Aviation Environmental Policy Effects on National- and Regional-scale Air Quality, Noise, and Climate Impacts

by

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ABSTRACT

The continued growth of the aviation industry poses a challenge to policy-makers and industry stakeholders as each decision represents a trade-off on efficiency, equity, and environmental impact. The Aviation environmental Portfolio Management Tool – Impacts (APMT-Impacts) module has been developed to calculate physical damages from aviation's impact on ambient noise, local air quality, and climate change. The main objective of this thesis is the continued development of a framework for examining aviation environmental policy by expanding the current modeling capability and addressing key shortcomings in decision-making practices.

First, climate modeling assumptions, particularly those related to background emissions scenarios and short-lived radiative forcing agents, are examined, and a temperature-response model based on a two-box ocean model with advective flux and diffusion is developed. Second, a cost-benefit analysis of a proposed NO_X Stringency policy is performed. The analysis shows that increased engine stringency is not cost-beneficial under several traditional lenses and discount rates. However, lenses accounting for conservative assumptions in air quality and uncertainty in technology cost estimates show benefits for a range of stringency increases highlighting the need for flexibility in the analysis approach, the use of engineering judgment, and open communication between decision-makers and analysts. This cost-benefit analysis is compared to a traditional cost-effectiveness approach. Finally, this thesis lays out the need for supplemental analyses on a regional scale to address who bears the cost and gains the benefits of a given policy.

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When I told my mother I wanted to become an engineer, she responded, "Why can't you be something more sensible, like a writer?" I hope she would be happy with this thesis.

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1 Introduction

1.1 Background

The environmental impacts of aviation, particularly noise, air quality, and climate change, have become increasingly important. Airplane emissions contribute to increased concentrations of particulate matter, which has negative impacts on human health. Like other users of fossil fuels, aircraft emit CO_2, NO_X, soot, water, and sulfates, which impact on the global climate. Moreover, because of the altitude at which the emissions are deposited, the effects on the climate can be accentuated, especially through the formation of contrails and high cirrus clouds. Aviation operations contribute to noise pollution with significant noise impacts being felt up to 20km from an airport. With a projected average industry-wide growth rate of 5% a year, it is important to understand the balances between the economic and environmental impacts of aviation for the future of aviation innovation and the development of appropriate aviation policy.

Many avenues forward exist for mitigating environmental damage from aviation including implementing new aircraft technology, improvements in air traffic management, and operational changes. Some of these improvements, such as continuous descent approaches, are win-win-win in that they provide benefits to noise, climate, and air quality, but many mitigation measures present trade-offs across these domains. Furthermore, decisions must not place inappropriate constraints on national and international mobility or the economy. These issues become especially difficult to solve considering the temporal and spatial variation of the environmental impacts, the long technology development times for aircraft, and the large capital costs of aircraft and industry infrastructure.

1.2 Motivation

Effective environmental policy must be environmentally beneficial, economically reasonable, and technologically feasible. However, a policy that looks to address aviation noise can have unintended consequences in the realms of climate change and air quality.

These trade-offs can occur through a variety of physical pathways. For instance, a noise reduction policy may prevent sleep disturbances and decrease general annoyance, but the corresponding increase in emissions may increase asthma incidences. Is this policy environmentally beneficial? If this policy will cost engine manufacturers and airlines several billion dollars over a decade, is this cost economically reasonable? Will the technology supported by this policy create high-switching costs, causing lock-in of inefficient aircraft? These questions are difficult to answer and are fraught with uncertainty. By placing environmental benefits across all environmental domains and total policy costs on a common scale, it is possible to better understand the net welfare change created by a policy.

In recent years, the Federal Aviation Administration's Office of Environment and Energy (FAA-AEE) has developed the Aviation environmental Portfolio Management Tool (APMT) to examine the interdependent effects of aviation on the environment. APMT has been used to examine policy decisions on emission and noise goals and stringencies through integrated cost-benefit analysis. APMT-Impacts, a set of modules in APMT for noise, air quality, and climate benefit calculations, takes forecasts of emissions and noise for aviation under a variety of scenarios, such as a range of policy stringencies, and for a baseline business-as-usual case. The models in APMT-Impacts calculate expected physical and monetary impacts of the policy relative to the baseline while accounting for scientific and policy uncertainties.

One shortfall of an integrated cost-benefit analysis is that, although it indicates the monetary costs and environmental benefits, it does not show who bears the costs or who receives the benefits of a particular policy. Thus, it provides only a limited indication of policy equity. The Environmental Protection Agency (EPA) recommends addressing who pays the cost and issues of environmental and social justice in its Guidelines for Preparing Economic Analyses (EPA 2002). Nor can integrated cost-benefit analysis account for how aviation policy is interpreted in the polis. Why is aviation noise the most dominant complaint regarding airport expansion and public response a major driver of policy and litigation? Whether it is a distributional problem where one effect is felt by only a few people while climate change and air quality are more dispersive, a perception problem, or simply the most costly environmental impact of aviation is a result that cannot be gleaned from the summed total of a cost-benefit analysis. An improvement and expansion of aviation environmental impact analyses is necessary to understand these key issues.

The objectives of this thesis are to continue the development of the APMT-Impacts tools, in particular the climate module; to demonstrate the capabilities of APMT to perform an integrated cost-benefit analysis, and to demonstrate the need to develop a framework for including distributional impacts from aviation policy in future analyses.

1.3 Thesis Organization

This section provides a brief overview of the organization of this thesis. The thesis is separated into six chapters. The content and structure of the remaining chapters are outlined below.

Chapter 2 introduces the three domains of aviation environmental impacts of interest: noise, local air quality, and climate. For each domain, the thesis provides a technical introduction of the pollutants of interest, a discussion of the physical and monetary impacts of those pollutants, and an overview of important physical and endpoint metrics. Finally, the chapter summarizes the current policy-making framework for aviation and the environment and introduces the regulatory bodies tasked with addressing these externalities.

Chapter 3 discusses the modeling assumptions of APMT-Impacts for the noise module, local air quality response-surface module, and the global climate module. The chapter pays particular attention to the APMT-Impacts Climate module and stresses recent work on background scenario selection, short-lived species modeling, and temperature-response model development and comparison.

Chapter 4 walks through the use of the APMT-Impacts modules to perform an integrated cost-benefit analysis of a proposed NO_X emissions stringency policy. This chapter provides background information on the Committee for Aviation Environmental Protection action to reduce aviation NO_X emissions. Next, the chapter examines the framework for performing an integrated cost-benefit analysis including forecast assumptions, time scales of concern, and environmental modeling assumptions. The chapter lays out the results of aviation environmental impacts in physical and monetary endpoints for a variety of proposed stringencies and compares these to estimated industry costs of enacting these stringencies. Finally, the chapter compares these results to a typical cost-effectiveness analysis and summarizes policy insights keeping in mind model uncertainty.

Chapter 5 introduces a supplementary policy analysis framework by examining the regional distribution of aviation environmental benefits. The chapter looks at the impact of the distance from an airport on both environmental and economic effects, and then lays out how concerns of environmental equity and environmental social justice impact and complicate the policy decision making process.

Chapter 6 summarizes the work of this thesis and addresses opportunities for future work.

1.4 Key Contributions

The work presented in this thesis represents one component of a comprehensive effort to create and utilize a set of integrated policy tools for analyzing aviation environmental policy. As such, the work presented is strongly indebted to those who have planned, built, and supervised this effort throughout the history of PARTNER – The Partnership for Aviation Noise and Emissions Reduction. Listed below are the key contributions of this thesis work to the development and use of these tools.

- An investigation of Emissions Background Scenarios of the IPCC and the Stanford Modeling Group, and the interdependency of GDP and CO_2 emissions on background scenario choice. This work was performed in conjunction with model comparisons and background investigations performed in Dorbian (2010) and Fan (2010).
- Continued development and updating of the APMT-Impacts climate module to align assumptions with recent literature.

- The development of a temperature-response model for the APMT-Impacts climate module that accounts for deep ocean feedbacks on temperature change.
- Validation and calibration of the temperature-response model through comparison of results to other models and literature.
- The performance of an integrated cost-benefit analysis of a proposed ICAO-CAEP NOx Stringency. This work builds upon the work of Mahashabde (2009) and is part of Mahashabde et al. 2011, most specifically Section 6 of that paper.
- The development of a framework for performing a regional distributional analysis of aviation environmental impacts and its impact on policy analysis.

2 Aviation Environmental Impacts

The structure and content of the following sections on aviation environmental impacts draw from, update, and expand upon Mahashabde (2009), Fan (2010), Mahashabde et al. (2010), and Dorbian (2010). The structure of the sections on aircraft noise closely follows the structure of the related chapter in Mahashabde (2009), while the expansion of content closely follows that of He (2010).

2.1 Aircraft Noise

Aircraft noise is the most readily perceived environmental impact of aviation. A 2000 Government Accountability Office (GAO) report to the House of Representatives Committee on Transportation and Infrastructure on the future of airport operations found that noise from aviation was the single largest environmental concern for the foreseeable future (GAO 2000). A 2007 follow-up report found that noise from aircraft operations would be a significant hindrance to air transportation expansion (GAO 2007). Although aviation noise has many sources including ground support operations at airports, the discussion here is limited to aircraft operations, which are the dominant source. This section presents a brief overview of metrics used to measure noise and the physical and environmental effects of aviation noise.

2.1.1 Noise Metrics

The basic unit of noise, the Sound Pressure Level (SPL), is expressed as the ratio of a reference pressure to a measured pressure and is measured in decibels (dB). The measurement can be expressed using a variety of frequency-weighted scales such as the Tone-Corrected noise level scale and the A-weighted scale. The tone-corrected noise level accounts for the difference in perception and preference of human hearing to pure tones and various frequency and tonal irregularities. The A-weighted scale weights frequencies outside the range of human hearing less than those between 1 and 5 kHz. See Cunniff

(1977) for more details on weighting schemes and He (2010) for as discussion of weighting applicability.

Aircraft noise incidents can be classified as either short-term single-events or as a cumulative time-averaged sound from multiple single-events. The maximum A-weighted noise level is an example of a single-event noise metric, and can be used to measure the likelihood of awakening from sleep due to aircraft noise. The Effective Perceived Noise Level (EPNL or EPNdB) is another single-event metric that takes into account the sound duration and tonal quality. The FAA and ICAO use EPNL for aircraft noise certification standards (FAA 2004a).

Cumulative event metrics, such as annoyance level, use weighted time-averages of the aggregated single events. Equivalent Sound Level is a metric that corresponds to a specific period of time and indicates the average single-event noise level from the aggregated single events during that period. The most common use of the Equivalent Sound Level is the Day-Night-Level (DNL), which indicates the average noise level over a 24 hour period while applying a 10 dB penalty for nighttime events, and has been established as the metric used in regulation by the FAA (FAA 2004b). The DNL and the Day-Evening Noise Level, which applies a 5 dB penalty to evening noise events, are also widely used in aviation impact and environmental assessments with the DENL being used primarily in Europe (ECAC 2005).

2.1.2 Noise Impacts

Behavioral and physiological impacts from aircraft noise exposure have been studied over short and long time scales. Behavioral impacts include sleep disturbance, annoyance, and deleterious school and work performance. Physiological effects range from stress-related hypertension to declining mental health. It is difficult to directly attribute behavioral effects to aviation as the impact is dependent on time of day, ambient noise level, fear of the noise source, and confounding tonal effects. The effect of aviation noise on community annoyance has been well studied, with an association between noise level increase and annoyance level shown in Table 1. For a more detailed discussion of aviation noise annoyance, see Kish (2008) and He (2010).

Table 1. Effects of noise on people (residential land uses only) (FICON 1992)

Effects DNL (dB)	Hearing Loss Qualitative Description	Annoyance % of Population Highly Annoyed	Average Community Reaction	General Community Attitude toward area
75 and above	May begin to occur	37%	Very severe	Noise is likely to be the most important of all adverse aspects of the community environment
70	Will not likely occur	22%	Severe	Noise is one of the most important adverse aspects of the community environment
65	Will not occur	12%	Significant	Noise is one of the important adverse aspects of the community environment
60	Will not occur	7%	Moderate to Slight	Noise may be considered an adverse aspect of the community environment
55 and below	Will not occur	3%	Moderate to Slight	Noise considered no more important than various other environmental factors

The proportion of people highly annoyed in annoyance studies and surveys has been used to generate relationships between the percent of the population highly annoyed and the DNL level from aviation. Kish (2008) presents the relationship between noise-response surveys and annoyance data shown in Figure 1. Aircraft noise has also been strongly linked to sleep awakenings and disturbances (Maguire 2009), with single-event sleep awakenings being well understood. However, there are few studies that link the likelihood and severity of sleep interruption and disturbance over an entire night due to aviation (Anderson and Miller 2007). Thus, it is difficult to quantify sleep disturbance impacts for policies that address cumulative noise events.

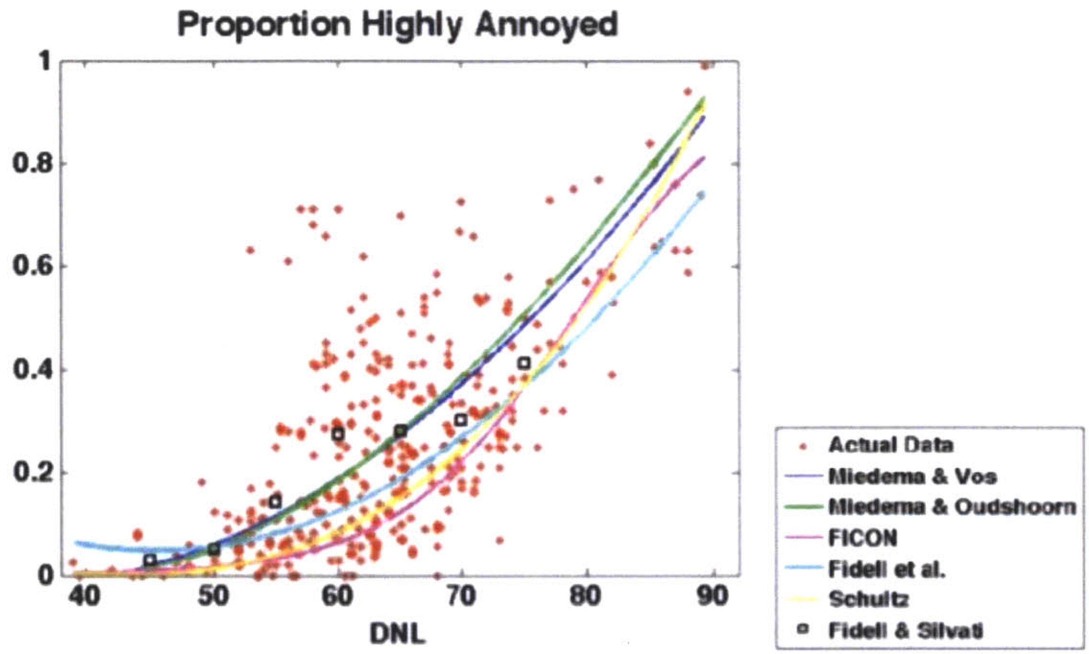

Figure 1. Noise-response relationships (Kish 2008)

Aircraft noise may also lead to long-term deleterious health impacts including hypertension, cardiovascular disease, and development of Type 2 diabetes. Although, the link between high blood pressure and increased noise exposure is known, there are no well-defined exposure-response relationships specific to aviation. Direct costs from the physical health impacts of noise are, therefore, not evaluated in this thesis. For a recent study on the relationship between hypertension and noise from aircraft and airport road traffic, see Jarup et al. (2008).

Housing value depreciation from aviation noise is a significant driver of environmental costs. Hedonic pricing studies are used to develop a Noise Depreciation Index (NDI) for specific airports that explains the decrease in property value corresponding to a one decibel increase in local noise level (Wadud 2009). Kish (2008) explains that, although often communicated independently, physical and monetary impacts may not be independent, and monetary impacts may represent a surrogate for aggregate noise impacts. He (2010) expands upon Kish (2008) by pointing out that monetary impacts, specifically those measured through hedonic pricing, do not necessarily encompass all costs from behavioral and physical impacts. In order for hedonic pricing to capture all monetary effects, the individuals whose preference is being measured must be able to understand and recognize the differences in property value, health impacts, and quality of life associated with the noise increase (EPA 2000). The methods presented in this thesis focus on the monetary impacts from hedonic pricing models with the understanding that further research on the interactions between physical and monetary impacts of aviation noise are necessary to better understand the aggregate environmental effects.

2.2 Aviation Air Quality

2.2.1 Air Quality Emissions

Aircraft jet engines produce emissions that have both primary and secondary impacts on local air quality. Engine exhaust is primarily water vapor (H_2O) and carbon dioxide (CO_2) with additional emissions of nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), unburned hydrocarbons or volatile organic compounds (VOCs), particulate matter (PM) of various sizes, and other trace compounds. CO_2 makes up 70% of emissions while H_2O makes up slightly less than 30% of total emissions with the remaining <1% consisting of the other species. The NO_X, CO, SOx, and VOC emissions are of particular interest for the impact of aviation on local air quality, and many of them are considered "criteria pollutants" associated with adverse health effects (FAA 2005). A brief description of the aviation emissions species most closely linked to air quality impacts follows.

Nitrogen Oxides (NO_X):

NO_X consists of both NO and NO_2, by-products produced when air passes through a high pressure and temperature combustion process. Utilizing results from epidemiological and observational data, the Environmental Protection Agency (EPA) integrated science assessment linked an increase in respiratory morbidity to NO_2 emissions (EPA 2008a). However, it is unclear if there is a direct concentration-response described by NO_2 emissions or if NO_2 is a surrogate for impacts from a different species or a variety of pollutants. Although highly dependent on ambient atmospheric levels of NO_X, aviation NO_X

emissions are a significant precursor to ground-level ozone (O_3). NO_X emissions also contribute to secondary particulate matter through the intermediate formation of ammonium nitrate and other inorganic oxidized nitrogen compounds (EPA 2008a).

Sulfur Oxides (SO_X):

Hydrocarbon based fossil fuels contain impurities and aromatics including small quantities of sulfur. Combustion processes and nucleation leads to the formation of various SO_x species including gas-phase sulfuric acid (H_2SO_4), sulfur dioxide (SO_2), and sulfur trioxide (SO_3). SO_2 is produced in the largest quantity, and it can further react to become secondary sulfate particles thereby leading to PM formation. Drawing evidence from health studies, the recent EPA integrated science assessment for sulfur oxides states there is a demonstrated causal relationship between SO_x exposure and respiratory morbidity and is suggestive of a causal relationship between short-term exposure and mortality (EPA 2008b).

Particulate Matter (PM):

Particulate matter (PM) refers to manmade and natural particles suspended in the air for various periods of time and includes dirt, soot, and liquid droplets. While all PM can contribute to environmental concerns from visibility to breathing comfort, small particles pose the greatest concern as they can be inhaled into the respiratory system. Fine particles can lodge deep into lungs and can accumulate along respiratory tracks. The discussion below is limited to particulate matter with an aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$). Unlike SO_x and NO_X, $PM_{2.5}$ does not refer to any family of chemical species, but is a term applied to all inhalable particles that form smaller than the ascribed aerodynamic diameter. Aircraft PM is a result of both direct emissions black carbon particles known as non-volatile particulate matter (nvPM) and through secondary effects from SO_x, NO_X, and unburnt hydrocarbon precursors (Rojo 2007). Particle bound water (PBW) associated with hygroscopic nitrate and sulfate species contributes additional weight to the total $PM_{2.5}$ (Abt Associates 2009).

2.2.2 Air Quality Impacts

Aviation emissions can have detrimental impacts on human health through induced changes in ambient air quality. When $PM_{2.5}$, is inhaled, the particles can become trapped in the lungs or can pass into the blood stream, potentially causing health problems. Exposure to increased PM concentrations has been correlated to adult early mortality, infant mortality, asthma, chronic bronchitis, restricted work days, respiratory hospital admissions, and cardiovascular hospital admissions (EPA 2004). A 2004 Journal of Medicine study estimates that PM inhalation leads to between 22,000 and 52,000 premature mortalities annually in the US alone (Mokdad et al. 2004). Brunelle-Yeung estimates that between 130 and 340 deaths are attributable to aviation $PM_{2.5}$ emissions from ground level to 3000 ft in the US in 2005, with the majority of mortality impacts coming from secondary PM formation (Brunelle-Yeung 2009). A recent study by Barrett et al. (2010) shows that excluding full flight emissions (those above 3000 ft) leads to an underestimate of total mortality from aviation impacts on local air quality by a factor of 5.

2.3 Aviation Related Climate Change

2.3.1 Climate Emissions

Aviation impacts the global climate by changing the planetary radiative balance. The Intergovernmental Panel on Climate Change (IPCC) defines radiative forcing (RF) as a measurement of the influence a given factor has in altering the incoming and outgoing energy balance of the earth-ocean-atmosphere system (Penner 1999). Aviation impacts the radiative balance through impacts on time scales that last for less than a day to those that persist for several centuries and on spatial scales from local to global. Furthermore, aviation has both positive and negative RF effects, meaning that aviation impacts can be either warming or cooling. This thesis will focus on RF changes through direct and secondary atmospheric effects from aviation emissions as they are expected to be the most severe. However, aviation may have other impacts on climate such as through surface albedo changes from soot particles (Yasunari et al. 2011). The following sections present a brief summary of impacts from aviation emissions forcing agents on climate.

Carbon Dioxide (CO_2):

CO_2 is a long-lived, well-mixed greenhouse gas. Thus, aviation CO_2 emissions behave the same way as CO_2 emissions from point sources or other mobile sources. CO_2 has a net warming effect (positive RF), and can persist in the atmosphere for centuries (Penner 1999).

Sulfates and Soot:

Aviation sulfate aerosols reflect radiation away from Earth providing a cooling (negative RF) effect. Soot particles, mostly composed of black carbon, absorb incoming radiation leading to a warming effect of similar magnitude (Penner 2009). The effects of both species last on the order of a few weeks in the atmosphere. Recent work by Jun (2011) has investigated the roll of sulfates and particles on cloud seeding and nucleation, but current scientific uncertainty in this area is significant.

Water Vapor (H_2O):

H_2O has a direct warming effect (positive RF) with a lifetime of several days. Although not inconsequential, H_2O from subsonic aircraft has a less significant climate impact than other emissions species. However, H_2O emissions from supersonic aircraft at stratospheric altitudes can have more significant warming impacts (Penner 1999).

Nitrogen Oxides (NO_x) :

NOx emissions have both a warming and a cooling influence on the climate at different spatial and time scales. The warming effect comes from the short-lived local production of ozone (O_3) and the cooling effect comes from the longer lasting destruction of methane (CH_4) from an increased oxidative capacity of the atmosphere due to OH radicals. This chain also has a primary-mode reaction of long-term reduction of O_3. The long-term NO_X -CH_4-O_3 reduction is on a decadal time scale, while the short-lived NO_x-O_3 generation lasts for a few weeks (Stevenson 2004). Although, the aggregate globally-averaged impacts of these two pathways are approximately of equal magnitude with opposite sign, the short-lived warming effect is more severe in the northern hemisphere, leading to potentially significant regional effects (Mahashabde 2009). Furthermore, a forthcoming paper by Barrett et al. (2012) indicates that a fourth aviation NO_X pathway results in an increased oxidation of non-aviation SO_2 to sulfate. This sulfate generation has a further regional net cooling impact. This pathway may offset the total NO_X warming effect, making aviation NO_X climate neutral on a globally aggregate scale.

Contrails and Aviation Induced Cirrus

Contrail formation is dependent upon water vapor emission, ambient pressure, temperature, and aircraft propulsive efficiency. Persistent contrails, under some conditions, can spread to form high cirrus-like clouds that are indistinguishable from naturally forming cirrus (Lee et al. 2009). Further cirrus structures may arise from the accumulation of aircraft emission particles that act as cloud condensation nuclei. Both linear contrail and cirrus cloud formation can have significant short-lived net warming impact on a regional to hemispherical spatial scale (Penner 1999). The combined impact of contrails and cirrus is known as aviation induced cloudiness (AIC). Although the impact of AIC is more uncertain than that of CO_2, estimates indicate that AIC has the most significant RF of all aviation emission species (Lee et al. 2009).

Lee et al. (2009) provides the most recent updates to the approximate RF contributions from various aviation emissions species along with their spatial scale and approximate uncertainty quantification shown in Figure 2. Lee et al. also rates the understanding of CO_2 impacts as High (well understood), NO_X effects as Medium, and other emissions species as Low. The understanding of the relative impact from AIC is ranked as Very Low, and the total contribution from aviation is presented both with and without the impacts from AIC to account for this uncertainty. For comparison, the global anthropogenic radiative forcing from various components is given in Figure 3.

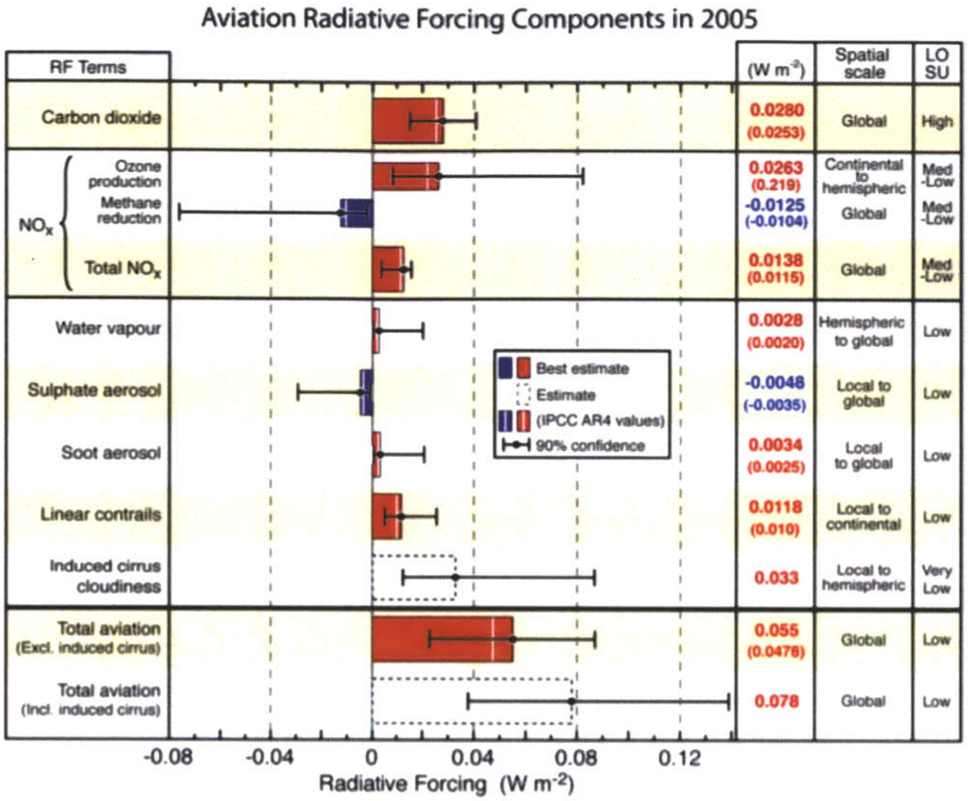

Figure 2. Speciated aviation radiative forcing estimates (Lee et al. 2009)

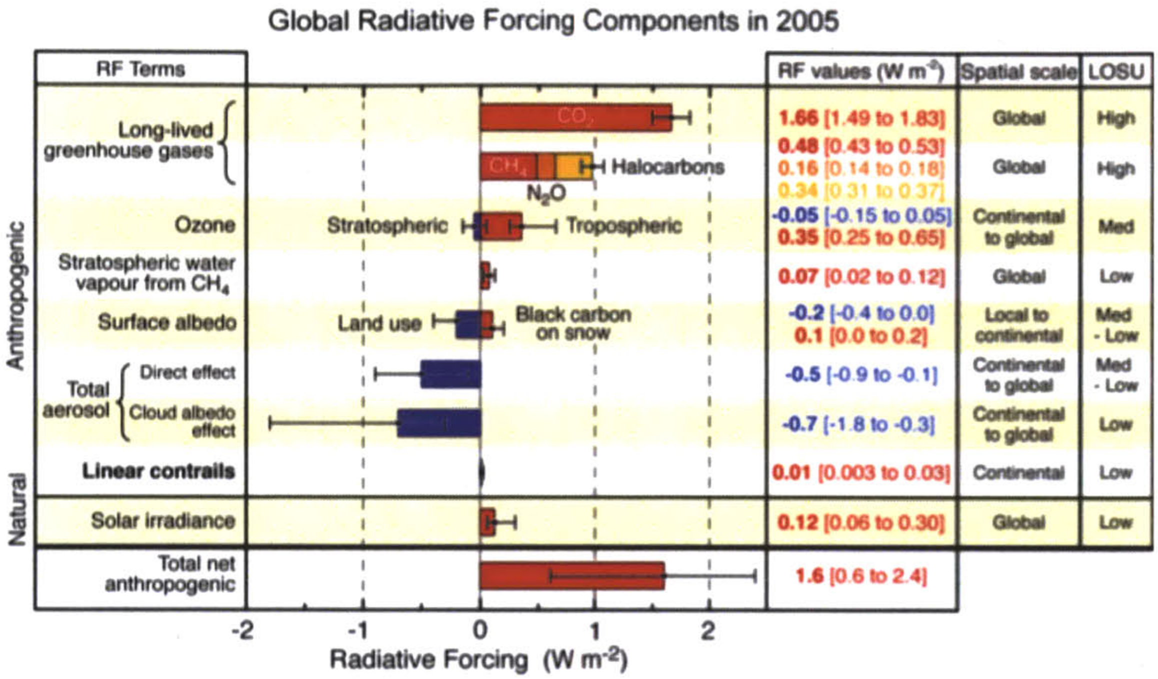

Figure 3. Global radiative forcing components (Lee et al. 2009)

2.3.2 Climate Impacts

The changing climate exerts pressure on many aspects of the earth's natural systems. Temperature changes can lead to extreme changes in both natural and managed systems. Hydrology and water resources, marine and terrestrial biosystems, cryosphere, human health, agriculture and land use are all domains that are impacted by changing temperature. These changes lead to detrimental impacts on societal welfare. However, establishing a causal relationship between climate change and societal damages is difficult and fraught with uncertainty. Human activity apart from greenhouse gas emissions also has an influence on major drivers of economic change such as water availability, loss of biodiversity, and land use. Costs from these changes are spread through direct impacts on human health and through mitigation and adaptation efforts across several domains. The following sections look at different metrics for evaluating climate change along several points in the impact pathway from underlying radiative forcing to the monetization of damages across many of the natural and managed systems impacted by climate change.

2.3.3 Climate Valuation Metrics

Greenhouse gas emissions, such as those from aviation, can be measured, characterized, and compared using a variety of metrics both qualitatively and quantitatively. Historically, the focus of practical climate change discussions has been on CO_2, which is reflected in the choices of endpoint criteria commonly used in both scientific and policy climate change analyses. However, as shown in 2.3.2, the radiative imbalance from total aviation impacts may be more than double the impact of aviation CO_2 alone. Furthermore, the substantial uncertainties that exist in both climate modeling and aviation forecasting as well as the variation in timescales among emissions species complicates the choice of metric for explaining aviation climate impacts. A description of several endpoint metrics for climate change and their potential use in aviation policy analysis follows.

Physical Metrics

The Global Warming Potential (GWP) is one of the most prevalent metrics for quantifying the impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) has used the GWP since the inception of its scientific assessments (IPCC 1990), and it is the primary metric of the Kyoto Protocol. The Global Warming Potential explains the impact of a given gas species compared to a reference gas (most commonly CO_2) by integrating the future impacts of both species as shown below in Equation 1:

$$GWP(x) = \frac{\int_0^{TH} a_x[x(t)]dt}{\int_0^{TH} a_r[r(t)]dt} \tag{1}$$

where x is the trace species of interest, TH is the time horizon over which the impacts are to be measured, a_x is the radiative efficiency of the gas, and *r(t)* and *x(t)* represent the species decay over time (IPCC 2001). The GWP is useful as it incorporates the future impacts of a pulse of emissions and accounts for potential differences in time scales. Thus, it has benefits for policy impacts of current or future emissions over instantaneous forcing metrics such as the Radiative Forcing Index, which is the total RF from a given gas or emitting sector (i.e. coal power plants, aviation, ground transportation) over the total current climate system RF. Furthermore, because the GWP utilizes RF, it is early in the impact pathway and is therefore subject to the lowest amount of uncertainty.

However, the GWP is widely contested, as summarized by Shine et al. (2005) and Dorbian (2011). Despite the implication of its name, the GWP does not indicate the impact on climate system warming or cooling that a temperature metric would give. Furthermore, because of the atmospheric lifetime of CO_2, the metric is highly sensitive to the time horizon chosen. An analysis by Tanaka et al. (2009) shows that GWPs alone do not give a good indication of expected impact even using a "best fit" time horizon. Even though its shortfalls are known, the GWP remains in widespread use. Thus, time-integrated radiative forcing can be an important endpoint metric for both scientific analyses and for setting environmental policy.

Moving down the emissions impact pathway, a comparison of temperature impacts may better explain the impact of a given GHG or emissions species and is easier to understand conceptually (Dorbian 2011, Shine et al. 2005). Two such temperature metrics are the Time Integrated Temperature Change (ΔT ratio) and the Global Temperature Potential (GTP). Like the GWP, the ΔT ratio looks at the time-integrated ratio of a pulse of a gas to that of a reference species as shown in Equation 2:

$$\Delta T\,ratio(x) = \frac{\int_0^{TH} \Delta T_x(t)\,dt}{\int_0^{TH} \Delta T_r(t)\,dt} \qquad (2)$$

where *TH* is the specified time horizon to be analyzed and *ΔT* is the time dependent temperature change. On the other hand, the GTP can be used to compare instantaneous temperature change of a gas impulse at some point in the future as shown in Equation 3:

$$GTP(x) = \frac{\Delta T_x(TH)}{\Delta T_r(TH)} \qquad (3)$$

where TH is the specified time horizon to be analyzed and ΔT is the instantaneous temperature change at that time. The ΔT ratio is more appropriate in a cost-benefit framework where total impacts of a climate policy over time are of greatest importance (Dorbian 2011), whereas GTP is more useful in a cost-effective framework (Tol et al. 2008). Despite being more descriptive of climate impacts, these metrics are subject to criticism similar to that of the GWP. They are subject to additional uncertainty due to being further down the emissions impact pathway, and because they represent changes in globally-averaged temperature changes, they may not be appropriate in local impact analyses or may overestimate or underestimate environmental policy benefits in some regions.

Additional physical metrics are used to assess different global system responses at different geographic scales and may be useful for policy analysis or for better understanding of the impact of temperature change on human systems. These metrics include sea level rise (SLR), local rainfall, disease rates, and severe hurricane incidences.

Monetary Metrics

At the furthest point along the aviation impact pathway are monetary valuation metrics. Economic costs of damages can be quantified as the Net Present Value (NPV) of total damages expected due to a given pulse of an emissions species. A common way to address monetary damages is the through use of a social cost of carbon (SCC). The SCC is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. Among the many impacts it encompasses, it includes changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. When examining a multi-gas approach, a Social Cost of Carbon Equivalent (SCC_{eq}) can be used to address total environmental damages. Because monetary environmental damages are easy to compare across a range of disciplines and can be directly contrasted to policy costs, SCC and total NPV are popular metrics for policy analysis. Appendix 15a to Executive Order 12866 provides a summary of the range, uncertainty, and use of SCC in addressing climate policy (IWG 2010).

A discount rate is used to convert future monetary damages into net present values. A discount rate of 0% would value future damages at the same rate as current damages whereas a discount rate of 5% would weight future damages by a rate of (1/1.05) for each year into the future the damages occurr. By weighting present damages over future damages, the discount rate acts in much the same way the time horizon behaves in the physical metrics. Results are highly sensitive to discount rate, but unlike other parameters, discount rate does not represent scientific uncertainty; it represents a policy worldview. The IWG provides SCCs for discount rates from 2.5% to 5% (IWG 2010), while the OMB suggests values between 2% and 7% for US policy analysis (OMB 2003). The choice of an appropriate discount rate and discounting method are a continuing source of debate in the policy and scientific communities (Gollier 2010, Sunstein 2008, Nordhaus 1997) and have implications on environmental policy equity as explained in Section 5.3.

Aviation Derived Ratios

Appropriate and wide-reaching climate policy requires a metric that is able to encompass all greenhouse gas emissions. This is especially true in aviation with its relatively high ratio of non-CO_2/CO_2 impacts. Since it can be cumbersome and perhaps counterproductive to regulate each emissions species separately, a multi-gas metric that places all emissions on a common scale, such as SCC_{eq}, is preferred. PARTNER has developed a set of aviation-derived ratios that can provide an SCC_{eq} given an exogenous SCC, and therefore, a total approximate environmental cost given a system-wide aviation fuel burn.

For a complete discussion of the development, use, and limitations of the derived aviation ratios, see Dorbian 2010 and Dorbian et al. 2011. An independent analysis by Azar and Johansson (2011) investigated the ratio of contrail and NO_X related damages to aviation CO_2 under a range of assumptions and found results that aligned with that of Dorbian et al. (2011). Derived Ratios representing the most up to date scientific and modeling understanding of climate impacts are shown in Table 2.

Table 2. NPV aviation specific derived ratios

Discount Rate	2%			3%			7%		
Lens	Low	Mid	High	Low	Mid	High	Low	Mid	High
CO_2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NO_X Total	-0.04	-0.03	-0.03	-0.05	-0.02	-0.05	0.12	0.21	0.11
Contrails	0.07	0.16	0.15	0.12	0.26	0.27	0.34	0.79	1.00
AIC	0.15	0.49	0.53	0.24	0.81	0.92	0.70	2.42	3.40
Sulfates	-0.39	-0.13	0.00	-0.63	-0.22	-0.01	-1.85	-0.64	-0.03
Soot	0.01	0.09	0.13	0.01	0.15	0.22	0.04	0.46	0.81
H_2O	0.01	0.09	0.12	0.01	0.15	0.21	0.02	0.43	0.79
Total	**0.65**	**1.18**	**1.37**	**0.46**	**1.33**	**1.65**	**-0.33**	**2.25**	**3.68**
Total with AIC	**0.73**	**1.51**	**1.74**	**0.58**	**1.87**	**2.30**	**0.02**	**3.88**	**6.08**

Because CO_2 marginal radiative forcing is dependent upon a complex carbon cycle and a logarithmic relationship, additional units of CO_2 emitted have a decreasing impact on radiative forcing. Therefore, in the future, the magnitude of the relative impact of short-lived species is expected to be greater. To account for this change, a yearly growth rate is applied to the derived ratio. The growth rates are discount rate and lens specific and shown in Table 3.

Table 3. Aviation derived ratios growth rates

2% Discount Rate			3% Discount Rate			7% Discount Rate		
Low	Mid	High	Low	Mid	High	Low	Mid	High
-0.8	0.4	1.1	-1.5	0.5	1.3	4.9	0.5	1.2

Derived ratios can also be specified for a variety of alternative fuel scenarios. For a discussion of derived ratios for synthetic paraffinic kerosene (SPK) fuels see Stratton 2011. Finally, derived ratios can be applied to physical metrics such as Integrated Temperature

Change for a given time horizon as explained in Dorbian (2011). Work from this thesis is used in both papers.

2.4 Other Aviation Environmental Concerns

Aviation operations impact the environment beyond noise and emissions. Airport ground operations affect the quality of local watersheds. Aircraft deicing, fuel spills, herbicides to manage airside grounds, and surface runoff from ground transport can all impact the quality of waterways, rivers, and streams surrounding the airport. Deicing procedures in the US lead to the discharging of 21 million gallons of aircraft deicing fluids into surface waters each year (EPA 2002). An overview of the environmental impact of deicing and other operations is provided in Marais and Waitz (2009).

Aviation operations and airport expansion can also have a negative impact on wildlife. Airside airport operations require large tracts of land, making siting of airports difficult. Significant airport expansion projects can require building on green field land or reclaiming wetlands. The resulting expansion can restrict or restructure water flow or lead to urbanization of previously rural areas further impacting ecosystems (Foster et al. 2004). The impact of operations on waterfowl and bird migration can be especially problematic both for the environment and for the safety of airport operations themselves (Allan 2000).

While these environmental impacts are important to consider in the context of future aviation decisions, it is assumed that these spheres are strongly decoupled from aircraft noise and emission stringency regulation. Thus, policy decisions impacting wildlife or local water quality are agnostic to policy decisions on emission or noise reductions considered here. However, some research indicates that noise reduction policies my lead to more bird strike incidences (Burger 2003).

2.5 Aviation Environmental Policy-Making Bodies and Decision-Making Frameworks

International standards and recommendations for emissions and noise reduction fall under the jurisdiction of the International Civil Aviation Organization (ICAO), established under the Chicago Convention of 1944. ICAO is a United Nations (UN) agency charged with overseeing and fostering aviation development in areas of safety, licensing, aircraft and airport operation and design, air traffic services, the environment, consumer treatment best practices, and litigation. CAEP, the Committee on Aviation Environmental Protection, is a specialized group within ICAO that oversees aircraft noise and emissions-related issues. The following section provides an overview of the development of aviation regulation and standards through international and national agencies and examines differences in decision-making best practices and policy approaches.

Aircraft noise was the first environmental impact to be regulated when ICAO published the *Annex 16: Environmental Protection, Volume I - International Noise Standards* in 1971. Although there has been increased regulation since that time, the most public complaints about aviation are still a result of aircraft noise. Emissions standards were next to follow. Section 7571 of the Clean Air Act of 1970 allowed provisions for aviation emission standards. Implementation of ICAO Standards and Recommended Practices (SARPs) for aircraft emissions followed in the 1980s to improve air quality in the vicinity of airports. ICAO emissions standards are summarized in *Annex 16: Environmental Protection, Volume II— Aircraft Engine Emissions* (ICAO 1982). Thus, while standard setting for both realms of environmental impacts are set under one agency, US regulatory decisions are split between the FAA and the EPA. Climate change is the last environmental impact to be regulated. ICAO-CAEP passed resolution A37-19, Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change, in 2010, thereby becoming the first UN agency to lead a sector on a unifying CO_2 emissions approach.

ICAO-CAEP's work and decision-making framework are to be guided by four areas of reference: environmental benefit, technological feasibility, economic reasonableness, and consideration of interdependencies. However, CAEP typically only modeled the effect of policy stringency and implementation with respect to environmental benefit and economic reasonableness (ICAO 2007). To wit, CAEP traditionally employs Cost Effectiveness Analysis (CEA) in its decision-making process. Mahashabde (2009) walks through the CAEP decision-making process in relationship to the CAEP/6 NO_X Stringency policy decision.

Conversely, in the United States, under Executive Order 12866, agencies are required, to the extent permitted by law, "to assess both the costs and the benefits of the intended regulation and, recognizing that some costs and benefits are difficult to quantify, propose or adopt a regulation only upon a reasoned determination that the benefits of the intended regulation justify its costs." This ruling promotes the use of an integrated cost-benefit in environmental policy analysis, except in conditions where a maximum allowable limit of a pollutant or toxin exists or where adequate information on the value of costs or benefits is unavailable.

Uncertainty is one of the major concerns with monetizing the environmental impacts in a policy analysis. Uncertainty is unavoidable, can be large, and comes from a variety of sources. Forecasting, model assumptions, and the breadth of scientific and economic knowledge can all add uncertainty to the monetary metric. However, these uncertainties are all associated with the modeling methodology, and a distinction should be drawn between these uncertainties and decision-making process uncertainty. While the modeling uncertainty grows further down the impact pathway, the uncertainty in the decision-making process typically decreases as better estimates of both the uncertainties, and of the ultimate impacts of the policy option, are made. For instance, it is difficult to decide the efficacy of an emissions reduction policy only knowing how many tons of emissions are reduced, but it is easier to make a decision on the policy if one knows how many lives are saved and even easier if one knows the total cost of environmental benefits. A notional understanding of the impact and importance of uncertainty in decision-making is shown in Figure 4.

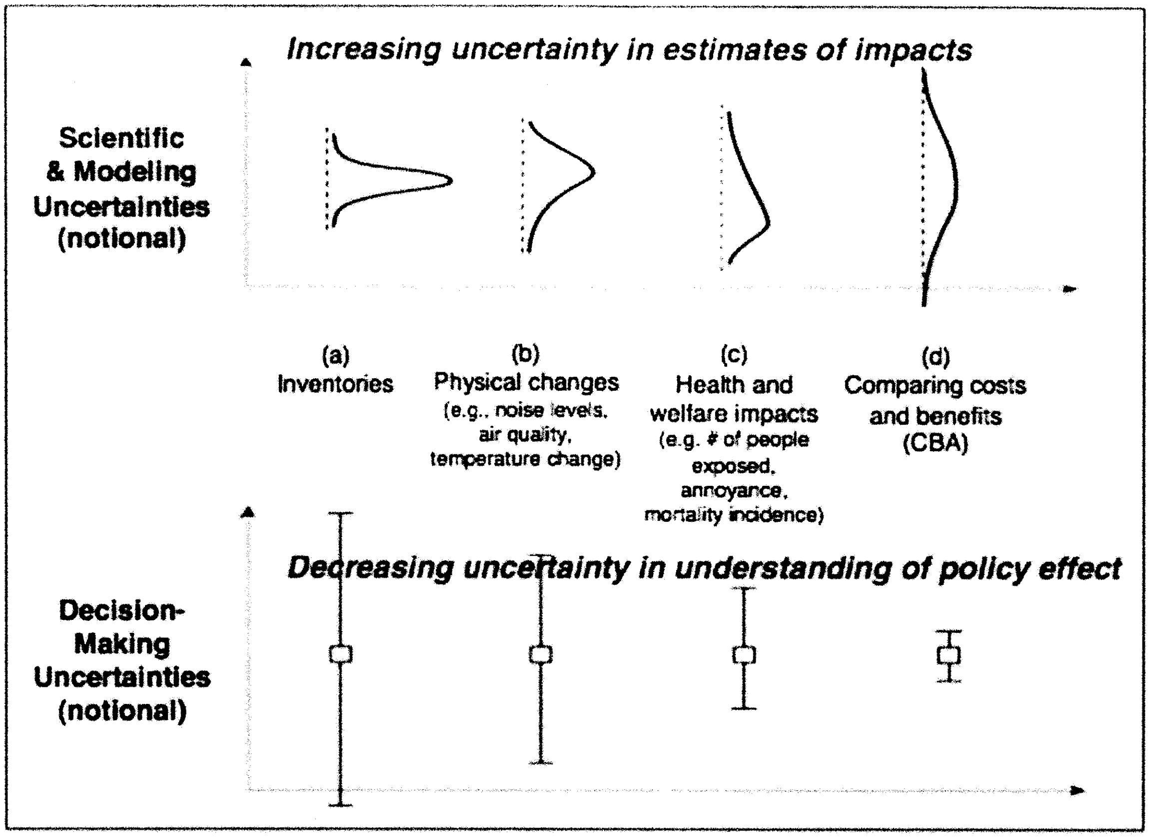

Figure 4. Notional scientific vs policy decision-making perspectives (Mahashabde 2009)

3 Aviation Environmental Impact Modeling Methods

The interaction among various aviation environmental externalities poses a large problem to policy developers. For instance, a policy meant to limit sulfate emissions could have a beneficial impact on local air quality, but could have a negative impact on the global climate. Furthermore, a comprehensive analysis must weigh the environmental impacts against economic and social objectives.

Chapter 2 described an overview of the physical and monetary impacts caused by the interaction of aviation and the environment. Chapter 3 introduces the methodology used to model and estimate the magnitudes of environmental impacts for a variety of industry projections in an effort to support the policy process. The Partnership for AiR Transportation Noise and Emission Reductions (PARTNER) is a US Center of Excellence that focuses on aviation environmental impact understanding, mitigation research, and decision-making process support. With support from the Federal Aviation Administration (FAA), NASA, and Transport Canada, PARTNER works to bring together academia, government, and industry to address complex aviation environmental problems.

PARTNER has helped develop the Aviation environmental Portfolio Management Tool, which focuses on economic and environmental impact analysis of various policy and strategy proposals impacting US and international aviation. The design of APMT allows researchers to examine the economic costs and environmental benefits of a proposed regulation. Additionally, APMT makes explicit scientific and value-based uncertainties that arise in the analysis, providing policy-makers with additional insights. In keeping with current best-practices, APMT was designed in accordance with a detailed FAA requirements document that followed an extensive review of environmental and economic analysis literature (Waitz et al. 2006). Mahashabde (2009) provides a list of the key documents consulted in the development phase, and the Transportation Research Board (TRB) prepared a review of the requirements document (TRB 2005).

APMT has two primary modules, APMT-Impacts and APMT-Economics, which fit within a broader FAA aviation environmental tools suite to provide detailed cost-benefit analyses. A graphical representation of the tools suite is shown in Figure 5. APMT-Impacts takes aviation emissions inventories for current and future year full-fleet scenarios and associated noise contours around several key airports to determine the physical damages from aviation over a given length of time. APMT-Impacts also monetizes these physical effects.

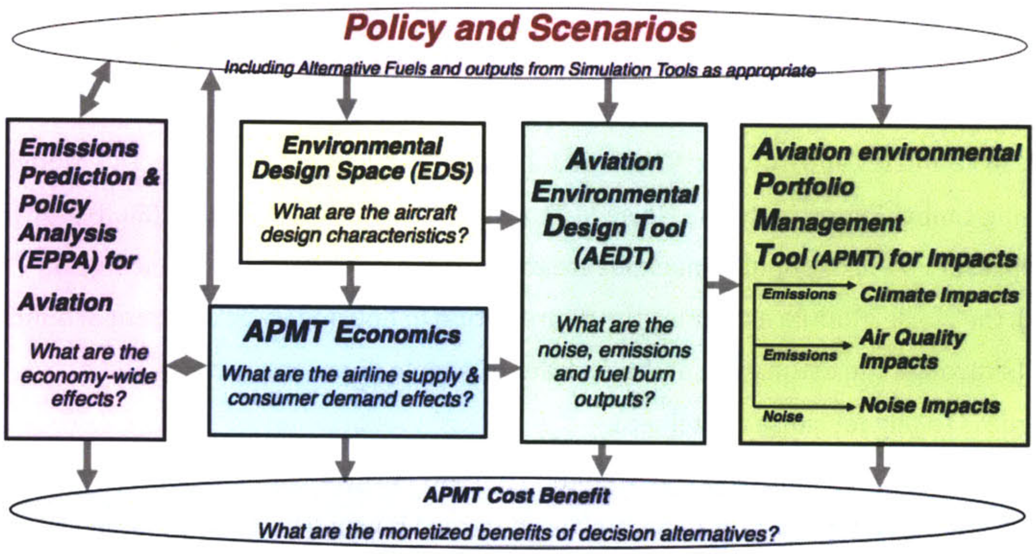

Figure 5. APMT system block diagram

In a similar fashion, the European Commission has founded the Tool Suite for Environmental and Economic Aviation Modeling for Policy Analysis (TEAM_Play). TEAM_Play combines existing models of noise, green house gas emissions, and local air quality models with macro-economic tools. TEAM_Play looks to investigate non-US assumptions and policy effects across Europe.

PARTNER is continuing to develop alternative and supplemental modeling techniques. Recent PARTNER research has focused on modeling air quality impacts over a variety of domains on several scales. Koo (2011) looks at utilizing an adjoint method for estimating aviation air quality impacts. Recent work has also focused on using a rapid dispersion model developed by Barrett and Britter (2008) to address very near-airport air quality impacts. The results in this thesis utilize the APMT-Impacts module described in the following sections. The APMT-Impacts modules for climate, air quality, and noise are probabilistic models to account for scientific and modeling uncertainty. Each model utilizes Monte Carlo simulations to choose between parameter values that span current scientific understanding of the three aviation environmental impacts.

3.1 APMT-Impacts Noise Module

The APMT-Impacts Noise Module estimates the US and global impacts of aviation noise in terms of both physical and monetary metrics described previously in Section 2.1.2. As a baseline, the noise module includes 95 US airports and 86 international airports located across 38 countries and Taiwan. These 181 airports are the majority of the 185 Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA) 'Shell-1' airports that represent 91% of population exposure to noise (FAA 2009). As described in He (2010), the Noise Module estimates the depreciation in housing value and rent around airports through the estimation of the number of people impacted by noise and a willingness to pay for noise abatement.

The current APMT-Impacts Noise Module overlays projections of aviation produced DNL around a given airport onto the census generated housing data. By mapping the noise in 5 dBA contours and assuming a given background noise level, the module produces an estimate of population affected by aircraft noise at different magnitudes as shown in Figure 6.

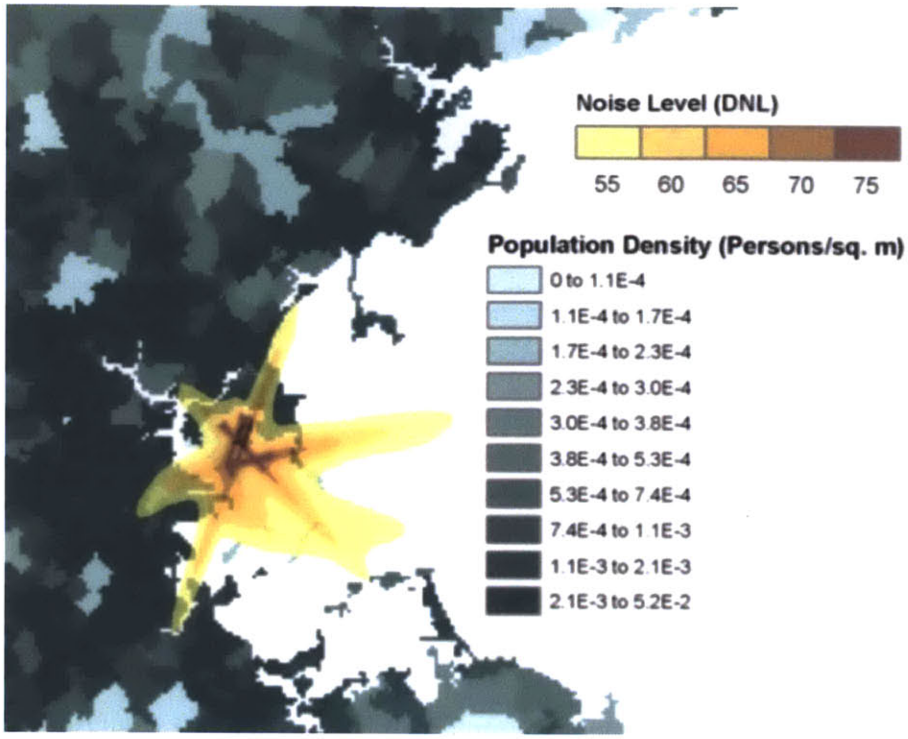

Figure 6. Illustrative example of the superposition of noise contours and population data (He 2010)

An analysis of 2005 global aircraft noise generation that excluded 3 Shell-1 airports in Pakistan (due to data limitations) indicated that 13.7 million people are exposed to aviation noise that exceeds ambient noise levels (He 2010). The spatial distribution of physical impacts from 178 of the 181 Shell-1 airports is shown in Figure 7.

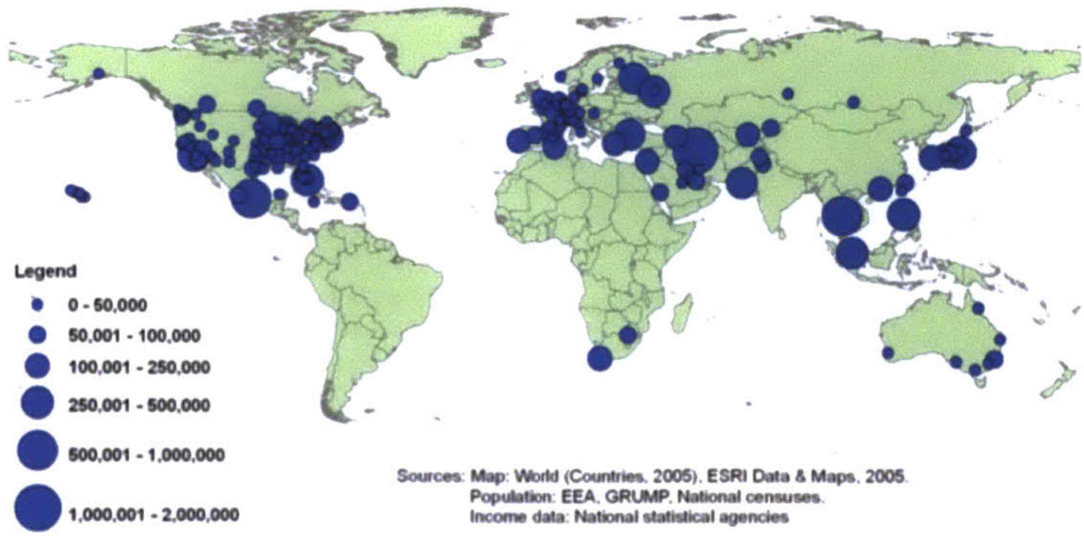

Figure 7. 2005 Aviation noise population exposed (Mahashabde et al. 2011)

The population highly annoyed from aircraft noise can be calculated by using exposure-response functions for each of the noise contour band levels (Miedema and Oudshoorn 2001). Other physical effects, such as noise-induced cardiovascular problems and sleep disturbances, are not directly estimated.

The impact of aviation noise on housing prices is estimated using the noise depreciation index (NDI) concept. In the hedonic pricing method utilized in the noise module, a person's willingness-to-pay (WTP) for a decrease in noise exposure is determined by the difference in housing prices between two communities of similar characteristics but with different aviation noise levels. The NDI then measures the loss in housing price related to an increase of 1 DNL dB. As explained in Section 2.1.1, housing depreciation is a proxy for the costs of several health and behavioral impacts of noise, but may not account for all environment costs. Direct costs from noise-related health impacts are not currently measured in APMT-Impacts.

Using a meta-analysis of over 60 hedonic pricing studies, He (2010) derives a relationship between average city-wide income level and yearly WTP for noise abatement. Furthermore, WTP is a function of whether the noise surrounds a US or an international airport. This methodology builds upon the work of Kish (2008) but is easier to apply because city-wide personal income data is more readily available and less computationally expensive than utilizing the detailed city-block housing data required by the Kish method. The WTP formula is given in Equation 4, and its derivation is described in detail in He (2010).

$$WTP = 0.0138 \times Income + Income \times NonUS - 30.3440 \qquad (4)$$

NonUS is a dummy variable that is equal to 0 for US airports and 1 for non-US airports. An analysis of the 178 airports shown in Figure 7 found that mean annual noise costs were $1.4 B in 2005 (Mahashabde et al. 2011). The spatial distribution of noise-induced monetary impacts are shown in Figure 8.

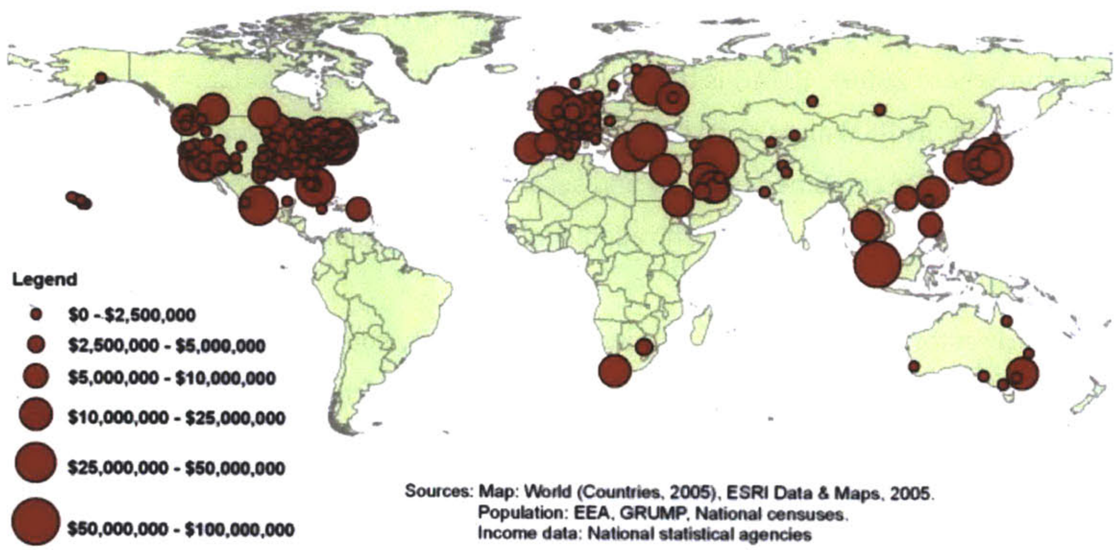

Figure 8. 2005 Monetary impacts of aviation noise (Mahashabde et al. 2011)

A detailed analysis of the APMT-Impacts Noise Module and its development including assumptions, sensitivities, and strengths and weaknesses of the approach is performed in He (2010).

3.2 AMPT-Impacts Air Quality Module

The APMT-Impacts Air Quality Module calculates the US physical and monetary surface air quality damages associated with aviation primary and secondary particulate matter with an aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$). Chemistry transport models (CTMs), complex atmospheric chemical reaction and transport mechanism models, estimate changes in particulate matter and other pollutant surface concentrations from aviation landing and take-off (LTO) cycles. Although CTMs often provide an incomplete suite of chemical reactions and transports, they are capable of high-fidelity analyses. However, these models involve long run-times and are computationally expensive, making them unattractive for the analysis of wide-ranging policy scenarios, particularly if probabilistic calculations are required to quantitatively estimate uncertainties as is the case for the use of APMT-Impacts.

The APMT-Impacts Air Quality Module uses a response surface model (RSM) built from linear correlations from a statistical analysis of simulations of the Community Multiscale Air Quality Modeling System (CMAQ), a 3-dimensional, high fidelity grid-based model (Byun and Schere 2006). CMAQ is the tool used by the US EPA for regulatory impact analyses. Both the RSM and CMAQ have spatial resolutions of 36 x 36 kms over the continental US. For combined primary and secondary $PM_{2.5}$, the RSM results have a root mean square error of 3.5%, making it reliable for policy modeling purposes (Brunelle-Yeung 2009).

To correct for model biases and limitations, air quality concentrations are then adjusted by correlating modeled results with empirical data from air quality monitors. The APMT-Impacts Air Quality module utilizes the Speciated Modeled Attainment Test (SMAT) to address these differences in accordance with EPA best practices, a process known as SMATing (EPA 2006). Most often, the SMAT process alters the speciating split of secondary outputs; in APMT, the result of SMATing is a domain-wide average shift in sulfates upwards and nitrates downwards (Dorbian 2010). For the NO_X Stringency analysis performed in Chapter 4, the effect of SMATing was a reduction in air quality benefits by approximately 25% for each stringency analyzed. The post-SMATed RSM distribution of PM2.5 for a baseline of aviation operations is shown in Figure 9.

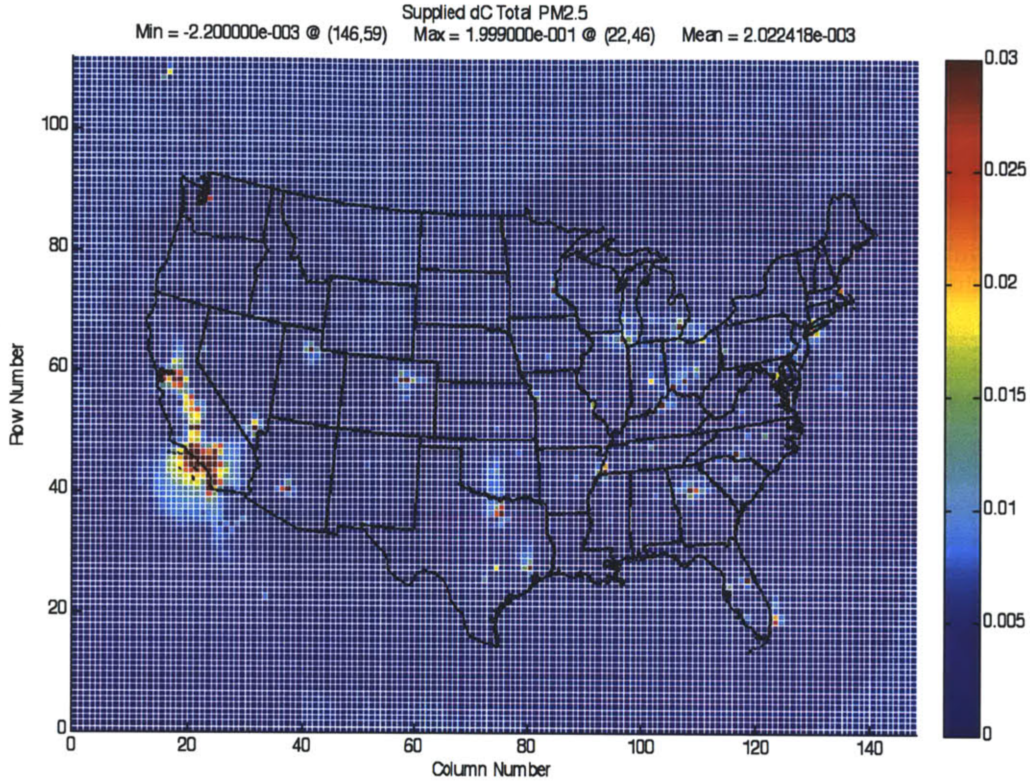

Figure 9. Post-SMATed RSM $PM_{2.5}$ distribution

Concentration-response functions, derived from natural experiments and epidemiological studies, relate changes in pollutant concentrations to human mortality and health endpoints over time (Brunelle-Yeung 2009). Population-weighted exposure is measured on a cell-by-cell basis across the RSM grid. The APMT-Impacts Air Quality Module then uses a value of a statistical life (VSL) for mortalities and cost of illness (COI) for each endpoint metric as explained in Rojo (2007). The valuation scheme can be adapted for different analyses depending on the best practice for the regulatory body of interest because acceptable VSLs are inconsistent among governing bodies or even from agency to agency (DOT 2009). The VSL is subject to considerable variation and large uncertainties (Dockins et al. 2004, Viscusi and Aldy 2003, Andersson and Treich 2009). Its use as a policy-making tool remains a source of discussion and controversy (Ashenfelter

2006, Sunstein 2004, Heinzerling 2000). A nominal concentration-response and valuation scheme are shown in Table 4.

Table 4. Concentration response functions and valuations for air quality health impacts (Brunelle-Yeung 2009)

$PM_{2.5}$-related endpoints	Risk Increase (% per $\mu g.m^{-3}$ $PM_{2.5}$)	Value of a Statistical Life or Cost of Illness
Adult premature mortality (adults age 30+)	Triangular 1.0 (0.6 – 1.7)	Lognormal distribution with mean \$6.3 M, σ \$2.8 M
Infant premature mortality	Triangular 0.7 (0.4 – 1)	Lognormal distribution with mean \$6.3 M, σ \$2.8 M
Chronic Bronchitis	Triangular 1.5 (1.3 – 2.0)	Mean \$0.34 M
Hospital admissions – respiratory	Triangular 0.2 (0.14 – 0.29)	Discrete distribution \$15,647 wp 0.75 \$31,294 wp 0.25
Hospital admissions – cardiovascular	Triangular 0.16 (0.14 – 0.19)	Discrete distribution \$18,387 wp 0.75 \$36,774 wp 0.25
Asthma emergency room visits	Triangular 0.8 (0.6 – 1.1)	Discrete distribution \$286 wp 0.75 \$572 wp 0.25
Minor Restricted Activity Days (MRADs)	Triangular 0.7 (0.6 – 0.9)	Discrete distribution \$25 wp 0.25 \$52 wp 0.5 \$25 wp 0.25

APMT-Impacts can be used to calculate air quality damage costs speciated by four PM components: non-volatile PM (nvPM), PM nitrates, PM sulfates, and PM organics. The APMT-Impacts air quality health impact analysis focuses on particulate matter and does not include ozone or hazardous air pollutants (HAPs) impacts as justified in Rojo (2007). Current limitations of the RSM include a lack of accounting for the health impacts of cruise emissions from aircraft, the scope of geographic coverage, the use of a fixed background scenario, and non-speciated concentration response functions. These areas remain topics of PARTNER research, and there are plans to account for these impacts in future versions of the RSM and other updates to the APMT-Impacts air quality module.

3.3 APMT-Impacts Climate Module

This section describes the modeling approach to estimating the physical and monetary impacts of aviation on climate change discussed in Section 2.3. The impact pathway used here is shown in Figure 10. Although this pathway is not aviation specific, it is described and modeled here in the context of aviation. Direct emissions from aircraft engines are propagated through to determine expected atmospheric concentrations. These concentration changes are used to calculate the change in the earth's energy balance and the expected impact this change has on temperature. From temperature change, socioeconomic and environmental changes and their subsequent damages to health and welfare are calculated. These damages are then monetized. As one moves down the impact pathway, uncertainty increases, but the usefulness of the information in generating effective policy also increases.

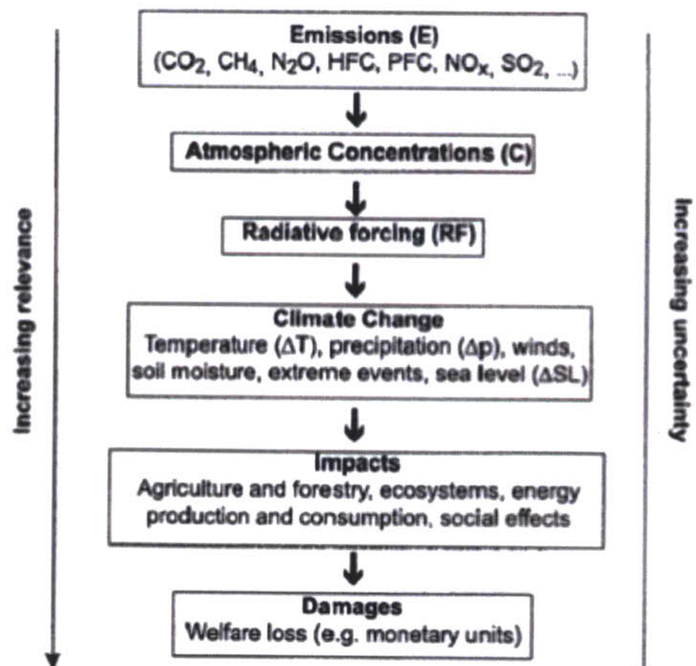

Figure 10. Impact pathway for climate change (Fuglestvedt et al. 2009)

The APMT-Impacts Climate Module estimates the physical and monetary impacts of CO_2 and non-CO_2 greenhouse gases from aviation using rapid, computationally inexpensive, reduced-order methods. This methodology allows for the timely analysis and comparison of several policy scenarios or the comparison of the benefits of a given policy scenario at several implementation timelines. The APMT-Impacts Climate Module uses for its approach the impulse-response model based on the work by Hasselmann et al. (1997), Sausen et al. (2000), Fuglestvedt et al. (2003), and Shine et al. (2005). The temporal resolution of the model is one year, while the spatial resolution is aggregated at the global mean level. The temperature spatial resolution can be further broken down into the global mean surface and the global mean deep ocean temperature in some cases. Long-lived CO_2 impacts are propagated from direct aviation emissions, while short-lived effects of soot, sulfates, aviation induced cloudiness and the short-lived impact of NO_X on ozone (NO_X-O_3 short) are scaled based on relative radiative forcing of the species to CO_2. Also included are the NO_X-CH_4 interaction and the associated primary-mode NO_X-O_3 effect (NO_X-O_3 long).

The APMT-Impacts Climate Module described here and used in the analyses of future chapters is Version 22, unless otherwise noted. The technical aspects of the code build upon the work in Marais et al. (2008), Jun (2008), Mahashabde (2009), and Dorbian (2010). The code design is based on the Version 20 revision of Wolfe and Ashok. In addition to the structural, speed, and computational footprint improvements discussed in the APMT-Impacts Climate Algorithm Design Document version 4 (Wolfe, Mozdzanowska and Waitz, 2010), the major contributions of this thesis include an investigation of the impact of background scenario that draws upon the work of Fan (2010), an update of the relative impacts of short-lived species, and a development of a new temperature-response function.

3.3.1 Emissions Modeling

Aircraft greenhouse gas emissions represent between 2-7% of background emissions. Thus, for modeling simplicity, aircraft emission policy changes can be estimated as having no impact on the underlying background scenario. Background scenarios are selected both from the IPCC SRES scenarios and the Stanford Modeling Group EMF scenarios (IPCC 2007 and IWG 2010). Background scenario CO_2 emissions are shown in Figure 11.

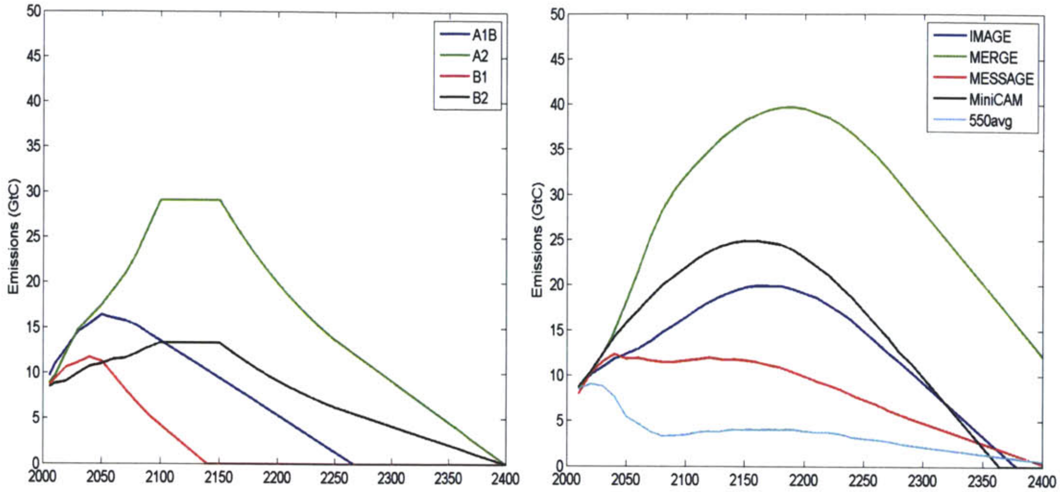

Figure 11. Extended SRES scenarios and EMF scenarios background emissions

The APMT-Impacts climate module simultaneously models a CO_2 background scenario and the same scenario minus the projected emissions from aviation. The marginal damages from aviation are taken as the difference between these two values. Aviation emissions are modeled as a pulse of emissions emitted at each year of a given policy. For CO_2 impacts, impulse response functions derived from complex carbon-cycle models are used to calculate atmospheric concentration changes, and superposition of pulses is used to determine temporal response from multi-year policies. The Bern carbon-cycle model expressed as the sum of a series of exponentials is the primary atmospheric concentration model utilized in APMT-Impacts climate (Marais et al. 2008).

The choice of background scenario for a policy analysis is not straightforward. The impact of the background scenario is dependent upon the time horizon, discount rate, and the policy lifetime to be examined. Furthermore, the choice of endpoint metric has an important impact from the background scenario. For instance, SRES Scenario A1B returns a median result for physical impacts, but because its corresponding GNP growth rate is so high, it provides the worst-case values for monetary metrics. The corresponding GNP growths are shown in Figure 12.

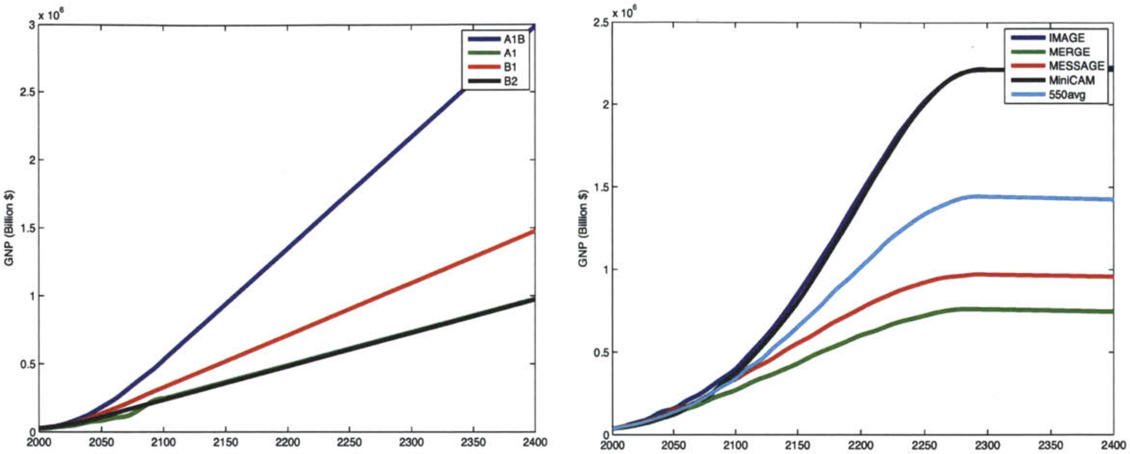

Figure 12. SRES and EMF background scenario associated GNP in billion $

Furthermore, strictly aligning choice of background scenario with policy assumptions may not be appropriate. For instance, Scenarios A2 and B2 represent potential pathways under the assumption of little to no significant global environmental policy action. Thus, it may seem logical to use one of these pathways to examine a business-as-usual case and either A1B or B1 to examine the impact of a strict environmental stringency. However, this would result in biased results. The SRES scenarios were developed as an ensemble of conditional cases representing a true scenario analysis. The down-selection of many model forecasts to these scenarios as representative concentration pathways (RCP) make them ill-suited for relative-likelihood projections relating to specific questions (Pitcher 2007). Furthermore, the adoption of strict environmental stringencies in the airline industry does not guarantee aggressive action across other industries.

3.3.2 Radiative Forcing Modeling

The next step down the emissions response pathway is radiative forcing imbalance. Radiative imbalance relates to CO_2 atmospheric concentrations through a logarithmic response relationship. From a given impulse, the resulting normalized radiative forcing, RF^*_{CO2} at time t can be calculated given the atmospheric CO_2 concentration at that time as expressed in Equation 5:

$$RF^*_{CO_2}(t) = \log_2\left(\frac{X_{CO_2(present)} + \Delta X_{CO_2}(t)}{X_{CO_2(1750)}}\right) \tag{5}$$

where the concentration of CO_2 in 1750 is 278 ppmv and the present-day concentration is taken from observations at Mauna Loa (Keeling and Whorf 2006). The RF is normalized such that $RF^*_{CO2} = 1$ for a doubling of CO_2 concentrations relative to 1750. The resulting RF change due to an aviation impulse of CO_2 can then be calculated for a distribution of the expected RF for a doubling of CO_2 (RF2XCO2).

The RF values of short-lived species (with the exception of NO_X) are calculated using the methodology described in Sausen and Schumann (2000). Relative radiative forcings as developed by Sausen et al. (2005) and updated in Lee et al. (2009) for short lived species are scaled to full flight fuel burn for future scenarios. Short-lived radiative forcing is estimated to last only for the year in which the species is emitted. APMT-Impacts assumes the impacts from soot, sulfates, water, and AIC are uncoupled. Because of the high uncertainty associated with AIC, the climate module calculates total impacts for all impacts including AIC and all impacts with cirrus only.

The RF of aviation NO_X emissions is more complicated. NO_X species do not have a well-defined gas-cycle model, thus NO_X impacts are modeled to follow current relative RF estimates from literature and scale linearly with forecasted NO_X emissions. To account for scientific and modeling uncertainties, APMT-Impacts climate utilizes RF values and species lifetimes from Stevenson et al. (2004), Wild et al. (2001), and Hoor et al. (2009). The RF lifetime of the primary NO_X -O_3 pathway is, for all three models, considered to last for only the year of emissions. The relative RFs and the species lifetimes for the NOx-CH_4 and the secondary NO_X -O_3 impacts are modeled as matched triplets; that is to say, a modeling run that utilizes the Hoor et al. NO_X -CH_4 relative RF parameter will also use the Hoor et al. NO_X -CH_4 species lifetime parameter.

Holmes et al. (2011) recently analyzed uncertainty in NO_X radiative forcing across a suite of models for all three NO_X forcing components as shown in Figure 13. The selection of models in APMT envelops the net steady-state radiative forcing of the models and the net CH_4 lifetime in Holmes et al. Although the relative long-lived CH_4 contribution from the model of Kohler et al. (2008) is greater than the representative models in APMT, the aviation NO_X lifetime in Kohler et al. (2008) is only 11.3 years, less than that of Stevenson et al. (2004) and Wild et al. (2001). Thus, the ensemble of models in APMT effectively captures the uncertainty presented in the models analyzed by Holmes et al. (2011).

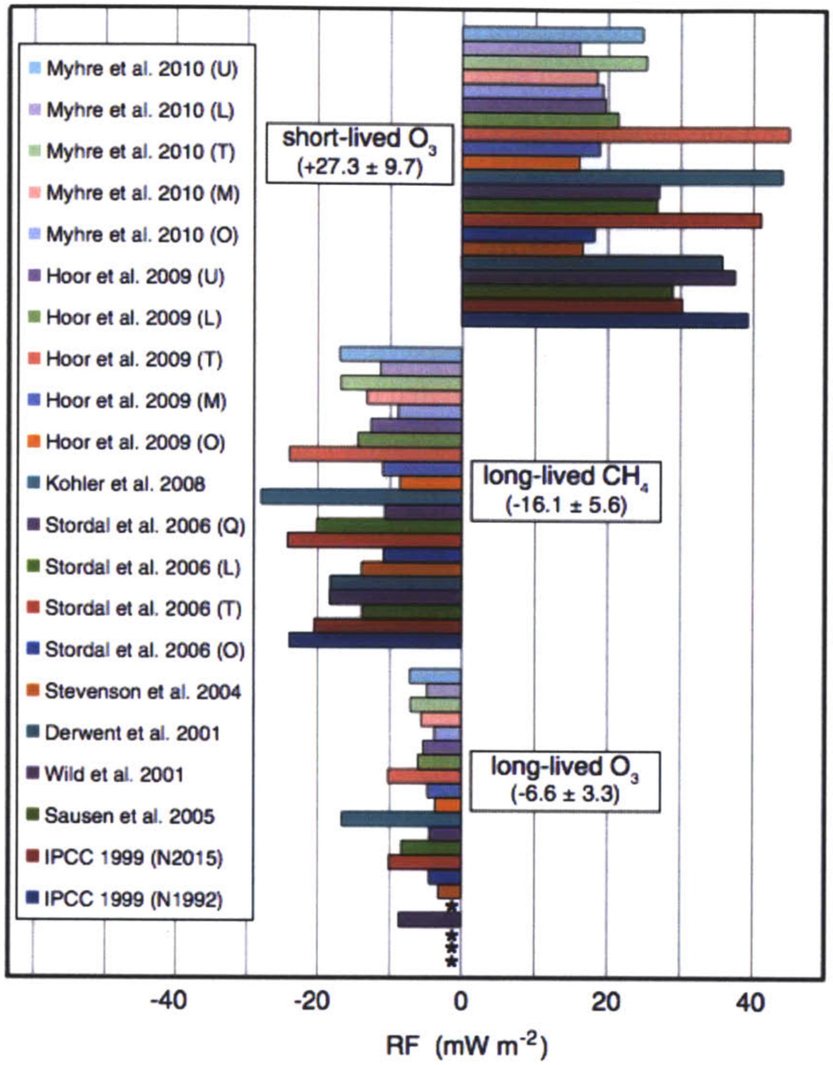

Figure 13. Suite of NO_X models RF component estimates (Holmes et al. 2011)

Substantial uncertainties remain in the field of aviation NO_X impacts. Furthermore, tertiary NO_X impacts on background forcing components and interdependences with other emissions species may exist. Potential Interdependencies not accounted for in the model include cooling from NO_X -Sulfate (Unger 2011 and Barrett et al. 2012 forthcoming) and a potential cooling from NO_X – Water vapor interaction (Myhre et al. 2010).

It is understood that different emissions species radiative forcing impacts may have different impacts on global temperature change. For instance, species such as contrails and NO_X-O_3 that can have continental or regional radiative forcing impacts may occur primarily over areas that have surface albedos greater than or less than the global average. This will result in a change in the balance of incoming and outgoing radiation not accounted for in a globally averaged RF metric. To this end, the efficacy concept has come into use. Efficacy is defined as the effective temperature response of a radiative forcing delta relative to the same delta from CO_2. Efficacies have been developed and used by the IPCC (2007), Hansen et al. (2005), and Weubbles et al. (2007). However due to parameter uncertainty, efficacies are not currently suggested for use in policy analyses (Weubbles et al. 2010). Thus, although APMT-Impacts climate has the capability for utilizing efficacies, it currently does not do so in its nominal lenses - efficacies are set to unity.

3.3.3 Temperature Response Modeling

The energy imbalance indicated in the radiative forcing leads to a change in earth's surface temperature. Although these impacts are not evenly distributed, an important benchmarking metric is the change in globally averaged surface temperature. Fully integrated earth-atmospheric-ocean models are computationally expensive, and are therefore not ideal for modeling large ensembles of policy stringencies. There are several accepted methods for estimating globally averaged surface temperatures, including direct calibration to more robust models, simple energy balance, and complex multi-box models. Examples of direct-calibration models can be found in Hasselmann et al. (1993, 1997) and Cubasch et al. (1992), and have been implemented to run in APMT to facilitate comparison with other models (Wolfe, Mozdzanowska, and Waitz, 2010). Three alternative models are described in detail below. Because APMT-Impacts analyzes a policy difference from a baseline, APMT minimizes the underlying model uncertainty. The fidelity of the policy minus baseline response is of greater importance than the robustness of the underlying model or submodel. Thus, the simple models described below are appropriate for APMT as they provide robust policy minus baseline that do not differ significantly from more complex hemispherical multi-box models while also providing significant gains in time and computational space.

Shine Temperature Model

The earth's heat balance can be described as follows (6):

$$Q \approx E \tag{6}$$

The underlying transient equation states that the incoming shortwave radiation (Q) is approximately equal to the outgoing longwave radiation (E). The incoming radiation can be thought of as a function of the mean solar irradiance and the coalbedo of the incidence surface. The outgoing thermal radiation is a function of temperature as related by the Stefan-Boltzman equation. Although these are approximately in balance, they are not exactly equal. Additional changes in atmospheric composition traps some of the longwave radiation creating an imbalance known as the greenhouse effect. This difference leads to a change in global energy balance as shown in (7).

$$\frac{dH}{dt} = Q - E \tag{7}$$

The change in heat can be related to the change in temperature and the heat capacity of the earth system. The Shine model assumes that the majority of the earth's heat intake can be approximated as occurring on a single time scale represented by the ocean mixed-layer (Shine 2005 and Fuglestvedt et al. 2003). Although land mass and the deep ocean also act as heat sinks either directly or through heat transfer from the ocean mixed-layer, these impacts are either negligible or occur on a millennial timescale that is not relevant for near-term policy analyses. The change in heat transfer can then be approximated as (8):

$$C\frac{d\Delta T}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda^*} \tag{8}$$

F is the global radiative forcing, the difference between incoming and outgoing radiation. λ^* is the climate sensitivity of the system normalized by the radiative forcing for a doubling of CO_2. Simplifying the model to assume a globally spatially uniform radiative forcing with a single climate sensitivity and one heat sink, the differential equation can be expressed as (9):

$$\Delta T(t) = \frac{1}{C}\int_0^t \Delta F(t')e^{\frac{t'-t}{\lambda^* C}}dt' \tag{9}$$

The mid-range Shine model used here assumes a median climate sensitivity of 3K with a triangular distribution from 2-4K as estimated by the IPCC 2007 report (IPCC 2007). The heat capacity of the climate system is taken as triangular distribution with a median of 4.41 x 10^8 J/Km^2 and boundaries of 1.897 x 10^8 J/Km^2 (Schwartz 2007).

The Shine model has a number of benefits. It is comprehensive of the climate system, but simple to use. The model is able to characterize broad uncertainties into two probabilistic variables, which can be used to provide bounds on the temperature-response. The model, however, does not take into account ocean upwelling and diffusion or temperature feedbacks on a variety of timescales. The model also assumes one globally-averaged climate temperature and one globally-averaged radiative forcing.

Raper-Wigley Temperature Response Model

The Raper-Wigley model described below is adapted from the work of Raper et al. (2001) and Wigley and Schlesinger (1985). It assumes a combined atmosphere ocean model. The ocean is modeled as a two-box system with a deep ocean and a mixed-layer ocean in thermal equilibrium with the above atmosphere. A visual representation of the model is shown in Figure 14.

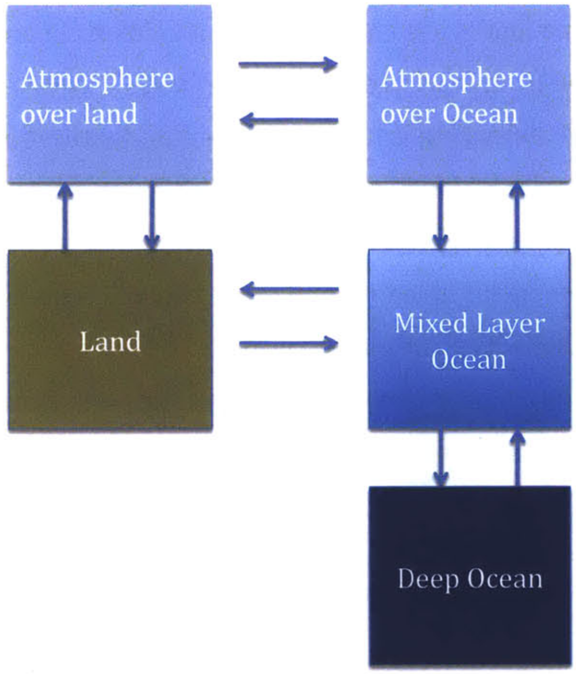

Figure 14. Two-Box ocean model overview

The Raper-Wigley model further simplifies this system by assuming that land can be assumed to have no heat capacity. The underlying equation updated from Shine is therefore given in (10).

$$C\frac{d\Delta T}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda^*} - \Delta L \qquad (10)$$

L is the heat flux at the bottom of ocean mixed-layer. The atmosphere is assumed to be in thermal equilibrium with the underlying mass. The exchange of heat among the boxes is represented by air-land (k) and air-sea (k_{as}) heat exchange coefficients and thermal diffusivity between the deep and mixed-layer ocean (κ). Thus, the coefficients of the differential equation can be further broken down by components. This method allows uncertainty to be characterized by compounded coefficients as in Shine or by their underlying parameters as shown in Table 5.

Table 5. Raper-Wigley Model Parameters

Parameter	Definition	Derivation
C	Specific Heat of Seawater	$C = \lambda \rho c h$
γ	Climate feedback scaling ratio (a function of the rate of transfer among air, land, and sea)	$\gamma = \frac{(1-f)(k+\lambda f)}{k+\lambda f(1-f)} + \frac{\lambda}{k_{as}}$
ΔL	Heat flux at the ocean mixed-layer and deep ocean boundary	$\Delta L = \mu C \frac{\Delta T}{\sqrt{\tau_d t}}$
τ_f	Characteristic time of mixed layer heat uptake	$\tau_f = \frac{\rho c h}{\lambda}$
τ_d	Characteristic time of heat exchange between deep-ocean and mixed-layer.	$\tau_d = \frac{\pi h^2}{\kappa}$

Here h is the mixed-layer depth, ρ is the average seawater density, f is the fraction of the earth covered by ocean, and c is the specific heat of seawater. In the climate feedback scaling ratio, the λ/k_{as} term is assumed to be negligible as the climate feedback (λ) is much less than the air-sea uptake. μ is a constant of integration that is a factor of the form of the radiative forcing and can range from 1.4 for step functions to 2.4 for exponential radiative forcing growth. The temperature-response function can then be estimated using a forward-time step approach as shown in (11).

$$\Delta T(n+1) = \left[\frac{\Delta t \Delta F(n\Delta t)}{\rho c h} - \Delta T(n)\Delta t\left\{\frac{1}{\tau_f} + \frac{\mu\gamma}{\tau_d \Delta}\right\}\right]\frac{1}{\gamma} + \Delta T(n) \qquad (11)$$

CICERO Temperature Response Model

The CICERO model is based on the work of Berntsen and Fuglestvedt (2008), which is itself based on the model of Schneider and Thompson (1981). The CICERO model uses a deep ocean component to simulate the long-term response, but unlike the Raper-Wigley model, the CICERO model separately models the temperature response of the deep ocean. The CICERO model assumes two interactions between the two ocean layers: turbulent mixing at depth and heat transport. The layers are assumed to maintain constant volume, so advective massive flux into the deep layer is equal to the advective flux from the deep layer into the ocean mixed layer. A simplified diagram of the model is presented in Figure 15.

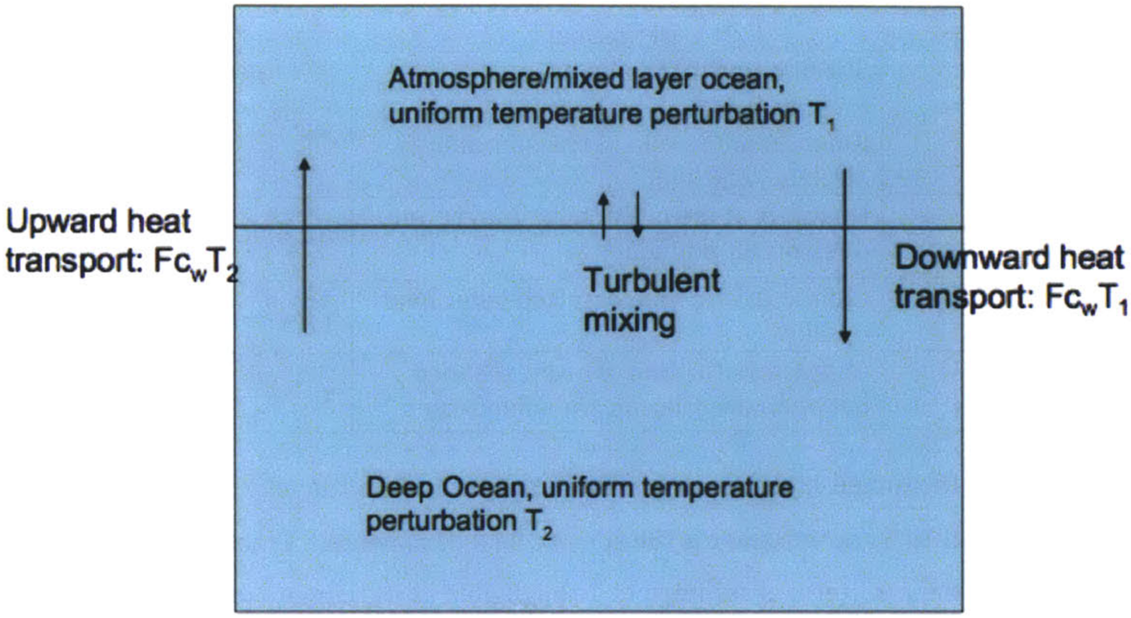

Figure 15. Illustration of the Cicero box model (Berntsen and Fuglestvedt)

Berntsen and Fuglestvedt model the temperature response of the ocean-atmosphere as a system of two simultaneous differential equations. The first equation models the temperature response of the atmosphere and mixed layer and the second equation models the temperature effect of the deep ocean whereas the Raper-Wigley model treats the deep ocean as a heat sink. The differential equations are as follows (12 and 13):

$$\frac{\partial T_1}{\partial t} = \frac{Q(t)}{C_1} - \tau^{-1}T_1 - \alpha_1(T_1 - T_2) \tag{12}$$

$$\frac{\partial T_2}{\partial t} = \alpha_1(T_1 - T_2) \tag{13}$$

where:

$$\alpha_1 = \frac{c_w}{C_1}\left(F + \frac{K_Z \cdot \rho}{\Delta z}\right) \text{ and } \alpha_2 = \frac{c_w}{C_2}\left(F + \frac{K_Z \cdot \rho}{\Delta z}\right)$$

As published in Berntsen et al., the parameters are utilized in the model deterministically. Although this gives a good indication of the best-estimate temperature response, it provides little insight into the uncertainty inherent in the model. Attempts to tune the model to current uncertainty values are discussed later. The key parameters and their as-published values are as follows:

Table 6. CICERO model parameters and as-published values

Parameter	Definition	As-Published Value
F	Advective mass flux of water from boundary layer to the deep ocean. It is assumed that this value is directionally symmetric and that F is constant in time and over all ocean and atmospheric temperature ranges.	1.23*10^-4 $kg/m^2/s$.
K_z	Diffusion coefficient for turbulent mixing of heat between the two ocean model boxes.	4.4*10^-5 m^2/s
Δz	Depth at which turbulent mixing occurs.	1000 m
C_1	Effective heat capacity of ocean mixed layer, assumed to be about 70m.	2.94*10^8 $J/K/m^2$
C_2	Effective heat capacity of the deep ocean, assumed to be about 3000m.	1.26*10^10 $J/K/m^2$
c_w	Specific heat of liquid water	4.2*10^3 J/K/kg
τ	Timescale of climate impacts (C_1*λ)	2.646*10^8 s

As-Published Parameter Comparison

The following section presents the 300-year time history profiles of the as-published values of the three temperature models. This analysis is used to assess the appropriateness of the temperature models. Probabilistic modeling was performed using a 10,000 run Monte Carlo simulation to account for scientific and modeling uncertainty.

The Raper-Wigley model as-published values contain some probabilistic distributions, such as the most-likely range of 1.7-2.4 for μ and the integration coefficient, which is input as a linear probabilistic distribution between the endpoint values. However, several parameters, such as the heat exchange coefficients, are only given probabilistic values that do not account for scientific or modeling-assumption induced uncertainty.

The CICERO model only provides deterministic values for key parameters. All uncertainty represents uncertainty in underlying radiative forcing.

The APMT-Impacts climate module was run with all three temperature-response models to measure the impacts of burning fuel equivalent to a 1-kilotonne pulse of CO2.

The results are shown in Figure 16. The CICERO model and Shine Model have similar temperature responses for the first several decades with the CICERO model indicating a more rapid temperature response. The long-term trend shows a lower magnitude temperature change for the CICERO. This is consistent with a comparison between the Shine model and the several more complex multi-box models shown in Figure 17. This result indicates that the CICERO model may more closely represent results from complex Atmosphere-Ocean global climate models. The Raper-Wigley model appears to under-represent total pulse induced-temperature change.

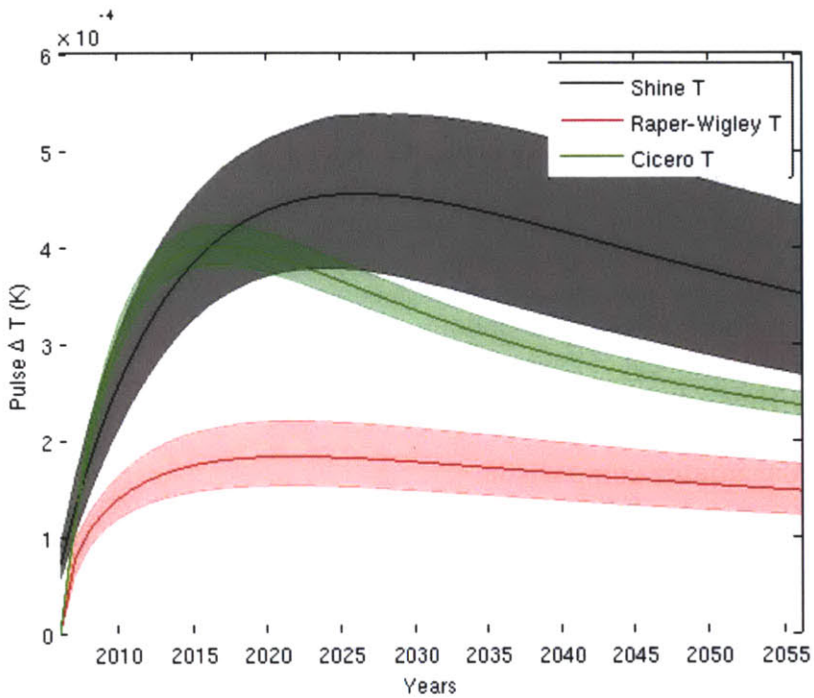

Figure 16. Temperature-response models, 1 kTonne pulse

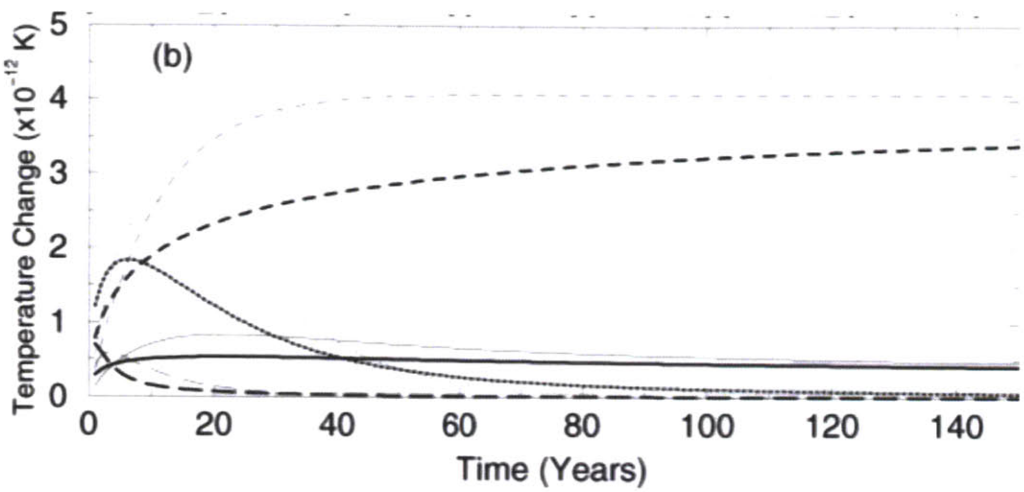

Figure 17 Shine and complex temperature-response function comparison
Thin lines are Temperature changes due to a 1-kg pulse of emissions for a variety of species as determined by the single time constant method of Shine et al. Thick lines are the same responses as determined using a complex, multi-box, energy balance model.

APMT-Impacts Climate is most applicable when measuring the impact of a policy scenario relative to a business as usual baseline projection. The three temperature models were run on a policy and baseline scenario drawn from the CAEP 8 NO_X Stringency analysis. Scenario 10, which presented the most stringent NO_X reduction and the most severe environmental costs, was used for these runs. The policy-baseline physical impacts are shown in Figure 18. The paired-Monte Carlo technique is used to rigorously propagate the model uncertainties to their effects on estimating policy-baseline results. The effect of underlying model uncertainty on predicting a "delta" is smaller than for predicting the baseline response. Thus, the policy-baseline results show that the choice of temperature-response model is less influential. The time-integrated temperature change was calculated for all three models at three different time windows starting at the year of policy introduction (2016). The results are shown in Table 7.

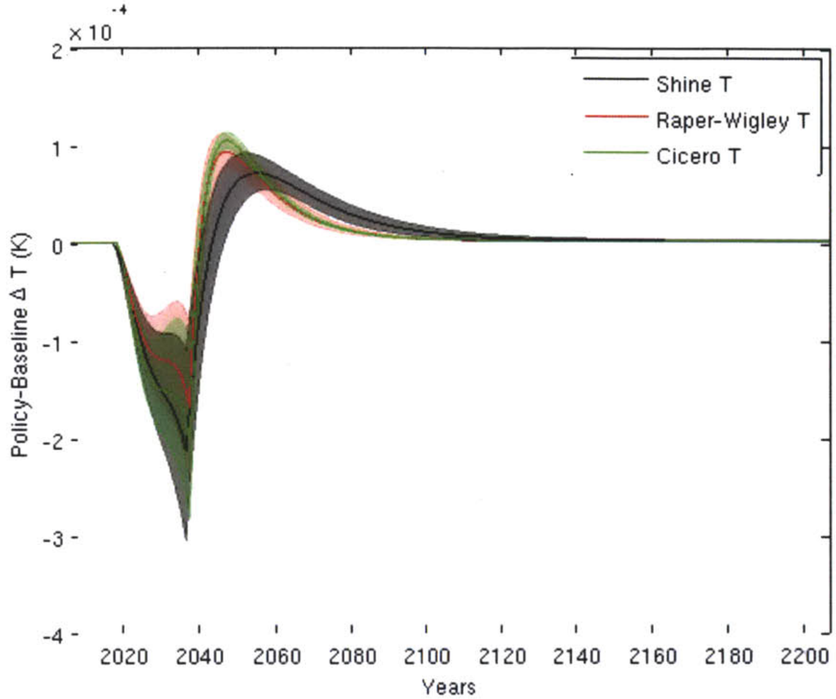

Figure 18. NO_X Stringency policy-baseline physical climate impacts for several temperature-response models

Table 7. Time-integrated temperature change policy - baseline for year 2016

	20		100		500	
Integrated dT APMT	-0.0024		-0.0004		0.0003	
Integrated dT Raper-Wigley	-0.0017		0.0000		0.0003	
Integrated dT CICERO	-0.0025		-0.0002		0.0002	
APMT (10 90)	-0.0015	-0.0033	-0.0015	0.0011	-0.0008	0.0019

When results are converted to monetary metrics, the influence of the choice of temperature-response model is further diminished. Figure 19 shows that the mean results of all three models fall within the 10-90% expected response from the Shine model throughout the lifetime of climate impacts.

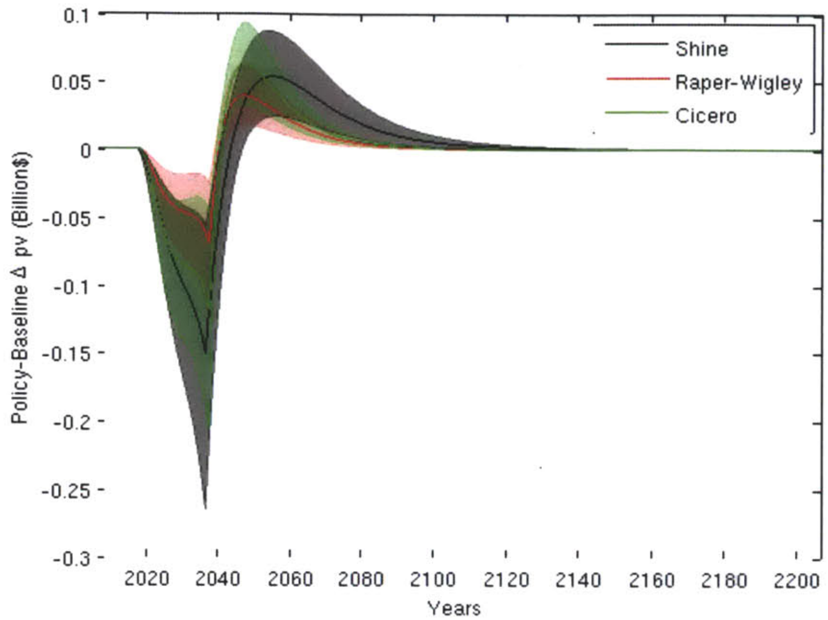

Figure 19. Present value vs time for midrange lens of several temperature-response models

Thus, both the CICERO model and the Shine model appear appropriate for use in APMT. The CICERO model represents an improvement over the Shine model by representing the long-term response of the deep ocean without leading to an extreme increase in code complexity. Although the policy-baseline results for a midrange lens are within the range of expected values, the Raper-Wigley model is less appropriate due to the fact that it does not account for long-term heat loss to the deep ocean. If the CICERO model is to be used in policy analysis, however, it must be calibrated to indicate the current understanding of scientific and modeling uncertainty of larger more complex models.

Calibration to IPCC Results

The Shine model temperature response function has a number of benefits: It is easy to assess the sensitivity and uncertainty of the model based on three key drivers: the climate sensitivity, the radiative forcing for a doubling of CO_2, and the ocean response. The climate sensitivity and radiative forcing together determine the overall temperature response of the model and the climate sensitivity and ocean response, modeled as a single system heat capacity, determine how rapidly the temperature changes. This simplicity makes the model easier to tune and calibrate to other models. An objective of the APMT-Impacts module is that it represents the range of results of more complex models in the literature.

The CICERO temperature response model has more variables, each with a unique impact on the temperature result of the model. The equilibrium temperature of the CICERO model is determined by the climate sensitivity. Figure 20 shows the CICERO response for a background scenario of a constant doubling of CO_2 relative to pre-industrial levels for a variety of climate sensitivities holding all other variable constant. The results of the midrange Shine models for the same background scenario and climate sensitivities are shown for comparison. As seen in the figure, the CICERO model approaches the equilibrium temperature of the Shine model, but the larger the climate sensitivity, the longer the model takes to reach equilibrium. For the upper bound on climate sensitivity of 4.5 K, the model takes several thousand years to reach equilibrium due to the large thermal mass of the deep ocean.

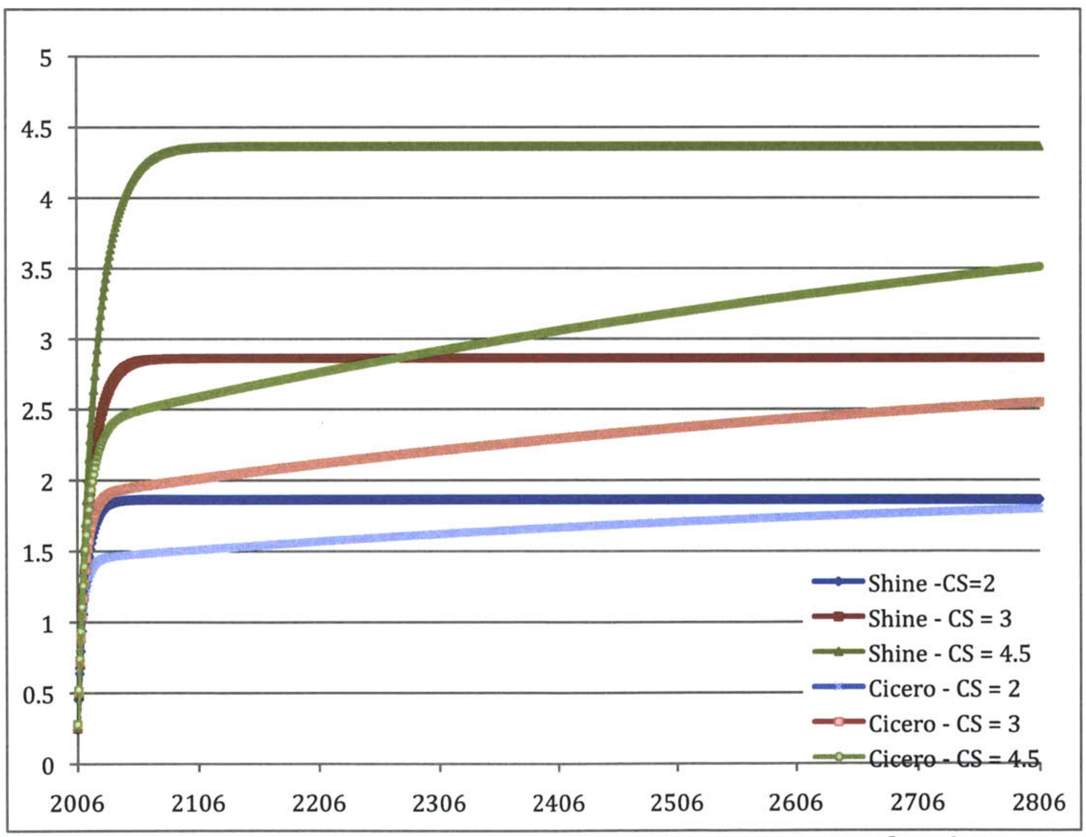

Figure 20. Effect of climate sensitivity on temperature-response functions

Climate sensitivity and mixed-layer ocean heat capacity are parameters in common between the two models. For these, it is appropriate to use the same values and triangular distributions for both models. These values are shown in Table 8.

Table 8. Parameters in common between models and their distributions

Parameter	Source	Distribution
Climate Sensitivity (λ)	*IPCC 4th Assessment*	3 [2 – 4.5] K
Mixed-Layer Ocean Heat Capacity (C or C_1)	*Schwartz 2007*	4.41 [2.53 – 6.31] *10^8 J/K/m^2

Key parameters in the CICERO model have varying levels of scientific uncertainty. For instance, the specific heat of ocean water is generally well understood. Although there may be some variation depending on salinity, impurities, depth, and pressure, this number will have less uncertainty and variation, and can be entered probabilistically as the as-published value.

Several ocean diffusivity constants are provided in literature. Wigley (1985) and Dickinson (1981) both estimate diffusivity to be at 0.0001 m^2/s, whereas the as-published CICERO model utilizes 4.4*10^-5 m^2/s (Berntsen and Fuglestvedt 2008). As these values bound the range of other estimates, a uniform distribution between these two numbers was utilized for diffusive heat transport.

The three other main parameters, advective flux, deep ocean heat capacity, and mixing depth, are uncertain and variable. Furthermore, the use of single variables without feedbacks for these parameters represents a modeling assumption that may need to be accounted for by artificially lowering or raising the parameter value. To attempt to indicate the uncertainty range found in the IPCC, these variables were all modeled as triangular distributions with the best-guess value being the CICERO as-published value, and the high and low boundaries being a factor of two away. Low lens values are all the low boundary values for all model variables and high lens values are the high boundary values for all variables.

Figure 21 and Figure 22 compare the IPCC SRES Scenario temperature profiles for 3 background scenarios. The IPCC presents the multi-model average of expected temperature change over time with a range of one standard deviation. The midrange lens +/- 1σ APMT output ranges are shown for both the CICERO and Shine temperature models over the same length of time. As shown, the Shine model somewhat over predicts the temperature response while the CICERO model more closely predicts the background scenarios with lower total warming while under-predicting the more carbon intensive scenario. The 10-90% ranges for Shine are larger than the +/- 1 standard deviation ranges of the multi-model averages from IPCC thereby possibly over representing uncertainty whereas the CICERO model behaves oppositely – under representing the range of the more complex climate models.

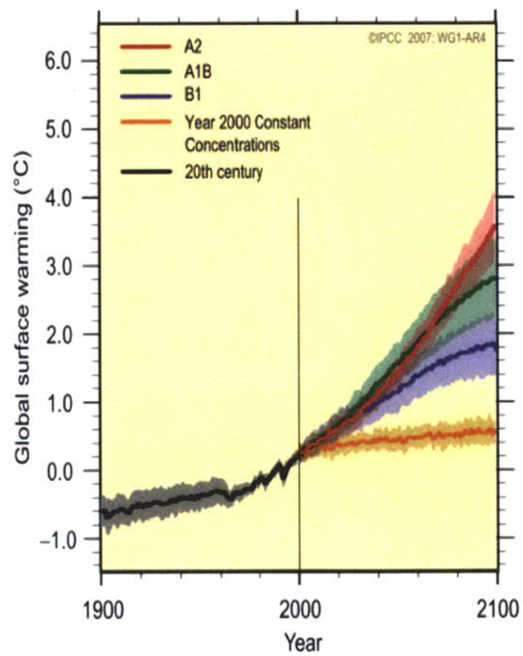

Figure 21. IPCC SRES scenario model-averaged temperature profiles (IPCC 2007)

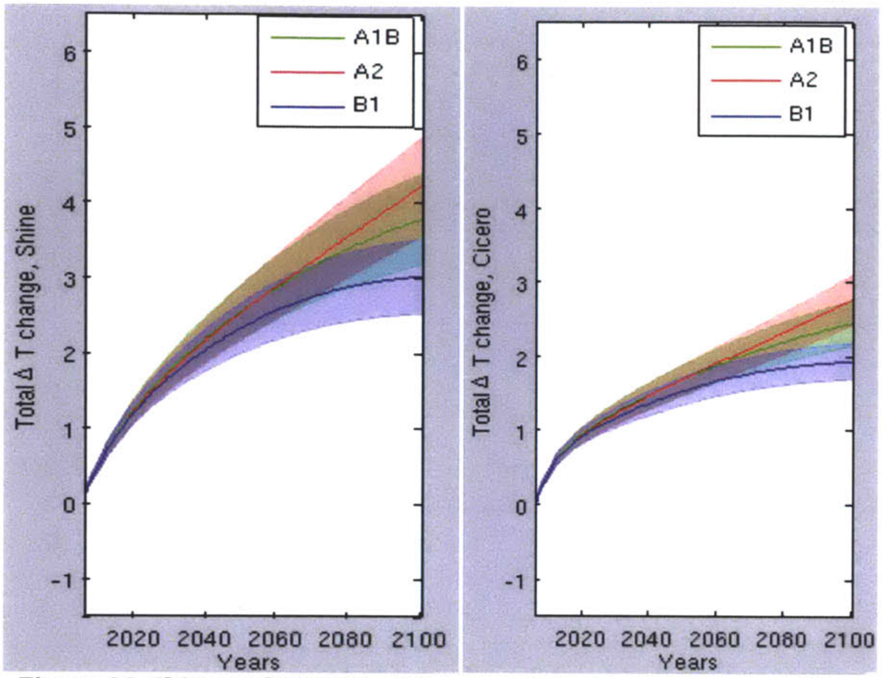

Figure 22. Shine and CICERO midrange +/- 1σ temperature profiles

In addition to the multi-model average temperature profiles, the IPCC presents a range for the most likely temperature change in the year 2100 for a variety of background scenarios. These most likely range calculations are based on the multi-model AOGCM averages shown above as well as from a hierarchical analysis of independent models and observational constraints (IPCC 2007). These temperature ranges in the year 2100 are compared among the IPCC, Shine model response, CICERO model as-published response, and the calibrated CICERO response from APMT shown in Figure 23. For this comparison, the ranges presented from APMT are the 10-90th percentiles, as 10-90th percentile intervals have been used to present expected outcome in previous policy analyses.

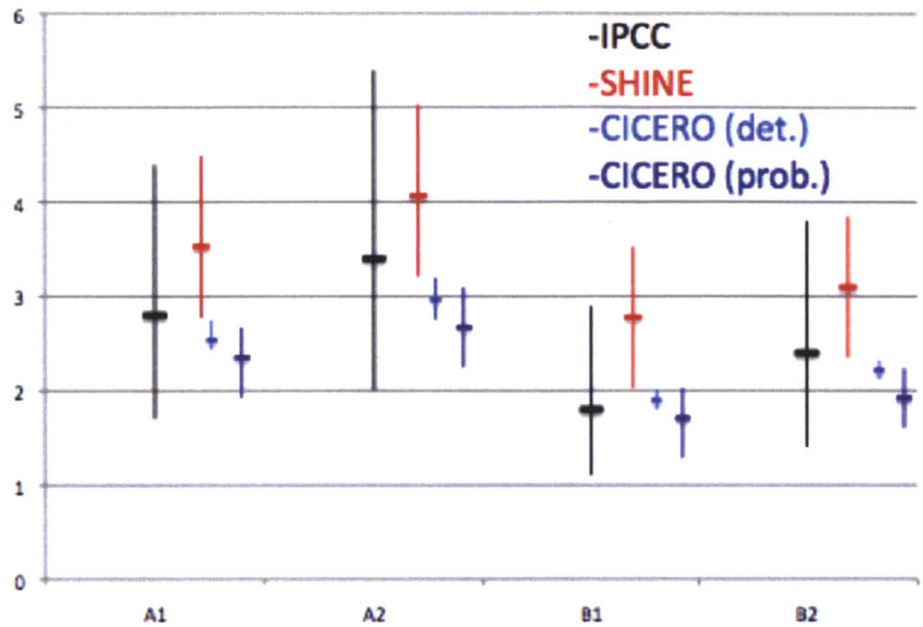

Figure 23. IPCC most-likely temperature values compared to midrange lens 10-90% range values for several temperature-response models

The low, mid, and high lens average temperature responses in the year 2100 are compared to the IPCC most-likely temperature response ranges in Figure 24. The results shown here indicate that the calibrated CICERO model closely approximates the temperature response for the first 100 years for a variety of future scenarios with less bias than the Shine model. Utilizing the lens analysis, the full range of uncertainty presented in the IPCC can be accounted for in both models.

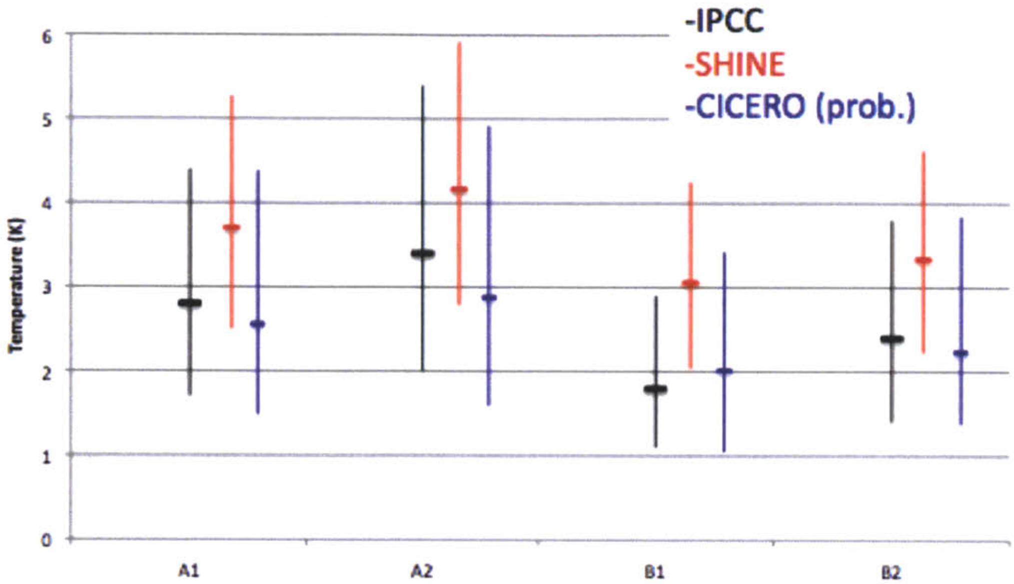

Figure 24. IPCC most likely temperature value range compared to high, midrange, and low lens mean values for several temperature-response functions

In conclusion, both the Shine temperature-response model and the CICERO temperature-response model developed and calibrated here approximately represent the expected temperature response for a given change in radiative forcing when applied in APMT-Impacts Climate. The model developed here based on CICERO provides an improvement to the temperature profile by including the interaction of the deep ocean and the ocean-mixed layer without significantly increasing computational time or complexity. This leads to a smaller bias relative to the range of results of more complex models. Future work will focus on better understanding the uncertainty of key parameters while continuing to calibrate the model to match the current scientific understanding of the earth-ocean system.

3.3.4 Physical and Monetary Damage Modeling

APMT utilizes the non-linear Dynamic Integrated Climate Economy (DICE) 2007 damage functions to monetize temperature effects (Nordhaus 2008). This aggregate damage curve is built from estimates of individual damage curves for twelve regions. The function includes losses from damages to agriculture, sea-level rise, adverse health impacts, nonmarket damages, and estimates of potential costs of catastrophic damages. The output of DICE 2007 is damage as a function of percentage of GDP. DICE 2007, like many comprehensive damage functions, is the subject of criticism for failing to monetize some damages such as loss of resource endowment or damage to fragile ecosystems as well as for monetizing the "inherently priceless" in arbitrary ways (Ackerman and Finlayson 2006). In the RICE 2010 and DICE 2010 models, the damages are disaggregated into temperature damages and damages from sea level rise (Nordhaus 2010).

Monetary damages are computed by multiplying damages by projections of GDP that are tied to the choice of background scenario. APMT uses a range of constant discount rates to account for the valuation of future damages. Nominally, these discount rates are 2%, 3%, and 5% or 7%. The OMB requires that analyses performed for federal agencies utilize discount rates ranging from 3% to 7% for near term impacts and recommends that a wider range of discount rates be used for assessing damages of future generations (OMB 2006).

3.3.5 Climate Model Inputs Summary

A summary of important climate module parameter values utilized in nominal lenses is provided in Table 9. A complete discussion of the use of Lenses in policy analysis is discussed in Section 4.4.

Table 9. Climate module inputs summary

Climate Assumptions	Low Lens (Best Case / Low Impact)	Mid Lens	High Lens (Worst Case / Conservative)
Climate Sensitivity	2 K	Triangular distribution [3, 2-4.5] K	4.5 K
NO_X – related effects	Stevenson et al. (2004)	Discrete Uniform distribution: Wild, Stevenson, Hoor (2009) values.	Wild et al. (2001).
Short-lived effects relative RF [AIC, Sulfates, Soot, H2O, contrails]	[11, -29.3, 0.56, 0.39, 5.4] mW/m^2	Triangular distribution [(11,33,87), (-29.3, -4.8, .79), (.56, 3.4, 20.7), (0.39, 2.8 20.3), (5.4, 11.8, 25.6)] mW/m^2	[87, 0.79, 20.7, 20.3, 25.6] mW/m^2
Background Scenario	A2	B2	A1B
Damage Coefficient	5th Percentile DICE	Normal Distribution DICE-2007	95th Percentile DICE
Mixed Layer Heat Capacity	2.53e8 $J/(K * m^2)$	Triangular Distribution [4.41, 2.53-6.31] 10^8 $J/(K * m^2)$	6.31e8 $J/(K * m^2)$
Advective Flux	2.46e-4 $kg/(m^2 * s)$	Triangular Distribution [1.23, 2.46-0.62] 10^{-4} $kg/(m^2 * s)$	6.2e-5 $kg/(m^2 * s)$
Diffusion	1e-4 m^2/s	Uniform Distribution 4.4-10 10^{-5} m^2/s	4.4e-5 m^2/s
Deep Ocean Heat Capacity	2.52e10 $J/(K * m^2)$	Triangular Distribution [1.26, 6.39-25.2] 10^9 $J/(K * m^2)$	6.3e9 $J/(K * m^2)$
Mixing Depth	500 m	Triangular Distribution [1000, 500-2000] m	2000 m

The APMT-Impacts model has several key limitations to its use. The model addresses climate change on a global spatial scale that does not capture regional variations in temperature change or welfare. The aggregation makes estimating damages on a regional scale difficult and potentially inappropriate, and the global scale does not capture the localization of short-lived species. Furthermore, although the model uses probabilistic radiative forcing and temperature response functions tuned to expected temperature changes from the IPCC, APMT-Impacts uses a simple deterministic atmospheric carbon model. While this model has been validated and widely used, it may provide lower fidelity carbon concentrations than more complex carbon models. The expected impact on monetized damages, however, is small. APMT-Impacts does not consider feedbacks in the climate system or in the global economy. These potential feedbacks may enhance or mitigate the associated aviation climate impacts. APMT-Impacts addresses the impacts of each emissions species separately, thereby not accounting for interactions among different chemical and physical mechanisms.

APMT is only recommended for use for full-fleet operational analyses. APMT is not appropriate for significant changes in flight routing or partial-fleet analysis due to the spatial-dependence of short-lived species. Finally, climate impact estimation in APMT implicitly assumes that future operational changes involve no significant changes in flight routes. APMT-Impacts Climate Module can be adjusted for fleet-wide changes in fuel, but it is not currently capable to address supersonic aircraft.

4 APMT-Impacts CAEP 8 NO_X Stringency Analysis

This chapter shows how APMT can be used to aid real-world policy decision-making processes by presenting the results of an analysis to inform the US position on a proposed ICAO-CAEP NO_X emissions stringency. The information presented in the following chapter closely follows the structure and content of Mahashabde et al. (2011). The analysis performed here builds from the preliminary work described in Mahashabde (2009) and represents original research that is a major contribution of this thesis. The work from this chapter was included in the formation of an Information Paper submitted by the US to the CAEP/8 meeting.

4.1 NO_x Stringency Policy Background

ICAO has regulated aircraft NO_X emissions from the 1980s to improve air quality in the vicinity of airports with increasingly stringent standards over the years for engines with a thrust rating of greater than 89kN. The standards control the engine NO_X characteristic or Dp /Foo, which is the ratio of NO_X emissions over the landing-takeoff cycle normalized by the maximum takeoff thrust rating for the engine. In 1981, the ICAO Committee on Aviation Engine Emissions (CAEE) adopted a NO_X efficiency standard. Standards have increased in stringency in the following three decades. The CAEP/2 meeting went beyond the first standard by increasing stringency by 20%, while grandfathering engines certified under the CAEE standard. At CAEP/4, there was an agreement to a further reduction in NO_X 16% below the CAEP/2 standard for all engines certified in 2004 or later. The latest NO_X standard was set at the 6th meeting of the CAEP in 2004 where the NO_X standard was increased by 12 percent as compared to CAEP/4 for engines manufactured after December 2007. The change in stringency varies with the overall engine pressure ratio (OPR) and thrust rating (Foo), with an allowance for engines with higher OPR values to emit more NOx.

One of the outcomes of the CAEP/6 meeting was an agreement to consider more stringent engine NO_X emissions standards in the eighth meeting of the CAEP in 2010 and to look at stringency requirements for both large and small engines. A substantial effort was dedicated to the evaluation of more stringent NO_X policy options and improvements in the decision-making practices and analyses for evaluating these policies. A short overview of some of the major developments from the NO_X reduction effort follows:

- Establishment of the Modeling and Database Task Force (MODTF) at the 7th CAEP meeting in 2007 to facilitate the evaluation of candidate models for analyses that will be required as a part of the work program for the 8th meeting of the CAEP. The outgrowth of the MODTF is the Modeling and Database Group (MDG).
- NO_X stringency analysis employed several different models across different impact spheres. A dry run of policy implications were tested through the development of the NOx Sample Problem, which examined a subset of potential stringencies and implementation years and a rough estimate of costs for scoping.
- Modeling of tradeoffs between emissions and noise by capturing the impact of fuel burn and noise penalties associated with some of the NO_X stringency options.

4.2 NO_X Stringency Scenarios

The CAEP/8 NO_X proposed scenarios range from 5% to 20% increases in stringency relative to CAEP/6 standards in increments of 5%. Stringency is applied to three categories of operation: small engines, large engines, and the slope of the stringency limit when plotting Dp/Foo as a function of the overall engine pressure ratio for large engines. The stringency limit for combined engines is the same as the stringency limit for large engines in all scenarios analyzed. The stringencies analyzed are shown in Table 10. Furthermore, implementation years of 2016 and 2012 were proposed for each stringency scenario. Only 2016 implementation years are examined here. For a sample comparison of stringencies with different implementation years, see Mahashabde (2009).

Table 10. CAEP/8 NO_X stringency scenarios (ICAO 2009b)

Scenario	Small Engine (26.7 kN - 89 kN Foo)	Large Engine	Slope >30 OPR
1	-5%	-5%	2
2	-10%	-10%	2.2
3	-10%	-10%	2
4	-5%	-15%	2.2
5	-15%	-15%	2.2
6	-5%	-15%	2
7	-15%	-15%	2
8	-10%	-20%	2.2
9	-15%	-20%	2.2
10	-20%	-20%	2.2

4.3 Scenario Forecasting

To understand the cost-benefit of a proposed stringency, the impact of each stringency on aircraft technology, airline fleet, and industry operations must be modeled for the lifetime of the stringency. The economic costs and the environmental benefits are then the difference between the state after an imposed stringency and the state after a background (or business as usual) case. It is, therefore, important to define the policy lifetime. For the NO_X Stringency analysis, per ICAO-CAEP practice, the lifetime of the policy is assumed to be 30 years. This does not imply that the aviation industry is modeled to end after 30 years; however, it assumes that in 30 years the impact of the stringency policy will no longer be a driving factor in industry costs or operational changes. It is helpful to view the policy as being technologically and operationally forcing; the stringency forces changes to the fleet mix and operations for thirty years, after which the background trend in technological change will be the primary driver. It is important to note that the timescale of the policy is not necessarily the same as the timescale of the environmental benefits or disbenefits. For instance, with climate change impacts, the influence of CO_2 from a change in fuel burn throughout the lifetime of the policy can have a lasting impact for centuries beyond the end of the policy timescale.

Of importance for this analysis are the forecasts for noise and emissions over the policy lifetime and the forecast of the proposed industry costs. Working Groups 1 and 3 within CAEP provided underlying inputs that enabled the modeling of environmental and economic impacts of the different policy options. These inputs included information on existing engines affected by different stringency levels, the engine emissions databank with data on emissions indices, the aircraft noise and performance database, the fleet growth and replacement database, the Campbell-Hill database with aircraft noise and emissions certification data and technology response data that quantified tradeoffs among NO_X emissions, fuel burn, noise, and costs. The Modeling and Database Taskforce (MODTF) primarily performed the noise and emissions modeling for the NO_X stringency analysis. The Modeling and Database Group (MDG) replaced MODTF after the CAEP/8 meeting (ICAO 2010). Forecasting for technological and operational changes starts with the Common Operations Database (COD), a database of detailed operational information for a starting year (2006). The COD includes data on roughly 25 million passenger flight movements for the operational starting year based on information from the Enhanced Traffic Management System (ETMS) from the FAA, the Enhanced Traffic Flight Management System from EUROCONTROL and the International Official Airline Guide's 2006 schedule (ICAO 2009a).

Six representative weeks are taken from the COD and scaled to represent a full year of operations. From there, modelers projected future fleet and operations using the AEDT Fleet and Operations Module (FOM), taking into account FESG fleet forecast, FESG Terminal Area Forecasts for traffic, and aircraft purchases, replacements, and retirements. Future technology responses were modeled for stringency cases assumed that all in-production aircraft-engine combinations that fail to meet compliance with the increased stringency will either undergo design modifications or will not enter into the future fleet. CAEP Working Groups 1 and 3 provided information on the necessary technology and design response to meet compliance. Three different categories of "Modification Status" (MS) levels were prescribed for necessary technology changes. The three MS levels are: MS1, minor changes; MS2, scaled proven technology; and MS3 new technology. Only MS3 technologies represent radical design changes. To account for technology uncertainties, MS3 technologies were modeled to have a 0-0.5% fuel burn penalty. The cost-benefit analysis was performed for stringencies both utilizing and ignoring this penalty (ICAO 2009b).

Noise was modeled using the AEDT/Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA) version 7.0. AEDT/MAGENTA provides 55, 60, and 65 dB DNL noise contours for a selection of worldwide airports. Due to domain restrictions in air quality modeling, results for this analysis are for US operations only. Furthermore, noise emissions were modeled for only one stringency (Stringency 10) as shown in Figure 25.

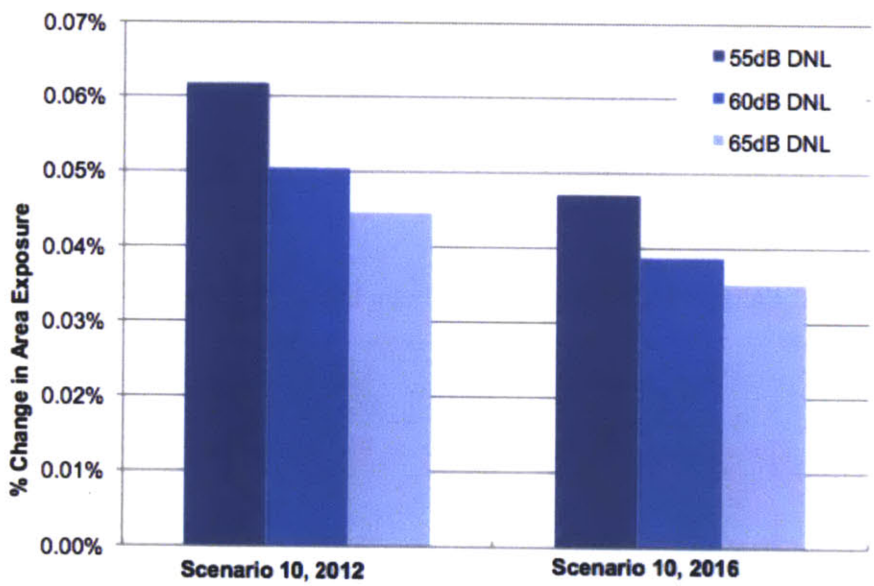

Figure 25. CAEP/8 NOx Stringency noise emissions area exposure difference from baseline

Emissions modeling for air quality (AQ) impacts are provided by the AEDT/Emissions and Dispersion Modeling System (EDMS) (CSSI 2007). These emissions represent ICAO times-in-mode (TIM) for taxi, takeoff, climb-out, and approach segments performed below 3000 ft above field level. Emissions relative to baseline for CO_2 and NO_X are shown in Figure 26 and Figure 27. In addition to CO_2 and NO_X, the APMT-Impacts Air Quality RSM takes SOx and black carbon as inputs. The domain of the RSM is the continental US, so only US emissions are considered. A comparison of modeling results for performance based and

TIM NO_X emissions indicated an anomaly of increased NO_X emissions relative to a baseline for small engines despite an increase in NO_X reduction stringency (ICAO 2009c). Small engine NO_X emissions accounted for less than 1% of total fleetwide emissions, and were therefore ignored for this cost-benefit analysis.

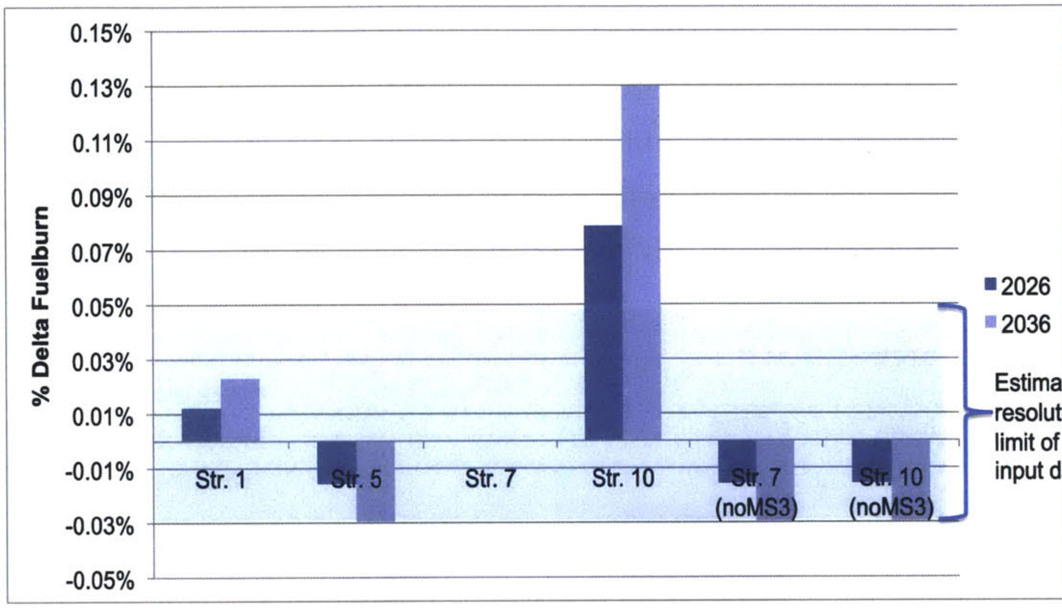

Figure 26. CAEP/8 NO_X Stringency fuel burn below 3k ft difference from baseline

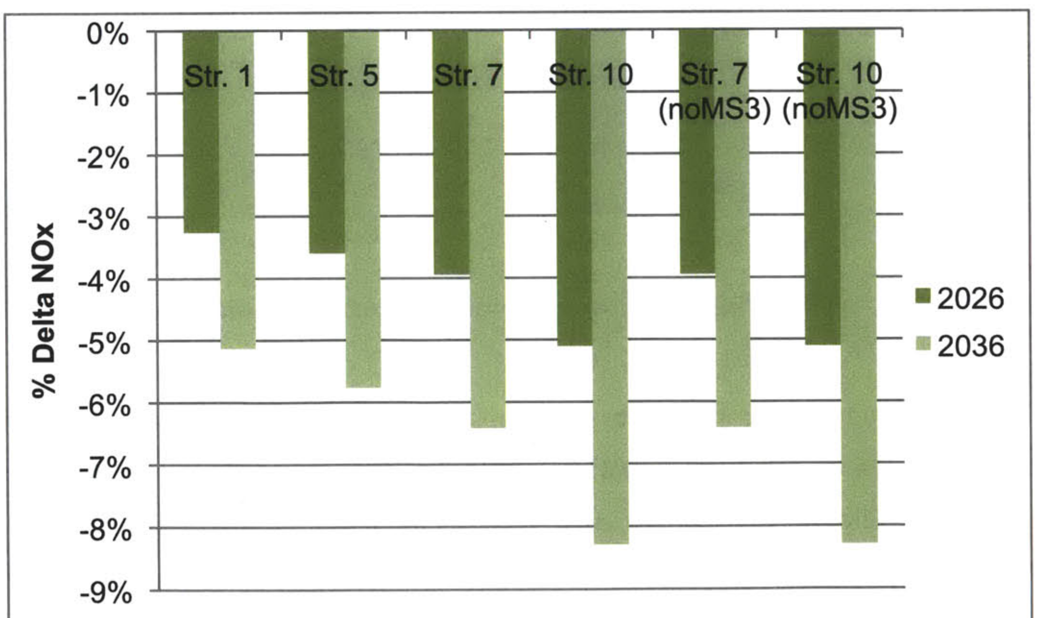

Figure 27. CAEP/8 NO_X Stringency NO_X emissions below 3k ft difference from baseline

APMT-Impacts Climate uses full flight emissions forecasts as shown below in Figure 28 and Figure 29. For consistency, this analysis only considers US emissions and fuel burn from large engines. The APMT-Impacts Climate module also takes full flight CO_2 emissions as an input. A fleet-wide constant emissions index of 3155 g CO_2/kg fuel burn is assumed for the lifetime of the policy.

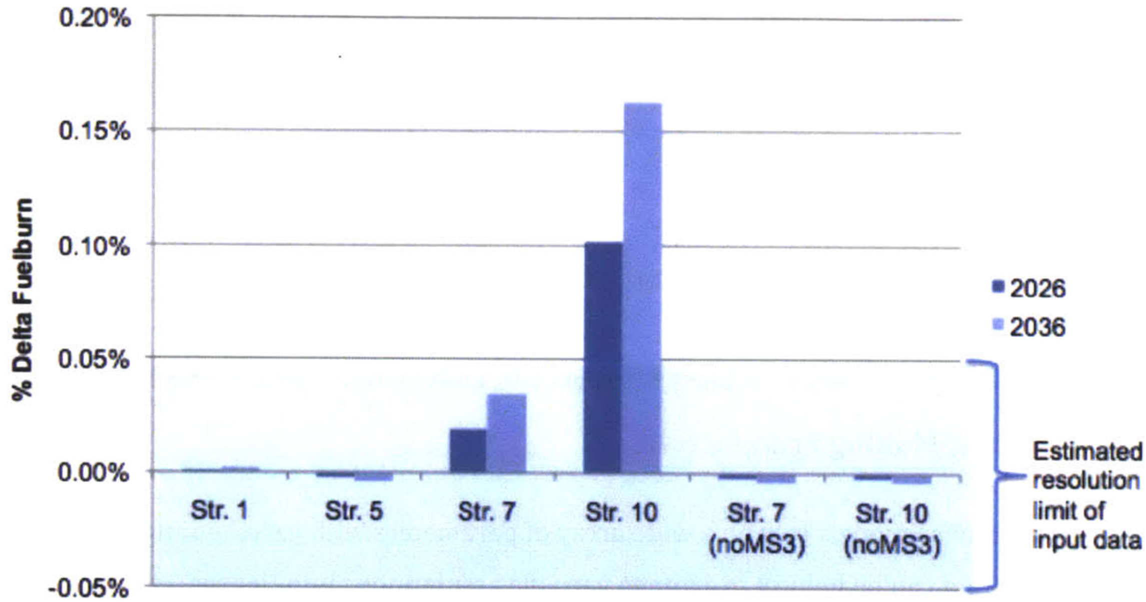

Figure 28. CAEP/8 NO_X Stringency full flight fuel burn difference from baseline

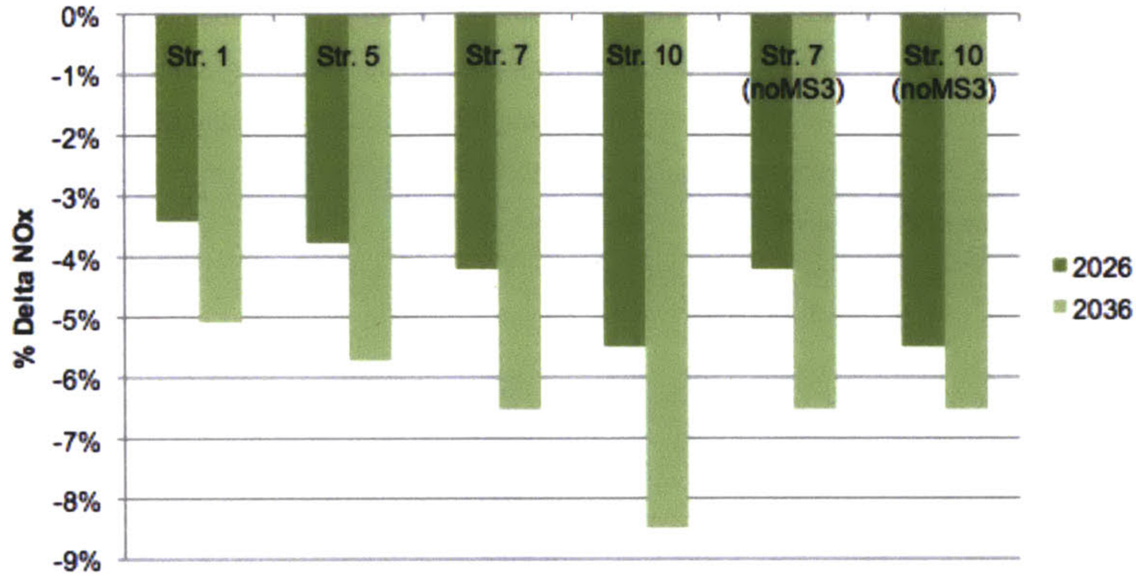

Figure 29. CAEP/8 NO_X Stringency full flight NO_X emissions difference from baseline

4.4 Decision-Making Framework

Because these models rely on a wide array of parameters with varying ranges of uncertainty, and can be helpful to arrange variable assumptions into "lenses". Each lens represents a unique perspective on a potential impact. Most commonly, APMT-Impacts uses three standard lenses: low impacts, midrange, and high impacts (conservative assumptions). A discussion of the sensitivity of different model metrics to input parameters and model global and local uncertainty can be seen in Jun (2008), Allair (2009), Mahashabde (2009), He (2010), and Dorbian (2010).

The lens parameters for APMT-Impacts Noise module are presented in Table 11. These lens parameters are based on a weighted-least squares regression for the relationship between willingness to pay for noise abatement and city-wide level income. A range of relationships for a variety of regression techniques is presented in He 2011 (forthcoming).

Table 11. APMT-Impacts Noise lens assumptions for the CAEP/8 NO_X Stringency analysis

Noise Assumptions	Low Lens (Best Case / Low Impact)	Mid Lens	High Lens (Worst Case / Conservative)
Income coefficient (approximated normal distribution)	0.0013	Mean = 0.0143 SD = 0.0079	4.5 K
Income interaction term (approximated normal distribution)	0.0154	Mean = 0.0170 SD = 0.0094	Wild et al. (2001).
Income intercept (approximated normal distribution)	-30.3440	Mean = -37.5292 SD = 207.8134	[80, -10, 10, 6, 30] mW/m^2
Background Noise Level	55 dB	Triangular distribution (mode = 52.5, range = 50-55) dB	50 dB
Income growth rate	0	0	0
Significance level	65 dB	Background Noise Level	50 dB
Contour Uncertainty	-2 dB	Triangular distribution (mode = 0, range = -2 to 2) dB	2 db
Population Growth Rate	No growth	No growth	No growth

The lens parameters for APMT-Impacts Air Quality module are presented in Table 12. Population is frozen in accordance with ICAO-CAEP modeling best-practices. Results were analyzed for both SMATed and unSMATed simluations, but only SMATed results are presented here. The impacts of particle bound water in the SMATing process were not considered in this analysis. Several modeling parameters and limitations of the RSM used in AMPT-Impacts in the ICAO-CAEP modeling process for air quality are assumed to be conservative. The resolution of the RSM does not capture the magnitude of near-airport air quality effects. Furthermore, fixing background atmospheric concentrations over the lifetime of the policy and utilizing only LTO emissions are assumed to be conservative. In discussion with policy-makers during the analysis, it was decided to account for these potential biases through the creation of an addition lens. The impact of cruise emissions on global mortalities was used as a scientifically justifiable proxy for these assumptions. The additional lens used a scaling factor of 4.7 on air quality impacts, based on the impact of cruise emissions from Barrett et al. (2010).

Table 12. APMT-Impacts Air Quality (RSM) inputs for the CAEP/8 NO_X Stringency analysis

Air Quality Assumptions	Low Lens (Best Case / Low Impact)	Mid Lens	High Lens (Worst Case / Conservative)
Population growth	No growth	No Growth	No Growth
Emissions multipliers 1. Fuel burn 2. SOx 3. NOx 4. Non-volatile PM	1. 0.92 2. 0.0066 (5th percentile) 3. 0.83 4. 0.52	1. Uniform [0.92 1.12] 2. Weibull [mean = 0.0627, std = 1.2683] 3. Uniform [0.83 1.23] 4. Uniform [0.52 2.06]	1. 1.12 2. 0.54 (95th percentile) 3. 1.23 4. 2.06
Adult premature mortality CRF	0.6	Triangular distribution (mode = 1, range = 0.6-1.7)	1.7
Value of a statistical life	$2.9 M	Lognormal distribution mean = $6.3M, std = $2.8M	$12M

The lens parameters for APMT-Impacts Climate module are presented in Table 13. These assumptions align with version 16b of the Climate module. Since the CAEP/8 NO_X stringency analysis, the APMT-Impacts Climate module has been updated as described in Section 3.3.5.

Table 13. APMT-Impacts Climate lens assumptions for the CAEP/8 NO_X Stringency analysis

Climate Assumptions	Low Lens (Best Case / Low Impact)	Mid Lens	High Lens (Worst Case / Conservative)
Climate Sensitivity	2 K	Beta distribution (alpha = 2.17, beta 2.41) to generate [median = 3K, range 2-4.5K].	4.5 K
NO_X – related effects	Stevenson et al. (2004)	Discrete Uniform distribution: Wild, Stevenson, Hoor (2009) values.	Wild et al. (2001).
Short-lived effects relative RF [AIC, Sulfates, Soot, H2O, contrails]	[0, 0, 0, 0, 0] mW/m^2	Beta distribution [alpha, beta, (range)] [2.14, 2.49 (0-80)], [2.58, 2.17 (-10-10)], [1.87, 2.56 (0-10)], [2.10, 2.58 (0-6)]. [2.05, 2.57 (0-30)] mW/m^2	[80, -10, 10, 6, 30] mW/m^2
Background Scenario	IPCC B2	IPCC A2	IPCC A1B
Damage Coefficient	5th Percentile of DICE	DICE-2007 (normal distribution)	95th Percentile of DICE

In addition to the standard low, mid and high lenses, two climate lenses specific to the NO_X analysis were developed. The nominal midrange lens was adjusted for the highest and lowest reliable estimates for full-flight NO_X emissions on climate change available in literature. These lenses are named the High NO_X and Low NO_X lenses.

The NPV results can be extremely sensitive to choice of discount rate. Unlike Mahashabde (2009), the choice of discount rate here is exogenous to the choice of lens assumption. This helps separate scientific uncertainty from the effect of policy-maker viewpoint on the valuation of future impacts. This methodology also allows for any discount rate to be applied to a given scenario and lens depending on regulatory body or policy-maker preference.

4.5 Results

The goal of the policy analysis presented herein is to weigh the economic costs against the environmental benefits for a representative subset of policy stringencies relative to a baseline business-as-usual projection. By monetizing the benefits and costs of all stringencies on the same scale, policy-makers can assess and compare the appropriateness of the proposed policies. The APMT-Impacts Climate Model Version 16a including the Shine temperature response model were used for the analysis. The section is arranged as follows: Section 4.5.1 shows key baseline physical effects trends for aviation environmental impacts, Section 4.5.2 discusses results from the integrated national aggregate cost benefit analysis, Section 4.5.3 provides insight into decision-making practice using a more conventional cost-effectiveness approach, and Section 4.5.4 presents a discussion of policy practices and insights based on APMT results, the ICAO-CAEP decision-making process, and the role of uncertainty in the analysis.

4.5.1 APMT Impacts Results

The results presented in this section represent the mean values for the mid-range lens model parameters unless otherwise noted. Monetary impacts are evaluated using a 3% discount rate unless otherwise noted. Results for other lenses and discount rates and associated uncertainties are discussed in Section 4.5.2. First, the baseline physical impacts of aviation noise are calculated. Under normal operations, just fewer than 4M people are exposed to aviation noise in their homes of at least 55 dB DNL in 2006. Growth in future operations under a business-as-usual baseline scenario leads to an increase in aircraft noise area exposure resulting in continuous increase in the number of people exposed to noise through 2036. These results are shown in Figure 30.

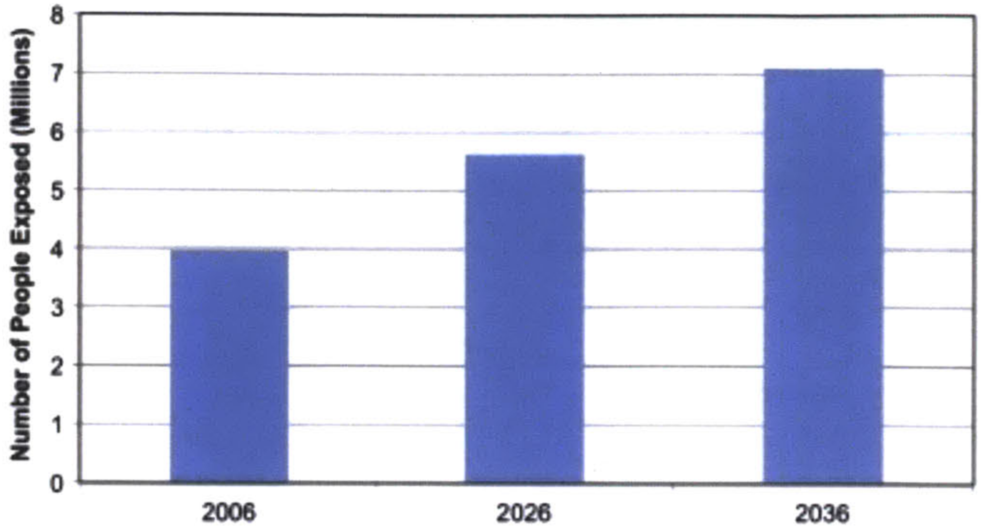

Figure 30. Baseline CAEP/8 NOx Stringency people exposed to aviation DNL >55 dBA

Baseline air quality impacts are primarily expressed in terms of yearly incidences of premature deaths attributed to exposure to $PM_{2.5}$ associated with aircraft emissions. The baseline physical impacts apportioned by species are shown in Figure 31. These totals include both adult and infant mortality, with a majority of the impacts being adult mortalities. Nitrates and sulfates dominate the physical impacts with EC and organics contributing to fewer deleterious physical effects. Figure 32 shows the difference between the projected policy physical impacts and the baseline case for a subset of scenarios. Although aircraft particulate matter related asthma, minor restricted activity days, and other physical health impacts are not presented in this section, the costs related to these incidences are included in the cost-benefit analysis. Costs related to mortality make up over 95% of total air quality environmental costs. Finally, the physical impacts shown here do not include potential effects of cruise emissions on air quality, the impact of background emissions growth, or a correction factor for poor near-airport resolution.

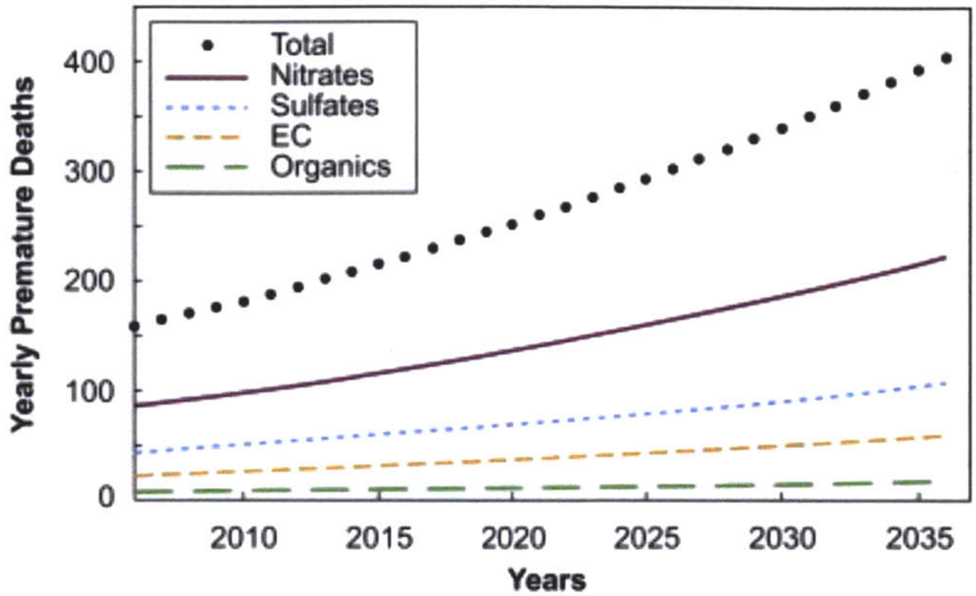

Figure 31. NO_X Stringency baseline air quality related premature deaths

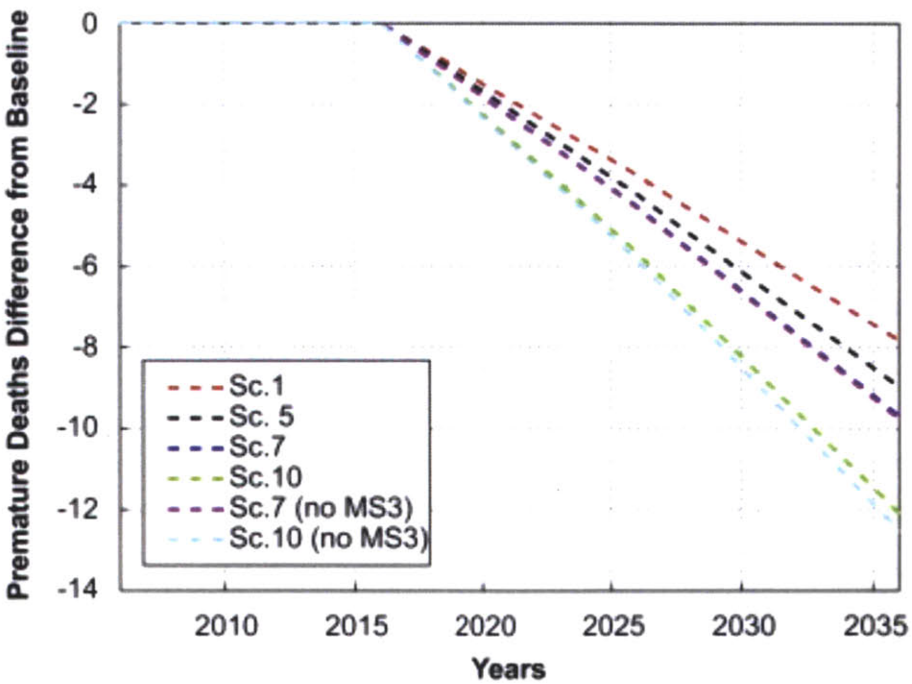

Figure 32. Select NO_X Stringency policies - baseline air quality related premature deaths

Climate physical impacts can be measured in terms of induced radiative forcing and in terms of temperature change. Radiative forcing impacts from short-lived agents such as sulfates, soot, H_2O, and aviation-induced cloudiness are modeled to occur only during the year they are emitted. NO_X radiative forcing has a decadal lifetime and CO_2 can persist for centuries. Figure 33 shows the temperature change associated with aviation emissions under a baseline stringency in the absence of policy change. CO_2 and cirrus have the largest total impact on temperature change with cirrus clouds dominating early effects and CO_2 persisting for over a century after the policy scenario length.

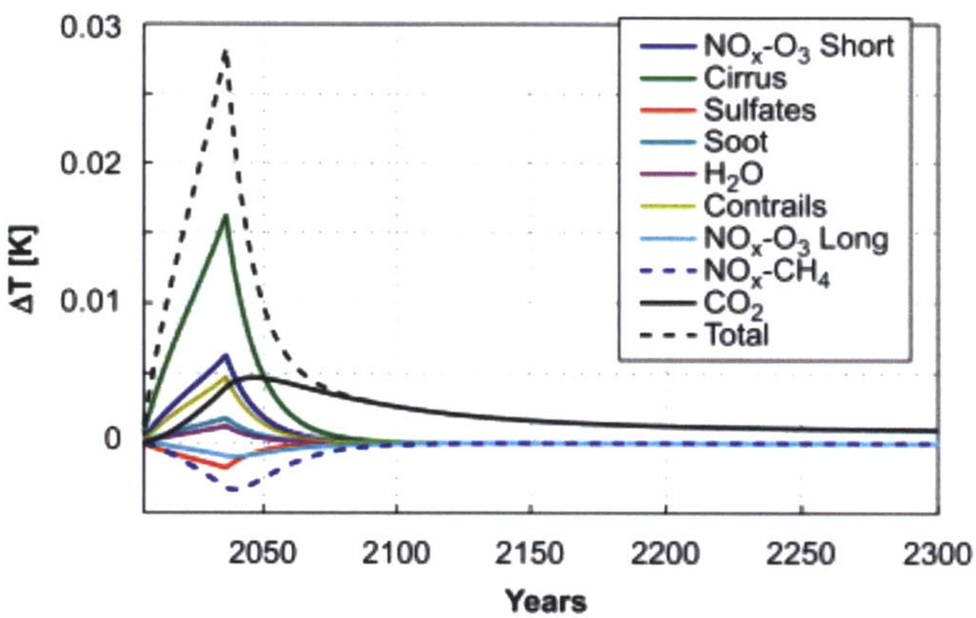

Figure 33. Baseline speciated temperature change

Figure 34 shows the temperature difference between the Scenario 10 stringency and the baseline case. Because CO_2 and fuel burn vary so little among stringencies, the NO_X effects dominate the policy – baseline change in temperature effects for both short term cooling and long term warming effects. This results in a total temperature change impact that is cooler in the near term but is warmer in the future. Although smaller in magnitude, effects that scale with fuel burn show increased warming in the policy scenarios due to the MS3 fuel burn penalty. The expected total temperature change across a selection of scenarios spanning stringency options is shown in Figure 35. Although all stringencies see a near-term temperature benefit, the disbenefit that persists for several years after the policy ends, an impact caused by the dominant long lifetime of CO_2, eventually dominates total integrated temperature change.

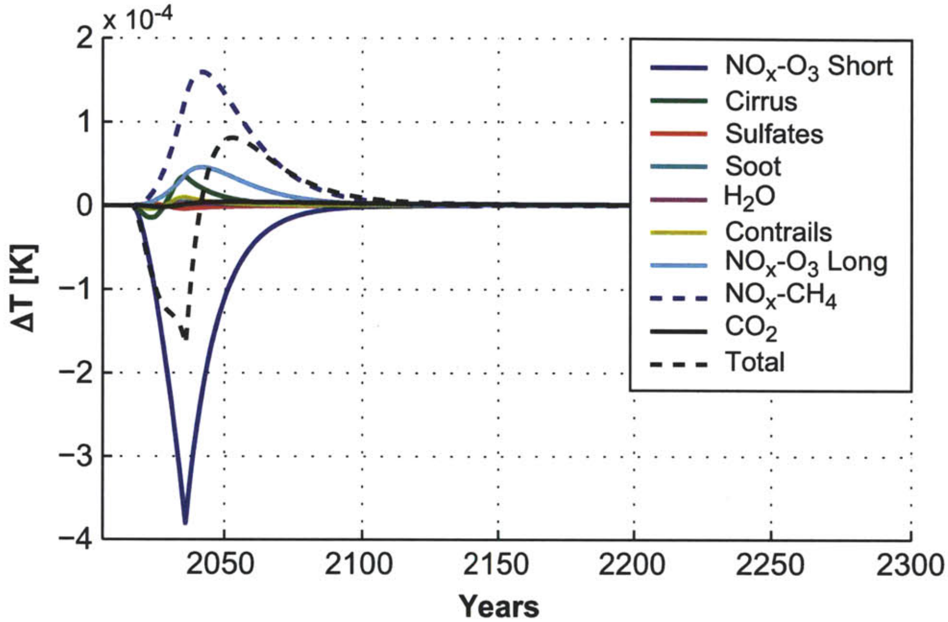

Figure 34. Scenario 10 MS3 - baseline speciated temperature impacts of aviation

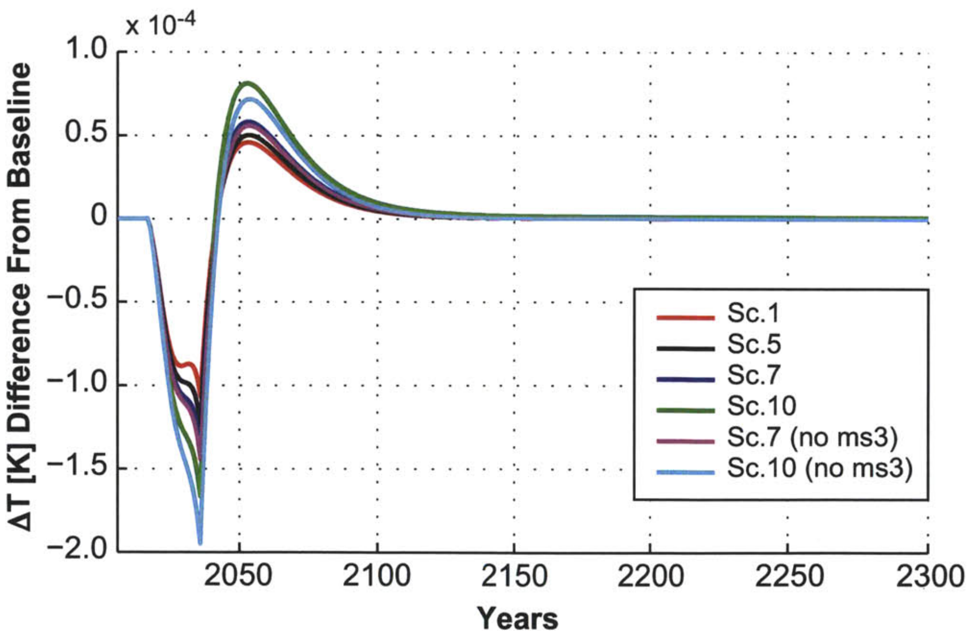

Figure 35. NOx Stringency policy - baseline for select stringencies

4.5.2 Integrated Cost-Benefit Analysis

Of importance in integrated cost-benefit analysis is addressing both intended and unintended consequences across all relevant aviation environmental impact pathways. Results for midrange lens, at 3% discount rate, for large engine emissions and combined engines for noise are presented in this section unless otherwise noted. Figure 36 shows the change in physical metrics across noise, air quality, and climate impacts. The change in noise impacts is driven by the increased area exposure from the MS3 noise penalty. The primary physical change driver is the decrease in local air quality induced mortalities, a benefit that improves with increasing stringency. This benefit is largely achieved through a reduction in secondary nitrate $PM_{2.5}$, but regional bounce-back effects do increase total sulfate $PM_{2.5}$. The increased full-flight fuel burn increases total integrated temperature change, outweighing any potential benefits to full-flight NO_X reduction on globally averaged surface temperature.

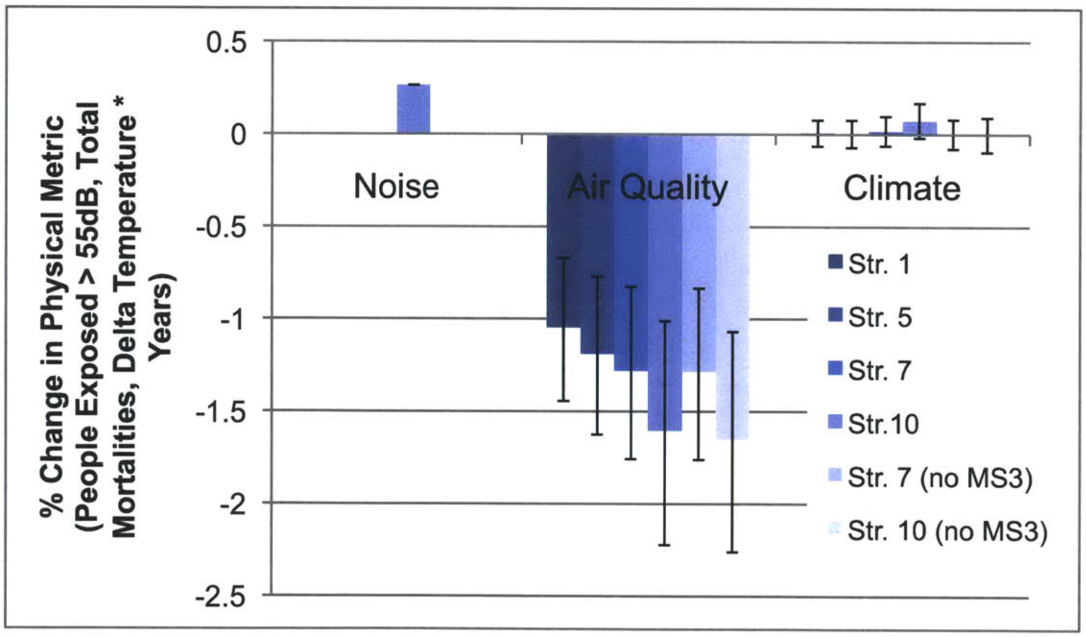

Figure 36. APMT physical impacts % change from baseline

Of greater benefit to policy-makers is a comparison across domains on a common scale. APMT-Impacts uses monetary net present value (NPV) valued to a consistent baseline year value, in this case 2009 US Billion $. A cost-benefit analysis across a range of policy lenses for a select stringency is shown in Figure 37. The monetized policy minus baseline impacts from each sector is shown along with the FESG policy cost estimates. The cost-benefit is then the sum of these values, with negative total values indicating a net beneficial policy. The height of the bars represents mean values and the error bars indicate 10^{th}-90^{th} percentile ranges from a paired Monte Carlo analysis. For a discussion of paired Monte Carlo analysis, see Mahashabde 2009 and He 2010. FESG US cost assumptions were estimated at 27% of total industry costs based on preliminary scoping runs with APMT-Economics, and uncertainties from the cost assumptions represent high and low FESG cost estimates. Trends are consistent across lenses, with the high lens being dominated by environmental costs in climate. The social cost of carbon (for CO_2 impacts only) estimates were \$13/tC, \$110/tC, and \$780/tC for the low, midrange, and high lenses respectively when averaged over the lifetime of the policy. These values are consistent with the range of SCCs estimated by the EPA (EPA 2008c) and fall within the range recommended by the Interagency Working Group (IWG 2010). Across all lenses, the policy is dominated by high industry costs.

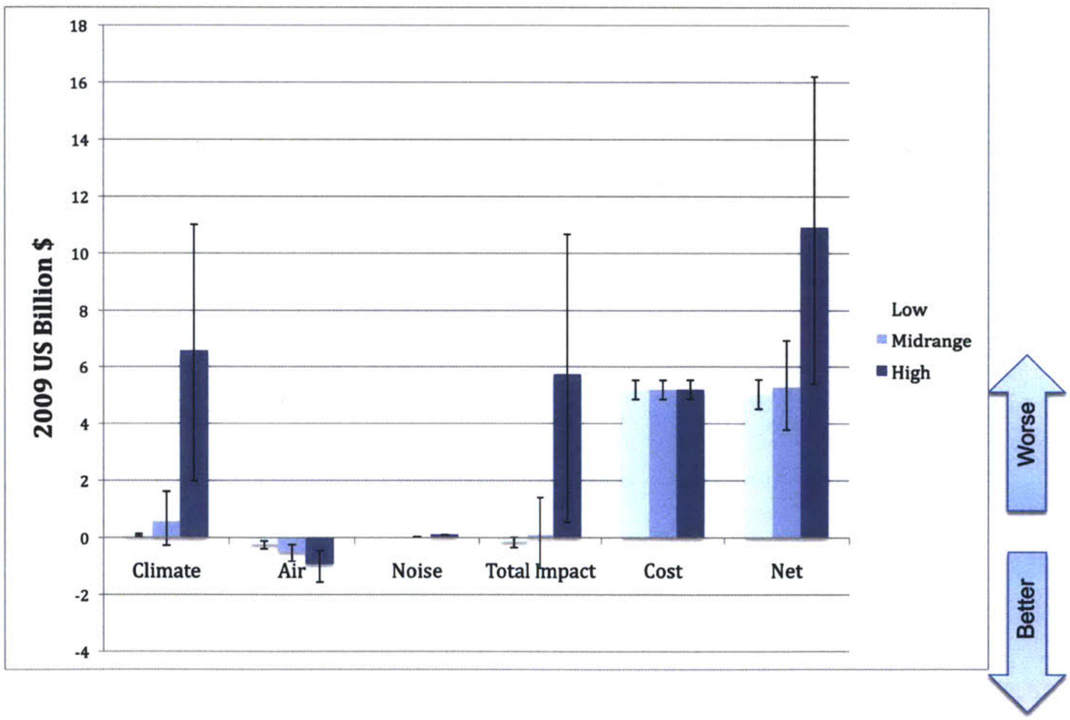

Figure 37. APMT cost benefit, multiple lenses, Stringency 10, with MS3 fuel burn penalty minus Baseline, 2016 implementation, 3% discount rate, no cruise air quality impacts, large engines only

Figure 38 shows the impact of discount rate on the analysis, again using Stringency 10 minus Baseline to illustrate trends. The results show that as discount rate increases, the change in full-flight NO_X outweighs deleterious long-term climate impacts from increased fuel burn. Although, a higher discount rate also leads to a lower net valuation of the air quality benefit, the aggregate environmental benefit is greater the more a policy-maker values near term impacts. Even under a high discount rate viewpoint, industry costs outweigh environmental benefits of a strict NO_X stringency. Figure 39 shows the results of a Stringency 10 cost benefit with the specified NO_X lenses described in 4.4. These results show that at 3% discount rate, the "best-case" NO_X impacts roughly balance the CO_2 warming.

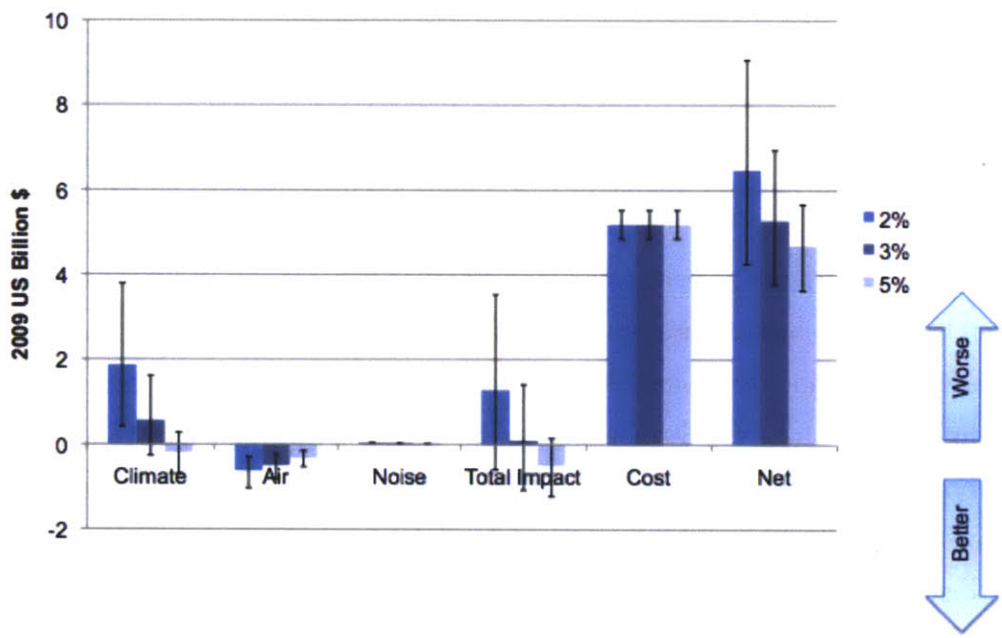

Figure 38. APMT cost-benefit at several discount rates, midrange lenses for Stringency 10 with MS3 Fuel Burn Penalty minus Baseline impacts, 2016 implementation, no air quality cruise emissions, large engines only

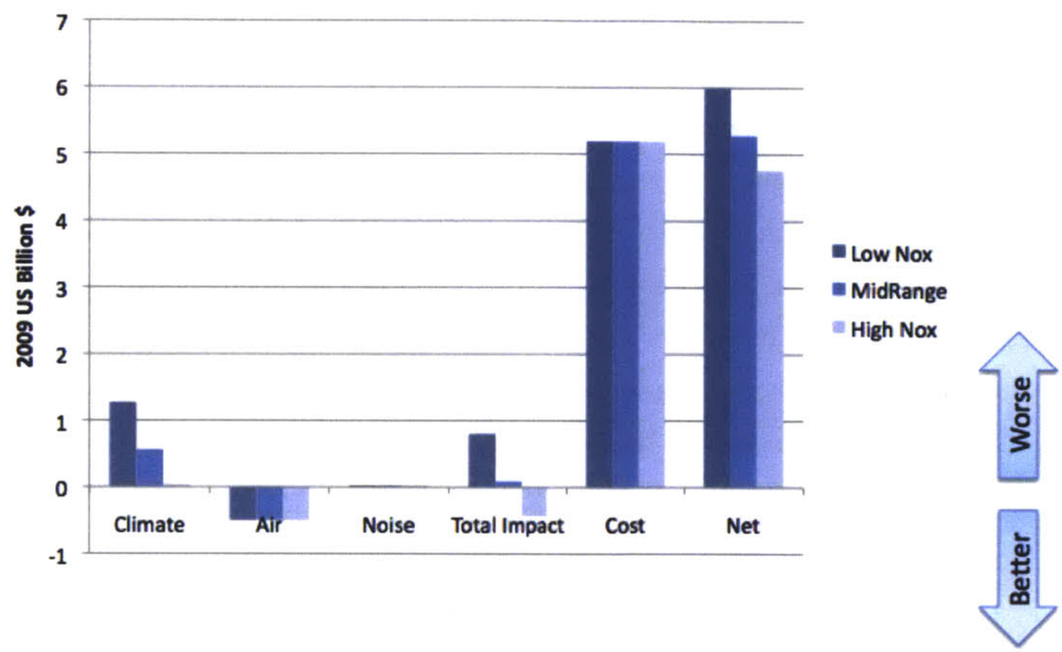

Figure 39. APMT cost-benefit specified NOx lenses for Stringency 10 with MS3 Fuel Burn Penalty minus Baseline impacts, 2016 implementation, 3% discount rate, no air quality cruise emissions, large engines only

The cost-benefit analysis was performed for a selection of representative stringencies at all discount rates and lenses. Figure 40 shows a snapshot of those results. Based on underlying assumptions and technology requirements, Stringencies 2-4 are expected to have results interpolated between Stringency 1 and 5, Stringency 6 is expected to have similar environmental results to Stringency 7 at reduced industry costs, and Stringencies 8 and 9 are expected to fall within Stringency 7 and 10. For all stringencies at a midrange lens and 3% discount rate, the policy is not cost beneficial. Industry costs and climate disbenefits outweigh monetized air quality benefits from NO_X reduction. The stringencies were reanalyzed with a first estimate of impacts on air quality from cruise emissions. In this lens, the full-flight NO_X reduction provides an approximate factor of five greater benefit to air quality monetized impacts. Using this approach, Stringency 1 and Stringency 5 become cost-beneficial and Stringency 7 becomes approximately a break-even point for a no MS3 additional fuel burn penalty assumption subject to irresolvable uncertainty.

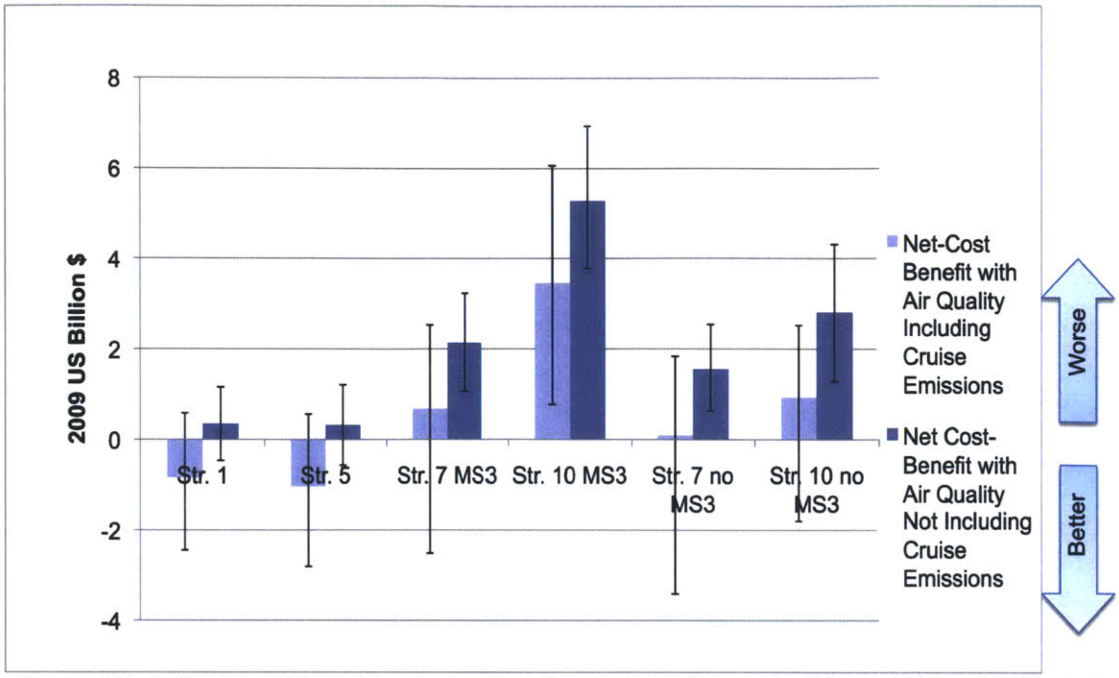

Figure 40. APMT Cost-Benefit across all stringencies with and without AQ Cruise Emissions, Stringency 10 minus Baseline impacts, midrange lens, 2016 implementation, 3% discount rate, no air quality cruise emissions, large engines only

Furthermore, it is expected that other underlying assumptions in our air quality module provide conservative results such as no changes in background concentrations over time. A recent study by Woody et al. (2011) estimates that including projections for background emissions will increase the spatial coverage of aviation emissions and the magnitude of the maximum aviation related concentration from 77 ng/m^3 to 113 ng/m^3 by 2025. A study by Levy et al. (2011) estimates that background emission effects will lead to a factor of 2.3 increase in aviation-related health impacts from 2005 to 2025, and that population changes will further increase aviation's impact on health by a factor of 1.3.[1] Also, RSM grid resolution may underestimate near airport mortalities. Resolving these assumptions is expected to improve air quality benefits. Thus, the local air quality benefits

[1] The current ICAO-CAEP modeling best practice assumes that population and income effects remain frozen throughout the policy lifetime for environmental effects. However, population and income changes are implicit in both the climate analysis background scenarios and the estimation of industry costs. Where the industry costs and climate impacts lead to significant costs while the air quality impacts of the policy provide a benefit, exclusion of population growth impacts may significantly undervalue the policy cost-benefit.

from cruise emissions can alternatively be viewed as a sensitivity analysis for assessing the influences of other conservative assumptions.

APMT cost-benefit results are sensitive to input cost assumptions. To demonstrate the impact of cost uncertainty, a range of cost assumptions from 0% to 100% of FESG costs were examined for all stringencies. The net cost-benefit is shown in Figure 41. At low cost assumptions, Stringencies 1 and 5 are modestly cost-beneficial, while Stringencies 7 and 10 are only cost-beneficial assuming 0% costs and no MS3 fuel burn penalty.

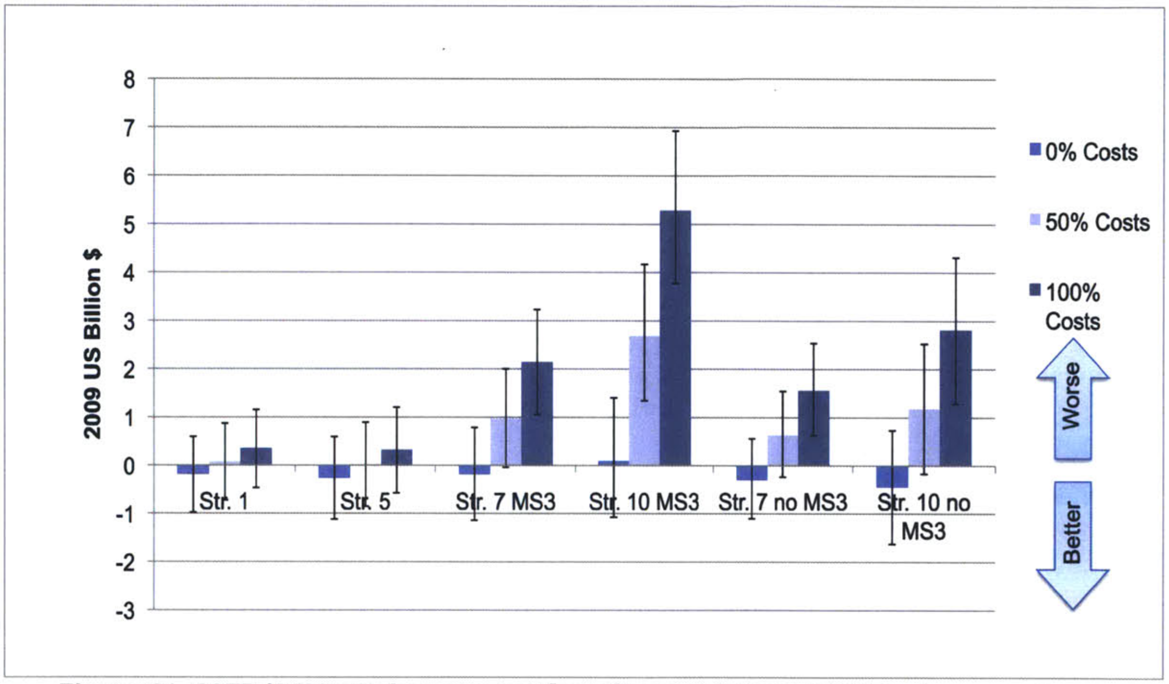

Figure 41. CAEP/8 NOx Stringency cost benefit sensitivity to FESG cost assumptions, midrange lens, 3% discount rate, 2016 implementation, no air quality cruise emissions

The analysis provided above indicates three important qualities of integrated cost-benefit analysis; cost-benefit analysis is a useful tool for examining trade-offs across different spheres of interest, analysis can be difficult in the face of scientific, model, and policy-maker uncertainties, and effective communication of results is essential for integrated cost-benefit. The lens concept, outlined briefly in Section 4.4, can help organize key variables and assumptions into concise bounding snapshots, but even then cost-benefit analysis can generate an overwhelming amount of data. For instance, to analyze 10 stringencies across 3 disciplines under 3 traditional lenses with 3 discount rates at 2 different implementation years, the researcher must examine 540 distributions of results.

To further examine impacts of cost assumptions and alternative lenses, the number of applicable distributions grows multiplicatively. The challenge for the researcher becomes how to distill this information effectively for a policy-maker. As shown here, providing snapshots of major trends is a way to communicate concisely while addressing uncertainty and policy preference, a scope lacking in deterministic analyses.

Thorough and open dialogue with policy-makers can improve the effectiveness of how the researcher presents results. In the CAEP/8 NO_X Stringency analysis, the development of the specified NO_X lenses, the air quality cruise lenses, and the cost sensitivity analysis involved feedback among PARTNER researchers and policy-makers. This dialogue led to the examination of the case shown in Figure 42. This case simultaneously takes into account the under-estimation of cruise NO_X impacts on air quality while addressing the potential for overestimating industry costs.

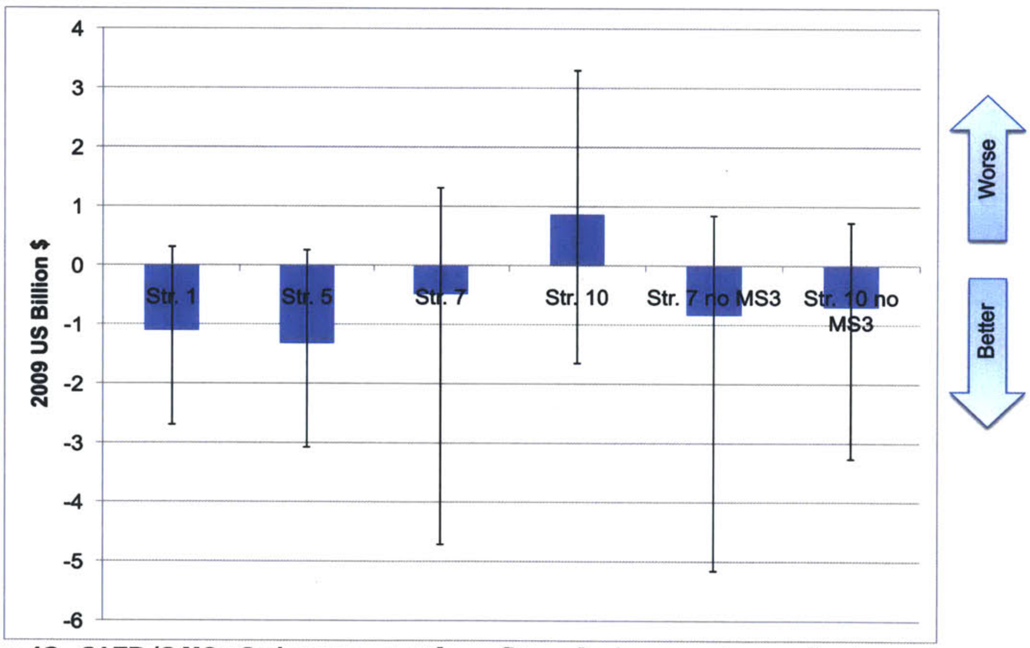

Figure 42. CAEP/8 NOx Stringency cost-benefit analysis assuming cruise impacts on surface air quality and 50% cost assumptions

4.5.3 Cost-Effectiveness Analysis

A cost-effectiveness analysis is a tool used more traditionally in the CAEP policy-making process. Cost-effectiveness is measured as the ratio of policy costs to policy goal. In the case of the NO_X Stringency analysis, this ratio is the sum of producer and consumer surplus over the total reduction in LTO NO_X emissions. The results of this analysis for a midrange lens at 3% discount rate are shown in Figure 43. This figure shows that less strict stringencies are more cost-effective, but it conveys no information about health and welfare impacts of reductions in NO_X emissions, and therefore, no information about whether the cost of enforcing the policy is reasonable and justifiable. Furthermore, the cost-effectiveness results show no indication of the impact of the policy on noise. Thus, this framework becomes less useful the more explicitly a policy represents a trade-off between environmental benefits in one sphere and environmental detriments in another.

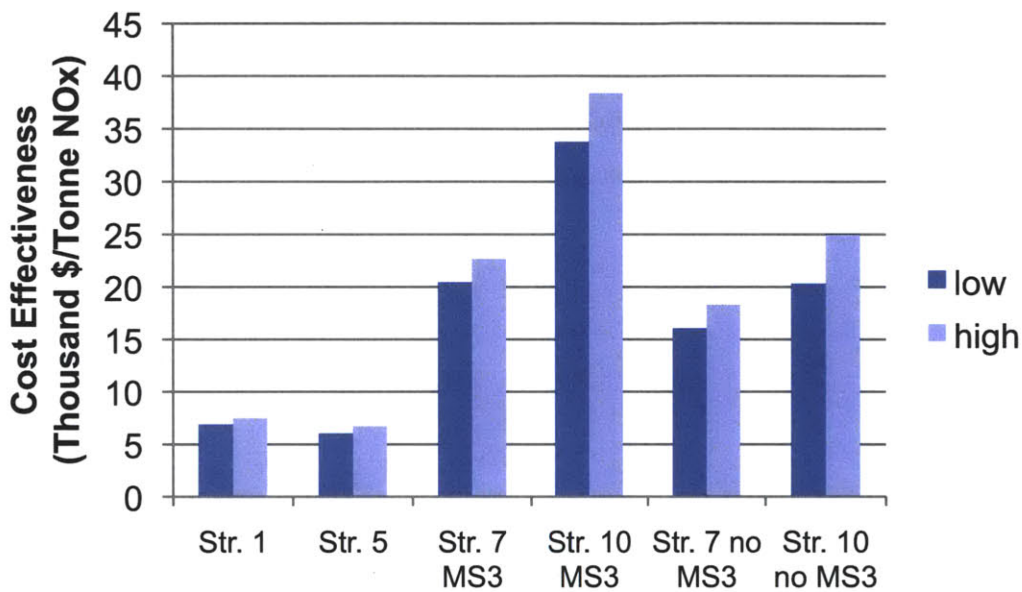

Figure 43. CAEP/8 NOx Stringency cost-effectiveness analysis

4.5.4 Policy-Making Insights

In February 2010 at the ICAO-CAEP meeting in Montreal, CAEP recommended Stringency 6, a 15% increase in stringency for large engines and overall fleet. Stringency 6 has similar emissions and noise contours to that of Stringency 7 with slightly lower industry costs. This result was based on cost-effectiveness analyses, as described in Section 4.5.3, which indicated that the cost per ton of NO_X reduced was commensurate with previous NO_X stringency decisions. The results of the cost-benefit analysis in Section 4.5.2 were used by the US to support this decision, and provided useful bounding conditions.

For instance, the 20% reduction in NO_X over CAEP/6 goals was shown to be neither cost-beneficial nor the most cost-effective policy option for any lens or discount rate at full FESG cost assumptions. It is important to note that the cost-benefit analysis does not provide a clear indication of a "best policy option"; it is only a tool for explaining potential outcomes of a policy choice. As shown in Section 4.5.2, different assumptions and preferences can drive outcomes, and this decision can be further clouded by uncertainty. However, the articulation of the range of outcomes is a valuable contribution to the policy-making dialogue and, as seen, can help guide decision-making.

Furthermore, while the analysis shows that increasing stringency is not cost-beneficial for some severity of increases over a variety of lenses, it fails to capture all political and social realities of the NO_X regulation problem. Issues of fairness and distribution are covered in Chapter 5. The political ability to regulate emissions to a higher stringency can also be a reason to increase stringency. In one case, the existence of an increased stringency will incentivize innovation. As current technologies are phased out, engine producers and airframe manufacturers will need to devote increased resources to research and development to continue to participate in the market. These developments have the possibility of improving technological capability beyond the incremental changes expected under a lower stringency. First, while these revolutionary technology changes are difficult to predict, and therefore are not accounted for in the industry cost estimates, their impacts can be significant. Settling for a lower stringency can cause lock-in, the continued reliance on environmentally inefficient technologies. This is especially a concern of the aviation technology industry where entry costs are high and equipment life spans and technology lead times are long. Second, by shifting the industry paradigm, the stringency may improve industry competition by lowering barriers for new technologies to come to market. Again this can have a wide reaching impact on an industry with few incumbent competitors. The impacts of these developments are likely not accounted for in industry cost estimates, as it is not in current stakeholder interest to consider economic efficiency improvements from increased productivity. Finally, the political climate may not permit further stringency improvements by the time those regulations are cost-beneficial. It may be prudent to take advantage of trigger-events that allow regulations to gain traction, as calls for regulation can fall in and out of favor over time.

5 Regional Distribution Analysis

Chapter 4 demonstrated how cost-benefit analysis can be a powerful tool in examining aviation environmental policy and how APMT-Impacts can be useful in performing such an analysis. However, cost-benefit analysis has shortfalls as a policy analysis tool. Cost-benefit analysis does not show who bears the costs or receives the benefits of a specific policy. This can be especially true in aviation where impacts of noise can be concentrated while climate change impacts are spatially diffuse. When policy impacts are not distributed equally, especially in the spheres of environmental and occupational health and safety, social equity concerns exist (Ashford 1976). This chapter presents one complementary framework for policy analysis through a regional distribution analysis utilizing the APMT-Impacts tools. Section 5.1 looks at the variation in expected environmental damages as a function of distance from a major airport. Section 5.2 examines the economic benefit provided by airport access as a similar function of distance from airport. Finally, Section 5.3 looks at the burgeoning field of environmental social justice and its relationship to aviation environmental policy.

5.1 Environmental Impact and Distance from the Airport

Aircraft noise is the most readily perceived environmental impact of aviation, and the first to be regulated when ICAO published he Annex 16: Environmental Protection, Volume I - International Noise Standards in 1971. Although there has been increased regulation since that time, aircraft noise still leads to the most public complaints about aviation (GAO 2001).

However, the baseline damages for a year of aviation operation indicate greater impacts from local air quality and climate change than for noise damages at comparable lenses. Figure 44 shows the total national damages for the three impact spheres for a year of aviation operations for a 3% discount rate. The snapshot of damages provided in Figure 44 is similar to the policy viewpoint of the cost-benefit analysis performed in section 4.5.2. Note that because underlying aviation damages are not a policy minus baseline scenario (unless one assumes a policy that would prohibit aviation entirely), uncertainty in the underlying model may have a greater influence on overall results.

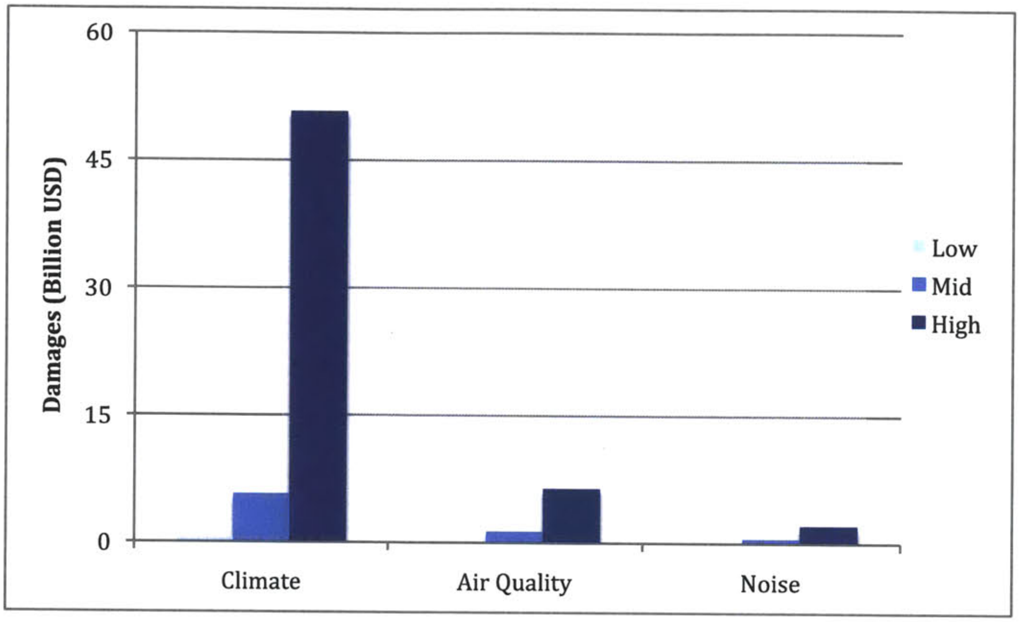

Figure 44. National damages for one year of aviation operations, midrange lens, 3% discount rate

For one year of operations climate damages dominate. The midrange and high climate lenses lead to a greater impact than Air Quality and Noise damages combined under any lens. Climate damages from CO_2 only are equivalent to a $19 SCC under the midrange lens, which aligns with the median SCC recommended for use in policy analysis (IWG 2010). Noise damages are the smallest of any domain by a factor of two, except under the high lens in which they are about equal to Air Quality damages under the high lens.

This viewpoint suggests that the number of noise complaints relative to air quality and climate complaints are not a function of actual monetary damages. One possible explanation for the discrepancy between aggregate damages and population response is the ability to perceive and understand noise damages. APMT-Impacts calculates noise damages based directly on the public perception of risk and annoyance through revealed preference (He 2010). Long term health impacts from noise that may not be easily perceived or for which the public may not be informed are specifically not quantified in the APMT-Impacts Noise module. On the other hand, air quality impacts are monetized real damages as opposed to monetized perceived damages. One might expect that in a comparison of perceived noise damage to perceived air quality damage, air quality damages would fall dramatically as individuals tend to undervalue damages from air quality for two reasons; individuals fail to account for incremental changes in risk (Robinson and Hammitt 2011), and while individuals may be aware of societal impacts of air quality, they are often unlikely to ascribe causation to environmental effects (Bickerstaff and Walker 1999).

While aviation noise pollution is the biggest hindrance to airport expansion, the overall societal response to climate change and air quality degradation should not be ignored. The public understanding and push for action on anthropogenic climate change has increased substantially over the past 30 years. While it may seem logical to attribute a percentage of this public response to aviation equal to the percentage of total anthropogenic radiative forcing attributable to aviation, it is unclear that public perception of aviation impacts matches the scientific understanding. Recent research has shown that public awareness of aviation impacts is low (Lee 2010) or that travelers place a greater value on freedom to travel than on responsibility for climate mitigation (Becken 2007). However, in the UK, public response may target aviation to a greater extent than actual damages due to heavy media coverage (Lee 2011). Thus, while it is important to note that there is significant public demand for climate mitigation, directly attributing this demand to aviation is difficult.

An alternative snapshot of the damages is to look at how they are distributed over the total number of people affected. Air quality damages are spread across the entire domain (in this case impacts are limited to the United States), but only people living under noise contours experience noise damages. Determining average damage per person affected by climate is more difficult. Climate damages are calculated on a global basis. Thus, one could simply divide total climate damages by global population. However, for this study, average damage by person affected in the United States is a more appropriate comparison. Determining a US specific damage function or a US specific SCC is still a topic of significant debate. A regulatory guidance on SCC usage in US policy analysis suggests using 7%-23% of global damages as a provisional and speculative estimate of US damages (IWG 2010) Figure 45 shows the impact burden per person for a year of aviation operations. US climate damages were taken as 7% of global damages, with the 23% value being shown by the error bar. This snapshot indicates that subset of the population impacted by noise are receiving a disproportionate share of total environmental damages. From this viewpoint, the noise complaints are rational on an impact-share basis.

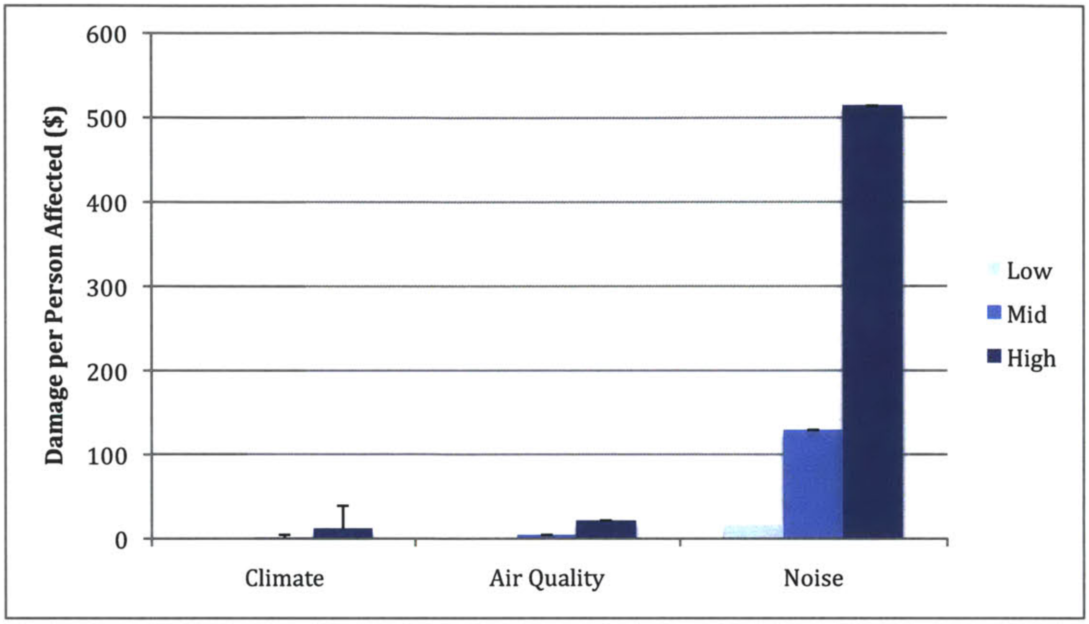

Figure 45. Baseline aviation operations damage per person-affected, midrange lens, 3% discount rate

The damage per person-affected viewpoint does not indicate a potential perception bias, but instead highlights that climate and air quality damages may be too temporally or spatially diffuse to garner broad policy support compared to noise damages. As more and more people experience environmental damages, the less incentive any rational individual has to act in minimizing that damage (Olson 1971). Thus, this snapshot reveals not a perception-bias, but a collective action problem.

While examining aviation environmental impacts on two different aggregate levels, total damages and damages per person affected, is helpful, it cannot fully contextualize aviation environmental policy. Two ways of examining the distribution of aviation environmental impacts are on a region-by-region basis and on an airport proximity basis. In the first case, for instance, Figure 9 shows that air quality damages are concentrated in Southern California. A policy that mitigates $PM_{2.5}$ at the expense of expanded noise contour areas may garner support in Los Angeles, but face opposition in Philadelphia. Likewise, airport proximity may also play an important role in policy acceptance. The remainder of this section examines the impact of airport proximity on average person environmental damage. This analysis attempts to better characterize underlying public response and understanding of aviation environmental damages and develop a framework for making more informed decisions in aviation environmental policy.

5.1.1 Methodology

This section lays out how damages per person are calculated as a function of distance from an airport for the three environmental spheres of interest.

Noise

Noise is a clear case in which distance from the airport is correlated to observed damages as only those living under 55DNL or higher noise contours will experience aircraft noise pollution[2], and these contours are most prevalent underneath the landing and take off flight paths of planes. The APMT-Impacts Noise Module overlays generated noise contours and US Census block group population data and then applies a formula based on willingness-to-pay for abatement as explained in Section 3.1. Data is mapped to the region being considered. Then using airport location coordinates from the FAA and VOLPE airports database, damages are calculated at each 5m along 36 evenly spaced radials as illustrated in Figure 46.

[2] The impact of aviation noise outside of 55DNL noise contours is an area of ongoing research. Noise contours are cumulative metrics and may fail to account for acute exposure to high levels of aviation noise. Furthermore, areas with low background noise, such as rural areas and national parks, may be more easily susceptible to noise damages from high altitude overflights (Gramann 1999, Lim et al. 2008). The FAA and the National Park Service have identified visitor and wildlife response to aviation noise in National Parks as critical research areas (TRB 2011).

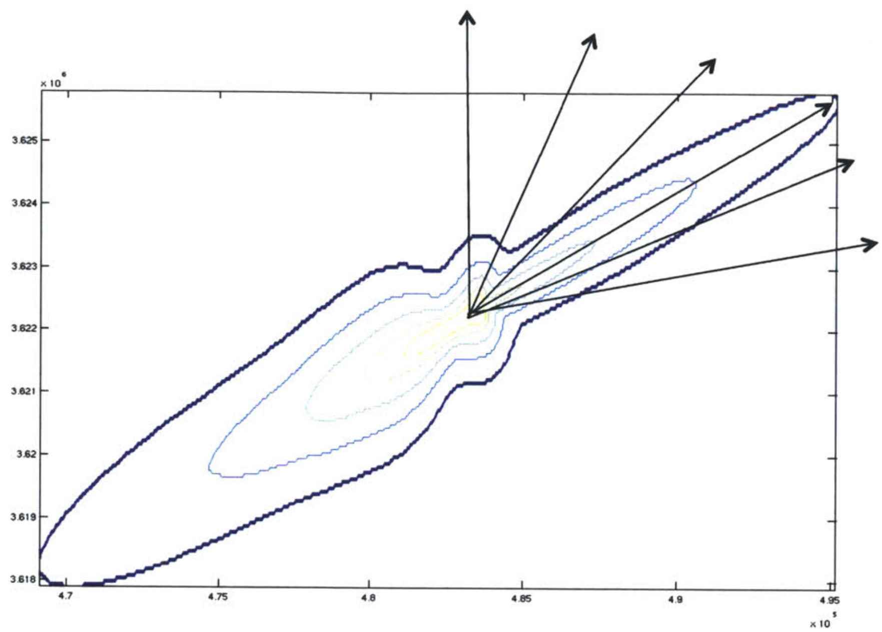

Figure 46. Illustration of the radial damage approach

The average damage and the range of damages per person can then be characterized as a function of distance from the airport as a function of radial azimuth. We can then assess national trends in airport damages by taking the average of damages across all Shell-1 airports. For this analysis, the noise code is run deterministically to better understand the underlying trends.

In addition to the concerns of benefit transfer from hedonic pricing methods, there are some additional concerns with utilizing the APMT-Impacts Noise Module for estimating geographic distribution of damages. While local and global sensitivity analyses performed in He (2010) show code robustness and comparable results to the model described in Kish (2008), no comparison has been performed to show sensitivity on a grid distance level basis. Furthermore, traditional NDIs may not be applicable for noise contours above DNL 75 dBA, leading to underestimation of damages at very near airport locations (Feitelson et al. 1996).

Air Quality

Like noise, air quality damages may be a function of distance from the airport as degradation is modeled from landing and take-off cycle emissions. The same radial damage summation technique as used for noise can be used to estimate average damage per person from aviation air quality impacts as a function of distance from an airport. With air quality, however, because damages are related to surface particulate matter concentrations, the resolution of the air quality model becomes a limiting factor. Because the APMT-Impacts Air Module RSM has a 36km x 36km grid resolution, using the RSM can indicate the difference between the average impact for people living within 18km of an airport and people living between 18km and 54km from the airport. However, the RSM is unable to accurately describe per person impacts near an airport boundary.

Higher resolution air quality model runs can provide context for air quality impacts at individual airports. These models can be computationally expensive and can require inputs of higher fidelity than are available for all airports. Thus, they are impractical for use on a national aggregate level, but are helpful in examining airport specific case studies.

Use of a reduced-order rapid dispersion model is one tool for estimating near airport air quality damages. A model developed by Barrett and Britter (2008) estimates dispersion of primary $PM_{2.5}$ based on airport emission profiles and local wind patterns. These primary PM2.5 results can then be superimposed on results from a chemistry-transport model such as CMAQ or the RSM using a method described by Isakov et al. (2007). Use of this methodology requires careful alignment of assumptions between models and is an ongoing area of PARTNER research.

Climate Change

Aviation impacts on climate change are diffuse and non-uniform. Radiative forcing from CO_2 may be appropriately assumed to be globally uniform, but NOx-O_3 pathways have significant hemispherical imbalances and aviation induced cloudiness can range from a local to a continental scale. Furthermore, the surface temperature change from climate change has significant global variation, even for areas that experience the same radiative forcing depending on feedback loops. A multi-model average of expected surface temperature change for three different climate projections shown in Figure 47 indicates significant regional and continental variation (IPCC 2007). Progressing down the emissions pathway to damages produces increasingly more heterogeneous results.

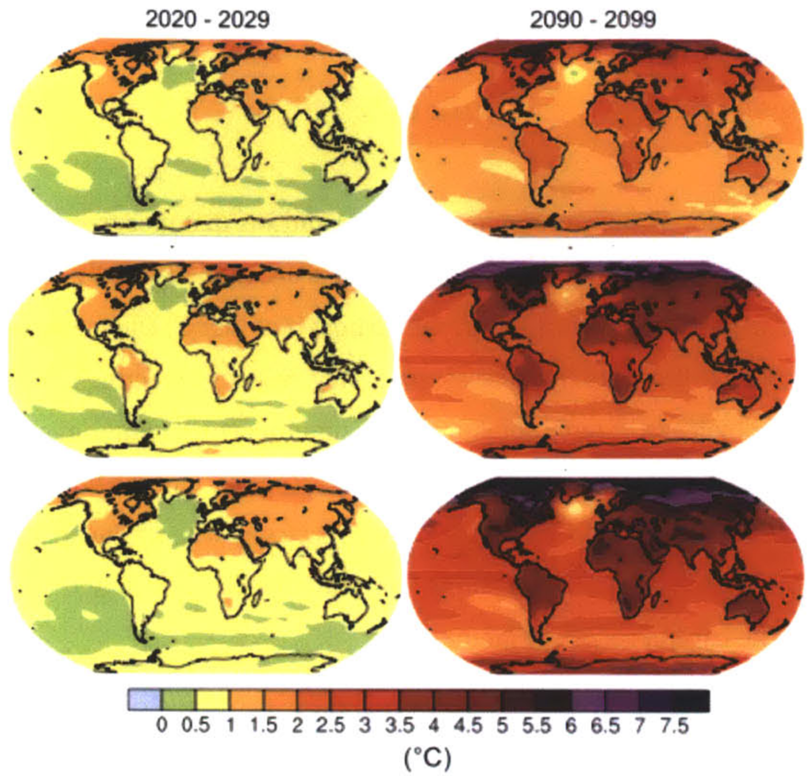

Figure 47. IPCC multi-model average surface temperature estimates for B1, A1B and A2 emissions projections (IPCC 2007)

For a proximity analysis, however, damages are assumed to be independent of distance from a Shell-1 airport. For the distances of concern (approximately 20km), one would expect the average damage from climate change to remain relatively constant. This assumption would not hold if a majority of airports are in low lying coastal areas, in which case damages may be greater at near airport locations. However, as a first-order approximation, assuming constant damages as a function of distance from the airport is reasonable. Therefore, the national average damage per person is taken as the average damage per person at all distances from an airport.

5.1.2 Noise Results

The national mean and 10-90th noise damages per person as a function of distance from an airport for three nominal lenses are shown in Figure 48. The results show that the relationship between noise and distance can be described using an exponential relationship with damages approaching $0 within 16km of an airport as shown in Equation 14 (for the midrange lens):

$$ND = 443\, e^{-0.543x} \tag{14}$$

where *ND* is noise damage per person in 2006 USD and *x* is distance from a Shell-1 airport in km. While results are fairly smooth and the means are monotonically decreasing, spread of results becomes greater within 1 km of the airport boundary. The mean damage in this area will be strongly influenced by runway geometry, with intersecting runways providing a greater percent coverage of high noise contours and therefore higher average damages. Results vary significantly from lens to lens, indicating that results are highly sensitive to choice of background noise level and noise sensitivity level. The decay factor is strongly correlated to total yearly airport operations (p = 0.0005). Results shown here are for a 3% discount rate in the capital recovery factor.

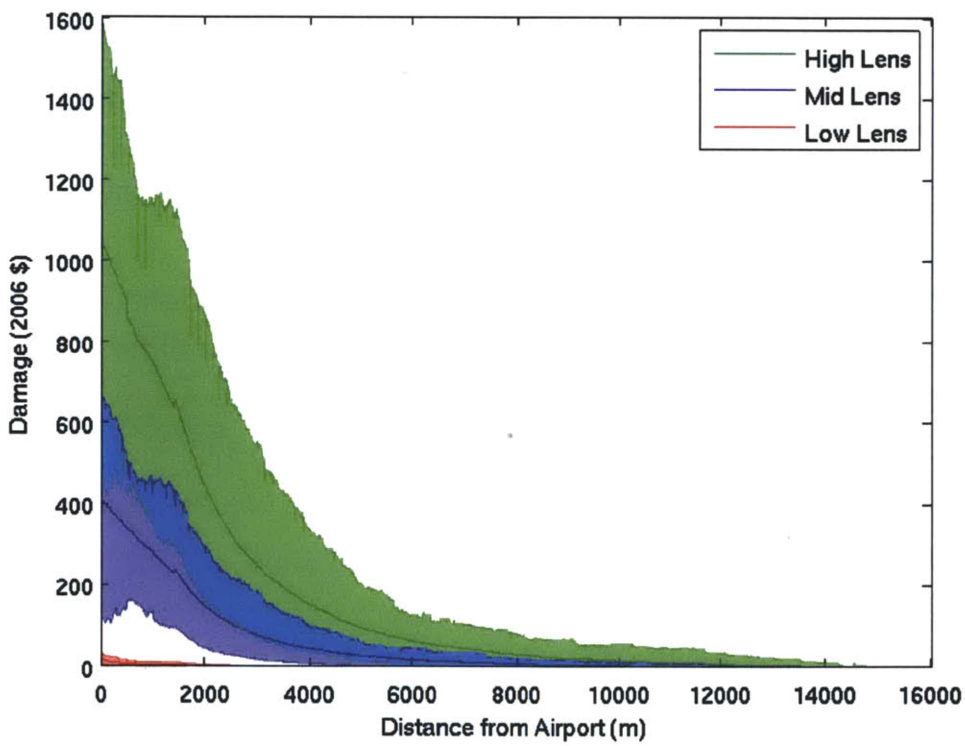

Figure 48. National average noise damage per person as a function of distance from an airport

While the mean damage per person across the nation is well-explained by a lens and discount rate specific exponential relationship, it is helpful to look at airports on an individual basis. Noise damage per person can be described using an airport and discount rate specific exponential relationship with an average R^2 across all airports of 0.971. SFO has the worst correlation between distance and damage per person, a result of its noise contours being located primarily over water. These contour shapes lead to a highly discontinuous relationship between damages and distance. The results for two representative airports are shown in Figure 49 and Figure 50. The individual airports show a fundamental relationship between airport noise and distance. While the exponential relationship may appear robust, minimum and maximum damage ranges at any distance can be substantial as noise contours are typically not circular but elongated along the directions of runways. For airports with a significant number of operations, populations living along radials aligned with runways may be exposed to damages as much as 15km further away from the airport than populations living along radials not aligned with runways.

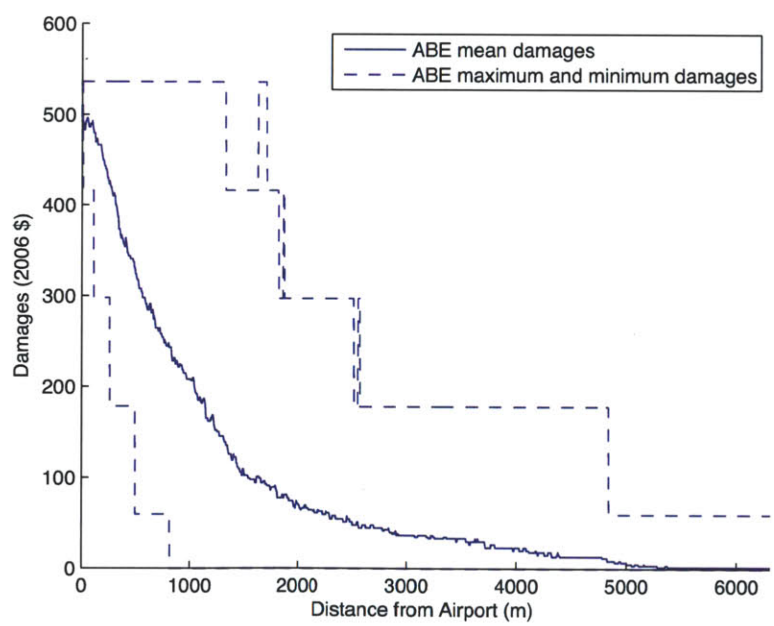

Figure 49. Noise damages per person as a function of distance from the airport for a representative airport <200,000 yearly operations

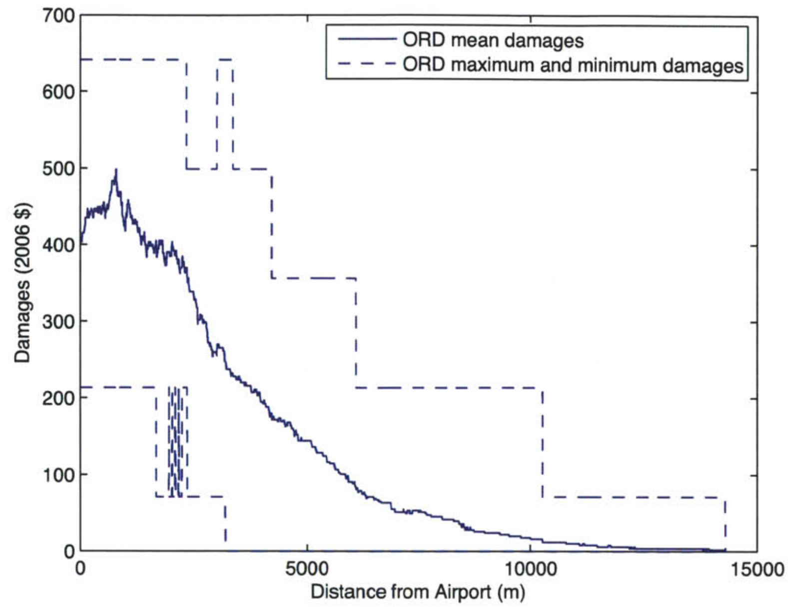

Figure 50. Noise damage per person as a function of distance from the airport for a representative airport >200,000 yearly operations

5.1.3 Atlanta Case Study

As discussed in Section 5.1.1, use of the RSM will underestimate the near-airport impact of air quality damages due to averaging of concentrations over large areas. To examine the impact of near-airport air quality, a case study of the Atlanta Hartsfield-Jackson International Airport (ATL) was performed. Atlanta is an attractive airport for a case study due to its size, its importance, and its location in a $PM_{2.5}$ non-attainment county, and it was chosen so as to leverage previous research efforts. Formatted emissions inventories from the Emissions Dispersion Modeling System (EDMS) for ATL operations were used to analyze particulate dispersion around ATL on a 4km x 4km grid. Emissions inventories and dispersion results were verified in Arunachalam et al. (2008) and Donohoo (2010). The SMATed results from Donohoo are used here to match current modeling assumptions. It is important to note that the assumptions behind the baseline operations for air quality are not strictly aligned with those for noise and climate change. Donohoo used scaling factors to convert a 2002 operational baseline to present day impacts, and these conversions are utilized here. For noise and climate change, the baseline scenario from the NO_X Stringency analysis was used.

A comparison of noise, air quality, and climate damages per person as a function of distance from ATL airport is shown in Figure 51. The thick lines correspond to mean damage per person while the shaded regions show the range of values at each distance. The results show similar mean damage per person profiles for noise and air quality and noise between 2 and 1.2 km. While the mean air quality per person damage dominates at a given distance, maximum damage per person from noise are often greater than those of air quality. This indicates that, although air quality damages are on average greater, large areas and populations may be more affected by noise. At distances very near the airport boundary, mean air quality damages approach double those of noise damages. SMATing resulted in a doubling of PM2.5 within 4km of the airport. Non-SMATed emissions maximum and mean damages more closely align with noise damages within 4km of the airport boundary.

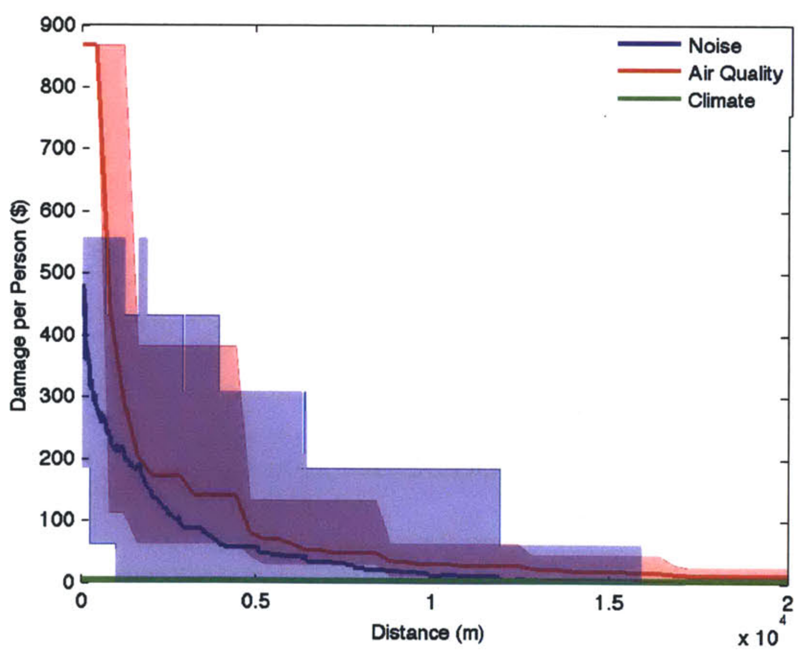

Figure 51. ATL damages per person as a function of distance from airport, 3% discount rate (midrange lens)

The choice of discount rate impacts the magnitude and relative ranking of environmental damages from noise and air quality. Because the air quality RSM concentration response functions indicate mortality and morbidity responses only for the year of concentration change, choice of discount rate has no impact on the damage per person due to air quality impacts of one year of operations. In the case of noise, discount rate is used to transform capitalized property damages into a time series of annuity payments. As discount rate increases, property owners value future annuities less and less, thereby increasing the valuation of the current year's damages. For climate damages, a higher discount rate diminishes the magnitude of future year damages due to the long lifetime of CO_2 and the inertia a of the temperature-response system. Thus, increasing the discount rate has countervailing effects that increase the magnitude of expected yearly damages per person from noise impacts and decrease the magnitude of expected yearly damages per person from climate impacts. Expected damages per person as a function of distance from the airport are shown for a 7% discount rate in Figure 52.

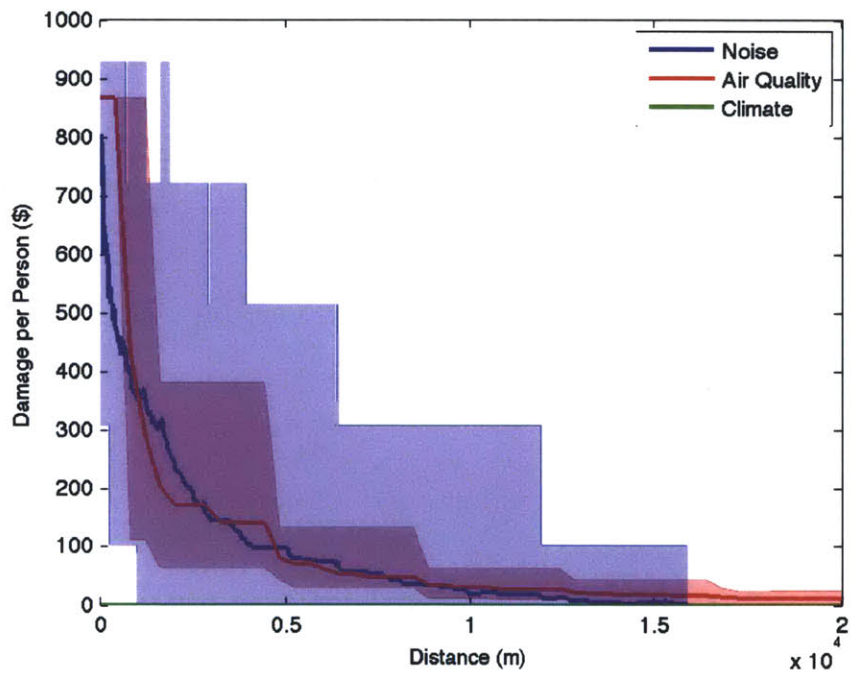

Figure 52. ATL damages per person as a function of distance from the airport, 7% discount rate (midrange lens)

At a 7% discount rate, noise damages at locations < 2 km away from an airport more closely resemble the magnitude of damages from air quality. While noise and air quality mean damages maintain similar profiles from 2 km to 12 km, maximum noise damages for a given distance dominate maximum air quality damages, indicating an increase in the disparity between communities seeing few noise damages and communities bearing the majority of noise costs for the same proximity to an airport. As discount rate decreases, noise impacts become less important relative to air quality while the magnitude of the climate impacts increases. For a 2% discount rate, climate damages per person increase by 55% over the 3% discount rate damages, but climate damages still represent less than 10% of average damages per person affected for distances less than 8km from the airport.

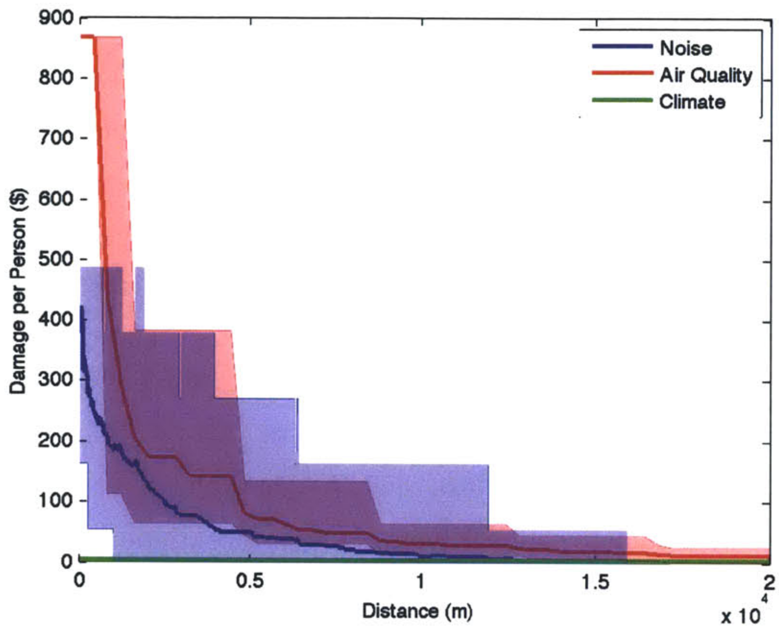

Figure 53. ATL damages per person as a function of distance from the airport, 2% discount rate (midrange lens)

It should be noted that as these are deterministic values, these results give no indication of the magnitude of uncertainty related with each of the environmental effects. Furthermore, differences in the assumptions of the underlying noise and air quality baseline data sets, may contribute to differences in localized peaks of damages. Finally, at distances very near the airport boundary, both noise and air quality impacts may be underestimated: air quality from resolution effects and noise from the inappropriateness of typical NDI's for DNL over 75 dBA.

5.1.4 Confounding Effects of Air Quality and Noise

Smith and Huang (1995) found, through a review of hedonic pricing studies, that air quality degradation can have a significant impact on housing prices with an observed

Marginal Willingness to Pay of between $0 and $100 for avoidance of 1 μg/m³ of total suspended particulates. Chay and Greenstone (2005) found that a reduction in particulate matter of 1 μg/m³ results in an increase in property value of 0.4-0.5% (0.3-0.4 elasticity) using regulation as an instrumental variable. These results show damages a factor of six greater than the largest estimates from the Smith and Huang meta-study.

The Chay and Greenstone (2005) results are based on 1970 and 1977 regulatory action instrumental variables, and it is difficult to abstract accurate present day damages from them for policy decision making. Nevertheless, it is useful to examine these numbers as a matter of scoping the order of magnitude of air quality impacts on housing. Because the overall air quality in the US has improved since 1977, the elasticities from Chay and Greenstone are utilized as opposed to the absolute percentage change in property value. Elasticity is the measure of the change in the value of one quantity (such as housing price) with respect to the change in another quantity (such as particulate matter) as shown in Equation 15.

$$E_{A,B} = \left|\frac{\partial \ln A}{\partial \ln B}\right| = \left|\frac{\partial A}{\partial B} \cdot \frac{A}{B}\right| \approx \left|\frac{\%\Delta A}{\%\Delta B}\right| \tag{15}$$

The aviation contribution to national average $PM_{2.5}$ concentration is estimated to be 0.01 μg/m³ and average overall concentrations are 12.6 and 17.76 for attainment and non-attainment areas respectively (Ratliff et al. 2009). For a negative marginal damage elasticity of 0.3-0.4, this results in percent change in total housing value loss of 0.024-0.031% for attainment areas and 0.017-0.023% for non-attainment areas. The total value of housing in the US for 2005 is 22.06T$ (Federal Reserve 2011). While 2005 was chosen to facilitate comparisons with available data from noise studies, it should be noted that the total housing value in the US dropped to 16.2T$ by Quarter 2, 2011. The resulting capitalized air quality damages on housing would be between 3.7-7B$, or between 35-65% of total capitalized noise damages. The resulting air quality impact values using the Smith and Huang results are between 5-10% of total capitalized noise damages.

The Atlanta Case study shows a mean increase of $PM_{2.5}$ of between 0.1-1.28 μg/m³ within 8 km of the airport and higher than 0.01μg/m³ contributions for distances within 16 km of the airport (Donohoo 2010). These indicate a factor of between 10 and 130 increase in air quality degradation at very near airport locations around ATL. The impact on housing value at near airport locations, especially in attainment counties where the percent change in air quality due to aviation will be higher, could be a significant confounding influence on the noise hedonic. Of the 63 airport noise hedonic studies included in the Wadud meta-study (Wadud 2009), not one included a control variable for air quality impacts.

Although air quality may have a confounding influence on the noise hedonic, the impact of aviation-related air quality on housing is small compared to that of its total influence on welfare. Chay and Greenstone (2005) estimate total savings to the US housing market to be $45B (2001 USD) from air quality improvements from 1970-1980. The EPA estimates the damages avoided by implementation of the Clean Air Act are valued at in 16.6T (1990 USD) from 1970 to 1990 (EPA 1997). The EPA analysis assumes that all mortality impacts occur in the year the decrease in emissions occurs, and that mortalities avoided remain relatively constant over the 1970 to 1990 period. Adjusting prices to 2001$, this assumes a reduction of between 7.6-11.46T (2001 USD) in air quality damages from 1970-1980. Thus, damages measured through housing values make up between 0.4-0.6% of damages from mortality. The EPA methodology has been called into question for significantly over-estimating mortality benefits in its methodology (Matus et al. 2008, Yang 2004). However, even if one excludes future year benefits to human health entirely under a general equilibrium model approach (Matus et al. 2008), air quality damages from housing still make up less than 10% of damages from mortality from 1970-1980. These results indicate that tracking air quality impacts on health is sufficient for monetizing air quality damages in policy analysis.

5.2 Economic Benefit and Distance from the Airport

Just as it is important to consider economic costs to achieve environmental benefits in an aggregate analysis, so too is it necessary to consider regional benefits and economic impact from aviation when considering regional environmental costs. Airports provide regional benefits including access to the national air system, high levels of safety, comfort and convenience of travel, as well as a source of recreation (FAA 1992). Airports and the airline industry provide direct economic benefits from operations at the airport, indirect economic benefits through increased demand for local intermediate services and products, and induced effects from employee spending. For a given airport, an approximately 10% increase in passengers leads to about a 1% increase in regional service-related employment (Brueckner 2003). Like environmental degradation, investigating the distribution of these benefits near airports is important in understanding aviation industry fundamentals and in investigating aviation environmental policy. Section 5.2.1 lays out an overview of some methods to investigate regional benefit on a scale relevant for comparison with environmental effects. Section 5.2.2 revisits ATL as a case study for investigating economic benefits from aviation.

5.2.1 Economic Analysis Approaches

Hedonic Pricing Approach

Because hedonic pricing methods are used to estimate noise damages, they are an attractive choice for valuing economic benefits per person or household. Of the sample of 65 hedonic studies utilized in developing the noise damage equations (He 2010), only 30 considered an airport access variable (Wadud 2009). Of these studies, the impact of airport proximity and economic benefit is unclear. A study by Espey and Lopez shows a positive correlation between airport distance and housing value, indicating that even controlling for noise there is an economic disbenefit for living near an airport (Wadud 2009, Espey and Lopez 2000). A study by Lipscomb (2003) shows a strong negative correlation between distance and housing value, but the study is limited to small urban communities. Tomkins et al. (1998), on the other hand, found the correlations between distance and housing value and between noise and housing value to be insignificant on their own, but the noise and distance interaction term was very significant. Finally, He (2010) showed that the inclusion of a dummy variable for airport access was not significant in determining WTP for noise abatement derived from a meta-study of hedonic pricing studies. Thus, the relationship between distance from the airport and economic benefit is unclear from hedonic pricing studies.

Input-Output Analysis Approach

Input-Output Analysis (IOA) uses a Keynsian economics demand model generated from industry specific input-output tables to estimate regional economic benefits. The advantages of this method are that data is easy to obtain relative to comparable techniques and it accounts for a wide range of private and external benefits of aviation operations (Malina and Wollersheim 2008). Several software systems with government and industry support including RIMS II, IMPLAN, and REMI can be utilized to perform airport input-output analysis with robust and comparable results (Rickman and Schwer 1995). While input-output analysis is useful in estimating regional benefit, it fails to account for locational attractiveness and therefore may underweight the impact of airport proximity. Furthermore, while IOAs exist for several airports, benefits are most often described as a step-wise production function for an entire metropolitan statistical area, giving poor resolution at the distance scale of air quality or noise damages (Batey, Madden and Scholefield 1993). However, as shown in the next section, input-output analysis can still be helpful in indicating benefit trends as a function of distance for a specific airport.

5.2.2 Atlanta Case Study Revisited

A 2005 study performed by the EDR Group examined the economic impact of the Hartsfield-Jackson Atlanta International Airport (ATL). The study included an economic IOA using models for the 28 counties in the Atlanta metropolitan statistical area and the state of Georgia based on the IMPLAN modeling system (EDRG 2005). The study produced estimated tax revenues on a per-county level for all 28 counties for direct, indirect, and induced economic effects. These values can be converted to tax revenue per person by dividing the total revenue by interpolating US Census county populations. To see if distance from the airport had a significant impact on regional benefit, these per person tax revenues were then mapped by average county distance to the airport. Figure 54 shows the geographic distribution of ATL economic impact related tax revenues per person.

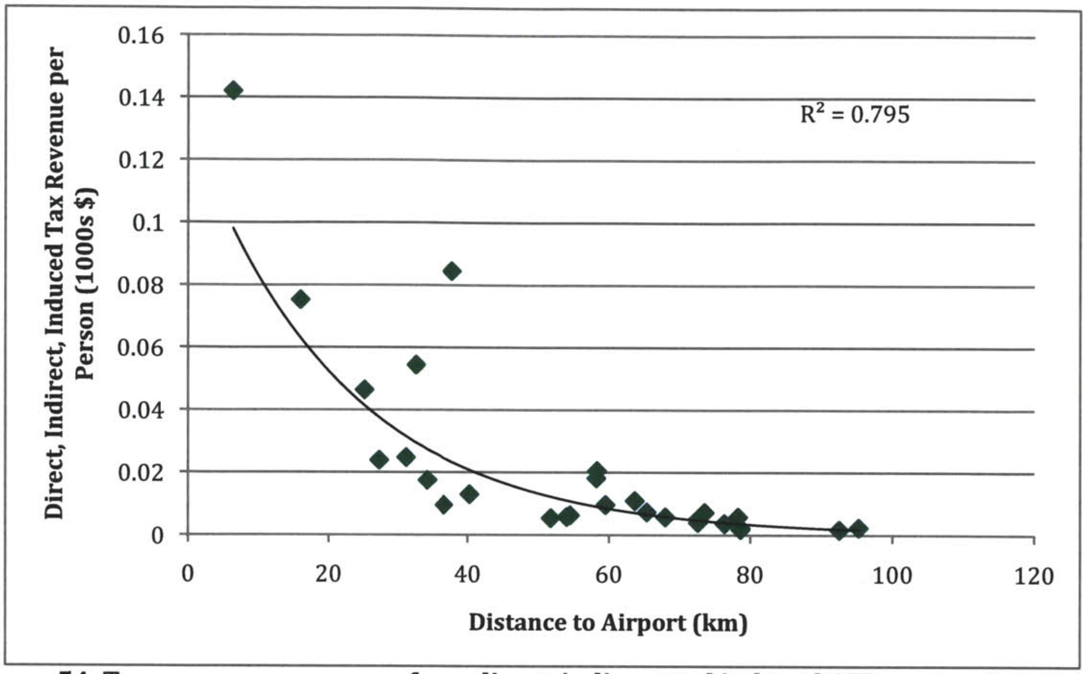

Figure 54. Tax revenue per person from direct, indirect and induced ATL economic impacts

Tax revenue per person is shown to have an exponential relationship with distance from an airport as described by Equation 16:

$$\ln(TR) = 4.49 + -0.102d \qquad (16)$$

where *TR* is the total tax revenue in 1000s $ (2005) and *d* is the distance from the airport in km. The fit has an $R^2 = 0.795$ and significance level of $p = 1.67E\text{-}7$. The data was tested against several other explanatory variables including county population, county-level average income, and unemployment. None of these were found to be significant at the $p < 0.05$ level when considered individually or in conjunction with distance. The distance to downtown Atlanta was also considered and found to be statistically significant. However, distance to downtown and distance to the airport are strongly correlated as expected (0.882) indicating multicollinearity. Considering distance to downtown alone results in an $R^2 = 0.493$, suggesting that distance to the airport better explains the data. An overview of the results of these multivariate regressions is shown in Table 14.

Table 14. Multivariate regression results for ATL direct, indirect, and induced tax revenues per person

Variable	p-value
Income Per Person	0.6928
Population 2005	0.5193
Unemployment Rate	0.3343
$Distance^2$	0.3209
Distance to Downtown	0.0002
Distance	1.68E-7

Georgia State Sales Tax is 4% and 5% in the city of Atlanta and state income tax rates range from 1%-6%. Thus, the EDRG data indicates about $2500 of economic activity generated per person within 20km of the airport, the distance considered in the environmental analysis in Section 5.1.3. While these economic benefits do not imply that individuals receive $2500 over a scenario where no airport exists, they do indicate that the Atlanta airport a distributed economic benefit in the same region that experiences the worst environmental costs. While there are limits to the appropriateness of direct benefit to cost comparison from this analysis, the data indicates benefits double that of total environmental midrange costs and about the same magnitude of total high lens costs. A 2009 follow-up report indicated an increase in direct business revenue to the state of Georgia of over 14 billion USD over the 2005 study (EDRG 2009).

5.3 Environmental Equity and Environmental Social Justice

The allocation of natural resource rights, from access to parks and wildlife, to freedom from environmental pollution, has increasingly become a concern of public policy. Costs of environmental degradation, especially those resulting from socioeconomic development such as transportation systems, tend to be unevenly distributed, often with poorer or marginalized groups bearing disproportionate shares (Syme and Nancarrow 2002). Thus, while the geographical distribution of costs and benefits provides a good complement to aggregated cost-benefit analysis, it may not make clear issues of environmental equity and social justice.

5.3.1 Environmental Equity

The right to a healthy environment for all citizens is a fundamental human right as affirmed by the Rio Declaration on Environment and Development (UNCED 1992). However, populations face different risk exposures and different policy-induced risk reductions. Environmental equity is the concept of equal sharing of risk burdens (Cutter 1995). Environmental equity examines spatial dispersion, temporal distribution, policy-making procedural equity, and social equity of decisions of natural resources and environmental externalities.

Addressing the spatial dispersion of environmental damages shown in Section 5.1 is an example of an environmental equity study. An attempt to explain geographic preference in policy can be made through the use of spatial discounting. A spatial discount can be thought of as the warranted rate of geographic preference (Perrings and Hannon 2001). The higher the rate of spatial discounting, the more the policy-maker favors decisions with respect to the dispersion point of the environmental degradation. However, the use of spatial discounting becomes difficult in integrated aviation policy where damages from different realms of environmental impacts have different spatial decay rates. Thus, applying spatial discounting to noise damages, which are monotonically decreasing, relatively smooth, and can be modeled as absolutely approaching zero in a fixed geographic range, may be appropriate in the Perrings and Hannon model, but applying the same method to climate damages or the combination of air quality and noise damages becomes more problematic. Furthermore, the extreme localization of effects from noise at an individual airport would suggest a highly decentralized approach to regulation under the Perrings and Hannon model (2001), which ignores the network effects of aviation policy.

Temporal distribution concerns, also called generational equity, are related to assuring fairness of a policy on future generations from current or past practices (Cutter 1995). In aviation environmental policy, this is most often represented through the effect of the discount rate. As described in Section 2.3.2, the discount rate is the method by which future damages are monetized in comparison to current year damages. The discount rate accounts for the fact that individuals have a positive time preference. This preference is explained because individuals expect to be wealthier in the future, because they are impatient, or from a combination of the two factors. Proponents of constant discounting or discounting environmental costs at market rates cite the partial Pareto improvement criterion: if aggregate welfare is higher under one policy, then a compensation mechanism can be implemented to transfer benefits between parties or generations (Goulder and Stavins 2002). Opponents of the discount rate cite intergenerational inequity, high costs and infeasibility of benefit transfers, and the inability to account for enjoyment costs and potential damage irreversibility such as species extinction (Ackerman and Heinzerling 2002). Efforts to separate the effects of pure rate of time preference and intergenerational differences have lead to the development of intergenerational discount rates to account for empirical and ethical concerns (Sumalia and Walters 2004). Sunstein and Weisbach (2008) provide a more detailed overview of discount rate that is not limited to intergenerational equity.

While concerns over discounting equity and uncertainty exist, they do not invalidate the approach as long as the extent and meaning of the uncertainties and the unaccounted for intergenerational inequities are conveyed to policy-makers (Goulder and Stavins 2002, Sunstein and Weisbach 2008). Finally, the temporal and spatial distributions of damages are often closely coupled, making damages diffuse over populations and generations and further complicating the issue of equity in aviation environmental policy.

Procedural equity concerns the method in which public policy and government enforcement are generated and applied in a non-discriminatory way (Cutter 1995). In aviation environmental policy, this can be difficult as non-discriminatory best practices in policy generation are different from country to country. Thus, when large international-centric policies are enacted, such as the CAEP/8 NO_X Stringency, procedural equity may not always be solvable. Furthermore, the intra-country policy procedural process is often not straightforward. Fan (2010) provides a case-study of the US aviation policy generation framework through an examination of the environmental impact of the Next Generation Air Transportation system program (NextGen). Fan finds that the traditional rational decision making framework fails to accurately describe policy-making in practice, and that aviation policy making in practice is more difficult. She highlights communication issues, knowledge gaps, and political influence as three areas of concern. Each of these domains provides barriers to procedural equity. Highly technical information with industry-specific vocabulary can be difficult to communicate, and the inability to present this information to people of all educational backgrounds can prevent entire populations from participating in the decision making process. Furthermore, as policy becomes wider reaching, the more high-level perspective an organization has the more generalized results it prefers (Fan 2010, Stone 1997). As results become more abstracted, any information on social equity may be lost. Thus, building procedural equity in the aviation environmental policy framework may not adequately prevent unfairness in regulatory decision-making.

Social equity refers to the roles of socio-economic factors such as race, gender, class, and political power in resource allocation, degradation, and consumption (Cutter 1995). Accounting for social equity can be difficult as assumptions and techniques to provide social equity in procedures, my result in countervailing trends that increase inequity. For instance, current best-practice in US transportation policy is to apply a uniform disaggregated value of statistical life (VSL) (DOT 2009). In theory, this is socially equitable as all populations are treated equally and environmental policy decisions will not permit an unfair burden of risk to fall upon groups of different ages or socio-economic status. However, in addition to the concerns of VSL limitations presented in Section 3.2, VSL aggregation may actually increase inequity among poorer populations by finding an environmental policy that is cost-beneficial for a group even though that group may be unwilling or unable to bear the costs of the policy (Sunstein 2004). Equity weighting is one method by which the distribution of environmental costs and benefits can be adjusted over populations of differing economic statuses (Anthoff et al. 2009). Environmental equity is closely tied to the field of environmental social justice, which looks at preventing or remedying injustice imposed on a specific group of people. A brief description of environmental social justice in the United States and the importance of the field in examining aviation environmental policy are presented in Section 5.3.2.

5.3.2 Environmental Social Justice

The principle of environmental social justice is the guaranteeing of rights for all people regardless of socio-economic status. These rights include the protection from unwarranted environmental degradation, the security of health and safety from environmental pollution, the assignment of culpability and responsibility to polluters, and the redressing of deleterious impacts with targeted remedial action of appropriate scale (Cutter 1995).

The field of environmental social justice has its roots in combined social and environmental activism. In 1982, the state government of North Carolina selected Afton, a poor, predominantly black community in Warren County, as the site for a hazardous waste landfill. In response, Benjamin Chavis, the head of the United Church of Christ's Commission on Racial Justice, coined the term 'environmental racism' as "racial discrimination in environmental policymaking, the enforcement of regulations and laws, the deliberate targeting of communities of color for toxic waste facilities, the official sanctioning of the life-threatening presence of poisons and pollutants in our communities, and the history of excluding people of color from leadership of the ecology movements" (Brulle and Pellow 2006). The decision ignited protests, eventually resulting in over 500 arrests. This event provided the impetus for a landmark government study on environmental pollution and race, *Siting of Hazardous Waste Landfills and Their Correlation with Race and Economic Status of Surrounding Communities* (GAO 1983, Bullard 2004).

Since 1990, the study of environmental racism has garnered support among ecologists and economists and has merged with the field of social justice. Social justice is rooted in the Rawlsian concept of justice as fairness. Rawls sought to develop a societal construct of fairness that improved upon the theory of utilitarianism because utilitarianism did not account for individual preference in quality of life utility and it could lead to situations where some people suffered harm in order that others could benefit (Flower 2010). Rawls basic principles were that everyone has an equal right to the most extensive set of basic liberties that would not prevent others from having access to the same scheme of liberties, that equality of opportunity would be upheld, and that social and economic inequalities would be arranged such that the greatest benefit is given to the least advantaged. Under these principles the field of environmental racism became environmental social justice.

Beyond racism, environmental social justice has expanded to include issues of class disparity and gender among other socio-economic concerns (Brulle and Pellow 2006).

Environmental social justice became a matter of national policy-setting best practices through President Clinton's signing of Executive Order 12898 (1994), which mandates that all federal agencies to take into account issues of environmental justice in their operations. Thus, issues of noise pollution, local air pollution, and climate change from aviation must consider not only what the environmental costs are and where those environmental costs occur, but who primarily bears those costs. In aviation policy, the two primary areas of concern are the siting of new airports and the control and management of aviation noise and emissions. The siting of airports does not directly affect the selection of criteria of noise and emission stringencies, and therefore falls outside the scope of this thesis. Bullard (2004) provides a general framework of environmental justice and the siting of locally unwanted land uses (LULUs).

Ensuring social justice is difficult in the management and mitigation of damages associated with noise and air quality. Air quality damages are a strong function of wind dispersion, and therefore difficult to control. Furthermore, the basis of the standard linear aggregate CRF methodology may institutionalize decision-making inequality. Although aggregate epidemiological research on macro-level factors identifies strong correlations between air quality degradation and health impacts, studies of environmental inequality and health disparities remain relegated to largely separate domains. There still remains a knowledge barrier about how risk is attributable to social factors or how separate social and environmental risks may combine to create cumulative or exponential burdens on the health of the least advantaged populations (Brulle and Pellow 2006). This can be seen as a limit of the air quality modeling methodology.

Noise, by virtue of being a more controllable pollutant than air quality, is perhaps more illustrative of the concerns of environmental social justice. Sobotta et al. (2007) examines the ethnicity of groups affected by noise pollution around a municipal airport and finds that Hispanic populations are more likely to be exposed to 65 dB DNL noise than non-Hispanic populations at the same distance away from an airport. Sobotta finds that being Hispanic is the best predictor of being exposed to 65 dB DNL at this airport with poverty and education being the next best predictors and that these results are robust over two decades.

5.4 Policy-Making Insights

There exists a fundamental tension between policy analysis at the national and regional scale, one with strong implications on the environmental impacts of aviation. Aggregate cost-benefit is a useful policy tool because, as opposed to cost-effectiveness, it indicates which policies present a net social benefit. It is easy to understand, the results are communicable, and it provides a lot of information across several domains in a condensed manner. Cost-benefit analysis is well suited for aviation policy as the industry can be thought of as national or global in scale and plays an important role in national and international transit. However, the scale of aviation environmental impacts can range from the local to the global and is both diffuse over time and contains large amounts of uncertainty. Thus, a distributional analysis of localized costs and benefits is essential for capturing fundamental information about a proposed policy. Furthermore, the examination of the underlying distribution of costs can reveal fundamental, sometimes conflicting, information about the nature of the human response to environmental damage.

Collective action problems and uneducated risk perception are two issues that can confound expected and actualized responses to aviation noise. These can be difficult to overcome, and actions in one realm may have unintended consequences in another. For instance, in the CAEP/8 NO_X Stringency proposal, improvements to air quality led to modest increases in noise damages and a potentially counterbalancing climate detriment and all impacts were subject to uncertainty. Choosing to pursue an increased NO_X stringency, while potentially increasing net societal utility, may necessarily harm individuals to achieve an overall gain.

While the analysis in Section 5.1, lays out a framework for considering distributional analysis in aviation environmental policy, it is not without flaws. First, it focuses on a baseline of aviation impacts and not on a policy minus baseline. Alternatively, it assumes the alternative to business-as-usual operations is a world without aviation. Not only is this assumption constraining, the methodology may increase uncertainty by not muting the underlying model uncertainty through a paired Monte Carlo analysis.

Second, when used in practice, it may oversimplify or under-simplify the relationship among airport distance, air quality, and noise damage. While national average damage from noise as a function of distance from an airport can be described by a negative exponential relationship, this formula may not accurately explain the noise at an individual airport where the geometry of noise contours may be better described by a range of minimum and maximum values. However, providing more information on environmental impacts may overwhelm decision makers, who already must process large quantities of data spanning many technical disciplines. Furthermore, policy-makers may strive for ambiguity to allow decision making to occur. By over-elucidating data, policy-makers will potentially alienate the proportion of the electorate harmed by the proposed policy. In this sense, big-picture ambiguity helps transform individual interests into collective decisions (Stone 1997), and therefore may be necessary to produce a beneficial policy.

Finally, our models may not effectively characterize interaction between air quality, noise, and climate change. Health impact interactions among different environmental sources are poorly understood and may have synergistic effects. Significant climate change may change background chemistry concentrations, leading to unaccounted for impacts on air quality. Likewise, background aerosol concentrations can play a significant role in overall climate forcing, further coupling air quality and climate change. There may also be confounding effects of noise and air quality on housing prices as seen in the studies of Smith and Huang (1995) and Chay and Greenstone (2000). While the total environmental effect captured in the housing market is small, although perhaps not negligibly so, compared to the damages seen through mortalities, the impact may have implications on the allocation of damages to the noise hedonic.

While protecting the environment through effective policy is an important goal, aviation environmental policy cannot fail to account for the benefit the airline industry provides to the economy and the national infrastructure. Underlying the economic analysis is a fundamental question of causality: do airports drive economic growth or is economic growth driving airport considerations, and how does one disaggregate the regional benefit (Freestone 2009, Green 2006). Furthermore, any expectation that economic benefits outweigh environmental costs with airport proximity may vary both by community around a single airport and from airport to airport. For instance, studies have shown that expected economic benefits are overstated for freight-dominated airports (Freestone 2009).

6 Conclusions

The focus of this work has been to continue the development of APMT-Impacts modules to allow for fast and effective policy analysis, to use these models in an integrated cost-benefit analysis of an aviation environmental policy, and to examine the distribution of the environmental impacts on a regional scale for the purpose of expanding the policy-making analysis framework. This chapter summarizes the major findings of this work and offers concluding thoughts on aviation environmental policy analyses on a national and regional scale. The chapter ends with a discussion of opportunities for future work.

6.1 Aviation Environmental Modeling

To effectively quantify the effects of a policy, the underlying impact on the environment must first be modeled. Aviation environmental modeling can be difficult as physical and chemical pathways can be poorly understood or subject to confounding factors and aviation impacts can be diffuse over time and space. APMT-Impacts models the impact of aviation on noise pollution through changes in housing property values. While property value degradation is a useful proxy for monetized environmental costs, it may not capture all physiological and behavioral impacts of noise. APMT-Impacts models the impact of aviation on local air quality through health impacts associated with $PM_{2.5}$, and it models the impact of aviation on climate change through total welfare change from CO_2, other greenhouse gas emissions, and changes in aviation-induced cloudiness.

Key contributions of this thesis include expansion, updating, and use of the modules above and a focus on the APMT-Impacts Climate Module. The climate system presents several key challenges for modeling. Background scenarios are highly uncertain and can have a significant impact on damage estimates. In considering background scenarios, it is important to examine both the projection of emissions and the projection of welfare changes. Understanding the appropriate use and limitations of representative concentration pathways is important for scenario analyses. This thesis also considered alternative functions for modeling the earth's temperature response to radiative forcing changes. While a variety of temperature models are available with varying degrees of fidelity, this thesis demonstrated that endpoint metrics of concern to policy makers are not highly sensitive to the underlying temperature-response model. However, a model that considers deep-ocean temperature change more appropriately models underlying background temperature responses and is, therefore, recommended for use in policy analyses. APMT-Impacts modules are most appropriate for fleet-wide aggregate policy-analysis, and have been used to develop aviation-specific metrics for air quality and climate damages.

6.2 Aggregate Cost-Benefit Analysis

Cost-Benefit Analysis is a useful tool for analyzing large-scale aviation policy that effects several economic and environmental domains. While the uncertainties are substantial and unavoidable, they do not invalidate the use of discounting or benefit–cost analysis, but analysts do have an obligation to acknowledge them in their policy evaluations (Goulder and Stavins, 2002). Using Monte Carlo analysis and a lens framework is a way to distill large amounts of information in a way that is useful for policy-makers. Here, aggregate cost-benefit analysis was used to examine an ICAO-CAEP NO_X Stringency policy. The results showed that despite the policy having positive effects for national air-quality, under a wide variety of future scenarios, no increase in stringency would be cost-beneficial due to high industry costs and trade-offs on climate and noise performance.

The APMT-Impacts Air Quality RSM was run under several conservative assumptions including no impacts from cruise emissions and a constant background emissions scenario. A factor of 4.7, taken from a study of cruise emissions on ambient air quality (Barrett 2010), was applied to the air quality benefits to account for these assumptions. When accounting for cruise emissions, Stringencies 1 through 5 are cost beneficial, with Stringency 5 being the most cost-beneficial. The results were very sensitive to industry costs. Under a reduced cost scenario, Stringency 5, a 15% increase in NO_X stringency, is the most cost-beneficial stringency. A cost-effectiveness approach showed Stringency 7 to be the most cost-effective. ICAO-CAEP ultimately recommended Stringency 6 for implementation.

Finally, this thesis used recommendations from Mahashabde (2009) to improve the communication of results among technical specialists and policy-makers. Using a reactive approach to policy analysis, including creating and revising lenses as part of a dialogue, analysts were able to better present results of interest to decision-makers. For example, the creation of specified NO_X lenses during the policy-making process helped isolate the impacts of increased CO_2 and decrease NO_X emissions on climate damages.

6.3 Regional Distribution of Impacts

Aviation environmental impacts are not distributed over areas and populations equally; there can be regional variations as well as a gradient of increasing damages as one approaches a major airport. To account for these variations, approaches that compliment cost-benefit analysis are necessary such as a distributional analysis. For a midrange lens and a 3% discount rate, noise damages as a function of distance from an airport can be estimated as $ND = 443e^{-0.543x}$ where ND is noise damages in 2006 USD, and x is distance from the airport in meters but are strongly correlated to number of operations at the airport. However, because noise contours generally follow runway directions, noise damages are better expressed as a relationship between minimum and maximum damages at a given distance.

A case study of the Atlanta airport using a midrange lens shows that from a distance of 2-12km, the average magnitude of yearly damages per person is similar for both noise and air quality. However, there is significant variability in the magnitude of noise damages, causing some populations to be disproportionally impacted by one impact or the other. At distances of less than 2km, air quality damages appear to dominate total aviation environmental damages, although this factor is heavily influenced by the SMATing post-processing.

The inequity of cost distribution has several policy implications. Failure to account for near-airport impacts may result in populations susceptible to unacceptable damages or unacceptable risks of mortality or illness. Conversely, airports provide benefits spread out disproportionately over time and space. Economic tools such as hedonic pricing methods and input-out analysis can be used to examine the distribution of benefits from aviation. Hedonic pricing studies on property values are inconclusive as to economic benefit as a function of distance from an airport. A case study of the Atlanta airport shows that utilizing countywide direct, indirect, and induced tax revenues from aviation as a proxy for economic benefit, a strong correlation between proximity to the airport and benefit is observed.

A regional-scale analysis is important for the environmental social equity and social justice of proposed policies and regulations. By varying the scale of the analysis, an understanding of the underlying trends helps indicate important interactions across different domains. For example, applying historical estimates of air quality damages on housing property values indicates that capturing health impacts alone from $PM_{2.5}$ is sufficient for estimating total damages. However, at a local scale, $PM_{2.5}$ contributions from aviation may be high enough that they interact with the noise hedonic.

6.4 Future Work

There are opportunities for continued research along every step of the aviation environmental policy analysis pathway. For aviation noise, research is necessary to better understand the impact of continued noise exposure on human health and the relationship between housing value and total environmental damages. Addressing background noise level and noise sensitivity, both in the underlying hedonic pricing studies and in airport specific estimations of damages, is a further area of uncertainty that can be improved through research. For air quality, continued progress in determining near-source dispersion of pollutants and the impact of full-flight emissions is important for higher fidelity damage estimates. This research is also necessary to better understand possible environmental compounding issues in the noise hedonic. Climate change modeling is a discipline with tremendous scientific and economic uncertainty. For aviation specifically, the impacts of NO_X emissions and aviation-induced cloudiness remain areas of significant interest. Research on altitude dependence, background atmospheric conditions, emission species interactions, and induced radiative forcing is necessary for further advances in modeling capabilities.

The applicability of regional-scale damage results for policy-making remains unproven. Utilizing higher-resolution air quality data across several airports is a necessary step to understand trade-offs among noise and air quality damages as a function of distance from the airport. The amount of data generated by a regional impacts analysis may need to be further distilled to be of use to policy-makers. Techniques to present results over multiple geographic scales should be investigated for use in future aviation regulatory analyses.

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