe by

2050 (2000 Reid), a result that underscores the exigency of further research into the effect of contrails and cirrus cloud enhancement on climate change.

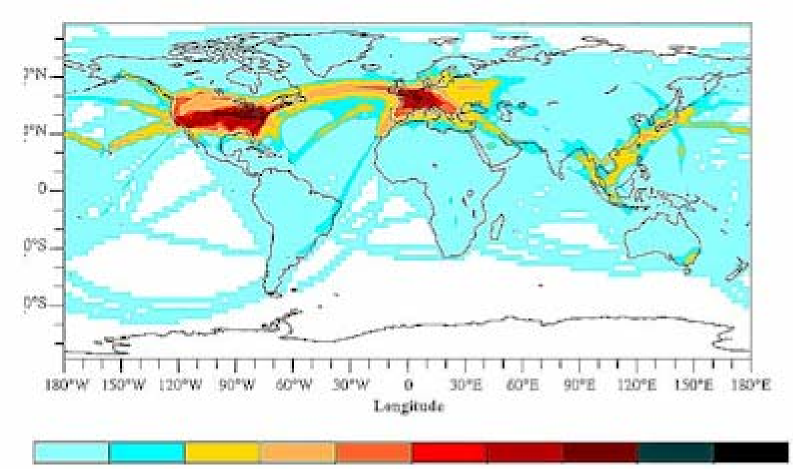

Figure 8: *This illustration displays data regarding persistent contrail coverage in the percentage of area covered as calculated for the total aviation fleet in 1992. This data assumes a linear dependence on fuel consumption (2006 Penner).*

4.2.5. Particulate effects induced by aviation

While the total impacts of particulates and other emissions components from aircraft exhaust play a much smaller role in climate change than the aforementioned effects, the radiative forcing values of these particles is by no means negligible. Aerosols like sulfuric acid droplets and soot accumulate in the upper levels of the troposphere and lower regions of the stratosphere and create indirect cloud formation effects that have only begun to be studied in greater depth within recent years (2003 Schumann). Differences in small particle matter emitted from aircraft engines may alter properties of cirrus clouds, though the formation of cirrus clouds also depends greatly on vertical atmospheric movement; however, both effects are difficult to quantify and require more accurate information if modeling predictions are to be made with a greater degree of precision. Owing to soot representing the largest fraction of aerosols in the upper troposphere, this aerosol accounts for perhaps the most significant cirrus enhancing effect of all atmospheric particulates, as this substance is believed to "induce heterogeneous ice nucleation" (2003 Schumann). However, many uncertainties accompany this statistic, as additional soot deposits generated by combustion in airplane engines also may reduce optical depth and consequently the radiative forcing factor contributed by soot particulates (2003 Schumann). Consequently, while aerosols emitted by airplane exhaust have been linked to the formation and alteration of cirrus clouds in the upper troposphere and the lower stratosphere, the overall climate change impact of particulates requires greater investigation in order to assess future effects of this component of aircraft emissions.

4.3. Assessing the total climate change effects of aviation

In endeavoring to quantify the overall cumulative impact of aviation on climate change, the IPCC has estimated the total radiative forcing, which measures the change in the amount of radiation entering the Earth's atmosphere and the amount exiting, of aviation (excluding the effects resulting from cirrus cloud production and enhancement) to be between two and four times the radiative forcing of carbon dioxide alone (2006 Penner). Some estimates have calculated that aviation currently accounts for approximately 5% to 6% of the total global warming effect cause by greenhouse gases when all radiative forcing effects are taken into account (2000 Reid). While some uncertainties remain in calculating the impacts of such factors as cloud formation, contrail effects, and total nitrogen oxide impacts, the general scientific consensus indicates that each of these factors exert some magnitude of an effect on the overall process of global warming (2006 Penner). Furthermore, researchers like Patrick Minnis stress that contrails and contrail-induced cirrus cloud formations and enhancements have exerted strong regional climate change effects and that, as air traffic increases globally, there is an increasing need to account for these effects quantitatively in calculating the overall radiative forcing caused by aviation (2003 Minnis). With annual growth rates of nearly 9% since 1960 (2006 Penner), the aviation industry will likely increase emissions rates of carbon dioxide alone by approximately 2% to 3% annually even with efficiency improvements in aircraft technology (2001 McClarty). Overall aircraft emissions are projected to double roughly every ten years and account for over half of the emissions potential for global warming emitted from ground transportation sources, even though current aviation emissions have a much lower absolute contribution to carbon dioxide emissions than land-based transportation systems (2000 Reid). Estimates from the IPCC suggest that the contribution of aviation to global warming may grow to 5% of overall global greenhouse gas emissions by 2050, and if appropriate policy measures are not established to curb aircraft emissions, aviation could account for up to 15% of the overall greenhouse gas emissions by this time (2006 Wikipedia). Moreover, if the aviation sector continues to expand exponentially, the continuous growth of the associated emissions would offset the attempt to institute emissions cuts in other industrial sectors. Although the Kyoto Protocol aims to reduce the emission of greenhouse gases by 8% by 2012, the uninterrupted growth of aircraft emissions would counteract nearly one fourth of the reductions needed to accomplish the emissions objectives (2005 EU).

Ultimately, while in theory the total impact of aviation and aircraft emissions effects on climate change and on atmospheric conditions can be quantified with the use of sophisticated computer modeling of global atmospheric chemistry and circulation, these calculations prove to be much more arduous in practice. The complexity in quantifying the total atmospheric effects of any system, especially one as complex as the whole of the aviation enterprise, can be attributed to many factors including the intricacy of chemical reaction cycles that results from significant and variable temperature dependencies and the difficulties in quantifying emissions in the upper troposphere and lower stratospheric regions that give rise to localized effects that fluctuate greatly depending on spatial and temporal factors (2001 Colvile). However, the technical complexities involving the precise quantification of climate change impacts of aviation should not make one lose the forest for the trees. Although further research is needed to improve scientific capabilities of modeling the complex mechanisms of climate change, the discoveries and breakthroughs that have been made in recent decades have provided mankind with many of the tools needed to better understand global warming and the implications that are associated with it. Thus, the greatest difficulty associated with climate change, particularly with regard to the effects of aviation, does not entail the precise quantification of the underlying science but instead involves the development of a comprehensive response to the problems posed by climate change.

4.4. Possible technical solutions to the problems posed by climate change effects of aviation

In order to reconcile the growth in the air transportation industry with the need to meet necessary cuts in carbon emissions, the two most common technological solutions concern the development of more efficient aircraft systems and the discovery of new fuel sources. Although aircraft fuel efficiency has increased by approximately 50% over the past three decades as a result of developments in engine and airframe technologies coupled with miscellaneous operational matters that consequently emit less carbon dioxide (2001 McClarty), industry forecasts predict that major advances in engine efficiency within the next twenty years are not likely. The Royal Commission notes that the essential gas turbine engine design has been the dominant form of aircraft engine for over fifty years, and it is unlikely that "this will change in the foreseeable future" (2006 Monbiot). However, although no significant developments in the aviation fuel efficiency are likely to occur within the near future, engine manufacturers have made minor fuel efficiency improvements in terms of emissions of both carbon dioxide and nitrogen oxides for each new manufactured design.

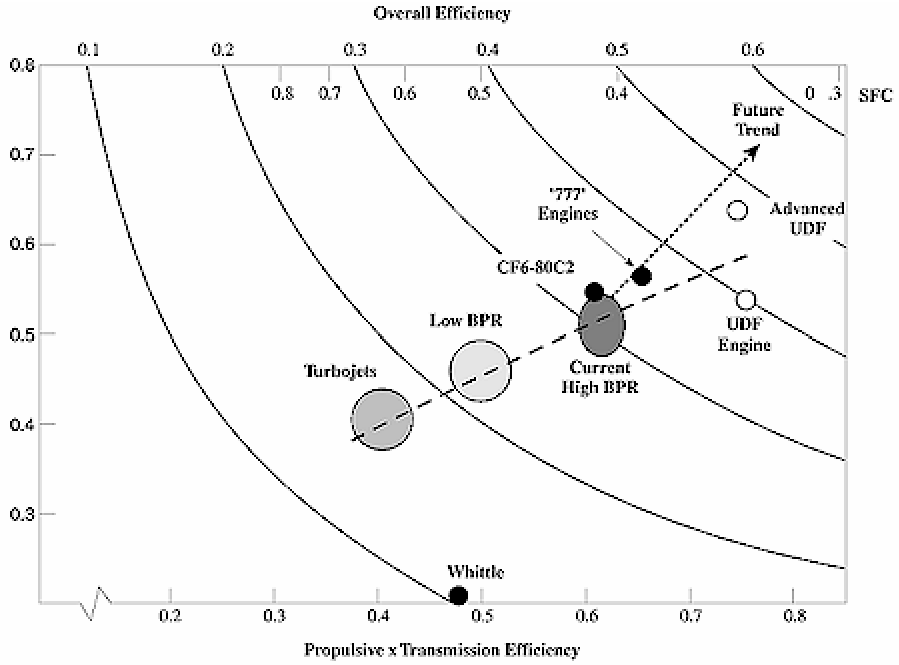

Figure 9: *This diagram illustrates the evolution of aircraft gas turbine efficiency (2006 Penner).*

Furthermore, aircraft manufacturers are constantly working to reduce emissions by making minor alterations to combustion processes, eliminating unneeded weight, and improving aircraft aerodynamics (2000 Reid). Companies like Rolls Royce have committed to reducing environmental effects brought about by the operation of aircraft systems by incorporating environmental considerations into the identification of materials for optimal use in aircraft engines and have established benchmarks for environmental performance in terms of emissions, fuel consumption, and noise that are to be met by the year 2010 (2001 McClarty).

Another option for reducing the emission of greenhouse gases from aircraft involves alternative fuel sources. Fueled by liquid hydrogen instead of kerosene, cryoplane technologies may be a viable alternative to more conventional fuel sources in the sense that such aircraft would not cause emissions problems associated with carbon dioxide, provided that LH2 fuel can be safely produced without a significant impact on climate, but instead would cause a number of new design challenges and different climate change effects. Owing to hydrogen fuel containing approximately four times less energy by volume than kerosene, aircraft designs would have to alter dramatically if reasonable passenger or freight standards were to be met, as current aircraft designs likely would only have enough space to carry only hydrogen-based fuel (2006 Monbiot). However, even if this significant design challenge could be overcome, the combustion of hydrogen fuel yields a significant amount of water vapor (approximately 2.6 times that of an airplane operating on kerosene). Consequently, owing to the larger airframe necessary to store the large quantities of fuel and the associated higher altitudes at which these aircraft would have to operate, the production of excess water vapor would cause detrimental climate change effects in the prime areas of the upper levels of the troposphere and lower stratosphere where contrails are most likely to form. Thus, the overall climate impact of hydrogen-fueled aircraft would be approximately thirteen times higher than a typical kerosene-fueled aircraft (2006 Monbiot). As a result of the dangers and inefficiencies associated with alternative fuel sources for aircraft, the IPCC has noted that, like fuel efficiencies for aircraft engines, at the present there are no "practical alternatives to kerosene-based fuels" and that such advances in alternative fuel technologies are not likely to arise "for the next several decades" (2006 Monbiot).

Although no immediate and universal technological solutions may exist to the problems of aviation's impact on global climate change, improvements in airspace management open new possibilities for allowing aircraft to be routed to cruising altitudes that are significant less sensitive to climate change effects, most notably those regions where contrails are not likely to form. However, this approach also involves a number of complexities that have yet to be addressed adequately and does not resolve the problems associated with the emissions of carbon dioxide and nitrogen oxides (2006 Wikipedia). Other minor yet practical prospects for reducing the overall climate impact of aviation operations involves the optimization of airspace use, flight timetables, route networks, and trip frequencies in order to increase relevant load factors and minimize the total air time, thus reducing overall aircraft emissions (2006 Wikipedia).

Many current initiatives to produce more environmentally friendly aircraft have focused on the development of particular aspects of aircraft design and functionality in order to change the composition and operating procedures of the existing aviation infrastructure. Although restraining the total number of takeoffs and landings for long range flights has been achieved by raising the passenger capacity of large airframe designs, this tactic proves considerably less effective for short and medium length flights, as approximately 70% of all flights last less than five hours yet carry roughly 50% of air traffic passengers (2004 Hepperle). Owing to this problematic trend, which accounts both for operational inefficiencies as well as increased greenhouse gas emissions, many new aircraft configurations have attempted to minimize the hiatus between subsequent landings and takeoffs by developing technologies that permit aircraft to approach and climb at steeper angles of attack while simultaneously offering the capacity to adjust the angle of attack for a particular flight path to provide optimal performance in varying air traffic scenarios. Such improvements would reduce trailing wakes from other aircraft and diminish the time between subsequent flights (2004 Hepperle).

Furthermore, the improvement of takeoff and landing performance can be achieved through the optimization of the climb and sink angles. The general governing equation for force equilibrium of an aircraft during climb and glide conditions can be expressed as:

$$\sin\theta = \frac{T}{W} - \frac{\rho_\infty}{2} v_\infty^2 \frac{S}{W} C_{D0} - \frac{W}{S} \frac{2k\cos^2\theta}{\rho_\infty v_\infty^2} \tag{1}$$

where θ is the climb angle, *T* is the engine thrust, *W* is the weight of the aircraft, ρ_∞ is the density of air, v_∞ is the aircraft speed, *S* is the total wing area, C_{D0} is the drag coefficient when the lift coefficient is zero, and *k* is the k-factor. According to an analysis Equation 1, maximum climb angles can be increased by enlarging the thrust to weight ratio, increasing the aspect ratio, or by improving the lift to drag ratio of the aircraft. Moreover, the optimization of the thrust to weight ratio exerts the largest quantitative effect on increasing the climb angle, a trait that favors twin jet configurations owing to more rigorous takeoff power requirements (2004 Hepperle). A slotted multi-element flap system (which generally consists of three elements such as a slat, the primary wing, and a flap) is typically employed as a technique for enlarging the total lift area and cambering the sections of the airfoil, which has the net effect of reducing total wing loading and increasing the lift coefficient. Additionally, making alterations to the planform of the wing by reducing the sweep angle or increasing the overall chord length also can yield increases in the effective lift coefficient (2004 Hepperle). This functional optimization tailored to specific flight conditions can curtail the distances between aircraft without significantly increasing the hazards associated with trailing vortex interactions (2004 Hepperle).

4.5. Possible policy solutions to the problems posed by climate change effects of aviation

While proposed technological solutions to problems involving the mitigation of climate change effects associated with aviation ostensibly offer a diverse assortment of methods for reducing the environmental impacts of aviation, these technofixes only account for an extremely small percentage of the necessary emissions reductions that are required in order to reconcile the growth in aviation with the need to meet minimum environmental sustainability standards. As a consequence of the inadequacies of strictly technological resolutions to this dilemma, some forms of policy initiatives must be implemented if the aviation industry is to meet necessary emission reduction objectives.

As a result of the continuously increasing impact of aircraft emissions on climate change, the most comprehensive policy measures are those that address the growth of aviation and the degree to which economic factors encourage the advancement and dissemination of new systems and technologies. To give a representative statistic regarding the scope of future growth in the aviation industry, tourism accounts for roughly 80% of air travel, and the World Tourism Organization estimates that the number of tourist arrivals worldwide by aircraft will increase over 120% between 2004 and 2020 (2005 EU).

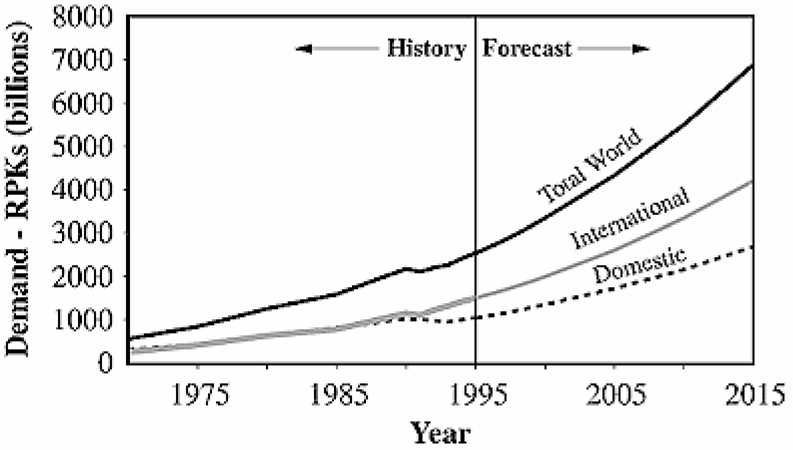

Figure 10: *This graph displays the history and forecasted predictions of passenger air traffic demand growth between 1970 and 2015 (2006 Penner).*

With these tremendously large growths in the demand for aviation, it is unlikely that necessary emissions reductions will be achievable from annual fuel efficiency improvements on the order of 1% to 2% per year. When the rapid expansion of air travel, and consequently with fuel consumption, is coupled with emissions cutbacks in other sectors, aviation's contribution to the dilemma of global warming is projected to increase both in absolute and relative terms in the coming decades unless other regulatory efforts are established (2005 EU). In other sectors of industry that exert large environmental impacts, regulation and taxation systems are established so that the external costs of environmental damage are partially internalized in the sectors' activities. Notwithstanding fiscal intentions, such taxes fulfill the objective of informing users via an appropriate price signal that their fuel consumption exerts negative impacts society that are not reflected in the price of the fuel alone. However, the aviation industry currently does not have to hold itself accountable for the external costs of its climate change effects, and analysts have referred to this shortcoming as a "market failure" that leads to "sub-optimal investment in and uptake of new technologies and operational procedures that [minimize climate change] effects" (2005 EU) and adds to the already excessive dependence of society on antiquated aviation technologies. Furthermore, international aviation policies within the past two decades have exacerbated this problem by opening up the aviation market (2005 EU). By relaxing regulations internationally, lesser control over the growth in the demand for air travel causes the chasm between the cost of flying and the mounting environmental impacts of aviation to widen. Moreover, a general reluctance to include aviation in large-scale programs to reduce greenhouse gas emissions also has contributed to the mounting externalization of environmental costs of air traffic. Other abovementioned climate change effects notwithstanding, carbon dioxide emissions from international flights are not covered in the Kyoto Protocol, an amendment to the United Nations Framework Convention of Climate Change that signifies one of the largest and most unified efforts to establish obligatory international greenhouse gas emissions reduction targets for all signing nations (2000 Lee). Additionally, the International Civil Aviation Organization has rejected proposals to endorse any measures that aim to regulate emissions from commercial aircraft and has even recommended that voluntary reduction charges not be discussed or pursued until the ICAO meeting in 2007 (2006 Gillespie).

As a consequence of the indirect costs of aviation, largely resulting from climate change impacts on the environment, not being reflecting in the costs to users of air transport, environmental costs are external to the transaction between air transport providers and air transport users; thus, the exclusion of appropriate price signals to indicate the costs associated with environmental impacts leads to a suboptimal system. From a philosophical standpoint, this dilemma relates closely to the well documented free riding problem. Although greenhouse gas emissions regulations can be implemented in such diverse forms as taxes on emissions, minimum emissions standards, emissions trading systems, or technology requirements, the greenhouse gas emissions of a nation-state (or any singular body for that matter) create global externalities in that the atmosphere is regarded as an all-access disposal well that is not subject to regulatory measures. However, the prevention of such global externalities is a universally-available, non-excludable benefit, as once the global climate has been improved, it would be unfeasible to prohibit any nation-state from enjoying such benefits. Nevertheless, while the advantages of greenhouse emissions reductions would be shared globally, the benefits that any single country receives from its own abatement efforts is only a small part of its total investment. Thus, the greatest challenge of establishing regulatory climate change policies both globally and within much smaller constituent sector (e.g., the transportation industry) is that "individual countries will tend to invest in less abatement than would be desirable from a collective global point of view" owing to a preference to avoid the costs of abatement efforts while enjoying the shared benefits of the emissions reductions of others, which in the case of climate change may make such enjoyment possible at all (2002 Schneider). Consequently, policy initiatives and instruments would help to overcome the free riding problem and facilitate collective action while creating an optimal socioeconomic system with a long term vision for sustainable progress.

In light of the need for aviation to participate in the global initiative to comply with climate change measures by establishing more environmentally benign standards that offset growth impacts, many proposals have been suggested that would give the aviation industry stronger incentives to mitigate climate impacts. Neglecting regulatory options widely considered to be either ineffective, impractical, or inadequate in terms of meeting policy aims, the three most prominent market-based regulatory options for curbing aviation-based greenhouse gas emissions include fuel taxation, emissions charges, and emissions trading. In terms of fuel or energy taxation for aviation, taxation exemptions for fuel and energy consumption in air travel are widespread and have been made legally binding by bilateral aviation agreements throughout the twentieth century (2005 EU). Article 24 of the 1944 Chicago Convention established the precedent that fuel taxes cannot be charged for international flights, and this general principle has been solidified through a network of over four-thousand bilateral treaties since that time (2006 Monbiot). However, many current legal frameworks permit fuel taxation on domestic flights, though legal obstacles make this limited form of fuel taxation only a marginal source of likely emissions reductions that will not yield any immediate environmental benefits (2005 EU). Although en-route aircraft emissions charges superficially present a more direct method of pursuing the environmental effects of aviation and avoid the legal difficulties of fuel taxation, this policy method generates a high degree of uncertainty about accomplishing desired environmental objectives and likely will be restricted internationally in terms of broader applicability. These negative factors, accompanied by a number of other disadvantages, make emissions trading a more preferable option for meeting greenhouse gas emissions standards (2005 EU).

As a testament to its broad applicability across the aviation industry and its optimal market-based approach, open emissions trading has been endorsed by the ICAO and implemented in the European Union, as this method presents a viable system of internalizing environmental costs of aircraft operations while curbing the growth of emissions. An emissions trading scheme would operate with the common currency of emission allowances, with a single trading allowance representing the right to emit one ton of a particular greenhouse gas. Although the current emissions trading system in the European Union only covers the release of carbon dioxide into the atmosphere, future emissions trading schemes should take into account other environmentally detrimental substances as well. By establishing an upper limit or placing a cap on the total amount of allowances allocated, a scarcity of need is established that allows a trading market to develop while simultaneously delivering environmental benefits. Although one type of trading scheme would implement emissions trading in an intra-sector manner (i.e., trading would occur only within the aviation industry), a much more comprehensive and robust approach to combating climate change challenges is to establish and inter-sector emissions trading structure that would allow such allowance exchanges to occur between different sectors and would be likely to optimize produced benefits from emissions trading. However, if the aviation industry were to participate in an open emissions exchange regime, increased radiative forcing effects caused by aviation's high altitude activities would have to be internalized or given special weights that would take into account spatial and temporal variability in creating a weighing function if such a trading system were to be comprehensive and effective (2000 Lee). Thus, the unique emissions and radiative forcing factors that aviation exhibits must be taken into consideration during the process of forming policies aimed to mitigate climate change effects. Consequently, companies that keep emissions below allotted levels are able to sell their excess emissions allowances to other companies that cannot meet such standards at a price determined by current economic values. In addition to purchasing emissions allowances, companies that emit greenhouse gases at a level above the permitted maximum can take immediate measures to reduce their emissions in the future (for instance, by investing in more efficient technologies) so that they will not be forced to purchase allowances from other companies. As such, individual companies can develop methods to reduce emissions, either by purchasing emissions allowances, improving efficiency standards, or a favorable combination of the two approaches in a manner that is most cost-effective. In order to yield an optimal environmental effect, emissions trading should encompass as many types of emissions as possible, covering the breadth of greenhouse gases on all types of flights. Furthermore, the total magnitude of the economic effect caused by the implementation of an emissions trading scheme would be rather small in the short term (costing approximately 0.002% of the global GDP) but would ultimately yield small economic gains in the long term, as estimates indicate that gains of approximately 0.026% of the global GDP would occur after ten years of implementation (2005 EU). Although a reduction in forecasted demand would imply a slower growth rate of the aviation industry, carriers likely would be able to maintain current profit margins by deferring any added costs to their customers, though this additional charge per ticket is not likely to be of a large magnitude (2005 EU). Any increases in the price of airline tickets brought about by an emissions trading scheme would likely be progressive in terms of its distributed impacts, as relative charge increases would imply that wealthier members of the population would tend to pay higher percentages of the total added costs (2005 EU). Thus, an open sector emissions trading regime at the current time presents the most robust method of meeting necessary emissions standards while offering an economically viable open market system that allows companies to meet in an optimal manner long term initiatives of environmental sustainability.

5. CONCLUSION

As these investigations related to aviation-induced contributions to ozone depletion and global warming suggest, assessing the total environmental impacts of aviation and evaluating the optimal courses of action to adopt in response to the challenges that these effects present involve a number of complex issues and considerations that must be approached from a broad range of academic standpoints. In order to begin dismantling the immense obstacles that obstruct progress in developing a sustainable society, an amalgamation of intellectual and speculative viewpoints must assemble a diverse range of problem solving tools if it is to examine and analyze all facets of this complex scientific, political, economic, and social dilemma with any adequate degree of rigor. While technological solutions to the problems posed by the environmental effects of aviation may only offer minor solutions in the short term, long range engineering and technological innovations must propel the aviation industry into a new future marked by the sustainable growths provided by more efficient technologies, alternative fuels and materials, and streamlined operational practices. However, these engineering innovations cannot take place without the coupled support of policies that responsibly encourage and fund the research and development of technologies that fall within the ken of public interest. Moreover, leaders in government and academia must take the lead in encouraging and promoting policies to address the aviation industry's need to manage effectively the simultaneous tasks of meeting the air transport requisites of society and of fulfilling demands of environmental benign operations.

Economic and ecological concerns constrain proposed solutions to management problems regarding increases in air traffic and necessitate the development of more efficient technologies and implementation of more effective policy measures that are more responsive to present demands for both cost optimization and sustainability. While environmental effects of aircraft design had been assessed in the past only after initial design configurations were developed, current conditions dictate that environmental impact considerations will exert a larger influence in the design process for present and future aircraft technologies and configurations. In a similar manner, the political processes that frame this scientific discourse not only must be responsive to the emerging problems and contextual shifts of the present but also must examine longer term implications of aviation's activities. Furthermore, in addition to considering the narrow spectrum of the immediate and far-reaching environmental impacts within single sector operations, aviation along with government, industry, and society must look at its activities as part of a more expansive dialogue aiming to reconcile the environmental, political, economic, and social facets within the wider context of growth. Thus, the forward-looking acumen of global society can adequately address the demands and constraints of expansion while avoiding the snares of suboptimal routines through the rigor and comprehensiveness of anticipatory problem solving and long term initiatives of sustainable development.

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