COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION (CAEP)

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Agenda Item 2: Review of technical proposals relating to aircraft engine emissions

CAEP/8 NO_X STRINGENCY COST-BENEFIT ANALYSIS DEMONSTRATION USING APMT-IMPACTS

(Presented by the United States)

SUMMARY

This paper updates the status and capabilities of the Aviation Environmental Portfolio Management Tool for Impacts (APMT- Impacts).[1] It also documents the use of the tool as a demonstration for the CAEP/8 NO_X stringency analysis.

The Federal Aviation Administration (FAA), in collaboration with the National Aeronautics and Space Administration (NASA) and Transport Canada, is developing a comprehensive suite of software tools to facilitate thorough consideration of aviation's environmental effects. The main goal of this effort is to develop a critically needed ability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios.

Results from the CAEP/8 NO_X stringency analysis with APMT-Impacts are included in the Appendix.

[1] The Aviation Environmental Portfolio Management Tool (APMT) was formally introduced to the CAEP Steering Group at the November 2004, Bonn meeting, and to the full CAEP in CAEP/7_IP/25. Since that time the Steering Group, FESG, and MODTF have been kept informed of APMT research and demonstration developments.

1. INTRODUCTION

1.1 In the past, modeling tools that supported CAEP generated either noise or emissions outputs, against which policy costs were calculated. CAEP considered the cost to implement a policy against a single environmental performance indicator (e.g., number of people impacted by noise). With the advent of the work on common databases and inputs, CAEP initiated a process to jointly consider noise, surface air quality, climate change, fuel burn, plus industry and consumer cost interdependencies. The Federal Aviation Administration (FAA), in collaboration with Transport Canada and the National Aeronautics and Space Administration (NASA), has developed a comprehensive suite of software tools to facilitate thorough consideration of aviation's environmental effects. The main goal of this effort has been to create a critically needed ability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios. The component of the tools suite that estimates the environmental impacts of aircraft operations through changes in health and welfare endpoints for climate, air quality and noise is entitled the Aviation Environmental Portfolio Management Tool for Impacts (APMT-Impacts).[2] Beginning in 2004, information on APMT has been submitted to CAEP and stakeholders, including the initial APMT requirements and architecture studies and prototyping plan.[3] APMT Progress was last reported to the CAEP in February 2007, in CAEP/7_IP/25.

1.2 At CAEP/7, transitioning to a more comprehensive approach for assessing and addressing aviation environmental impacts was considered, as documented in CAEP/7-WP/68, Para 4.14. The CAEP/7 report notes that *"to fully assess interdependencies and analyses of the human health and welfare impacts, CAEP would need to: (1) employ tools that (are) capable of looking (at multiple) environmental parameters; (2) frame the impacts of these parameters on common terms, so that it can understand the implications of the interdependencies…. Following the discussion, the meeting:*

a) *acknowledged the growing complexity associated with assessing noise and emissions effects of aviation, especially when considering impacts and their influence on benefits-costs, as well as the case for CAEP to get a better understanding of these impacts and the benefits of environmental mitigation based on establishing the value of such reductions in addressing the stated problem ;*

b) *endorsed the consideration of a transition to a more comprehensive approach to assessing actions proposed for consideration by CAEP/8;*

c) *specified that traditional cost-effectiveness analyses of policy scenarios requiring economic analysis be provided for CAEP/8, but that environmental impacts and cost benefit information and analyses also be provided in the form of a sample problem which may enable CAEP/8 to put the new information into context, and to further consider how to integrate environmental impacts and interdependencies information into its decision-making; and*

d) *note that the tool suite under development by the United States and Canada is intended to have the capability to enable implementation of this more comprehensive approach in a manner that is consistent with the interdependencies framework established for the CAEP/8 work programme."*

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[2] APMT-Impacts was formerly named the APMT Benefits Valuation Block (BVB)

[3] Requirements Document for the APMT. Ian Waitz, et al. June 2006. (Report No. PARTNER-COE-2006-001), http://mit.edu/aeroastro/partner/reports/apmt-requirmnts-rpt2006-001.pdf;
Architecture Study for the APMT. Ian Waitz, et al. June 2006. (Report No. PARTNER-COE-2006-002), http://mit.edu/aeroastro/partner/reports/apmt-arch-rpt2006-002.pdf;
Prototype Work Plan for the APMT. Ian Waitz, et al. June 2006. (Report No. PARTNER-COE-2006-003), http://mit.edu/aeroastro/partner/reports/apmt-prototype-rpt2006-003.pdf

1.3 This paper serves to update CAEP on the progress and capabilities of APMT-Impacts. The paper also fulfils task MOD.07, going beyond the traditional cost-effectiveness analysis to provide environmental impacts and cost-benefit information for the CAEP/8 NO_X stringency analysis.

2. FESG – MODTF ANALYSIS

2.1 CAEP tasked the Forecasting and Economic Support Group (FESG) and Modelling and Database Task Force (MODTF) to conduct an analysis of stringency scenarios to reduce emissions of nitrogen oxides (NO_X) relative to the ICAO CAEP/6 Standard as an element of the CAEP/8 work programme. Ten stringency options were analysed for two potential implementation years, 2012 and 2016, with potential changes ranging from between 5% and 20% compared to the current Standards. The analysis was based on an assessment of the changes in emissions inventories and costs that would result from modifying, where appropriate, the existing in-production engines to meet the range of scenarios. For the analysis, MODTF assessed emissions reductions and potential environmental trade-offs for the scenarios. FESG established the costs assumptions and assessed overall cost-effectiveness of the stringencies. The final cost-effectiveness results were presented as costs per tonne of NO_X reduction for the ICAO Landing Take-Off (LTO) cycle in a joint MODTF-FESG paper to CAEP/8 (WP015).

2.2 Noting that the large engines dominate the NO_X reductions calculated by the analysis, the joint MODTF-FESG effort concluded that (1) the cost per tonne NO_X reduced is lowest for stringency scenarios #1 through #5, (2) the cost increases by a factor of three to four for scenarios #6 and #7, and (3) the cost further doubles for scenarios #8 through #10.

3. POLICY ANALYSIS APPROACHES

3.1 Regulatory agencies in many world regions use economic analysis to guide policy decisions through an explicit accounting of the costs and benefits associated with a regulatory change. Economic policy evaluation approaches commonly used in policy assessments include cost-benefit, cost-effectiveness and distributional analyses. Cost-effectiveness analysis (CEA) is meant to be used for evaluating policies with very similar expected benefits; a policy that achieves the expected benefits with the least costs is the preferred policy.[4] A cost-benefit analysis (CBA) requires that the effect of a policy relative to a well-defined baseline scenario be calculated in consistent units, typically monetary, making costs and benefits directly comparable. The cost-benefit approach is aimed at identifying approaches that maximize the net social benefit, where the net benefit is defined as the benefits of the regulation (e.g. number of people removed from a certain noise level) minus the costs of the regulation (e.g. the additional costs of technology).[4&5]

4. ANALYZING IMPACTS & INTERDEPENDENCIES

4.1 In October 2007, CAEP convened a scientific “Impacts Workshop” to assess the state of knowledge and gaps in understanding and estimating noise, air quality and climate impacts of aviation. The workshop concluded that intrinsic physical interrelationships exist between noise, air quality and climate; that interdependencies are important; and that trade-offs are routinely made (e.g. modern aircraft

[4] Kopp, R.J., A.J. Kuprick, and M. Toman, “Cost-Benefit Analysis and Regulatory Reform: An Assessment of the Science and the Art,” Resources for the Future Discussion Paper, No. 97-19, 1997

[5] Revesz, R., and M. Livermore, “Retaking Rationality: How Cost Benefit Analysis Can Better Protect the Environment and Our Health,” Oxford University Press, 2007

design and mitigation strategies). There was also strong consensus that CEA was not appropriate for assessing interdependencies among noise, air quality and climate impacts. A report was issued to document the workshop; but, CAEP has not generated any guidance on appropriate methods or procedures for analyzing the environmental impacts of aviation.

4.2 To quantify the environmental impacts of aircraft operations, APMT-Impacts uses methods and assumptions that are documented in peer-reviewed scientific journals. The tool assesses the physical and socio-economic environmental impacts of aviation using noise and emissions inventories as the primary inputs. Impacts and associated uncertainties are simulated based on a probabilistic approach using Monte Carlo methods. The APMT-Impacts tool is comprised of three different modules to address noise, air quality, and climate impacts. Table 1 lists the impacts modeled under each area and the corresponding metrics. Additional information on methods is in Appendix A, Section 4.

Table 1: Overview of Environmental Impacts Modeled in APMT

Impact Type	Effects Modeled	Primary Impact Metrics	
		Physical	Monetary
Noise	Population exposure to noise, number of people annoyed Housing value depreciation, rental loss	Number of people	Net present value
Air Quality	Primary particulate matter (PM) Secondary PM by NO_X and SO_x	Incidences of mortality and morbidity	Net present value
Climate	CO_2 Non-CO_2: NO_X-O_3, Cirrus, Sulfates, Soot, H_2O, Contrails, NO_X-CH_4, NO_x-O_3long	Globally-averaged surface temperature change	Net present value

4.3 As noted during the Impacts Workshop, there is a range of assumptions that can be used for modelling impacts and benefits. The APMT-Impacts process organizes these assumptions into a decision-making framework, which is referred to as "lenses." Each lens represents a combination of compatible inputs and assumptions. These combinations of inputs and model parameters can be thought of as describing a particular point of view or perspective through which to consider a policy and are thus designated as lenses. Some example lenses include a lens with mid-range environmental and economic impacts; one with worst-case environmental impacts and mid-range economic impacts; one focused on short or long-term environmental impacts; or one that adopts a conservative perspective for one impact while keeping a mid-range perspective on others. Several lenses can be decided upon prior to policy assessment with guidance from users to evaluate a given policy from different perspectives.

4.4 Information on uncertainties accompanies APMT-Impacts analysis results, which is in accordance with best practice in the scientific community to communicate uncertainties with results and findings. Individuals who are new to this information may be inclined to value data with identified uncertainties less than traditionally presented cost-effectiveness results that lack a similar quantification of uncertainties. It should be noted that both cost-effectiveness and cost-benefit analyses employ discount rates, which have an inherently high degree of uncertainty regardless of whether the uncertainty is quantified. Thus, greater confidence should not be assumed when there is an absence of information on the uncertainties for the cost-effectiveness results.

5. APMT-IMPACTS FINDINGS

5.1 A comprehensive description of the methods and results from use of the APMT-Impacts tool as a demonstration for the CAEP/8 NO_X stringency analysis are included in Appendix A. The main findings from the analysis are as follows:

a) Large engines dominate the NO_X reductions calculated by the analysis, with reductions ranging from -5% to -8% relative to the baseline by 2036.

b) Noise changes are not a significant influence on the analysis of costs and benefits.

c) Input data from the MODTF analysis show that fuel burn inventories are relatively unchanged (below 0.05%) relative to the baseline for all stringencies until the MS3 fuel penalty is added to the -20% stringencies, at which point the maximum change by 2036 is 0.15%. Therefore, the climate costs of the CO_2 emissions changes are typically smaller than other costs and benefits.[6]

d) There were no combinations of assumptions, sensitivity studies, or methods in which the APMT-Impacts analyses found the -20% stringency scenarios to provide benefits that appreciably exceed costs (i.e. by more than the uncertainties in scientific understanding and modelling methods).

e) Stringencies 1-5 were found to be cost-beneficial when anticipated modeling limitations and uncertainties for airport-local effects, cruise emissions, and future background changes were included in the APMT-Impacts analyses.[7]

f) Stringencies 6 and 7 also become cost-beneficial when the anticipated air quality modeling limitations and uncertainties are considered and the costs incurred to implement NO_X reductions are considered to be half of the FESG provided costs incurred to implement NO_X reductions.

g) APMT-Impacts calculations that use only peer-reviewed methods and use the FESG implementation costs do not produce cost-beneficial estimates for any of the policies, regardless of the environmental lens assumptions.

6. COMPARISON OF COST-EFFECTIVENESS AND COST-BENEFIT

6.1 For both CEA and CBA methods the results are strongly driven by the assumptions for the industry costs incurred to implement NO_X reductions, and the fuel burn penalty assumptions.

6.2 As discussed in Section 3, the cost-effectiveness approach allows for a selection among options, based on which achieves the least per-unit cost ($/tonne NO_x reduction). Cost-effectiveness does

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[6] Depending on the literature sources used, the impacts from changes in NO_x on climate can be more prominent. Nonetheless, the warming and cooling effects of NO_x reductions may counterbalance one another to some extent and may also be counterbalanced by the changes in CO_2 emissions.

[7] These known modeling limitations and uncertainties are likely to lead to an under prediction of the magnitude of air quality impacts (discussed further in Appendix A, Section 4.1.2), and were not included in previous APMT-Impacts methods since they are just now being established in the literature (i.e., the first papers are presently under peer review) and/or the modelling methods are still being developed to formally incorporate them; thus, they have a high uncertainty.

not, however, assess whether the costs incurred are justified in light of the benefits projected. For the CAEP/8 NO_X stringency analysis, the cost-effectiveness approach does not directly take into consideration tradeoffs with noise and climate impacts as a decision criterion. Thus, the MS3 fuel burn trade-off is only indirectly accounted for by incorporating increased fuel costs; the environmental impacts of increased fuel burn are not considered in the cost-effectiveness analysis. The cost-effectiveness analysis concludes that the lowest stringencies are the most cost effective; however, they also result in the lowest NO_X reductions.

6.3 The cost-benefit analysis presents a more comprehensive assessment of the policy options by quantifying more of the environmental impacts. Articulating the uncertainties in the impacts under various assumptions is itself a valuable contribution to understanding potential policy outcomes. Given that ICAO has not previously considered impacts and cost-benefit analysis results, the more complete information can make the "best" policy choice less obvious. Further, the many permutations of the analyses presented in Appendix A, though not exhaustive, do result in a range of outcomes that can be daunting. Nonetheless, given the new nature of this method for CAEP, articulating the broadest possible range of outcomes for the full spectrum of assumptions should be a value in considering the future role for impact and cost-benefit analyses.

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APPENDIX

APMT-IMPACTS: ASSESSING THE ENVIRONMENTAL IMPACTS OF AVIATION

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1. INTRODUCTION

The environmental impacts of aviation, in particular those related to community noise, air quality, and climate change, have become increasingly important over the last 50 years. Many options exist for mitigating these impacts, including aircraft and engine technologies, advances in air traffic management and operational procedures, alternative fuels, and government policies. However, in choosing among these options, it is important that we make good decisions. The costs and benefits of mitigation options are often not easy to discern because of complex interdependencies among environmental impacts, aircraft design, operating procedures, and industry responses to policies. Making the wrong decisions can be costly if important health and welfare concerns are not addressed, and/or if inappropriate constraints are placed on our mobility and economy. Moreover, because of the time required for technology development (~10 years), and extended use in the fleet (~25 years), we must live with our decisions for a long time—especially considering that the emissions can persist in the atmosphere for centuries.

This paper focuses on the methods and processes for choosing among options for reducing the environmental impacts of aviation. Currently accepted methods and processes are based on an incomplete accounting of costs and benefits. They typically focus on quantities of emissions rather than estimates of impacts, and they typically do not explicitly quantify interdependencies with other environmental effects. We show that explicit assessment of the interdependent environmental impacts can provide a different and valuable perspective for decision-making.

1.1 Aviation environmental regulations and decision-making practices

Aircraft noise, with the most readily perceived community impact, was the first area to be regulated in the 1960s by the International Civil Aviation Organization (ICAO). ICAO published the Annex 16: Environmental Protection, Volume I - International Noise Standards in 1971 with subsequent increases in stringency since that time [1]. Emissions Standards were next to follow with the implementation of ICAO Standards and Recommended Practices (SARPs) for aircraft emissions 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 [2] for nitrogen oxides (NO_X), hydrocarbons (HC), carbon monoxide (CO) and smoke.

In the last few years, many activities to address climate change impacts of aviation have been initiated. For example, ICAO recently established the Group on International Aviation and Climate Change (GIACC), which is responsible for providing policy guidance to ICAO for addressing commercial aviation's climate change impacts [3]. The United States Federal Aviation Administration (FAA) has recently developed the Aviation Climate Change Research Initiative (ACCRI) with participation from the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA) and the United States Environmental Protection Agency (US EPA) with the aim of promoting aviation-related climate change research to support decision-making [4]. The European Commission has issued a directive that requires the inclusion of aviation in the EU emissions trading scheme as a part of a post-Kyoto agreement for the next commitment period starting in 2012 [5]. This new directive targets flights arriving to and departing from airports located in EU Member States (with some exceptions). The European Commission has published a list of expected participating aircraft operators along with guidelines for monitoring and reporting fuel usage, CO_2 emissions, and distance flown in a given year with reporting set to begin in 2010 [6, 7]. Within the United States, the EPA has published an advance notice of proposed rule-making inviting public comments on the implications of regulating greenhouse gases under the Clean Air Act which also includes mobile sources [8]. The US EPA has also finalized a rule requiring mandatory reporting of greenhouse gas emissions from large sources, including aircraft, to collect data for informing future policy decisions with reporting to begin in 2011 [9].

Given typical projected growth rates for commercial aviation activity of about 5% per year over the next 20-25 years [10], the environmental impacts of aviation are expected to gain more significance against a background of declining impacts from many other sources. Thus, it is critical to assess which aircraft and engine technologies, air traffic management strategies, and government policies should be employed to balance desires for more mobility with those for reduced environmental impacts. Such an assessment requires understanding the trade-offs among technologies, operations, policies, market conditions, manufacturer and airline economics, and the environmental impacts including noise, air quality, and climate change.

Conventionally, the Committee on Aviation Environmental Protection (CAEP) within ICAO has addressed aircraft noise and emissions impacts independently of each other through measures such as engine NO_X emissions certification Standards or aircraft noise certification Standards. Regulatory decisions have been based on cost-effectiveness metrics where reductions in aircraft noise levels or quantities of emissions are evaluated relative to the expected implementation costs of a proposed policy. There has been no explicit estimation of the environmental benefits of proposed measures, and uncertainties involved in regulatory analysis have been treated in a limited manner. The shortcomings of current decision-making practices have been recognized both within and beyond the ICAO-CAEP. The seventh meeting of the ICAO-CAEP held in 2007 recognized the necessity for comprehensive analyses that assess the tradeoffs among noise and emissions impacts and economic costs to better inform policymaking decisions [11]. Developing tools and metrics to assess and communicate aviation's environmental impacts is also one of the recommendations made in a recent Report to the U.S. Congress on aviation and the environment [12].

1.2 Paper Overview

The main objective of this paper is to illustrate how a direct assessment of environmental impacts, with explicit consideration of interdependencies among impacts, can change the decision-making perspective. We take as a relevant current example an assessment of some of the engine NO_X emissions certification stringency options considered for the eighth meeting of the ICAO-CAEP in February 2010. We use the same assumptions and detailed emissions inventories and industry cost estimates as those used for the officially sanctioned cost-effectiveness analysis.

For our analysis we use the Aviation environmental Portfolio Management Tool (APMT), which is a component of the aviation environmental tool suite being developed by the Federal Aviation Administration's Office of Environment and Energy (FAA-AEE) in collaboration with the National Aeronautics and Space Administration (NASA) and Transport Canada. While the discussions focus on APMT and the analysis of an engine NO_X emissions certification Standard, the broader conclusions are generally applicable to other models being developed, and to other technological, operational, and policy options for mitigating aviation's environmental impact. In addition to providing environmental and economic impact estimates, this work also quantifies uncertainties throughout the policy analysis process and explores the sensitivity of results to variability in model inputs and parameters. Finally, issues in communicating results from a comprehensive policy analysis given various sources of uncertainty are also discussed.

The organization of the paper is as follows. Section 2 provides an overview of the health and welfare impacts of aviation activity. Section 3 reviews recommended practices for economic analysis of environmental regulations and describes current practices within ICAO-CAEP for aviation-specific environmental policy analyses. Section 4 provides an overview of estimation methods for aviation environmental impacts employed within APMT. Section 5 discusses the role of model evaluation and quantification of uncertainties in policy analyses, and highlights the issues concerning the communication of results from such a set of analyses. Section 6 is focused on the NO_X stringency analysis using the CAEP/8 assumptions and inputs. A summary and conclusions are provided in Section 6.5.

2. AVIATION ENVIRONMENTAL IMPACTS: AN OVERVIEW

This Section provides an overview of the noise, air quality, and climate change impacts of aviation. Water quality impacts associated with airport de-icing fluid and storm-water runoff are not addressed here. The methods we use for estimating aviation noise, air quality, and climate impacts in both physical and monetary metrics are discussed in Section 4.

2.1 Noise impacts

Aviation noise is the most readily perceived environmental impact of aviation activity, and has historically been one of the most significant sources for community complaints about airports—leading to vigorous objections to most airport expansion projects [12]. While there are multiple noise sources at airports, our discussion is limited to aircraft-related noise, which is usually the dominant source. This Section presents commonly used noise scales and metrics, followed by a discussion of noise impacts.

Noise is measured in decibels and is typically scaled to reflect the sensitivity of human perception to different frequencies. Two widely-used frequency-weighted scales are the A-weighted scale and the tone-corrected perceived noise level. The A-weighted scale weighs different frequencies with respect to the frequency sensitivity of the human ear and is the preferred scale for noise impact assessments and the generation of noise exposure area maps or contours. Tone-corrected perceived noise levels account for human perception of pure tones and other spectral irregularities and are used in aircraft design and ICAO noise certification Standards [13].

Aircraft noise metrics are classified as either single-event or cumulative metrics. Single-event metrics measure the direct effects of a single aircraft movement and include metrics such as the Maximum A-weighted Sound Level, the Sound Exposure Level (SEL) and the Effective Perceived Noise Level (EPNL). The Maximum A-weighted Sound Level is commonly used for airport noise monitoring while the EPNL metric is used by ICAO for its certification Standards for new aircraft. Cumulative noise metrics are of interest when determining long-term exposure to aircraft noise based on an aggregation of all the single events indicating overall airport activity. The Equivalent Sound Level which indicates the average single-event noise level of all the single events experienced during a given time period is a common cumulative noise metric. The Day-Night-Level (DNL) derived from the Equivalent Sound Level averages noise over a 24-hour period and applies a 10 dB penalty for nighttime events. The A-weighted DNL is used widely for noise impact assessments [13].

Table 1: Aircraft Noise Effects on Residential Areas [14]

Effects [1] Day-Night Average Sound Level in Decibels	Hearing Loss Qualitative Description	Annoyance [2] % of Population Highly Annoyed [3]	Average Community Reaction [4]	General Community Attitude Towards 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	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 aspects of the community environment
55 and below	Will not occur	3%	Moderate to Slight	Noise considered no more important than various other environmental factors

Table 1 lists the varying impacts of aircraft noise on people in residential areas for different day-night average noise exposure levels [14]. Both behavioral and physiological impacts from long- and short-term exposure to aircraft noise have been studied extensively. Behavioral impacts include general annoyance, sleep disturbance, and disruption of work performance and learning, while physiological effects range from stress-related health effects including hypertension, to hormone changes and mental health effects. Attributing behavioral impacts to specific aircraft operational and performance parameters is challenging due to the confounding effects of acoustical factors, such as time variation in noise levels and ambient noise levels, and non-acoustical effects such as lifestyle, attitude towards noise, income-level, etc. Among the various behavioral impacts associated with exposure to aircraft noise, community annoyance and sleep disturbance are some of the better-understood impacts with well-defined exposure-response relationships in the literature. However, even these relationships represent average responses when the underlying data reflect a high variability in response to aircraft noise as shown in Figure 1. Figure 1 presents the variability in annoyance experienced as a result of exposure to aircraft noise based on several studies from the literature [15]. Data obtained from annoyance surveys as seen in Figure 1 have been used to derive exposure-response functions for quantifying the number of people affected by a given noise level (for instance, see [16-19]). Such exposure-response functions are appropriate for predicting community-wide response; individual responses may vary significantly from the average responses captured by exposure-response functions.

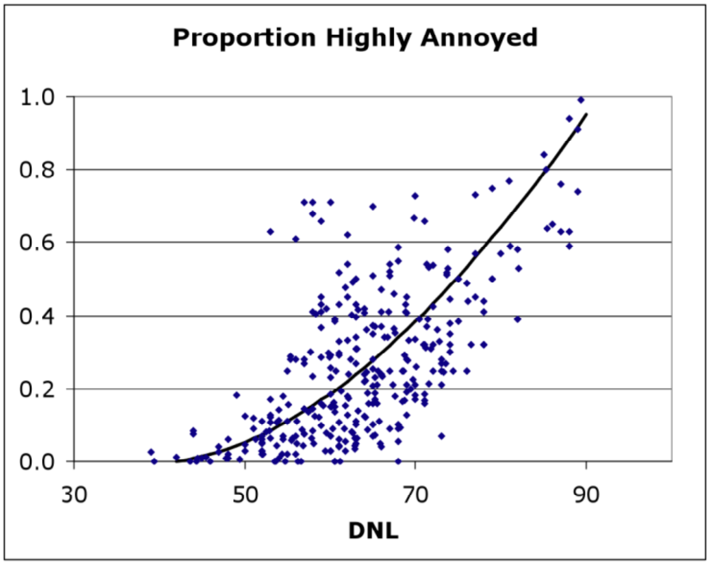

Figure 1: Annoyance Data for Aircraft Noise Exposure [15]

Similarly for sleep disturbance, there have been several studies that assess impacts in terms of sleep awakenings from aircraft noise and provide exposure-response functions. While there has been extensive research on sleep awakenings from single-events, few studies focus on awakenings from a full night of aircraft noise - which may be a more relevant metric for policy analysis (see [20] and [21]). Aircraft noise has been linked to learning disruption in students with effects such as lower reading comprehension and performance on tests, but there are currently no exposure-response functions to quantify this impact [22-25]. Physiological impacts such as hypertension are better understood as compared to mental health effects and hormone changes, which currently lack conclusive evidence to establish a strong causal relationship with aircraft noise [14, 26]. Hypertension has been closely linked to aircraft noise as shown by several studies, but the few exposure-response functions in the literature have not yet been widely-accepted [27, 28].

These varied effects of aircraft noise are also reflected in housing prices around airports and this has been used as a primary economic basis for valuing the impacts of noise. There are two basic approaches for estimating impacts of aircraft noise on housing prices around airport: revealed preference and stated preference. However, it is also generally understood that such valuations may under-represent the costs for environmental impacts that are not accurately perceived by the community (e.g., long-term health impacts that one may not directly attribute to noise).

Revealed preference methods include the hedonic method, and infer the value people place on the environment through the choices they make. In the hedonic method, the value people associate with aircraft noise exposure is inferred from the housing price difference between locations with different airport noise exposure after correcting for other differentiating factors. Noise impacts on housing prices are summarized with a Noise Depreciation Index (NDI), which is defined as the percentage loss in housing price per decibel change in noise exposure. Nelson provides an estimate of a US national average NDI value of 0.67 % change in property value per dB based on a meta-analysis conducted using NDI estimates at 23 different airports in the United States and Canada [29]. Thus for regions around airports where the noise due to aviation may be 5dB to 15dB above the background noise level, the impacts on property values can be as large as 10%. Major challenges associated with the revealed preference methods are finding data that allow for isolating the environmental effect while controlling for other factors that contribute to price changes. The hedonic approach also has been criticized for its underlying assumption that inferred values based on present day studies will be applicable to values future generations will place on environmental amenities [30]. The stated preference approach relies on surveying people to determine how they value environmental good, producing estimates of willingness-to-pay for mitigation of environmental impacts. Stated preference methods also have shortcomings as they are based on hypothetical situations and do not reflect real choices that consumers make when faced with tradeoffs between money and the environment [30]. The Nelson NDI values were compared by Kish [31] to 28 other international willingness-to-pay and hedonic valuation studies and were found to represent the mean of reported responses well. A meta-analysis of an expanded set of 65 noise studies (including those used by Nelson) forms the basis for the estimates of noise in this paper. This is discussed further in Section 4.1.1.

2.2 **Air quality impacts**

Emissions from aircraft jet engines include carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_X), carbon monoxide (CO), sulfur oxides (SO_X), unburned hydrocarbons (HC) or volatile organic compounds (VOCs), particulate matter (PM), and other trace compounds. Approximately 70% of aircraft emissions are CO_2 emissions; H_2O makes up slightly less than 30% while the rest of the pollutant species amount to less than 1% each of the total emissions [32]. Many of these compounds are understood to either directly or indirectly lead to adverse health impacts. The following discussion provides a brief overview of each of the aviation pollutants linked to air quality impacts based on recent US EPA findings [33-36].

2.2.1 Nitrogen oxides (NO_X)

The atmospheric modeling community defines oxides of nitrogen (NO_X) as both NO and NO2. These chemicals are by-products of high pressure and high temperature combustion of hydrocarbon fuels in air. Based on both epidemiological or observational data, and human and animal clinical studies, the recent US EPA integrated science assessment of NO2 concludes that there is a positive association between short-term exposure to gaseous NO2 and respiratory morbidity [35]. However, recent evidence does not clearly establish whether the association is solely due to NO2 or whether NO2 is a surrogate for impacts related to a different pollutant. Additionally, a concentration-response relationship between NO2 and respiratory morbidity cannot be clearly defined based on current health data. However, NO_X along with VOCs, hydrocarbons, and CO leads to the formation of ozone and NO_X is also a precursor for other organic and inorganic oxidized nitrogen compounds contributing to ambient particulate matter (PM) [35]. In the aviation context, ozone-related health impacts have been estimated to be small as compared to PM impacts (less than ± 8%) and will not be discussed further here [37, 38].

2.2.2 Carbon monoxide (CO)

CO emissions form as a result of incomplete combustion of fossil fuels. The EPA reports no significant health risks from CO based on current ambient concentrations in the US [33].

2.2.3 Sulfur oxides (SO_X)

Combustion of sulfur containing fossil fuels leads to the formation of sulfur dioxide (SO2), sulfur trioxide (SO_3), and gas-phase sulfuric acid (H_2SO_4) which are referred to as sulfur oxides or SO_X. SO2 is the dominant species with trace concentrations of SO_3 and H_2SO_4. SO2 can also be transformed into secondary sulfate particles depending on atmospheric conditions thereby leading to PM formation. The recent US EPA integrated science assessment for SO_X states that evidence from health studies points to a "causal relationship between respiratory morbidity and short-term exposure to SO_X" and is "suggestive of a causal relationship between short-term exposure to SO_X and mortality" [36]. However, uncertainties in the magnitude of health effect estimates and in determining whether impacts are due to SO_X alone or from a mixture of pollutants prevent a robust quantification of a concentration-response relationship [36].

2.2.4 Particulate matter (PM)

Particulate matter emissions from aircraft are in the form of fine particles or $PM_{2.5}$ where the aerodynamic diameter of the particles is less than 2.5 µm [38]. Aircraft $PM_{2.5}$ impacts result from both primary and secondary PM. Primary PM is composed of non-volatile carbon (primarily soot) particles that are emitted directly from the engine, and other exhaust components that agglomerate or condense on the carbon core as the emission plume cools. These latter constituents include sulfuric and nitric acid nuclei, water, and the heavier hydrocarbons with carbon numbers on the order of C-23 to 30. The size of this primary PM is on the order of a few tens of nanometers. Aircraft PM impacts are largely comprised of secondary PM. Secondary PM constituents associated with aircraft emissions will consist in part of atmospheric reaction products derived from the primary PM and the gaseous aircraft emissions such as NO_x, SO_2, and the lighter hydrocarbons. Here, the primary PM and existing atmospheric aerosols, serve as a sites and receptors for these processes. These products include ammonium sulfates, ammonium nitrates, and other constituents (usually hydrocarbons) resulting from both light and dark atmospheric reactions. The resulting secondary PM will develop over the course of hours and days and as a result will be well removed from the airport vicinity by the time it contributes to increased ambient levels of atmospheric PM concentrations. The size of the resulting aerosol is self limited to less than 2.5 microns. Recent work by Brunelle-Yeung attributes 70% of PM formation to NO_X emissions, 14% to non-volatile PM, 12% to SO_X emissions, and another 4% to PM formation from hydrocarbons [40]. Figure 2 shows the changes in annual $PM_{2.5}$ concentrations in the US (in g/m3) attributed to aircraft emissions [41]. The US EPA sets the National Ambient Air Quality Standard for $PM_{2.5}$ at 15 g/m3. These results were obtained based on emissions below 3000 feet for aircraft operations from June 2005 to May 2006 at 325 US commercial airports representing 95% of US operations with filed flight plans. The changes in ambient $PM_{2.5}$ concentrations were modeled with the Community Multiscale Air Quality (CMAQ) simulation system used by the US EPA for its regulatory impact analyses. Aircraft emissions were found to increase average annual $PM_{2.5}$ concentrations by <0.1%. $PM_{2.5}$ increases are also strongly regional in nature with high impacts seen in California as shown in Figure 2.

Changes in ambient $PM_{2.5}$ concentrations can be related to health impacts through concentration-response functions derived for different health end-points based on epidemiological studies. Exposure to $PM_{2.5}$ has been linked to premature mortality and morbidity effects including cardiovascular and respiratory ailments [34]. The US EPA uses the Environmental Benefits Mapping Program (BenMAP) for performing health impact analyses to evaluate incidences and costs of different health effects [42]. Reference [41] estimates aviation-related risk of premature mortality to be 64-270 yearly deaths using BenMAP [41]. Brunelle-Yeung estimates 210 incidences of premature mortality attributable to aircraft PM emission in year 2005 (90% confidence interval of 130-340 yearly deaths). These premature mortality impacts are dominated by secondary PM formation from precursor NO_X and SO_X emissions, with relatively minor contributions from non-volatile PM (soot) and secondary PM from hydrocarbons [40]. Several studies in the literature indicate that health impacts from aircraft PM emissions outweigh impacts from other aircraft pollutant species (see [37, 38, 40]).

	With aircraft emissions (µg/m³)	With aircraft emissions removed (µg/m³)	Percent Change
Non-Attainment Areas	17.76	17.75	-0.06%
All Counties	12.60	12.59	-0.08%

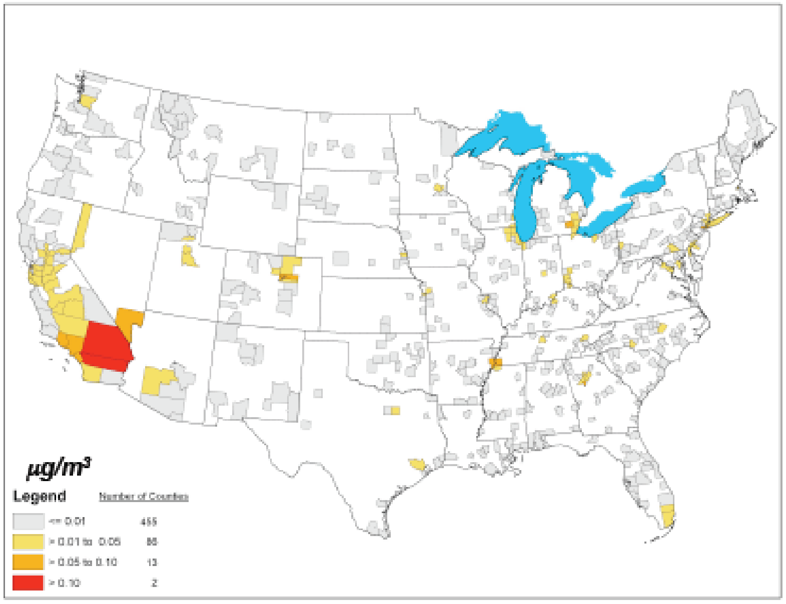

Figure 2: Change in Annual PM2.5 Concentrations Attributed to Aircraft Emissions [41]

Conventionally, air quality impact analysis for aviation has been focused on landing and takeoff emissions below 3000 feet. The ICAO-CAEP emissions certification Standards are for landing and takeoff emissions owing to air quality concerns around airports. However, recent research indicates that aircraft cruise emissions (above 3000 feet) may constitute a substantial portion of the total air quality health impacts of aviation. Barrett et al. in a forthcoming paper estimate that premature mortality impacts from global aircraft cruise emissions comprise 80% of the total health impacts of aviation [43]. With further research, future assessments of aviation air quality impacts may need to include full flight emissions to account for the full impact of aviation emissions. In this paper we include a preliminary estimate of the impacts of cruise emissions as one of our sensitivity studies.

2.3 Climate impacts

The Intergovernmental Panel on Climate Change (IPCC) has published a comprehensive report on the climate impacts of aviation identifying the main pathways through which aviation perturbs the planetary radiative balance [44]. The IPCC defines radiative forcing (RF) as a "measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system" [45]. A positive RF implies a warming effect, while a negative RF indicates a cooling effect. The more recent IPCC Fourth Assessment Report estimates the total radiative forcing attributed to subsonic aviation in 2005 to be about 3% of the total anthropogenic radiative forcing not accounting for cirrus cloud enhancement (with a range of 2-9% skewed towards lower percentages) [45]. The aviation-specific climate impacts described here focus on commercial subsonic aviation where aircraft typically fly in the upper troposphere and the lower stratosphere between an altitude range of 9-13 km. Aviation emissions directly or indirectly perturb the planetary radiation balance through effects that are diverse in terms of time-scales and spatial variations involved. Next, a brief description of the characteristics of the different forcing agents associated with aviation emissions is provided.

2.3.1 Carbon dioxide (CO_2)

Aviation CO_2 emissions have the same climate change impacts as CO_2 emissions from any other sources given that CO_2 is a long-lived, well-mixed greenhouse gas. CO_2 emissions have a net warming effect with a positive radiative forcing. CO_2 emissions lead to spatially homogeneous impacts and have an atmospheric residence time on the order of centuries [44].

2.3.2 Water vapor (H_2O)

H_2O emissions have a direct warming effect with a lifetime on the order of days. Water vapor emissions in the troposphere due to aviation do not have a major climate impact; however, for supersonic aircraft which fly in the stratosphere, H_2O can be a significant greenhouse gas [44].

2.3.3 Nitrogen oxides (NO_X)

NO_X emissions have two indirect effects - warming from ozone production and cooling from the destruction of methane. NO_X emissions increase the oxidative capacity of the atmosphere; this decreases methane (CH4) concentrations and has an associated primary-mode reaction that decreases ozone in the long run. NO_X-related radiative forcing perturbations strongly depend on seasonal variations in solar insulation and background NO_X and HO_X concentrations, and show large spatial variations in radiative impacts [44]. The short-lived O3 warming effect from NO_X emissions lasts on the order of a few months and thus produces impacts largely in the northern hemisphere where aircraft fly. The longer-lived NO_X-CH_4-O_3 cooling effect has a decadal lifetime [46, 47] and thus produces impacts on a global scale. When globally-averaged the short-lived NO_X- O_3 effects, and the long-lived NO_X-CH_4-O_3 effects are of roughly equal magnitude with opposite signs when integrated over their full time horizon of impacts; however regional variations can be significant (with the sum of the effects leading to a net warming influence in the northern hemisphere and a net cooling influence in the southern hemisphere).

2.3.4 Contrails and aviation-induced cirrus

The formation of linear contrails and aviation-induced cirrus from persisting linear contrails is a warming impact unique to aviation and depends on water vapor emissions, (and to a less certain extent) other engine emissions, ambient conditions (pressure, temperature and relative humidity), and the overall propulsive efficiency of the aircraft. Linear contrails can persist for hours while cirrus can persist from several hours to days [44]. Because of the short life-time the radiative forcing is regional in nature. The climate impact of contrails and induced cirrus cloudiness is the most uncertain of the different aircraft effects, with radiative forcing estimated to range from close to zero to more than double that of CO_2.

2.3.5 Sulfate aerosols and particulate matter

Sulfate aerosols from aircraft reflect sunlight with a cooling effect; black carbon or soot on the other hand absorbs sunlight and has a warming effect. Sulfates and black carbon have a residence time lasting from days to weeks. Aerosol emissions from aircraft may also serve as cloud condensation nuclei or alter the microphysical properties of cirrus clouds thereby modifying their radiative impact; this is an area of ongoing research [44].

2.3.6 Carbon monoxide (CO) and volatile organic compounds (VOCs)

CO emissions from aircraft are significantly smaller in magnitude as compared to other sources of CO and are generally considered to have a negligible impact on tropospheric ozone chemistry. Aircraft unburned hydrocarbons or VOCs are also found to have a negligible climate perturbation [44].

Current scientific understanding of the different climate change mechanisms attributed to aviation varies across the different effects described. The most recent updates to radiative forcing estimates from the IPCC [44] are provided by Lee et al. [48], and are shown in Figure 3. It is important to note that the RF estimates shown in Figure 3 are indicative of the impact of aviation emissions in 2005 and do not fully capture the time-integrated effects of the different mechanisms. While the RF impacts due to short-lived effects such as NO_X-O3, contrails, and cirrus formation are reflective of aircraft emissions in year 2005, RF impacts from long-lived pollutants such as CO_2 and NO_X-CH¬4 are cumulative in nature and result from emissions not only in 2005 but also from prior years. Moreover, for these long-lived effects the future impacts are not represented (e.g., the CO_2 effects of current day emissions will persist for hundreds of years in the future). Because of these shortcomings in evaluating relative impacts using radiative forcing (taken at a single point in time), time-integrated changes in surface temperature are a more appropriate measure of the marginal impacts of different mechanisms, and these time integrated marginal changes form the basis for the damage estimates we present later in this paper. Nonetheless, Figure 3 provides some indication of the relative impact these aircraft sources are having today and describes the relative uncertainties associated with each impact. CO2 has a relatively well-understood impact while as noted above, the aviation-induced cirrus effect has the highest uncertainties. Figure 3 does not provide a mean estimate for the cirrus effect but provides bounds on the radiative forcing reflecting the poorly understood processes that lead to cirrus formation and the resulting impacts. The indirect effect of aerosols on cirrus properties is not indicated on this chart. The level of understanding for NO_X-related effects is rated as medium to low while that of all other effects is rated as low by Lee et al. [48].

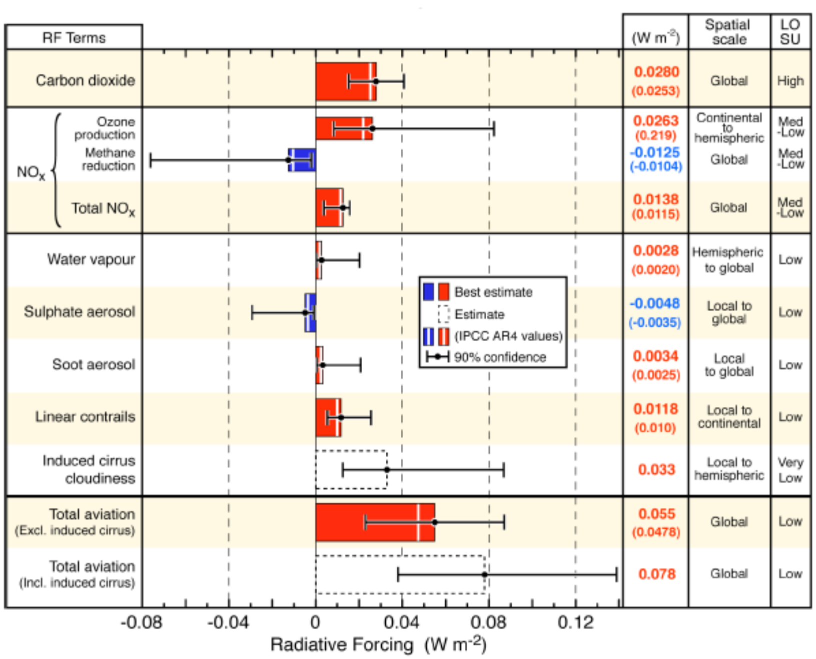

Figure 3: Radiative Forcing from Aircraft Emissions in 2005 [48]

3. CURRENT DECISION-MAKING PRACTICES FOR AVIATION ENVIRONMENTAL POLICIES

3.1 Common Approaches for Economic Policy Analysis

Regulatory agencies in many world regions use economic analysis to guide policy decisions through an explicit accounting of the costs and benefits associated with a regulatory change. Economic policy evaluation approaches commonly used in policy assessments include cost-benefit, cost-effectiveness and distributional analyses. A cost-benefit analysis (CBA) requires that the effect of a policy relative to a well-defined baseline scenario be calculated in consistent units, typically monetary, making costs and benefits directly comparable. The cost-benefit approach is aimed at maximizing the net social benefit of regulation, where the net benefit is defined as the benefits of the regulation (e.g. number of people removed from a certain noise level) minus the costs of the regulation (e.g. the additional costs of technology) [49, 50]. Cost-effectiveness analysis (CEA) is meant to be used for evaluating policies with very similar expected benefits; a policy that achieves the expected benefits with the least costs is the preferred policy [50]. Finally, a distributional analysis is meant to address the question of who benefits and who bears the costs of the proposed policies [51].

Within the United States, all federal agencies are mandated to evaluate costs and benefits of regulatory measures including environmental measures as issued by executive orders and directives from the Office of Budget and Management [51, 52]. Although CBA is the recommended basis for assessing policy alternatives in many governments (see, for example: [53], p59; [54], p2-3; [52], p11; [55], p23; and [56], p22), other forms of economic analysis are used in the absence of adequate information to quantify costs and/or benefits. A common method is CEA, where policies are compared on the basis of cost when similar benefit outcomes are expected. In practice within the ICAO-CAEP for example, analysis is carried out under the heading of CEA where benefits are quantified in terms of a physical measure, such as tons of NO_X reduced, or number of people removed from a certain noise level, even when similar benefit outcomes are not expected. The next Section discusses the methods adopted by the ICAO-CAEP and illustrates the shortcomings of the CEA approach for aviation environmental policy analysis.

3.2 ICAO-CAEP Environmental Policy Analysis

The International Civil Aviation Organization (ICAO) established under the Chicago Convention in 1944, is a specialized agency within the United Nations charged with fostering a safe and orderly development of the technical and operational aspects of international civil aviation [57]. The ICAO establishes Standards and Recommended Practices (SARPs) which not only include the environment but also focus on safety, personnel licensing, operation of aircraft, airports, air traffic services, and accident investigation. Within ICAO, the Committee on Aviation Environmental Protection, CAEP, oversees the technical work in the environmental area for aircraft noise and emissions. CAEP consists of five working groups and one support group. Two of the working groups deal with aircraft noise issues, while the remaining three focus on the technical and operational aspects of aircraft engine emissions; the support group provides information on economic costs and environmental benefits of proposed regulations [58]. Next, an overview of conventional ICAO practices for conducting economic policy analysis is presented through considering the NO_X stringency analysis done to support the sixth meeting held in 2004. The analyses methods used to support the upcoming eight meeting to be held in 2010 are substantially the same, and it is these most recent analyses that we take as an example to compare CBA results to CEA results in Section 6.4.

NO_X stringency analysis refers to a consideration of technology changes necessary and additional costs incurred for lowering the current allowable level of NO_X emission from aircraft engines. All new aircraft engines are required to be tested and certified to have NO_X emissions below the latest CAEP Standard expressed in terms of grams of NO_X emissions normalized by the maximum engine takeoff thrust rating. The increased NO_X stringency level is typically applicable to new engines being introduced into the fleet, but may also lead to early retirement of non-compliant engines. Figure 4 provides an overview of the increasingly stringent CAEP Standards for engine NO_X emissions for engines with a high thrust rating (greater than 89kN) [59].

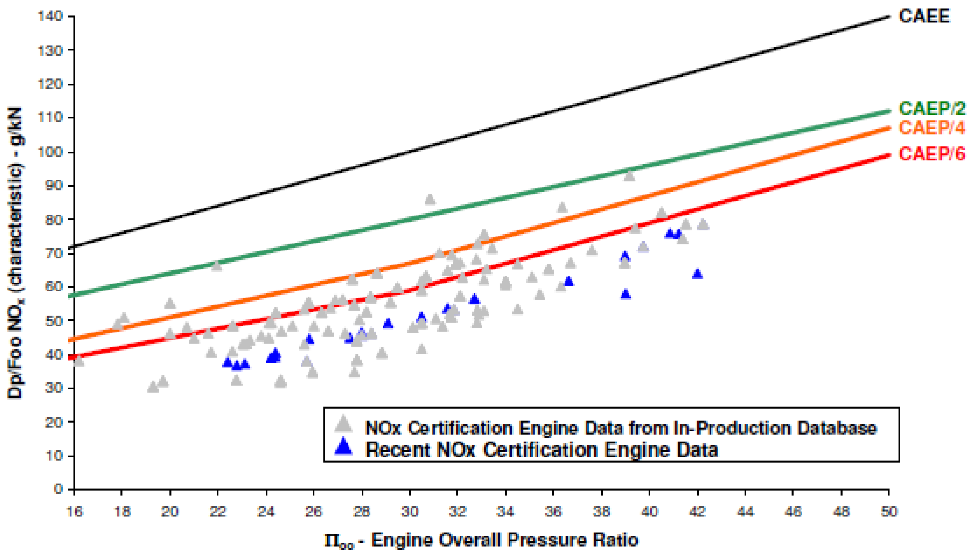

Figure 4: ICAO-CAEP NOX Stringency Standards [59]

The ICAO NO_X emissions Standards only apply to engines with a thrust rating of greater than 26.7kN. 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. The first NO_X certification Standard was adopted in 1981 by the ICAO Committee on Aviation Engine Emissions (CAEE). The CAEP/2 meeting made the first Standard more stringent by 20% for newly certified engines produced after December 31, 1999. The next stringency increase was agreed upon at the CAEP/4 meeting to be 16% greater than the CAEP/2 Standard for engines certified after December 31, 2003. Finally, 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% as compared to CAEP/4 for engines manufactured after December 2007 [60]. The stringency increase typically refers to the value at an overall pressure ratio of 30 for high-thrust engines (greater than 89kN). 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 NO_X.

In support of the CAEP Standards on NO_X emissions for the sixth meeting of the CAEP, the Forecasting and Economic Analysis Support Group (FESG) within CAEP presented a cost-effectiveness analysis of NO_X emission stringency options (to be referred to as CAEP/6-IP/13) [61]. The CAEP/6 NO_X stringency analysis considered lowering the allowable level of NO_X emissions by increments of between 5% and 35% with implementation in 2008 or 2012. Outcomes of this analysis as well as negotiations with stakeholders resulted in the decision to reduce certified emissions levels for new engines by 12% starting in 2008.

CAEP/6-IP/13 presented a comprehensive cost analysis that accounted for both non-recurring and recurring manufacturer and operator costs and loss in value of the existing fleet. Non-recurring manufacturer costs varied by the level of technology change necessary for different non-compliant engine families while recurring manufacturing costs accounted for higher production costs resulting from increased complexity and the use of more expensive materials. Recurring operator costs included the cost of additional fuel and the cost of additional maximum take-off weight to preserve mission capability for those engine families that incurred a fuel burn penalty from technology change. Additionally, recurring operator costs also included increased landing fees from additional take-off weight of aircraft, changes in maintenance costs, and increases in maintaining spare engine inventories due to loss of fleet commonality from stringency compliance. The loss in fleet value accounted for costs of retrofitting existing engine types to make them compliant with the new stringency Standards. The analysis did not pass costs on to passengers through increased fares as the impacts of increased fares on consumer demand were assumed to be negligible.

On the benefits side, the FESG estimated reductions in NO_X emissions over the landing and take-off cycle resulting from technology changes. The analysis also reported changes in CO_2 emissions resulting from a fuel burn penalty for some engine families. Impacts of the fuel burn penalty were accounted for on the costs side, but not on the benefits side (e.g., the potential impacts on climate). The benefits or reductions in NO_X emissions were not monetized for a direct comparison with the costs. The analysis did not explicitly evaluate the health and welfare impacts of changes in air quality and climate that would be associated with increased NO_X certification stringency. The fuel burn penalty for the lower NO_X technology engines was assumed to lead to increases in aircraft weight in order to preserve aircraft payload-range capabilities; these increases in aircraft weight may result in increased noise levels. The FESG study did not account for interdependencies between noise and emissions stringency Standards.

Figure 5 shows the results from the CAEP/6 IP/13 analysis; stringency levels ranging from 5% to 35% relative to CAEP/4 Standards for two implementation years 2008 and 2012 were assessed.

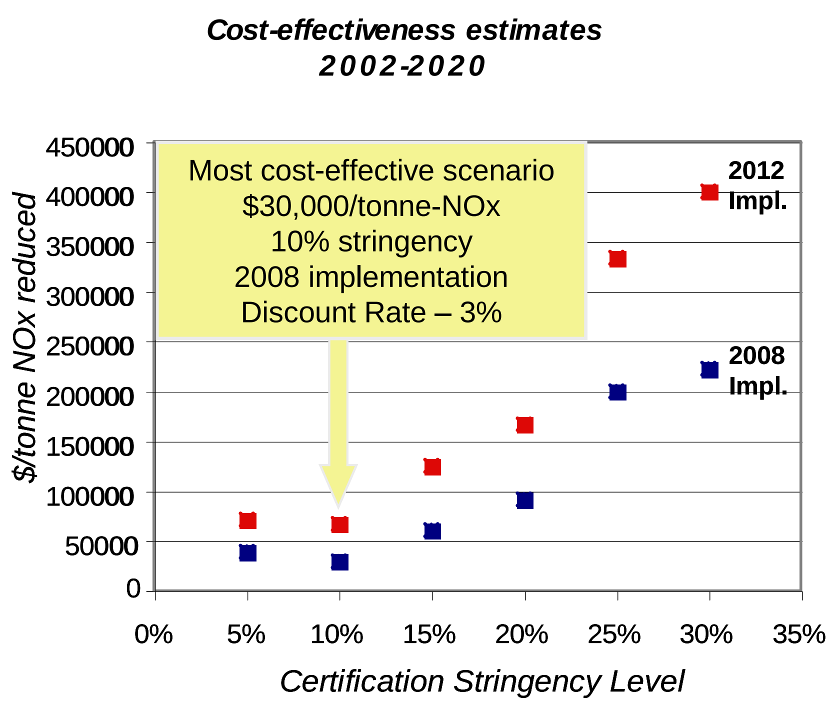

Figure 5: CAEP/6 FESG Economic Analysis [61]

Based on the assumptions described previously, for a 3% discount rate, the 10% stringency option implemented in year 2008 was found to be the most cost-effective scenario at $30,000/tonne- NO_X.

However, the conclusions from the cost-effectiveness analysis can be misleading if there is a non-linear relationship between the intermediate physical measure of the benefits (in this case reductions in NO_X emissions) and the ultimate health and welfare benefits, or if other costs and benefits are not addressed (for example the impacts on climate or noise). Additionally, the cost-effectiveness ranking of a policy measure does not indicate whether the net benefits of the policy measure exceed the anticipated costs. The US EPA guidelines for economic analysis state that "Cost-effectiveness analysis does not necessarily reveal what level of control is reasonable, nor can it be used to directly compare situations with different benefit streams" [53]. In the case of a NO_X stringency analysis, reductions in NO_X emissions alone do not provide an estimate of the resulting impacts on air quality and climate, or an assessment of whether or not the $30,000/tonne- NO_X costs are justified. Notably, the estimated costs of implementing the policy ranged from $5 billion to $15 billion, depending on the assumptions; so even relatively small changes in stringency can lead to large costs underscoring the importance of making good decisions.

Growing uncertainty in estimating policy impacts is the reason commonly cited for not including environmental impact assessment in the policy analysis process. As policy impacts are estimated further along the impact pathway (e.g. going from emissions inventories, to physical changes in the atmosphere, to health impacts, to monetary estimates), uncertainty in the estimated impacts increases. Moving further down the impact pathway involves incorporating knowledge from several disciplines, which in turn brings along uncertainties from different fields. Evaluating monetized environmental impacts not only includes uncertainties associated with estimating emissions inventories but also related to the current understanding of atmospheric processes and associated health impacts as well as valuation approaches. However, when considering uncertainties, it is important to recognize the distinction between uncertainties in the modeling methods and uncertainties in the decision-making process. 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. Moving further down the impact pathway despite the modeling uncertainties makes impact estimates more relevant for policymakers as they represent direct changes in human health and welfare. This is shown schematically in Figure 6 using notional uncertainty distributions.

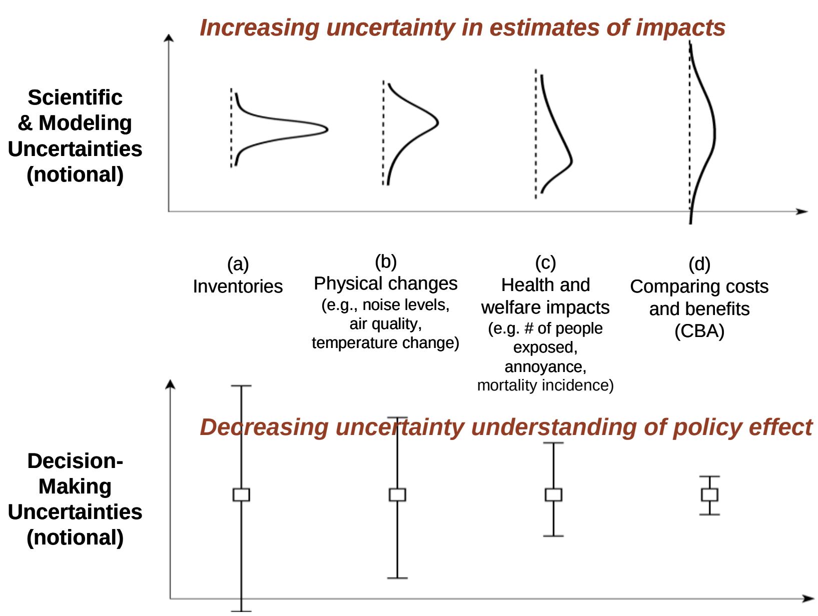

Figure 6: Scientific vs. Policy-Making Perspectives on Uncertainty

For example, CAEP has historically taken action to reduce NO_X emissions because of the relationship between NO_X and poor air quality, especially ozone. However, analyses such as those presented by the EU CAFE program, and by the US EPA, suggest that the dominant health impact of NO_X is through serving as a precursor for the formation of secondary ambient particulate matter. Relative to particulate matter impacts, the impacts of NO_X on ozone are much smaller (and may be positive or negative depending on the location) [35, 37, 38]. Moreover, it is now recognized that NO_X has both positive and negative impacts on radiative forcing and thus also contributes to climate change. NO_X may lead to detrimental impacts through multiple environmental pathways such secondary particulate matter formation, positive and negative effects on radiative forcing, and positive and negative effects on ozone. Consequently, it is not possible to evaluate the benefits of a policy by only considering changes in NO_X emissions inventories. More information (i.e., moving from inventories to impacts), even though it is more uncertain, improves the decision-making process. Also, such benefits assessments are required in many cases for comparing different policies—for example comparing the benefits of a low sulfur fuel Standard to the benefits of NO_X stringency. Emissions inventories alone do not allow such a comparison, which necessitates comparison of health benefits.

Section 6 presents both cost-benefit and cost-effectiveness analyses for a representative subset of NO_X stringency options considered for the eighth meeting of the ICAO-CAEP in February 2010. The illustrative CAEP/8 NO_X stringency analysis explicitly models environmental impacts in the areas of noise, air quality, and climate change and accounts for economic impacts captured through the producer and consumer surplus. Section 6 seeks to highlight the differences between cost-effectiveness and cost-benefit analyses and show how different conclusions can be drawn about the same policy measures when explicit accounting of environmental impacts is included in the analysis.

4. METHODS FOR ASSESSING TRADEOFFS AMONG AVIATION ENVIRONMENTAL AND ECONOMIC IMPACTS

There are several research initiatives that are focused on improving the understanding of aviation environmental impacts, exploring policy options, and supporting the decision-making process. A large portion of work in this area falls under the auspices of two major research programs - the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) Center of Excellence in North America and the Opportunities for Meeting the Environmental Challenges of Growth in Aviation (OMEGA) in the UK. The PARTNER Center of Excellence, supported by the US Federal Aviation Administration, the National Aeronautics and Space Administration, and Transport Canada is a consortium of members from academia, industry, and government that conducts basic and applied research on aviation environmental impacts and mitigative measures. OMEGA – funded by the Higher Education Funding Council for England (HEFCE) – is an alliance among nine UK universities to study scientific, operational, and policy-relevant aspects of the environmental impacts of aviation [58].

In terms of developing tools to assess the tradeoffs between environmental and economic impacts of aviation, two major research initiatives are currently in place. The first one is the Cambridge University (UK) Aviation Integrated Modeling (AIM) project that is developing a policy assessment capability which accounts for environmental and economic impacts of aviation [62]. The AIM framework consists of inter-linked models that address aircraft and engine technology changes, demand for air transport, airport activity and operations, global climate change, local air quality and noise impacts as well as regional economic impacts of aviation activity. The Aviation Environmental Tools Suite is the second initiative. The FAA, in collaboration with NASA and Transport Canada, is developing a comprehensive suite of software tools to facilitate thorough consideration of aviation's environmental effects. The main goal of this effort is to develop a critically needed ability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios.

Figure 7 is a schematic of the Aviation Environmental Tools Suite. The main functional components of the Tools Suite are summarized below; and, additional information is available on the FAA website [http://www.faa.gov/about/office_org/headquarters_offices/aep/models/]

- *Environmental Design Space* (**EDS**): estimates source noise, exhaust emissions, and performance for potential future and existing aircraft designs;

- *Aviation Environmental Design Tool* (**AEDT**): models aircraft performance in four-dimensional space and time to produce fuel burn, emissions and noise;

- *Aviation environmental Portfolio Management Tool for Economics* (**APMT-Economics**): models airline and aviation market responses to environmental policy options;

- *Aviation environmental Portfolio Management Tool for Impacts* (**APMT-Impacts**): estimates the environmental impacts of aircraft operations through changes in health and welfare endpoints for climate, air quality and noise; and

- *Cost Benefit with the Aviation environmental Portfolio Management Tool* (**APMT-Cost Benefit**): combines Tools Suite output to perform cost benefit analyses.

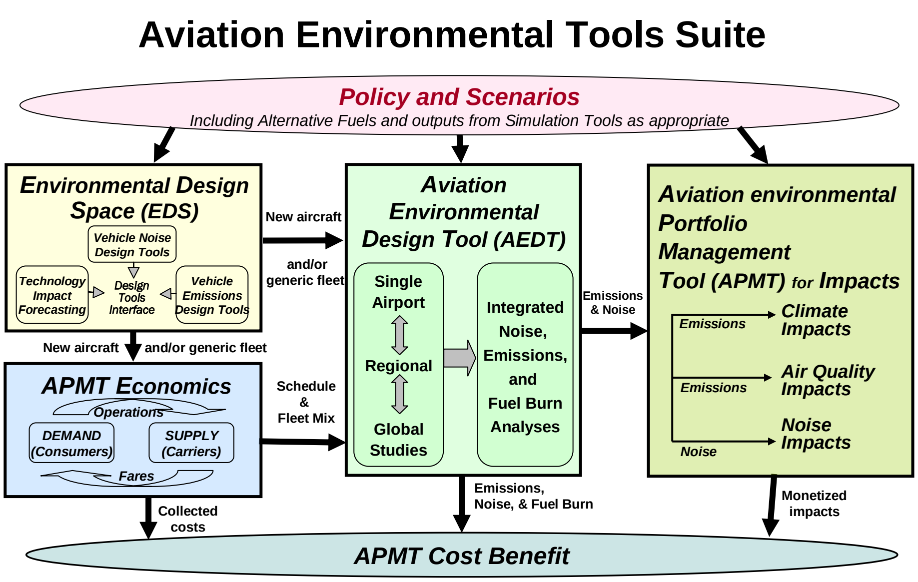

Figure 7: The FAA-NASA-Transport Canada Aviation Environmental Tool Suite

For the analysis conducted in this paper, the Aviation environmental Portfolio Management Tool (APMT) was employed. APMT aims to better inform decision-makers by providing the capability to assess different policy measures in terms of their implementation costs, environmental benefits, and associated uncertainties. This Section is devoted to an overview of the environmental and economics impacts modeling methods within APMT; additional information is available on-line at http://www.apmt.aero.

APMT development was preceded by an extensive survey of guidance documents on recommended practices for environmental policy analysis. Some of the key documents consulted include EPA Guidelines for Preparing Economic Analyses [53], OMB Circular A-4, Best Practices for Regulatory Analysis [52], UK HM Treasury Green Book on Appraisal and Evaluation in Central Government [56], UK Cabinet Office, Better Regulation Executive Regulatory Impact Assessment Guidance [63], OECD The economic appraisal of environmental projects and policies - A practical guide [55], Transport Canada Guide to Benefit Cost Analysis in Transport Canada [64], WHO Air Quality Guidelines for Europe [65], Resources for the Future, Cost Benefit Analysis and Regulatory Reform: An Assessment of the Science of the Art [50], Peer Review of the Methodology of Cost-Benefit Analysis of the Clean Air for Europe Programme [66], and Clean Air for Europe (CAFE) Programme Methodology for the Cost-Benefit Analysis for CAFE Vol. 1 [67]. The survey findings have been summarized in the Requirements Document for the Aviation environmental Portfolio Management Tool [68] and were reviewed by the Transportation Research Board of the US National Academies [69]. The requirements document laid out detailed functional requirements and provided guidance on implementation, presented supporting discussions to place requirements within context of current practice, recommended time frames for development and defined the geographical and economic scope for analyses. The APMT Requirements Document recommended the scope of functional capability for APMT to not only encompass the conventional cost-effectiveness approach adopted by CAEP but also to advance current methods for aviation environmental policy analysis to include cost-benefit and distributional analysis. Noise, air quality, and climate change impacts were the primary environmental impact areas identified by the Requirements Document for APMT tool development. As per the recommendations laid out by the Requirements Document, APMT development was meant to initially focus on US-centric, direct environmental and economic impacts of aviation activity limited to the aviation sector. Future development would include expansion of modeling capabilities to include both direct and indirect impact categories at the global level that also involved interaction with other economic sectors [68]. Presently, APMT is built upon the foundations laid out by the initial survey of economic guidance documents and the tool continues to evolve to incorporate new knowledge as well as expand modeling capability.

APMT has a modular arrangement consisting of two different modules: the Economics module, which models the economics of the aviation industry, and the Impacts module, which estimates environmental impacts. The economic cost outputs from APMT-Economics and environmental impact estimates from APMT-Impacts are integrated to enable comprehensive cost-benefit and cost-effectiveness analyses. As per conventional economics terminology, monetary flows in the aviation industry are defined as costs and environmental impacts (e.g. health impacts or noise exposure) as benefits. Both costs and benefits can be positive or negative. Next, an overview of the modeling methodology adopted in APMT is provided. The following discussion provides a brief overview of environmental and economic modeling methods adopted in APMT.

4.1 APMT - Impacts

The APMT-Impacts module assesses the physical and socio-economic environmental impacts of aviation using noise and emissions inventories as the primary inputs. Impacts and associated uncertainties are simulated based on a probabilistic approach using Monte Carlo methods. APMT-Impacts is further sub-divided into three different modules: Noise, Air Quality, and Climate. Table 2 lists the effects modeled under each impact area and corresponding metrics. Note that in earlier documentation of APMT the APMT-Impacts module was previously referred to as the Benefits Valuation Block.

Table 2: Overview of Environmental Impacts Modeled in APMT

Impact Type	Effects Modeled	Primary Impact Metrics	
		Physical	Monetary
Noise	Population exposure to noise, number of people annoyed Housing value depreciation, rental loss	Number of people	Net present value
Air Quality	Primary particulate matter (PM) Secondary PM by NO_X and SO_x	Incidences of mortality and morbidity	Net present value
Climate	CO_2 Non-CO_2: NO_X-O_3, Cirrus, Sulfates, Soot, H_2O, Contrails, NO_X-CH_4, NO_x-O_3long	Globally-averaged surface temperature change	Net present value

4.1.1 Noise Module

Section 2.1 addressed the physical impacts associated with exposure to aircraft noise characterized by behavioral and physiological effects. Monetary impacts of noise exposure are commonly attributed to costs from noise-related health effects, loss of work productivity, and depreciation of property values around airports [70]. The APMT-Noise Module estimates global impacts of aviation noise in terms of both physical and monetary metrics for 178 airports located in 38 countries plus Taiwan. These 178 airports are part of the 185 ‘Shell-1’ airports represented in AEDT and are estimated to be responsible for approximately 90% of global noise exposure [118]. Physical metrics in the Noise Module include estimates of population exposure to a given noise level and the number of people highly annoyed due to aircraft noise. The Noise Module also estimates housing value depreciation and rent changes around airports, which are used as a proxy for the complex set of health and welfare impacts associated with aircraft noise. The current method is described by He et al. [71] and builds on the work of Kish [31].

The APMT-Noise Module accepts noise contours of the day-night average sound level (dB DNL) around airports as inputs; the noise contours are overlaid on population and housing data to estimate the physical and monetary impacts. The exposed population is determined simply by counting the people inside a given contour. Typical results are shown in Figure 8. In 2005 we estimate approximately 14 million people were exposed to noise levels greater than 55 dB day-night noise level for 178 commercial service airports worldwide.

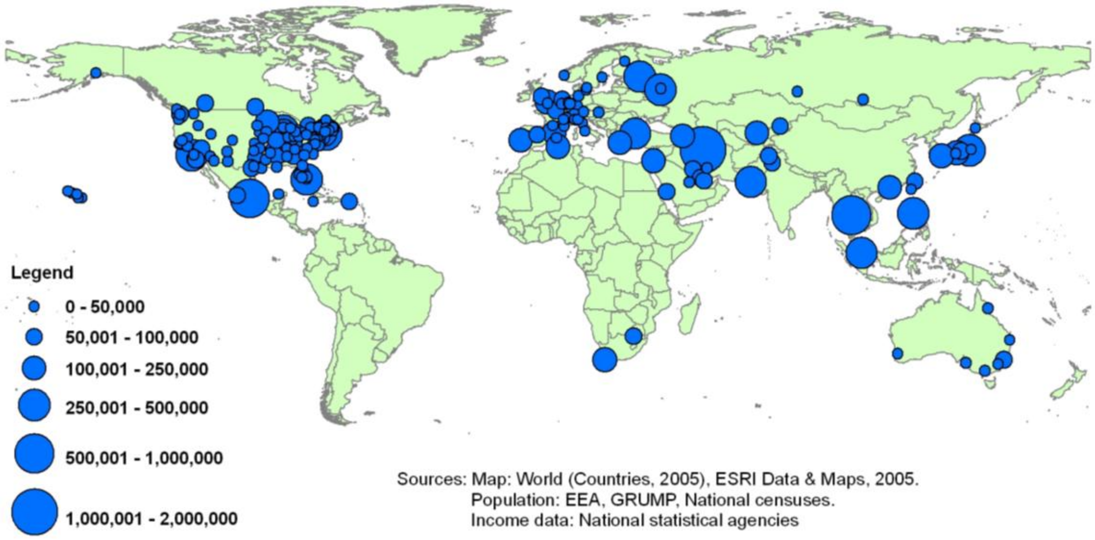

Figure 8: Population impacted by aircraft noise greater than 55dB day-night noise level in 2005 (He et al. [71])

The number of people who are highly annoyed is determined using Miedema & Oudshoorn's exposure-response function for the percent of people highly annoyed at each day-night average sound level [17]. Noise impacts on housing prices are estimated based on hedonic pricing analyses from the literature using the concept of a Noise Depreciation Index (NDI). In the hedonic method, the value people associate with noise exposure is inferred from the housing price difference between two communities with different airport noise exposure after correcting for other differentiating factors. The NDI is defined as a coefficient relating the percentage loss in housing price to a unit decibel change in noise exposure. He et al. [71] performed a meta-analysis of 60 hedonic studies of housing depreciation associated with aircraft noise. Using these studies and city-level income and housing data, they performed statistical analysis to derive a relationship between personal income and yearly willingness-to-pay for noise reduction. This relationship is easier to apply within APMT than that of Kish [31] because city-wide personal income data are more easily collected for the 178 international airports than are detailed housing price data (which are required by the Kish methods). Willingness-to-pay (WTP) values derived from the hedonic studies are shown in
Figure 9. The resulting relationship derived by He et al. [71] is:

$$WTP = 0.0138*Income + 0.0154*Income*NonUS - 30.3440$$

(where *NonUS* is a dummy variable equal to 1 for non-US airports and zero for US airports) The relationship is also plotted in
Figure 9 for US and non-US airports. The mean annual noise damages are shown in Figure 10. These are computed to be: \$1.4 B globally (178 airports), and \$0.56 B for the U.S. (95 airports). The results take account of both the population exposure and also the income levels. Thus, relative to the population exposure results in Figure 8, the regions with higher income are accentuated compared to those with lower income.

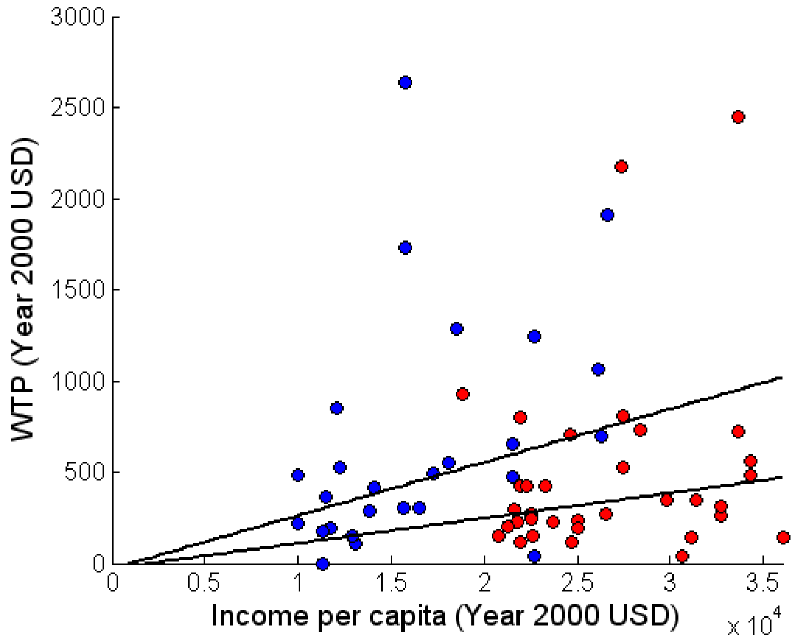

Figure 9: Yearly willingness to pay for aircraft noise reduction as a function of income per capita based on 60 hedonic studies of housing price depreciation (He et al. [71]). The blue symbols are studies of non-US airports; the red symbols are studies of US-airports. The two lines are the regressions.

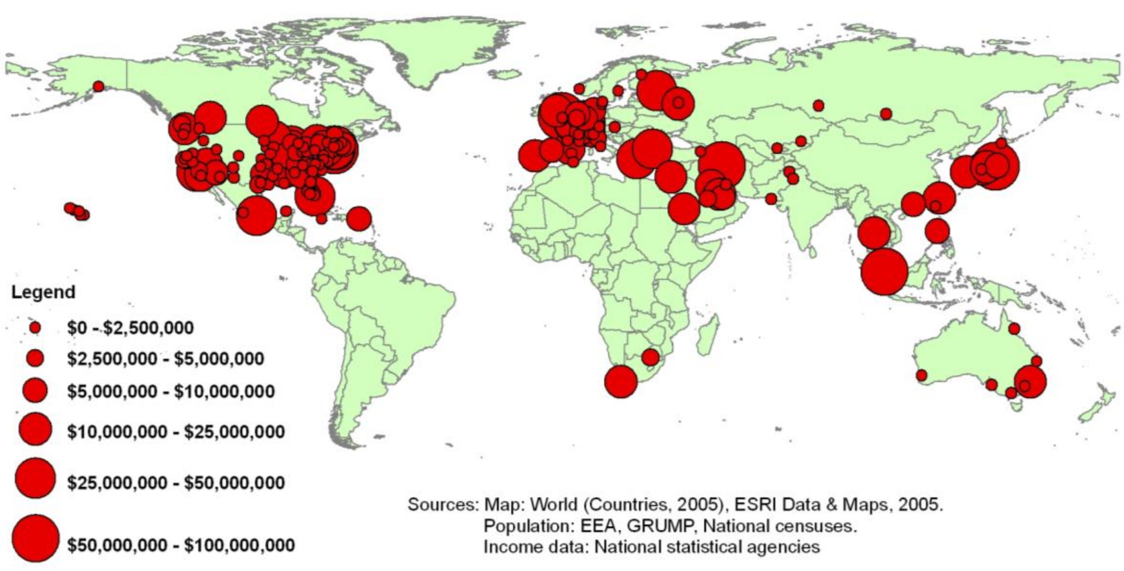

Figure 10: Mean annual noise damages in 2005 (He et al. [71])

4.1.2 Air Quality Module

The Air Quality Module within APMT-Impacts estimates the health impacts of primary particulate matter (primarily soot) and secondary particulate matter (aerosols formed from SO_X, NO_X, and gaseous hydrocarbon emissions) emissions from aircraft for the landing-takeoff cycle. As discussed in Section 2.2

ozone-related health impacts are not considered here as they are estimated to be insignificant relative to PM-related impacts (less than ± 8%) both by studies within the APMT development effort (see for example, [38]), analysis conducted in support of the Energy Policy Act [72] and [41], and external studies such as the Clean Air for Europe Baseline Analysis [37]. APMT quantifies PM-related health impacts in terms of incidences of premature adult mortality, infant mortality, chronic bronchitis, respiratory and cardiovascular hospital admissions, emergency room visits for asthma and minor restricted activity days (MRADs) and their associated costs. Rojo [38], Masek [73], and Brunelle-Yeung [40] provide detailed information on the modeling methodology for the Air Quality Module (with the latest methods being those described by Brunelle-Yeung [40]).

The impact pathway within the Air Quality Module begins with aircraft emissions (NO_X, SO_X, non-volatile PM, and fuel burn) inputs for operations below 3000ft (below we discuss current understanding of the impacts of cruise emissions on surface air quality). Aviation emissions are related to changes in ambient concentrations of particulate matter through a response surface model (RSM) developed using the high fidelity Community Multiscale Air Quality (CMAQ) simulation model [74] [75]. CMAQ is the air quality modeling tool used by the US Environmental Protection Agency for its regulatory impact analyses. Spatial resolution for both the RSM and CMAQ is a 36x36 km grid resolution over the continental US. The RSM captures complex chemistry modeled by CMAQ through statistical linear regressions for each grid cell derived from 25 CMAQ simulations; the RSM design space was selected to capture likely aircraft emissions scenarios over the next 20 years. National impacts are estimated by aggregating impacts over all grid cells. The 25 CMAQ simulations used to develop the RSM uniformly varied emissions across the US making the RSM an appropriate tool for assessing policies implemented at the national level; in order to conduct regional analyses, additional CMAQ runs will have to be incorporated in the RSM design space. The RSM yields a root-mean-square prediction error of approximately 3.5% for total $PM_{2.5}$, thereby providing a reliable surrogate for the computationally expensive CMAQ model for estimating national impacts [40].

The RSM computes changes in ambient $PM_{2.5}$ concentrations broken down into four different groups of PM species: 1) elemental carbon (non-volatile primary PM), 2) organic PM (from volatile organic PM or VOCs), 3) ammonium-nitrate (NH_4NO_3) and 4) ammonium-sulfate ($(NH_4)_2SO_4$) and sulfuric acid (H2 SO_4). The RSM estimates the relative contributions to total aviation PM impacts approximately as follows: 70% due to NO_X emissions, 14% from non-volatile PM, 12% from SO_X emissions, and another 4% from PM formation from hydrocarbons [40]. The US EPA-recommended Speciated Modeled Attainment Test (SMAT) approach is then used to reconcile modeled changes in PM concentrations with data from air quality monitors [40, 76]. This alters the apportionment of PM impacts across the different PM species modeled such that secondary PM formation from SO_X emissions makes a larger contribution to total aviation PM [40]. A typical apportionment of impacts is 55% due to NO_X emissions, 26% from SO_X emissions, 15% from non-volatile PM, and 4% from hydrocarbons. The RSM does not account for potential changes in background pollutant concentrations (i.e. those from other sources) that are likely to occur in the future. Incorporating this effect is an area of on-going research.

The framework used for the health impact analysis is based on the review of the best practices for air quality policy making both in Europe (ExternE program [77]) and the United States (EPA analyses using BenMAP [42]). Changes in ambient PM concentrations estimated by the RSM are related to incidences of mortality and morbidity by using grid-level population data and linear concentration response functions (CRFs) derived from epidemiological studies that relate population exposure to particulate matter to health endpoints. The RSM does not differentiate between PM species in terms of the CRFs used; an equal toxicity is assumed for the different PM species given the lack of species-specific CRFs. The final step in the analysis is the valuation of the health incidences in monetary terms using Value of a Statistical Life (VSL), willingness-to-pay (WTP), and cost-of-illness (COI) estimates from literature. The Air

Quality Module uses a VSL of 6.3 million US $2000 with a standard deviation of 2.8 million US $2000, which is based on US EPA recommendations and adjusted to be in 2000 US dollars [40, 78]. Rojo provides detailed information on the valuation of other health endpoints which were derived from a literature survey of current U.S. and European methodologies [38].

Major limitations of the APMT-Air Quality module include the scope of geographic coverage and consideration of health impacts from landing and takeoff emissions only. Future work plans for APMT-Impacts include developing a response surface model for Europe, and incorporating health impacts of cruise emissions.

The contribution of cruise emissions to surface air quality impacts is not presently considered in our models and is an area of active research. However, because of the potential significance of these effects we include a preliminary estimate of the magnitude of these impacts as one of the sensitivity studies presented in Section 6. The basis for our estimate is documented in a 2009 Ph.D. thesis and a forthcoming article [43], which shows that aircraft cruise emissions may cause degradation of air quality over a hemispheric scale. In particular, Barrett et al. [43] estimated that ~8,000 premature mortalities per year are attributable to aircraft cruise emissions. It was found that due to the altitude and region of the atmosphere at which aircraft emissions are deposited, the extent of transboundary air pollution is particularly strong. Figure 11 describes, in a simplified form, some of the key transport processes that enable aircraft cruise emissions to impact surface air quality. Barrett et al. [43] noted that aircraft-attributable aerosol and aerosol precursors reach the surface via subsiding air masses, in which wet removal processes are inefficient, and that impacts are displaced significantly to the east of emissions due to strong zonal winds aloft.

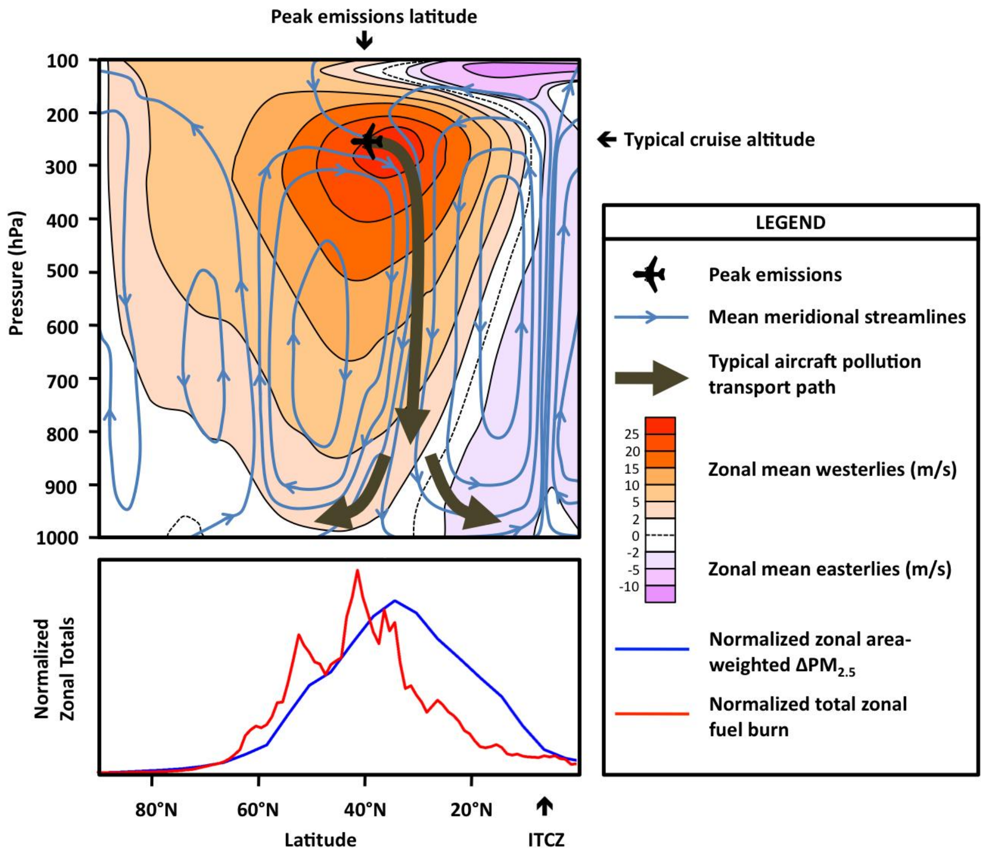

Figure 11: The upper panel shows mean meridional streamlines in light blue (i.e. contours of constant stream-function). The polar, Ferrell and Hadley cells can be seen from left-to-right. A significant fraction of aircraft fly in the upper part of the Ferrell cell. Also shown in the upper panel is the mean zonal wind speed. At typical cruise altitudes, the latitudes of peak aircraft emissions are in a region of strong zonal westerlies, allowing for rapid transport of pollutants to the east. The lower panel shows normalized zonal fuel burn, and normalized ground-level area-weighted $\Delta PM_{2.5}$ attributable to aviation (weighted by zonal area to be proportional to the total aviation attributable $PM_{2.5}$ mass in the surface layer). There is a mean southerly shift of 500 km from emissions to $\Delta PM_{2.5}$ impacts. The green arrows indicate the overall transport path for aircraft-attributable aerosol and aerosol precursors, with the ground-level aviation $PM_{2.5}$ perturbation being nearly symmetric about the subtropical ridge. The intertropical convergence zone is labeled as ITCZ.

Of relevance to NOx stringency, to be considered later, Barrett et al. [43] showed that aircraft NOx emissions impact surface air quality not only by increasing ozone and nitrate concentrations, but also by increasing sulfate concentrations. The mechanism for increasing sulfate concentrations is that aviation NOx emissions increase oxidant concentrations, which increases oxidation of SO2 to sulfate. It was found that aviation-attributable surface sulfate concentrations can be attributed approximately evenly to aircraft SOx emissions and NOx emissions.
Figure **12** shows results from 20 GEOS-Chem calculations demonstrating this.

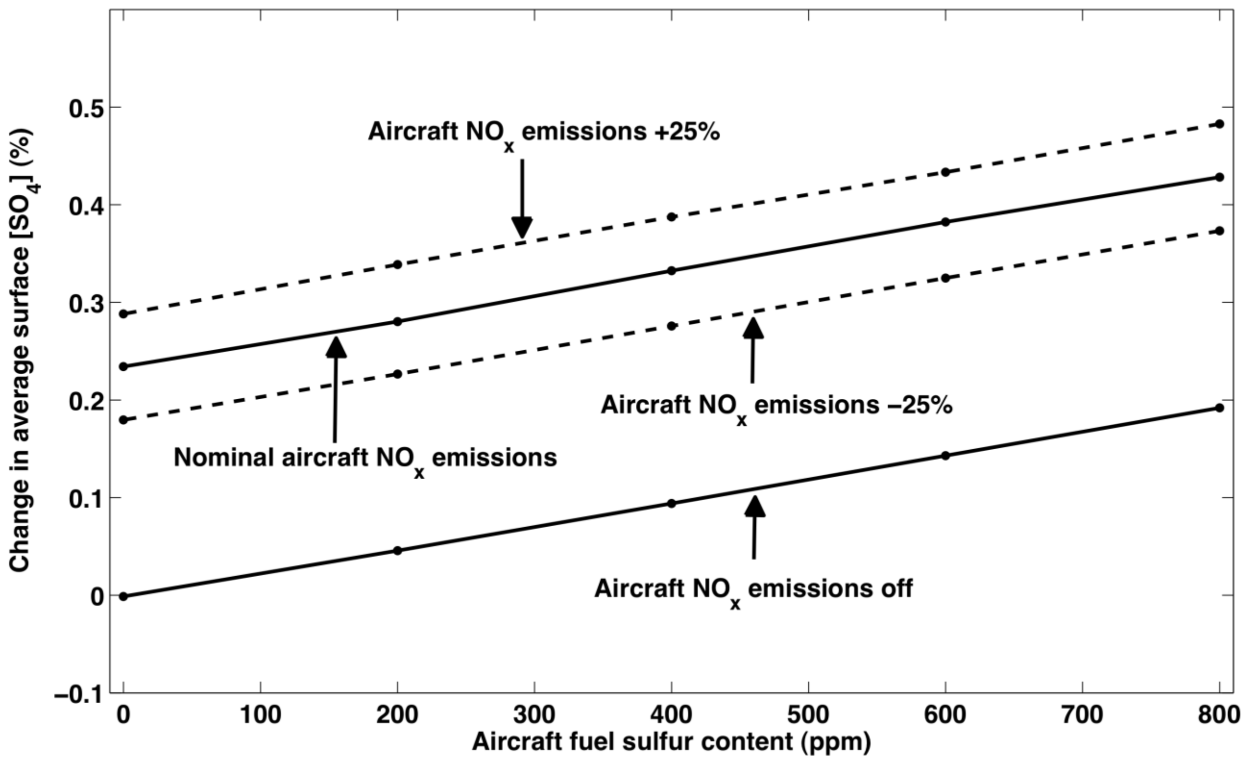

Figure 12: Relative change in average surface sulfate concentration attributable to aircraft emissions as a function of assumed fuel sulfur content for aircraft NO_x emissions at their nominal value, perturbed by ±25%, and switched off. Results from 20 GEOS-Chem full year calculations are shown.

4.1.3 Climate Module

As indicated in Table 2, the APMT-Impacts Climate Module estimates CO_2 and non-CO_2 impacts using both physical and monetary metrics. The APMT Climate Module adopts the impulse response modeling approach based on the work by Hasselmann et al. [79], Sausen et al. [80], Fuglestvedt et al. [81] and Shine et al. [82]. The temporal resolution of the APMT Climate Module is one year while the spatial resolution is at a highly aggregated global mean level. The effects modeled include long-lived CO_2, and short-lived non- CO_2 effects including the short-lived impact of NO_X on ozone (NO_X-O_3 short), the production of cirrus, sulfates, soot, H_2O, and contrails. Also included are the NO_X-CH_4 interaction and the associated primary mode NO_X-O_3 effect (referred to as NO_X-O_3 long).

Aircraft emissions are treated as pulse emissions emitted each year during a scenario, ultimately leading to changes in globally-averaged surface temperature. Pulses of aircraft CO_2 and NO_X emissions lead to direct and indirect radiative forcing effects. Aircraft fuel burn is used as a surrogate for other short-lived climate effects such as contrails, induced cirrus cloudiness, water vapor, soot, and sulfates. Longer-lived radiative forcing impacts associated with yearly pulses of CO_2 and NO_X emissions decay according to their e-folding times, while the RF from short-lived effects including the warming NO_X-O_3 effect is assumed to last only during the year of emissions. A superposition of decaying pulses or a convolution of the perturbation with the impulse response function of the system provides the temporal variation in the different effects modeled. A detailed description of the APMT Climate Module can be found in [83, 84].

Starting with aviation emissions, we proceed along the impact pathway to globally-averaged radiative forcing (RF) and surface temperature change. For CO_2 impacts, impulse response functions derived from complex carbon cycle models are used to calculate atmospheric concentration changes. The RF due to

CO_2 is estimated based on a logarithmic relationship between concentration changes and RF. The RF due to non-CO_2 effects is scaled based on most recent RF estimates from Sausen et al. [85], Wild et al. [47], Stevenson et al. [46], and Hoor et al. [86]. To compute globally-averaged surface temperature change from the estimated radiative forcing, a simplified analytical model by Shine et al. [82] is used. Although this approach has a lower fidelity as compared to using impulse response functions derived from detailed general circulation models (GCMs), it enables us to explicitly capture the impacts of uncertainty in climate sensitivity on the model results. For non-CO_2 impacts, the most recent efficacy values provided by Hansen et al. [87] and the IPCC [45] are used, where efficacy is defined as the global temperature response per unit radiative forcing relative to that resulting from a CO_2 forcing.

Next, the health, welfare, and ecological impacts are modeled using damage functions and discounting methods in terms of percentage change of world GDP and net present value of damages. APMT employs the general analytical framework of the damage function from the latest version of the Dynamic Integrated model of Climate and the Economy (DICE-2007) to estimate aviation-specific climate damages [88]. The DICE-2007 model is an integrated assessment model that couples economic growth with environmental constraints to assess optimal growth trajectories in the future and impacts of potential policy measures. APMT only uses the damage function approach within the DICE-2007 model, which builds upon the previous versions of the DICE model [88, 89]. The Nordhaus approach has received criticism for its simplifying assumptions such as excluding some non-market impacts (for instance, loss of natural beauty or extinction of species) [90]. However, estimating non-market impacts is a contentious issue faced by the broader environmental impact assessment community and is not unique to the DICE-2007 model [10]. Uncertainty in damage estimates is captured by sampling from a Gaussian distribution specified by Nordhaus [88]. APMT uses a range of constant discount rates from 2% to 7% following the recommendations of the US Office of Management and Budget (OMB) to estimate the net present value of future impacts [52].

Key limitations of the APMT-Impacts Climate Module include the use of a global spatial scale that does not capture regional variations in short-lived aviation climate effects, the lack of consideration of feedbacks in the climate system which may enhance or mitigate the climate impacts associated with aviation emissions, and independent treatment of aviation effects which does not account for interactions among some of the different physical and chemical mechanisms. Finally, climate impact estimation in APMT implicitly assumes that future operational changes involve no significant changes in flight routes. Future research areas for the APMT-Impacts Climate Module include incorporating altitude dependence of NO_X and contrails/cirrus effects and comparisons of APMT results with those from a complex AOGCM to improve characterization of uncertainties as well as test the robustness of the assumption of independence of effects.

4.2 APMT-Economics

The APMT-Economics Module models air transport supply and demand responses necessary at the regional and global levels to meet future growth demand. Given an initial baseline demand forecast, the Economics Module matches supply and demand to attain a partial equilibrium; impacts on other markets are not captured. The matching of supply and demand is based on input information about projected demand growth scenarios and changes in fleet capacity derived from retirement of aircraft currently in the fleet as well as replacement by existing and new technology aircraft. Three different categories of policy measures can be modeled within APMT-Economics - regulation policies that specify stringency levels for noise or emissions (and thus impact the available fleet and costs), financial policies that levy fees or taxes, and operational policies that require changes in flight operations. Responses to policy measures are categorized as supply side, demand side, and operational responses. Airlines may change their fleet mix or characteristics of aircraft in their fleet in response to a policy measure and this constitutes the supply side response. Policies that impact airline costs will also impact how those costs are passed on to passengers through fare changes inducing a change in passenger demand.

The Economics Module begins by modeling the Datum year (currently set at 2006) demand, fleet, operations and operating costs. Next, the baseline or no policy measure scenario is modeled using the Datum year as the starting point. The baseline scenario development uses demand and capacity forecasts and retirement curves as inputs along with information on availability of future aircraft types. Non-intervention related changes in fuel cost or other known changes in airline costs can also be included in the baseline, if they are consistent with the underlying assumptions in the demand and capacity forecasts used. The policy scenario development requires information on policy type, announcement and implementation years in addition to the inputs necessary for the baseline scenario. Replacement aircraft available in the policy case may be different from the baseline case depending on the nature of the policy. Changes in costs can be passed down to passengers through fare changes which may in turn alter the future air travel demand - this process closes the loop between projected demand and the impact of anticipated changes in supply and costs on the projected demand. APMT-Economics outputs include disaggregated operations data, operator costs and revenues, and fares. Operating costs and revenues can also be used to determine economic impacts on other stakeholders such as manufacturers, airports, air traffic control, the repair, overhaul and maintenance sector, as well as consumers and governments. Policy impacts relative to the baseline are quantified in terms of changes in producer and consumer surplus. Additional information about the APMT-Economics module can be found in [91, 92]. Note that APMT-Economics was previously referred to as the Partial Equilibrium Block.

The primary focus in the development of the APMT-Economics module has been supporting the NO_X stringency economic analysis for the upcoming eighth meeting of the CAEP in 2010, and as such the module has been extensively compared with previous CAEP economic analysis tools such as the AERO-MS model [93]. Future work entails developing modeling capabilities to address other types of policy options such as market-based measures.

5. MODEL ASSESSMENT AND COMMUNICATION OF RESULTS

This Section addresses the treatment of uncertainties in the policy analysis process and communication of pertinent results to aid the decision-making process. The focus of this discussion is on challenges faced in providing relevant information to support decision-making; this Section does not delve into decision theory or formal methods for evaluating optimal policies. There is a substantial body of literature that addresses the use of formal policy analysis models as aids in decision-making and communication issues at the science-policy interface. Recommendations from literature have strongly emphasized effective communication of uncertainties in results and findings [94-97]. The public and policy-makers form opinions about the likelihood of events, in this case about the environmental impacts of aviation, and it is important that these opinions are based on the state of current knowledge. Uncertainty assessments help describe the nature of the problem even if the information presented is imperfect [95]. For example, among other challenges in their experience with the EU Water Framework Directive, Brugnach et al. [96] state that “the overriding remaining issue was the need for a more explicit and comprehensive statement of a model's assumptions and limitations and better information provided on the sensitivity and uncertainty inherent in the model outputs.”

Model development efforts within the FAA-NASA-Transport Canada aviation environmental tool suite have placed an emphasis on quantitative and qualitative assessment of the tools and their functionality. There are multiple sources of uncertainties associated with the different components of the tool suite; here the discussion is limited to assessment activities specific to APMT. Key objectives of APMT assessment activities include developing an understanding of how uncertainties in inputs and model parameters contribute to variability in model outputs, and identifying limitations in model functionality that may impose restrictions on tool applicability. Assessment efforts also highlight areas for further research to reduce uncertainties in the outputs and expand modeling capabilities.

APMT assessment involves separate quantitative and qualitative procedures for APMT-Economics and the three APMT-Impacts modules [98]. Quantitative methods include formal parametric sensitivity studies and uncertainty analyses, and sample problems. Qualitative assessment methods such as external reviews by experts in the respective modeling domains have also been employed. System-level assessment is an area of future research that will focus on the integrated tool suite and will incorporate lessons learned from the module-level assessment studies. For APMT-Economics an additional assessment component was included which was a model comparison between APMT-Economics and AERO-MS. AERO-MS is a comprehensive economic modeling tool that has been used extensively in previous ICAO-CAEP analyses. Details of the APMT-Economics and AERO-MS comparison can be found in [93].

The final step in the policy analysis process is the distillation and communication of results to the relevant stake-holders and policy-makers. Model assessment plays an important role in facilitating the transfer of high-level policy-relevant information. It sheds light on the most critical inputs and assumptions that drive impact estimation and influence the conclusions that can be drawn about proposed policy measures. Policy evaluation through APMT provides information on the environmental benefits and economic costs resulting from the implementation of the policy relative to the unregulated baseline scenario. In conveying this information to decision-makers, also indicated are the uncertainties in the quantified impacts and the key assumptions about inputs and model parameters, which produce the particular set of results shown. Impact estimates are strongly driven by assumptions about inputs and model parameters made prior to the analysis, therefore it is important to provide transparency into the modeling process. This allows for a better understanding of how APMT models impacts and provides users with an opportunity to modify inputs and model parameters to reflect a range of scenarios and assumptions that may be of interest to them. Section 5.1 presents the APMT approach for conducting uncertainty analysis, Section 5.2 presents an uncertainty analysis for the APMT-Impacts Climate Module, while Section 5.3 discusses the challenges associated with communication of results in greater detail.

5.1 **Methods for Conducting Uncertainty Analysis**

Uncertainty is broadly categorized as either epistemic, which is related to limitations in the current state of knowledge, or aleatory, which refers to natural randomness [98]. The basis for most of the uncertainty analysis in APMT is Monte Carlo simulations. Inputs and model parameters are defined as random variables with probability distributions when possible. Certain types of inputs and model parameters that fall under the epistemic classification are less usefully defined as random variables—such as projections of future anthropogenic activity. For such parameters, results are simulated using different realizations of epistemic modeling uncertainties to capture uncertainty in the parameter as suggested in [98]. For instance, to capture uncertainties in future anthropogenic emissions growth scenarios, four different scenarios are used that represent a range of expected growth rates. Model calculations are performed using random draws from the defined parameter distributions to produce outputs for a given sampling of model parameters. Hundreds to thousands of trials of model calculations are run, each being a different draw from model parameters distributions, thereby producing a distribution for the desired output [99]. The output distribution computed is then used to determine the statistical properties of the output such as the mean and the variance.

Using Monte Carlo methods in assessing policy impacts relative to the baseline better reflects the reduced uncertainties in outputs when one has many modeling uncertainties common to both the policy and the baseline scenario (thus, often the difference between two scenarios can be predicted with less uncertainty than the baseline impacts themselves). In estimating policy impacts, a paired sampling approach is therefore used where the same random draws for model parameters are applied to both the baseline and the policy scenarios. The only difference between the two scenarios is driven by the effect of the policy such as a change in the emissions inventory. Figure 13 provides an illustration of the paired sampling concept for a simple linear model. The output, y, can be determined either by generating a common sample (paired sampling) of the model parameter, a, or by generating two separate samples for two sets of baseline and policy inputs, i.e., unpaired sampling. The model output shown as the difference between the policy and baseline cases is seen to have a larger variance for the unpaired sampling analysis as compared to the paired sampling analysis. Since the uncertainty associated with model parameter, a, is common to both the baseline and the policy analysis, following the paired sampling approach avoids double-counting uncertainties thereby reducing the estimate of the uncertainty in the policy impact results.

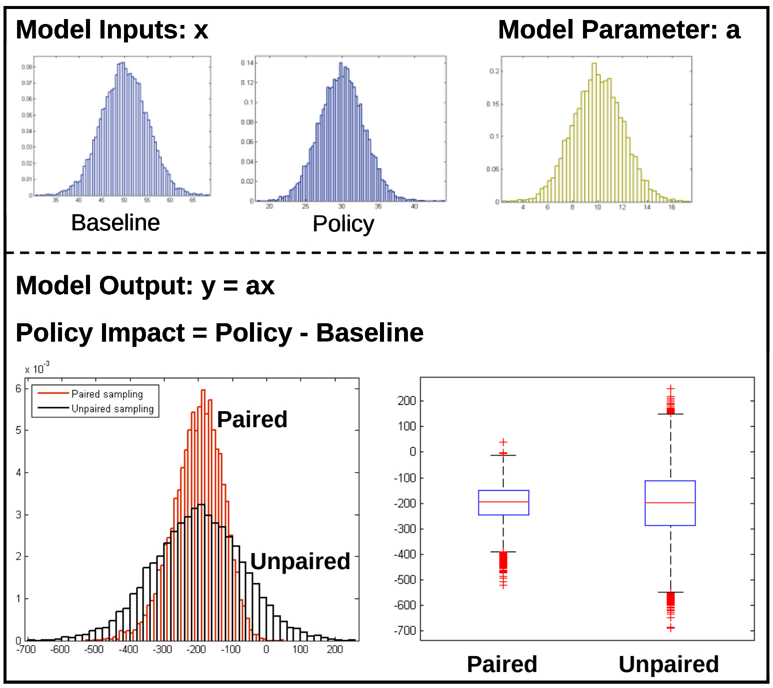

Figure 13: Paired Sampling for Monte Carlo Analysis

Monte Carlo methods are also used to conduct global and local sensitivity analyses; the reader is referred to [98] for details on the sensitivity analysis approaches. The assessment process is conducted following a double-loop approach (see [98, 100] for further details). The inner loop sampling or the global sensitivity analysis (GSA) apportions output uncertainty among different inputs and model parameters that can be expressed as random variables with probability distributions. Contribution of a parameter to output variability is expressed in terms of its main and total effect sensitivity indices. The main effect sensitivity index of a parameter refers to the contribution to output variance due to that parameter alone while the total effect sensitivity index shows the contribution of a parameter and its interactions with other parameters to output variability [101, 102]. Results from a GSA analysis can then be used to rank inputs and model parameters that can expressed as random variables in terms of their influence on output variance. GSA analyses were conducted separately for each of the APMT-Impacts modules and for

APMT-Economics, which helped identify the most influential inputs and model parameters for each component (see [31, 40, 98, 103, 104] for more details).

The outer-loop sampling designated as the local sensitivity analysis (LSA) assesses variability in outputs resulting from different realizations of certain epistemic modeling uncertainties that are expressed as modeling choices and are not captured through probabilistic distributions. Examples of parameters included in the LSA for the APMT-Impacts Climate Module include future anthropogenic growth scenarios, discount rate, and choice of a carbon-cycle impulse response function. Also included in the LSA are those parameters identified by the inner-loop GSA to be significant contributors to output variance. Monte Carlo simulations are conducted by shifting each parameter one at a time while holding all other model parameters at their nominal values. For certain parameters, such as climate sensitivity, the LSA involves shifting the parameter value to its possible minimum and maximum values. For other parameters, such as future growth scenarios, values are shifted to all possible realizations while holding all other parameters at their nominal values. Other inputs and model parameters not examined through the LSA are treated as random variables and sampled from their distributions through the Monte Carlo analysis. Together the LSA and GSA identify the most influential inputs and model parameters in each of the modules that determine the environmental and economic impacts estimated and uncertainties in those impacts.

Based on GSA and LSA approaches, influential contributors to output uncertainty can be grouped into different categories of uncertainty. These categories are listed below.

- **Scenario**: The scenario category includes alternative forecasts of future anthropogenic activity, such as aviation demand growth, population estimates, GDP projections, and background emissions levels.

- **Scientific and modeling uncertainties**: Scientific and modeling uncertainties are epistemic in nature and arise from the limitations in scientific knowledge or the modelling approaches.

- **Valuation assumptions**: The valuation category refers to monetization methods used to quantify noise, air quality, climate impacts, and depends on the selection of parameters such as the discount rate and value of a statistical life (VSL).

- **Behavioral assumptions**: The behavioral category relates to different assumptions about economic behavior of aviation producers, operators, and consumers that may be employed in APMT-Economics. Some examples include assumptions about the percentage of producer and operator costs passed down to consumers through fare changes and the consumer demand response to fare changes.

This categorization helps separate modeling uncertainties that arise from lack of scientific understanding from those which may be scenario dependent, or are more dependent on user preferences. Epistemic uncertainties that fall into the scientific and valuation categories can be expected to be reduced in the future as the state of knowledge improves. However, changes in policy impacts that result from policymaker choices can only be addressed by evaluating policies using different parameter values; some examples of such parameters include discount rate and future anthropogenic growth scenarios. The next Section demonstrates the GSA approach for the APMT-Impacts Climate Module. Similar analyses have been conducted for all components of APMT.

5.2 Global Sensitivity Analysis for the APMT-Impacts Climate Module

The inner-loop GSA for the APMT Climate Module is conducted for those inputs and model parameters that can be expressed through probabilistic distributions. Total sensitivity indices are provided for the GSA in Table 3 and are presented graphically in Figure 14. The total sensitivity index (TSI) is estimated following the mean-subtracted alternative GSA approach presented in [103, 105]. The TSI for each model parameter is computed by re-sampling the distribution for the given parameter while holding the distributions for other parameters fixed at their base sampled values. Given the tradeoff between desired accuracy and computational time, 10,000 Monte Carlo simulations were used to estimate the TSI. While additional Monte Carlo draws can improve the accuracy of the TSI estimates, the ranking of inputs in terms of their contributions to output variability is not expected to change.

Table 3: Global Sensitivity Analysis for the APMT-Impacts Climate Module - total sensitivity indices for model parameters with probability distributions

Model Parameter	**Temperature Change**		**Net Present Value**	
	Baseline	Policy Impact	Baseline	Policy Impact
Fuel burn and CO_2 emissions uncertainty	0.018	0.001	0.003	0.0004
NO_X emissions uncertainty	0.00002	0.004	0.00001	0.003
RF for doubling CO_2	0.013	0.001	0.008	0.004
RF value for short-lived effect	0.363	0.029	0.112	0.020
RF for NO_X effects	0.003	0.695	0.001	0.426
Efficacies for non-CO_2 effects	0.006	0.240	0.002	0.168
Climate sensitivity	0.612	0.050	0.256	0.155
Reference temperature change since pre-industrial times	0	0	0.002	0.001
Damage function	0	0	0.696	0.422
Total	1.015	1.021	1.080	1.199

TSI are presented in Table 3 and Figure 14 for temperature change and net present value of damages from aviation climate impacts. While Table 3 lists TSI for all model parameters include in the GSA, Figure 14 only presents the most important contributors to output variability and combines the minor effects in a single category labeled as Others. This uncertainty analysis is conducted using the aviation scenarios for the CAEP/8 NO_X Stringency Analysis described in detail in Section 6. The baseline TSI presented here refers to the unconstrained future growth scenario for aviation, while the policy impact TSI is the difference between the policy and baseline scenarios. The policy scenario corresponds to a 20% increase in engine NO_X stringency certification Standards implemented in 2012 (referred to as Scenario 10 in Section 6).

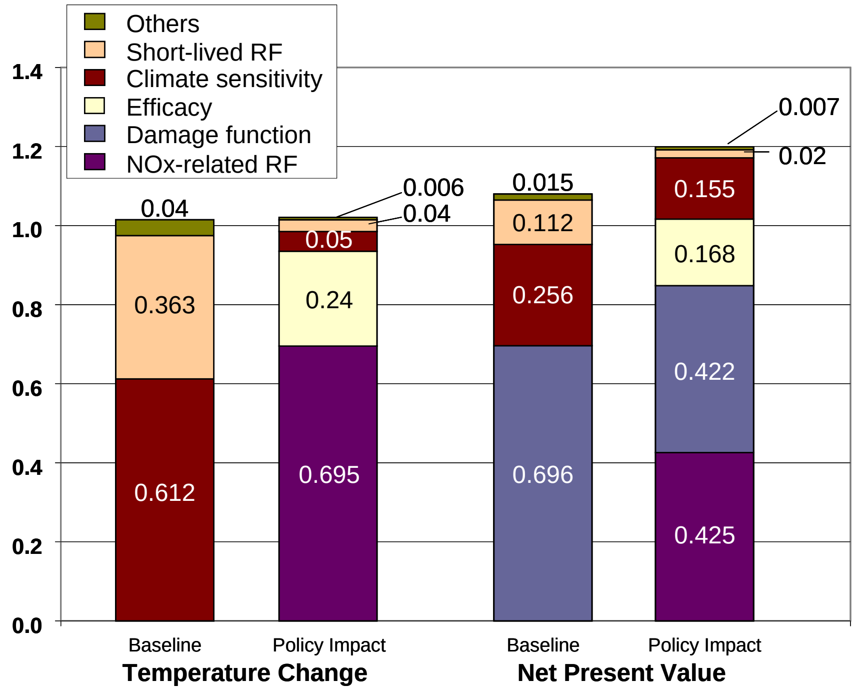

Figure 14: Global Sensitivity Analysis for the APMT-Impacts Climate Module - total sensitivity indices for key model parameters

Climate sensitivity is the most important contributor to uncertainty in baseline temperature change followed by radiative forcing due to non- NO_X and non-CO_2 short-lived effects (contrails, cirrus, H_2O, SO_X, and soot) and other model parameters. Note that damage function and reference temperature change since pre-industrial times do not contribute to uncertainty in temperature change as these model parameters are not used for computing temperature change. For the baseline net present value (NPV) of climate damages, the TSI ranks the damage function, climate sensitivity, and RF from short-lived effects as the three most important contributors to output variability. The sum of all TSI for the NPV of climate damages is greater than that for temperature change indicating stronger interaction effects.

The paired Monte Carlo analysis approach is used to conduct the GSA for the baseline and policy scenarios and the TSI for the policy impact are computed by subtracting the baseline results from the policy results. The policy scenario for this analysis results in decreased NO_X emissions and increased fuel burn relative to the baseline case (see Section 6 for further details). Consequently, in apportioning uncertainties in the policy impact among model parameters, model parameters associated with NO_X-related effects are seen to have more significant impacts for the policy impact as compared to the baseline case. Table 3 and Figure 14 indicate that for the policy impact temperature change the NO_X-related RF and associated efficacy are major contributors to uncertainty followed by climate sensitivity, RF from short-lived effects and other model parameters. Similarly, for the policy impact NPV, the NO_X-related RF, damage function, efficacy, and climate sensitivity are the most significant outputs in terms of uncertainty apportionment

5.3 Communication of Results

Given the complex nature of APMT with several inputs and model parameters that are influential in determining the results of any policy analysis, conveying all the critical policy-relevant information in a clear, concise manner becomes a challenging task. An emphasis is placed on relaying three different kinds of information: quantified environmental and economic impacts, uncertainties in these impact estimates, and the inputs and model parameters that provided the results. In providing this information, the assessment efforts described in Section 5.1 are important foundational elements.

The assessment activities allow for a distillation of the large amounts of information accumulated through multiple Monte Carlo runs. For all components of APMT, the assessment results indicate five or six inputs and model parameters to which the respective outputs are most sensitive. Based on this condensed information, a decision-making framework was developed to enable an interactive application of APMT, where users dictate the terms of analysis to be conducted depending on their preferences and perspectives. The selection of each of these influential parameters is described through a lens; Section 5.3.1 describes the lens concept in further detail.

A second issue of concern with the communication of results is the selection of a time-frame over which the impacts of a proposed policy are evaluated. Given the different temporal characteristics of the various environmental impacts, not all the impacts from aviation activity are realized in an immediate time-frame. For instance, CO_2 impacts tend to accrue over several centuries and this needs to be factored into the decision-making process. Section 5.3.2 delves further into the selection of timescales for policy analysis.

5.3.1 Decision-making framework – Lenses

As mentioned previously, there are about five to six parameters for each APMT module, which are most influential in determining the magnitude of the estimated impacts and associated uncertainties. These influential parameters are derived from a global sensitivity analysis that has been conducted separately for each module and is used to rank parameters in terms of their contribution to output variability [31, 40, 98], [103], [104]. Impacts can be represented in physical or monetary terms, with the computation of monetary metrics introducing additional influential parameters relative to the important parameters for the evaluation of physical effects. One can conceive of thousands of unique combinations of inputs and model parameters that may be of interest in assessing different policy options.

In order to extract meaningful insights about the possible costs and benefits of a policy, it is therefore necessary for the analysis options to be synthesized into a set of pre-defined combinations of inputs and assumptions. These combinations of inputs and model parameters can be thought of as describing a particular point of view or perspective and are thus designated as lenses. Some example lenses include a lens with mid-range environmental and economic impacts; one with worst-case environmental impacts and mid-range economic impacts; one focused on short or long-term environmental impacts; or one that adopts a conservative perspective for one impact while keeping a mid-range perspective on others. Several lenses can be decided upon prior to policy assessment with guidance from users to evaluate a given policy from different perspectives.

Figure 15 shows a lens with mid-range assumptions for all inputs. Each box shown represents a different impact area with its respective influential parameters. The lens worksheet also provides the shapes of input distributions with appropriate values; inputs with no distributions are shown as discrete choices (see for instance, the discount rate). Inputs that are discretely selected have blue boxes drawn around them while inputs that are randomly drawn from their distributions have their distributions highlighted in blue. Discount rate is a common influential input for all impacts - it is used to convert future costs and benefits to their net present value. Table 4 provides a short description of the different inputs graphically represented in Figure 15. Influential parameters for APMT-Economics are determined by the policy analysis under consideration and depend on whether the development of a future fleet forecast is done internally within APMT-Economics or externally. It is important to note that each of APMT modules involves more inputs and model parameters than those shown in Figure 15; only those inputs and model parameters critical to output variability are presented here. Section 6 demonstrates how the lens formulation can be utilized through an illustrative engine NO_X stringency analysis.

Preliminary experience in applying the lens concept for APMT policy analysis thus far has indicated a mixed response by users. The lenses are received well by users of the tool familiar with the overall modeling approaches within APMT. However, the lenses were perceived as being too detailed and inaccessible by decision-makers and other users unfamiliar with APMT modeling methods. A further distilled and simplified explanation with descriptive names for the lenses was found to be more desirable by decision-makers. An important area of future work would be to investigate how the environmental benefit and economic cost information provided by APMT is adopted by decision-makers in their policy-making processes. This activity can provide valuable information for developing communication strategies for conveying policy-relevant APMT results to decision-makers.

Table 4: APMT Lens Inputs and Model Parameters

APMT-Economics	**Description**
Non-recurring costs	One-time costs for manufacturers
Recurring costs	Recurring costs for manufacturers and operators
Fuel costs	Uncertainty in future fuel prices
Consumer impacts	Fraction of recurring costs passed on to consumers through fare changes
APMT-Impacts: Noise	**Description**
Noise Depreciation Index (NDI)	Index relating housing price change to noise level changes
Background noise level	Noise level above which aircraft noise affects housing value
Housing growth rate	Growth rate for future housing prices
Significance level	Noise level above which housing impacts are included in benefits estimation
Contour uncertainty	Uncertainty in the magnitude of noise contours
APMT-Impacts: Air Quality	**Description**
Population growth	Growth in population in the future
Emissions uncertainty	Estimate of uncertainty in fuel burn; SO_X; NO_X; nvPM
Adult premature mortality CRF	Concentration response function relating PM exposure to mortality
Value of a statistical life	Value of statistical life used for estimating monetary impacts
APMT-Impacts: Climate	**Description**
Climate sensitivity	Climate sensitivity for CO_2 doubling relative to 1750 levels
NO_x-related effects	Uncertainty for aviation-NO_x RF
Short-lived effects RF	Uncertainty for other aviation effects RF - cirrus, sulfates, soot, H_2O, contrails
Anthropogenic growth scenario	Anthropogenic CO_2 emissions and GDP growth scenario
Aviation scenario	Aviation growth scenario
Damage coefficient	Uncertainty in estimating societal damages

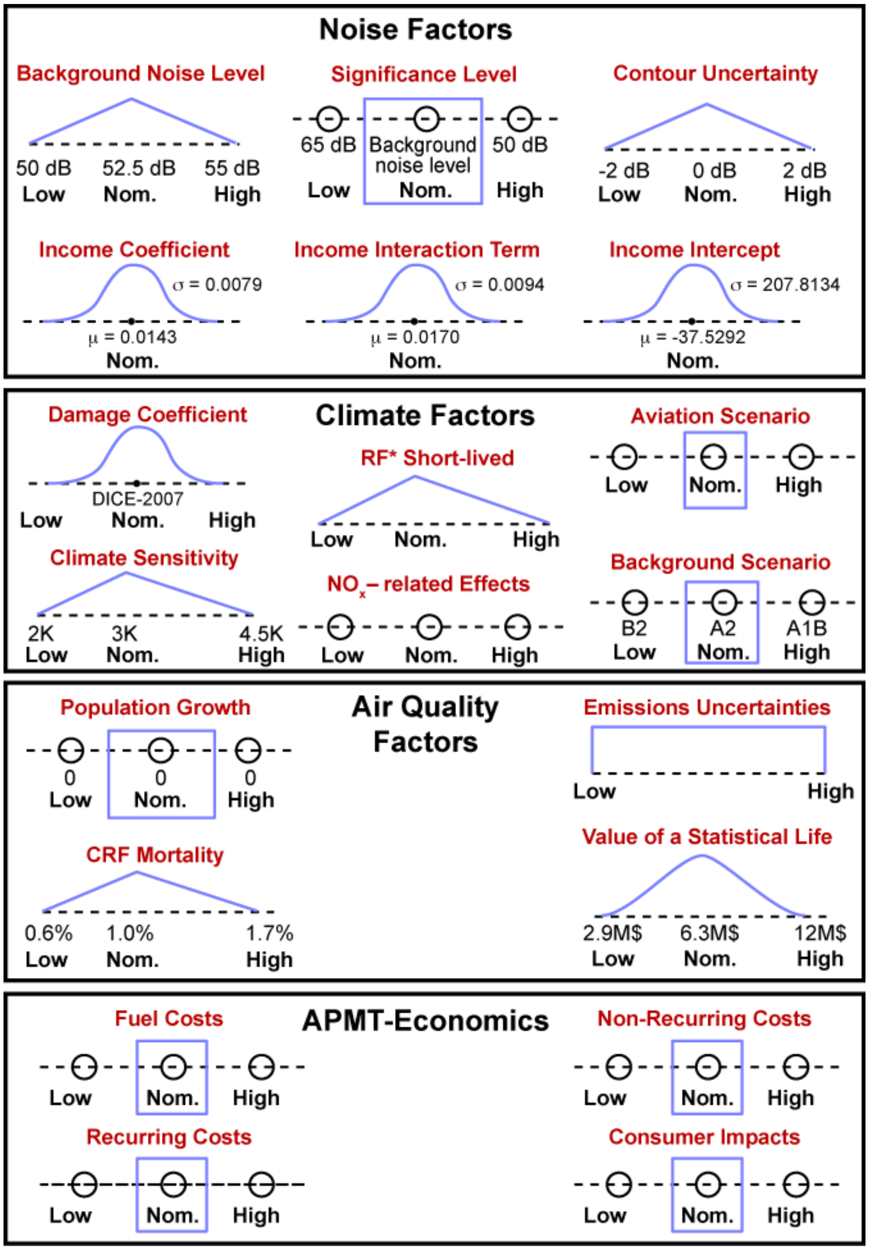

Figure 15: Lens with Mid-Range Assumptions for Environmental and Economic Impacts

5.3.2 Timescales

Defining timescales over which the policy analysis is conducted and over which the costs and benefits are accrued is an important issue in the communication of results. Selection of the analysis timescale can significantly alter the conclusions drawn about the efficacy of a proposed policy measure and therefore warrants a brief discussion here. There are two timescales embedded in a policy analysis. The first timescale is the policy influence time period, which is the duration over which a policy is assumed to significantly influence aviation activity. The second timescale is the time period over which the impacts of the different environmental effects attributed to the activity persist. As illustrated in Figure 16, in order to evaluate a proposed policy measure relative to a baseline scenario, aviation activity is modeled for the duration of the assumed policy influence time period (typically 20-30 years in ICAO-CAEP practice).

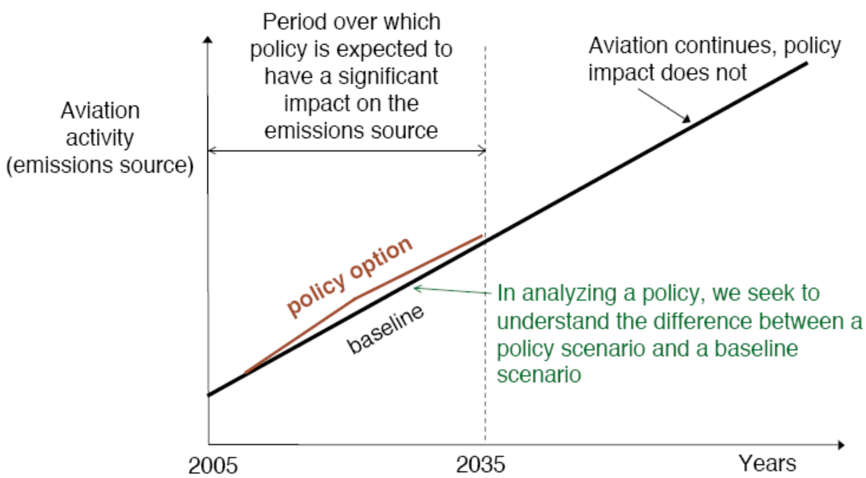

Figure 16: Timescales in Policy Analysis

The time period over which the impacts of the policy are felt on the environment is typically longer. For example, climate change impacts related to changes in aviation activity will persist for centuries. Thus, we model the environmental impacts for hundreds of years beyond the assumed policy impact period.

Distinctions between the timescales become important when one wishes to aggregate economic costs and environmental benefits resulting from a proposed policy measure relative to a baseline scenario. The time period over which the costs and benefits are accrued may change the balance between costs and benefits making a policy seem more or less desirable, especially when one considers different discount rates that weight the value of long and short term benefits and costs differently. For the policy analysis presented in Section 6 costs and benefits aggregated over the full environmental impacts time period are compared, which extends well beyond the policy influence period. The policy influence time period is typically chosen to be 30 years which is consistent with the ICAO-CAEP forecasting and analysis practice for assessing policy measures, and approximately the same as the time-scale for the development, adoption, and significant use of new technology in the fleet.

6. NO_X STRINGENCY POLICY ANALYSIS

NO_X emissions include both NO and NO2 and are a byproduct of combustion of hydrocarbon fuels in air at high temperatures and high pressures. NO_X emissions are of concern for both air quality and climate impacts. As described in Section 2, there is limited scientific evidence indicating the direct health impacts of NO_X; however it plays an important role as it perturbs atmospheric ozone chemistry and is a precursor to particulate matter in the form of nitrates [77]. In terms of climate impacts, NO_X leads to ozone production at altitude with a short-lived warming effect and also increases the abundance of OH radicals in the atmosphere, which reduces CH4 concentrations. The NO_X-related CH4 reduction is a long-lived effect with a e-folding time of approximately a decade [46], [47, 86] and also has an associated O3 reduction effect. This long-lived NO_X-CH4-O3 effect has a cooling impact that to a large extent counter-balances the short-lived warming O3 effect when integrated globally over the full time horizon of impacts.

As discussed in Section 3.2, the decision-making process for the CAEP/6 NO_X emissions Standard selected the most cost-effective stringency option among the options analyzed by the FESG. The CAEP/6 FESG analysis described in Section 3.2 found the 10% stringency level implemented in 2008 to be the most cost-effective option, with further negotiations among policymakers leading to an agreement to adopt a stringency increase of 12% relative to CAEP/4 Standards as the new CAEP/6 Standard [60]. The CAEP/6 NO_X stringency analysis did not explicitly model health and welfare impacts of reductions in NO_X emissions or account for interdependencies between noise and emissions impacts [61]. This Section analyzes a subset of engine NO_X emissions stringency options being considered for the CAEP/8 (February 2010). The assumptions and inputs we use for the emissions inventories and industry costs are identical to those used within the officially sanctioned cost-effectiveness analysis used to support the CAEP/8 decision. A comparison of the key policy insights obtained from the conventional cost-effectiveness approach with a more comprehensive cost-benefit approach that incorporates the following elements is provided.

- Estimation of the physical and monetized noise, air quality, and climate change impacts from reductions in NO_X emissions and the associated fuel burn and noise penalties
- Quantification of uncertainties in modeling both environmental and economic impacts attributed to aviation activity
- Assessment of tradeoffs between environmental benefits and economic costs associated with the proposed NO_X emissions stringency options

Using the APMT tool described in Section 4.1, this chapter illustrates how including an assessment of health and welfare impacts through a cost-benefit analysis can provide significant additional information in the evaluation process for aviation environmental policies. The following Sections first discuss the CAEP/8 NO_X Stringency scenarios, present key modeling assumptions within APMT, and finally present cost-effectiveness and cost-benefit results. This work also tests the sensitivity of results to modeling assumptions made both within APMT and in developing the CAEP NO_X stringency options.

6.1 **CAEP/8 NO_X Stringency Options**

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. In preparation for the CAEP/8 meeting, there was a substantial work effort dedicated to the evaluation of more stringent NO_X policy options relative to CAEP/6. There have been several changes to the analysis procedure employed for the CAEP/8 process as compared to the CAEP/6 analysis. Some of the major changes include:

- 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 [58].
- NO_X stringency analysis derived from several different models as compared to the CAEP/6 analysis which solely used the FAA Emission and Dispersion Modeling System (EDMS) tool for environmental benefits modeling and the FESG model for economic costs. A list of the models exercised for the NO_X analysis can be found in [106].

- 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.

The NO_X stringency analysis requires coordination and data flow among the various working groups in the CAEP, the MODTF, and the FESG. The process can be briefly described as follows - Working Groups 1 and 3 within the CAEP provide inputs to the MODTF and FESG that enable the modeling of environmental and economic impacts of the different policy options. The Working Groups provide inputs including 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 quantifies tradeoffs among NO_X emissions, fuel burn, noise, and costs. The FESG to develop future fleet and traffic forecasts and fleet retirement curves based on consensus inputs from industry and ICAO. The MODTF uses inputs on future operations from the FESG and the Working Groups to model environmental benefits in terms of terminal area noise and emissions as well as full mission fuel burn and emissions. Finally, the FESG conducts its economic cost-effectiveness analysis using environmental benefits modeled by the MODTF and costs incurred by manufacturers and operators for future operations determined by their response to the NO_X stringency level.

To ensure good coordination among the different groups involved and refine modeling assumptions, the groups engaged in several sample problem analyses and conducted two rounds of modeling for the NO_X stringency assessment. Here the analysis focuses on the final round of modeling for the NO_X stringency analysis. The next Sections provide a brief overview of the modeling assumptions utilized by the MODTF and the FESG as relevant to the policy analysis presented in this paper. For additional details on the databases and assumptions used in the CAEP/8 NO_X stringency analysis, the reader is referred to [106].

6.1.1 NO_X Stringency Scenarios

The CAEP/8 NO_X stringency options range from 5% to 20% stringency increases relative to CAEP/6 Standards, in increments of 5%. The ten different scenarios considered are shown in Table 5 with stringency levels listed by engine categories; the analysis is conducted for both the small and large engine categories separately and for all engines combined. Small engines are defined as having a thrust rating between 26.7kN and 89kN, while large engines have a thrust rating of greater than 89kN. Table 5 also indicates the slope of the stringency limit when plotting Dp/Foo as a function of the overall engine pressure ratio for the large engines. The analysis presented in this chapter focuses mainly on large engines, but also includes combined engine results for the noise analysis.

Table 5: CAEP/8 NO_X Stringency Scenarios [106]

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

Environmental and economic results provided by MODTF and FESG for the baseline or no stringency case are modeled for years 2006, 2016, 2026, and 2036. The stringency options have two different implementation years - 2012 and 2016. Policy options implemented in year 2012 are modeled for years 2016, 2026, and 2036, and policy options with an implementation year of 2016 are modeled for years 2026 and 2036. Results for the in-between years are interpolated for our impacts analyses.

6.1.2 FESG Fleet and Traffic Forecast

The FESG fleet and traffic forecast is based on an assumption of unconstrained growth in the future which implies no physical (airport-level) or operational (airspace) constraints to air traffic growth. The FESG forecast includes a passenger traffic forecast in revenue passenger kilometers (RPKs), a passenger fleet mix forecast, forecast for aircraft less than 20 seats and a freighter traffic and fleet forecast. Aircraft with less than 20 seats are not modeled by the MODTF group in the environmental assessment and will not be discussed further here.

The passenger traffic forecast is based on scheduled operations of commercial civil aviation aircraft and chartered flights but does not include general aviation or military operations. The FESG traffic forecast is a consensus-based forecast with inputs from ICAO and industry and is developed for the period 2006-2026; a 10-year extension to the base forecast to 2036 is also estimated. The forecast estimates average annual traffic growth for 23 major international and domestic route groups to be 4.9% over 2006-2026 and 4.4% from 2026-2036. The forecast extension is based on differences in market maturity across the globe modeled by applying a growth decline factor to the consensus-based forecast for different route groups [107].

The FESG models the passenger fleet mix over a 30-year period from 2006-2036 using the Airbus corporate model. Fleet growth modeling requires passenger traffic growth as an input along with assumptions about seat categories, load factors, and aircraft utilization over the forecast period. The passenger fleet forecast shows an annual average fleet growth rate of 3 to 3.2% between 2006 to 2036 resulting in a doubling of the fleet by 2026 relative to 2006 and the fleet in 2036 being 2.5 times that in 2006. The FESG also develops retirement curves for passenger aircraft in service to determine the number of aircraft to be replaced in the current fleet over the 30 year period in consideration [107].

Finally, the freighter traffic forecast from 2006-2036 is developed using a modified version of the Boeing corporate forecast methodology. The freighter traffic is expected to grow at an average annual rate of 6% over these 30 years. The freighter fleet mix composed of currently in-service aircraft, new aircraft, and passenger aircraft converted to freighter is based on assumptions about seat categories, load factors, and an average retirement age of 40 years [107].

6.1.3 Noise and Emissions Modeling

The starting point for all noise and emissions modeling within the MODTF is the Common Operations Database (COD) for 2006. The COD consists of detailed operations data for year 2006 based on information from EUROCONTROL's Enhanced Traffic Flight Management System (ETFMS), the FAA's Enhanced Traffic Management System (ETMS) and the International Official Airline Guide's 2006 schedule. The NO_X stringency assessment is based on operations data from six representative weeks from the COD scaled up to represent operations for one year. Future fleet and operations are modeled by the AEDT Fleet and Operations Module (FOM) that uses the FESG fleet and traffic forecast, aircraft retirement curves, and the aircraft growth and replacement database. The AEDT-FOM provides all emissions and noise modelers with the flight operations data to simulate noise contours and emissions inventories for the baseline and stringency options under consideration. Noise and emissions modelers also use information on the technology response by the different engine families affected by the new NO_X stringency to compute future noise and emissions. Section 6.1.4 discusses the different technology response categories and associated costs, fuel burn, and noise penalties [106].

Noise and emissions modeling is limited to the aircraft level, no other airport sources are modeled. Several noise and emissions models have been used for the CAEP/8 NO_X stringency analysis; however, for the purposes of this chapter, results provided by the Aviation Environmental Design Tool (AEDT) are used. Noise results are provided by the AEDT/Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA) version 7.0, which is consistent with both the Society of Automotive Engineers (SAE) Procedure for the Calculation of Airplane Noise in the Vicinity of Airports, AIR-1845 [108] and the European Civil Aviation Conference (ECAC) Document 29 [13] in its methodologies. AEDT/MAGENTA provides results in the form of population exposure and noise contours for 55, 60, and 65 dB DNL noise levels for 210 airports worldwide.

Emissions modeling is divided into air quality (AQ) or terminal area emissions and greenhouse gas or full mission emissions. AQ emissions are provided by the AEDT/Emissions and Dispersion Modeling System (EDMS) [109] and full mission emissions are provided by the AEDT/System for assessing Aviation's Global Emissions (SAGE) [110, 111]. The AEDT models aircraft emissions including carbon dioxide (CO_2), water (H_2O), sulfur oxides (SO_X), nitrogen oxides (NO_X), total hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM), non-methane hydrocarbons (NMHC), and volatile organic compounds (VOC) for all flight segments. AQ emissions are modeled using ICAO times-in-mode for the taxi, takeoff, climb-out, and approach flight segments below 3000 feet. Full mission emissions are based on great circle trajectories and do not use radar track data for determining flight tracks [106].

While emissions and noise data are provided on a global basis, for the analysis presented in Section 6.4, continental US-only results are utilized given current APMT data limitations. AEDT environmental results used for modeling noise, air quality, and climate impacts in APMT are presented in Section 6.3.

6.1.4 Technology Response

Future fleet composition under increased NO_X stringency is based on the assumption that any in-production aircraft-engine combination that fails the new stringency will either undergo necessary modifications to comply or will no longer be a part of the future fleet. The primary engine design tradeoffs involved in reducing NO_X emissions include penalties in fuel efficiency leading to the formation of other pollutants such as soot, CO, CO_2, HC, and detrimental impacts on stable and reliable engine operation across the flight envelope. NO_X formation occurs at high temperatures in the combustor and technologies to reduce NO_X emissions tend to focus on lowering combustor temperatures and/or reducing the residence time of gases in the combustor. CAEP Working Groups 1 and 3 provide information on the technology response required by the different engine families for the stringency options under consideration. Any proposed changes are assumed to be applicable to the entire engine family to reduce costs. Here only the technical aspects of the technology response are discussed, the associated costs are provided in Section 6.1.5. Three different categories of technology response designated as “Modification Status” or MS levels are described in [106]:

- ***MS1 - Minor Change***

  As the name suggests, the MS1 level refers to minor changes to existing engines that are expected to result in NO_X reductions of about 1-5%. Some examples of minor modifications include changes to cooling flows around the combustor and to the engine control system resulting in changes in engine performance and potentially requiring additional testing and re-certification.

- ***MS2 - Scaled Proven Technology***

  The MS2 level is applied in the case where an engine manufacturer can apply its best-proven certified combustor technology which is in use in a different engine family to an engine family that fails the new NO_X stringency. The MS2 modification is expected to require significant modeling and design work along with ground as well as flight testing of the modified engines. NO_X reductions are anticipated to be at least 6% for the MS2 level.

- ***MS3 - New Technology Applying Combustor Performance from Research Programs***

  The MS3 level requires significant investment in development time and costs for new technology acquisition either from other manufacturers or through research programs. NO_X reductions of at least 10% are feasible through a MS3 change. Radical design changes are necessary in the case of the MS3 which necessitate extensive iterative analysis and testing. The MS3 level is the only technology response level with an associated fuel burn penalty of 0-0.5% and a noise penalty of 0-1dB. Noise penalties are modeled either as changes in noise levels or as costs incurred to mitigate the expected noise increases. For the analysis presented in Section 6.4 the noise penalty is expressed through changes in noise levels and resulting changes in population impacts and housing value and rental loss.

6.1.5 Costs of Stringency Options

Costs related to the different stringency options are classified as recurring or non-recurring and associated with engine manufacturers or airline operators. These distinctions also prevent the possibility of double counting in the economic analysis. Table 6 lists the different cost categories by the different MS levels [112, 113] and the following discussion briefly describes each of the cost categories. It is important to note that only those cost assumptions included in the analysis are shown in Table 6. The FESG CAEP/8 analysis also included tests with additional costs impacts, such as loss in fleet value for affected engines. The spare engine inventory of airlines is expected to change at the MS3 level where the modified engines are substantially different from existing engines leading to a loss in fleet commonality. The lost asset value category refers to the loss in fleet value for those engines that are delivered before the stringency implementation date and will have to be retrofitted to comply with the new Standard.

Table 6: Costs of CAEP/8 NO_X Stringency Options [113]

Modification Status	Non-Recurring Costs		Recurring Costs				
	Engineering and development [$M]	Noise trade-off [$M]	Incremental manufacturing [$]	Fuelburn penalty [%]	Engine maintenance [$/EFH]	Lost revenue payload/ range constraints	Spare Engine Inventory [%]
MS1	8 (1-15)		0	0	0	0	0
MS2	75 (50-100)		20,000	0	1 (0-2)	0	0
MS3	300 (100-500)	$0, $10M, $100M	40,000	0-0.5%	2 (0-4)	5% twin-aisle aircraft operations, 0.5% single-aisle aircraft	50%

6.1.5.1 Non-recurring costs

Non-recurring engineering and development costs are incurred by manufacturers in adopting the required MS level technology changes for affected engine families. Cost estimates are listed with a central value in Table 6 and a range provided in parentheses [112].

6.1.5.2 Recurring costs

There are five different cost categories included under recurring costs as shown in Table 6. Manufacturer recurring costs are related to higher production costs for modified engines which have increased complexity and require the use of more expensive materials. For airline operators recurring costs include costs of additional fuel resulting from the MS3 fuel penalty, increased engine maintenance costs, and lost revenue from changes in payload-range capability. Costs of additional fuel are specific to the MS3 level and are estimated using an average fuel price of $100/barrel (a high fuel price estimate of $150/barrel is also used as a sensitivity test). Increased maintenance costs for the modified engines with increased complexity are listed as costs per engine flight hour in Table 6. For long range missions operated at the margins of the aircraft payload-range capability, the MS3 fuel penalty requires offloading of passengers or cargo to carry the additional fuel necessary resulting in revenue loss. This loss in revenue from the MS3 incremental fuel burn impact depends on average aircraft utilization at the payload-range limit and airline yields [112]. The analysis also assumed that 50% of the MS3 aircraft would require a spare engine inventory adding additional costs.

Because the FESG cost data are estimates for global operations, we used APMT-Economics to estimate the fraction of these costs that are attributed to US-only operations. For a wide range of cases the percent of global costs attributed to the US operations was between 27% and 28%. For all of the analyses presented here, we have used 27% of the FESG cost inputs to approximate the US costs.

6.2 APMT Modeling Assumptions

Section 6.1 discussed modeling assumptions upstream of APMT within the CAEP analysis groups; here a description of modeling assumptions within APMT-Impacts is provided. For the analysis presented, FESG cost results are used rather than those from APMT-Economics to enable a direct comparison with the results of the CAEP/8 cost-effectiveness analysis (note that the FESG cost results have been checked/compared with the APMT-Economics results and they are very similar). The APMT NO_X stringency analysis presented is limited to continental US-related impacts given the geographic scope of the air quality modeling within APMT to ensure that the economic costs and environmental benefits are compared in a consistent manner. There are several key sources of uncertainty involved in conducting an analysis of the CAEP/8 NO_X stringency options. These uncertainties can stem from the CAEP/8 modeling process such as from developing future aviation growth scenarios, technology response and cost assumptions, and modeling noise contours and emissions inventories, as well as from the APMT model. While exploration of the uncertainties in the CAEP/8 modeling process described in Section 6.1 is limited by the scope of the data available from the CAEP analysis, the impacts of uncertainties related to the APMT model can be explored in greater detail by utilizing the extensive assessment efforts described in Section 5.

This Section describes the lenses selected for conducting a cost-benefit analysis using the APMT model. Three different lenses capturing low, mid-range, and high environmental impact estimates are presented—where low, mid-range, and high input and model parameter assumptions in each impact category are grouped together. We also consider two lenses where mid-range assumptions are used for all environmental impacts with the exception of changing the assumptions for the climate impacts of NO_X to represent the highest and lowest estimates available in the literature. Although the impacts of cruise emissions on surface air quality are still an emerging area of study, they could be influential in assessing the value of NOx reductions. Therefore, we include a lens where we have scaled the air quality impacts to provide a first order estimate of these effects. Finally, because the FESG cost estimates were developed with significant input from industry and thus may be biased high, we were asked to consider additional lenses with mid-range environmental assumptions, but industry with costs set to zero and 50% of the FESG provided values. The only parameter not grouped in the lens assumptions was the discount rate. This was done so that the full range of discount rates could be applied to each result regardless of the lens selected for analysis.

6.2.1 APMT-Impacts

This Section describes the high, mid-range, and low lenses within APMT-Impacts. Table 7, Table 8, and Table 9 show the lens assumptions for the Noise, Air Quality, and Climate Modules respectively. Noise and air quality impacts are modeled over the 30-year period from 2006 to 2036. Climate impacts are modeled over their full time horizon lasting for 800 years following the 30-year aviation activity period to capture impacts from long-lived effects such as CO_2. Impacts are expressed in both physical and monetary metrics (although discounting reduces the effective period of significant climate impacts to a few hundred years).

For noise, the assumptions are shown in Table 7. The mid-range lens is set using our best estimates for the relationship between noise and impacts on property values. We use a relationship between willingness-to-pay for noise and city-level income that best reflects the 65 hedonic studies in the underlying meta-analysis described in Section 4.1.1. This is reflected in the choice of the first three regression parameters in the table. We also use a triangular distribution for the background noise level from 50dB to 55dB with a peak at 52.5dB. This is representative of typical ambient noise levels in populated areas around airports. For the low-impact lens, we pick a coefficient relating willingness-to-pay for noise to income that corresponds with the 5% point of the distribution of the regression results (thus a low willingness to pay), we assume the background noise level (above which the aircraft noise is perceived) is higher (55dB), and we further count only the noise impacts in areas that exceed 65dB DNL. For the high-impact lens, we pick a 95% level within the distribution for the willingness-to-pay for noise reduction as a function of income, we assume the areas around the airports are 50dB, and we assume all aircraft noise in excess of 50dB contributes to property value depreciation.

For all lenses, we assume zero population growth and income growth, consistent with CAEP practices for policy analysis.

Table 7: APMT-Impacts Noise Assumptions for the CAEP/8 NO_X Stringency Analysis

Noise Assumptions	Low Lens	Mid Lens	High Lens
Income coefficient Approximated normal distribution	0.0013	Mean = 0.0143 SD = 0.0079	0.0272
Income Interaction Term Approximated normal distribution	0.0154	Mean = 0.0170 SD = 0.0094	0.0154
Income Intercept Approximated normal distribution	-30.3440	Mean = -37.5292 SD = 207.8134	-30.0440
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 = -2-2) dB	2 dB
Population growth rate	No growth	No growth	No growth

The air quality analysis assumptions are given in Table 8. The population growth rates are again specified as zero consistent with typical CAEP modeling practice; this will lead to an underestimate of the future air quality benefits of NO_x stringency. The emissions uncertainties are set to reflect our estimates of biases and uncertainties in the emissions inventories (all given as multiplicative factors, except for SO_X which is expressed as fuel sulfur concentration). For the mid-range lens a distribution is used, with the high and low lenses assuming fixed factors corresponding to the high and low range of the potential biases and uncertainties. The concentration response function relating changes in ambient particulate matter concentrations to premature mortality risk is drawn from a distribution for the mid-range lens and from the tails of the distribution for the low and high lens. The same approach is adopted for the value of a statistical life. For all analyses we assume a 2001 US National Emissions Inventory background emissions scenario (from other sources) that does not change with time.

We include an additional lens where we have used data from Barrett et al. [43] to scale the mid-range impacts to provide a first estimate of the potential impacts of cruise emissions on surface air quality. Barrett et al. [43] calculated global mortalities attributable to aviation given nominal NO_x emissions and with NO_x emissions perturbed. As a first estimate, we have taken these results and interpolated for each NO_x stringency scenario, and corrected for the different the concentration-response functions used in APMT and Barrett et al. [43]. This inclusion of cruise emissions impacts in this simplified fashion increases the air quality benefits associated with a NO_x stringency scenario by a factor of approximately five. A key limitation is that we have assumed the relative reduction in mortalities (calculated on a global basis in Barrett et al. [43]) applies proportionally to the U.S. Because of the regional distribution of health impacts this may lead to an underestimate of the air quality benefits of NO_x stringency associated with cruise emissions.

Table 8: APMT-Impacts Air Quality Assumptions for the CAEP/8 NO_X Stringency Analysis

Air Quality Assumptions	Low Lens	Mid Lens	High Lens
Population growth	No growth	No growth	No growth
Emissions multipliers a. Fuel burn b. SO_X (FSC) c. NO_X d. Non-volatile PM	a. 0.92 b. 0.0066 (5th percentile) c. 0.83 d. 0.52	a. Uniform [0.92 1.12] b. Weibull [mean = 0.0627, std = 1.2683] c. Uniform [0.83 1.23] d. Uniform [0.52 2.06]	a. 1.12 b. 0.154 (95th percentile c. 1.23 d. 2.06
Adult premature mortality CRF (% per µg/m-3 $PM_{2.5}$)	0.6	Triangular distribution (mode = 1, range = 0.6-1.7)	1.7
Value of a statistical life	$2.9M (US2000) 90% CI lower	Lognormal distribution (US2000) Mean= $6.3M, std= $2.8M	$12M (US2000) 90% CI lower
Background emissions	NEI 2001	NEI 2001	NEI 2001

For the climate analysis assumptions we used a similar procedure for defining the low, mid and high range lenses as shown in Table 9. For the midrange lens we assumed a distribution for climate sensitivity (the relationship between radiative forcing and temperature response) that reflects the range given in the recent IPCC report [85] with the low and high lenses being set at either end of this distribution. For NO_X impacts on climate, we draw on three different studies available in the literature as described in [114]. Each contains estimates for the magnitude of the three effects of NO_X emissions on climate (short term ozone production, long term methane removal and the associated long term ozone reduction). We take matched sets of these three effects from the literature, but choose randomly among the three literature sources for the midrange lens. For the high lens we take the result from the literature the represents the highest global warming potential for the combination of the three effects (Wild et al. [47] as it appears corrected in Stevenson et al. [115]. For the low lens we take the lowest net NO_X effect reported in the literature as provided by Stevenson et al. [115]. For all other non-CO_2 effects we take distributions (and high and low values) that are consistent with the most recent estimates provided by Sausen et al. [85]. For background emissions and corresponding GDP growth scenarios, we draw on a low, mid, and high range values provided by the IPCC [116]. For the relationship between globally-averaged surface temperature change and percent change in global GDP we use the most recent estimates from the Nordhaus DICE model [88] with associated uncertainty distributions and high and low values for those respective lenses. As noted previously, in addition to the low, mid and high range environmental impact lenses, we also analyzed the policy options with lenses using midrange settings, but changing only the NO_X climate response to high and low values. We did this because of the high uncertainty in NO_X impacts on climate, and the particular relevance of this uncertainty to the policy option we analyzed. We labeled these lenses as “High NO_X” and “Low NO_X”. For reference, the social cost of carbon values (calculated for the CO_2 impacts only) for the low, mid, and high lenses, when averaged over the 30-year policy period, were $13/tC, $110/tC, and $780/tC, respectively. These are consistent with the range of SCCs estimated by EPA [117].

Table 9: APMT-Impacts Climate Assumptions for the CAEP/8 NO_X Stringency Analysis

Climate Assumptions	Low Lens	Mid Lens	High Lens
Climate sensitivity	2K	Beta distribution (alpha=2.17, beta=2.41) to generate [mean=3K, range 2.0-4.5K]	4.5K
NO_X related effects	Stevenson et al.	Discrete uniform distribution (Stevenson et al., Hoor et al., Wild et al.)	Wild et al.
Short-lived effects RF [Cirrus, Sulfates, Soot, H_2O, Contrails]	[0, 0, 0, 0, 0] mW/m2	Beta distribution [alpha, beta, (range)] [2.14, 2.49 (0, 80)], [2.58, 2.17 (-10 – 0)], [1.87, 2.56 (0 – 10)], [2.10, 2.58 (0 – 6)], [2.05, 2.57 (0-30)] mW/m	[80, -10, 10, 6, 30] mW/m2
Background scenario	IPCC SRES B2	IPCC SRES A2	IPCC SRES A1B
Aviation scenario	CAEP/8 scenario	CAEP/8 scenario	CAEP/8 scenario
Damage coefficient	5^{th} percentile of Dice (deterministic)	Dice 2007 (normal distribution)	95^{th} percentile of Dice (deterministic)

6.3 AEDT Noise and Emission Inputs

AEDT noise inputs for this analysis are noise contours around 91 US airports expressed in terms of the average day-night noise level at the 55dB, 60dB, and 65dB levels. These US airports are a part of 185 AEDT/MAGENTA Shell-1 airports worldwide that account for 91% of total global noise exposure (102 of the Shell-1 airports are located in North America) [118]. Figure 17 shows the growth in total area exposure to aircraft noise at three noise levels from 2006-2036 for the unconstrained baseline case. Figure 18 shows growth in area exposure for Scenario 10 options relative to the baseline case summed over the 30 years of the scenario. Operational growth leads to increasing area exposure to aircraft noise at all three noise levels for the baseline case in Figure 17 with the most growth seen at the 55dB DNL noise level. The noise penalty for the MS3 technology response described in Section 6.1.4 leads to minor increases in area exposure (<0.1%) for Scenario 10 over the 30 year period as shown in Figure 18. As expected, the Scenario 10 option implemented in 2012 is seen to have a greater noise penalty as compared to the 2016 implementation option.

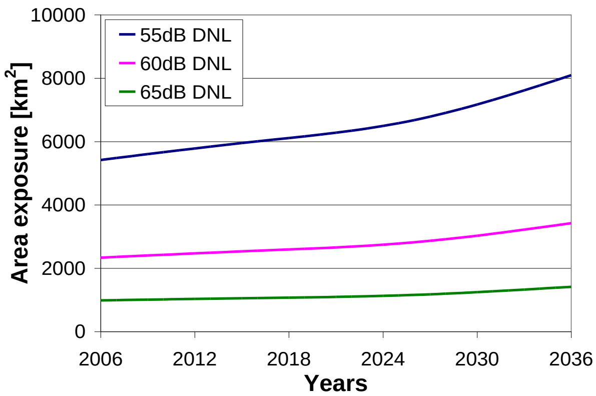

Figure 17: Baseline Yearly Area Exposure to Aircraft Noise

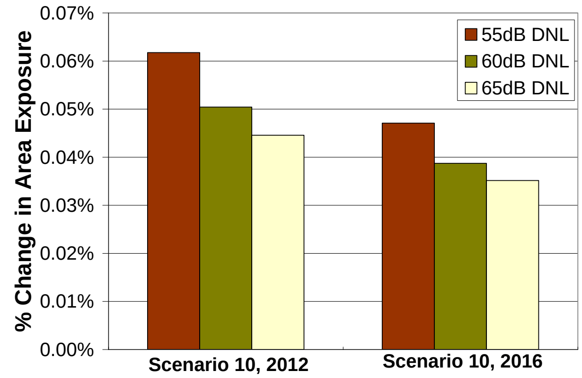

Figure 18: %□Area Exposure to Aircraft Noise Summed Over 30 Years

AEDT inputs to the APMT-Impacts Air Quality Module include fuel burn, emissions of NO_X, SO_X and non-volatile PM below 3000 feet for the landing and takeoff flight segments. Some species, such as SO_X emissions scale directly with fuel burn with an assumed emissions index (EI) of 1.1712 g/kg-fuel based on a fuel sulfur content of 600ppm. Figure 19 and Figure 20 show the percent change in fuel burn and NO_X for different representative stringency levels (1, 5, 7, and 10 as given in Table 5). For stringencies 7 and 10, we consider scenarios with and without the MS3 fuel burn penalty described in Section 6.1.5. Note that all of our air quality and climate analyses are limited to data for large engines because of anomalies with the small engine inventory estimates. The large engines are responsible for over 85 percent of the overall fuel burn and thus provide a good representation of the total effects. It can be seen in Figure 19 that the change in large engine fuel burn is not always positive as anticipated. This occurs due to resolution limits of AEDT sourced to engine and airframe matching assumptions. The resolution limit in distinguishing among policies is estimated to be less than 0.05% of fuel burn. Notably, only stringency 10 exhibits a change in fuel burn larger than this value. This issue was addressed in the impacts analysis, by specifying a 0.05% uncertainty on predicted differences in fuel burn within the Monte Carlo analyses.

As shown in Figure 20 all of the policies lead to changes in emissions inventories that are smaller than the change in certification stringency since aircraft in the existing fleet may be used for 20-30 years and new technology aircraft are only introduced to satisfy growth and retirements. NO_X reductions range from -5% to -8% compared to the baseline by 2036 (with the percent change in integrated emissions over the 30-year policy analysis period being about half of this).

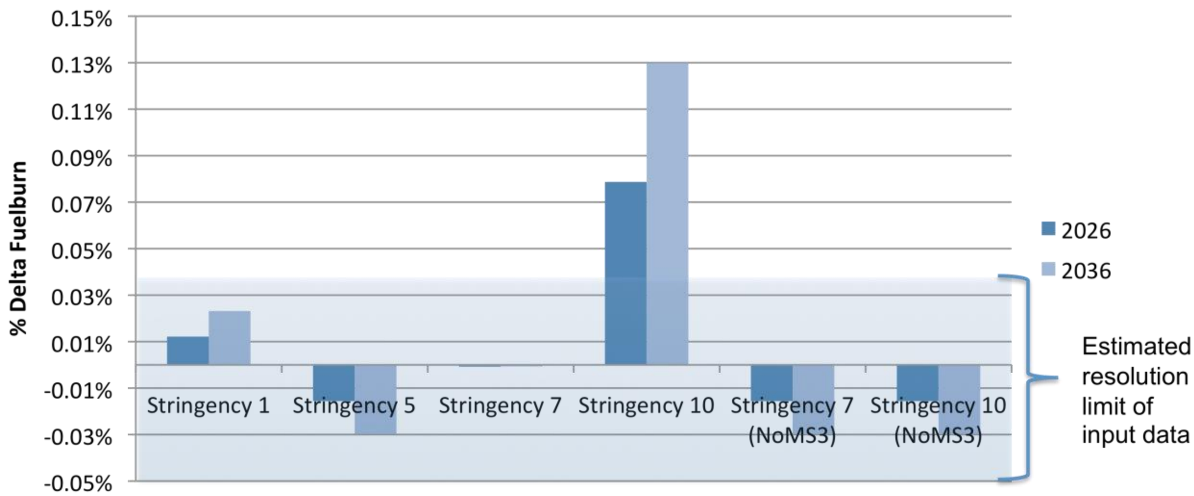

Figure 19: Air Quality Inputs; % Change in Fuel Burn Below 3000 feet (large engines only)

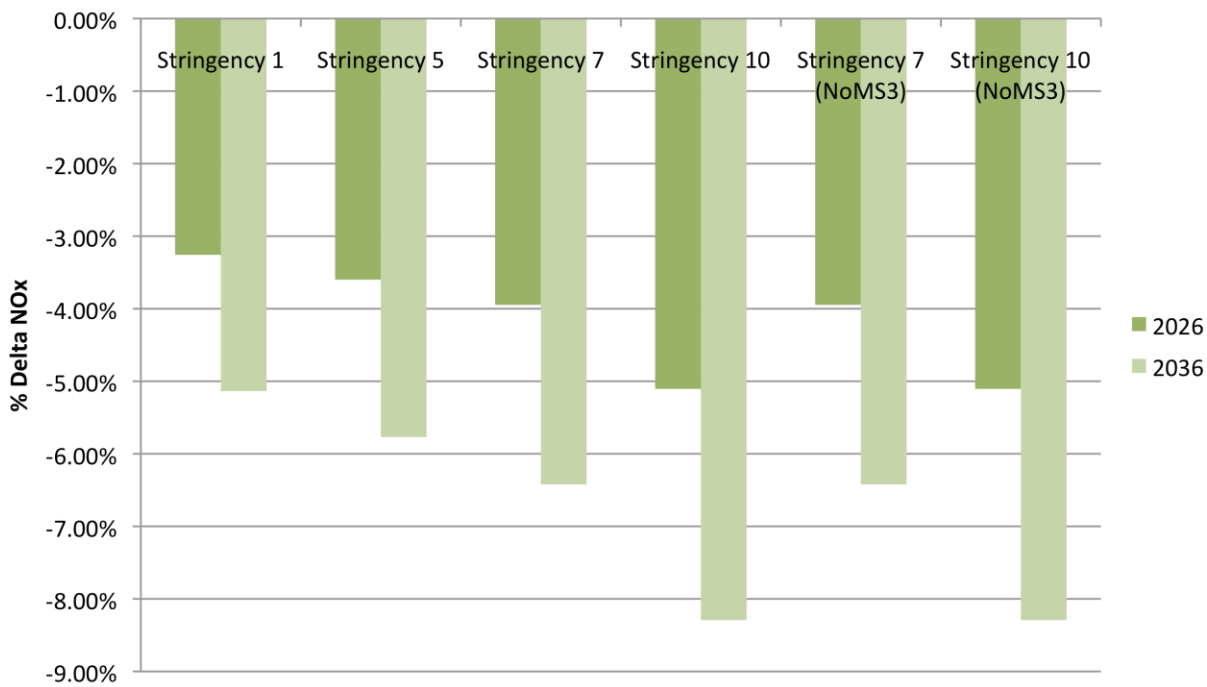

Figure 20: Air Quality Inputs; % Change in NO_X Emissions Below 3000 feet (large engines only)

Emissions inputs for the APMT-Impacts Climate Module include fuel burn, CO_2, and NO_X emissions. CO_2 emissions scale directly with fuel burn with an EI of 3155g/kg-fuel and are not presented here. Figure 21 and Figure 22 show the percent changes between selected stringencies and the baseline for full mission fuel burn and NO_X. AEDT results for full mission emissions are provided for North America and US emissions have been scaled from AEDT results assuming that US operations account for 93% of North American operations. This scaling is based on year 2005 results from the second round of the NO_X

Sample Problem analysis conducted by the MODTF in preparation for CAEP/8 [119]. These data also exhibit a resolution of limit 0.05% for distinguishing changes between policy and baseline cases; again for large engines, only stringency 10 has a percent change larger than this estimated resolution limit.

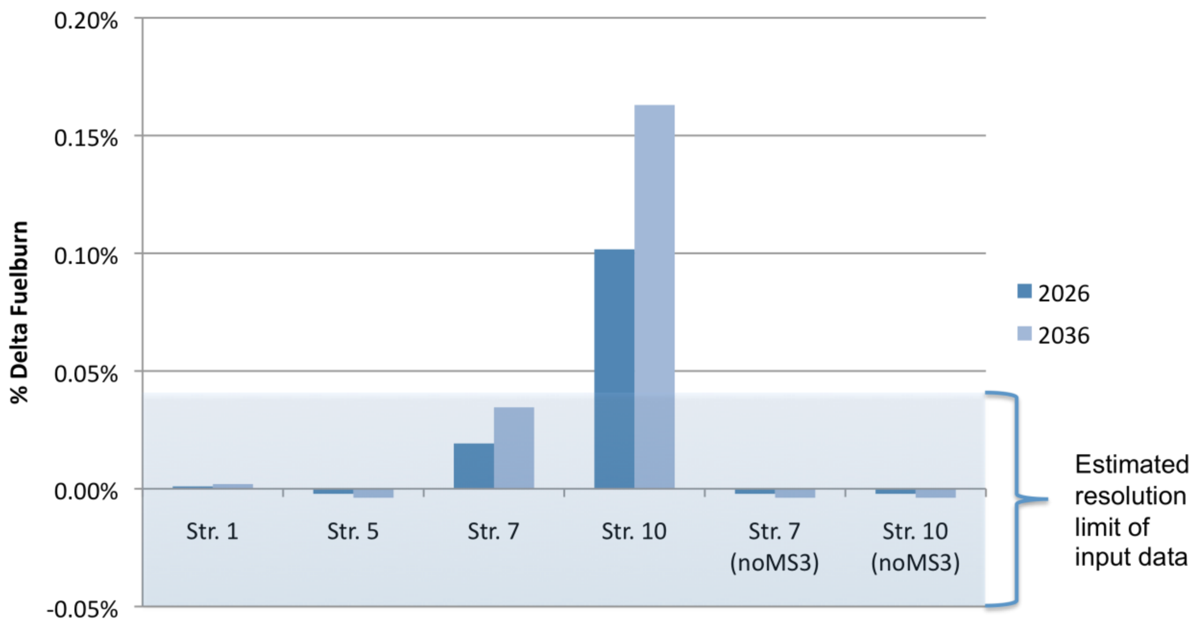

Figure 21: Climate Inputs; % Change in Full Flight Fuel Burn (large engines only)

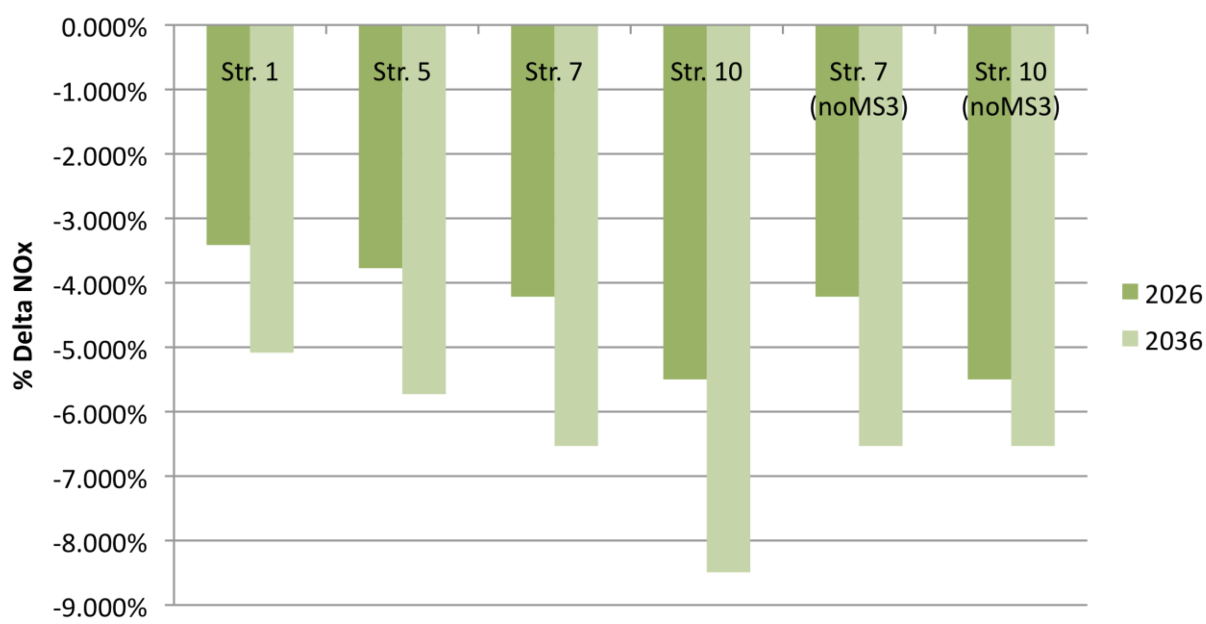

Figure 22: Climate Inputs; % Change in Full Flight NO_X (large engines only)

In addition to inputs for analysis using APMT modules, FESG costs were used as input for the cost-benefit analysis presented in the following section. Figure 23 shows the costs per stringency in 2009 dollars for large engines at a 3% discount rate for global operations. It can be seen that the costs range from about $2 to $20 billion and increase with increasing NOx reduction and are higher when a fuel burn penalty is present. For US costs, we take values that are 27% of those shown in Figure 23.

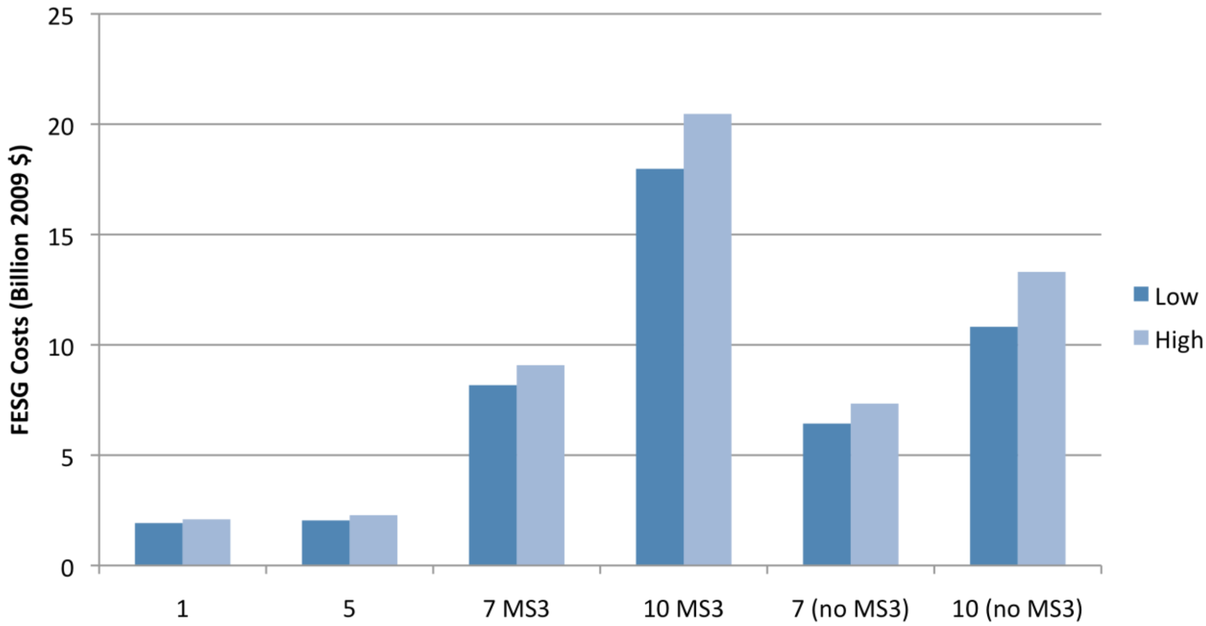

Figure 23: FESG Input cost data (global operations, large engines only). For US costs, we assume values that are 27% of those shown.

6.4 Results

The goal of the policy analysis presented in this Section is to examine the environmental benefits and economic costs of several representative NO_X stringency options relative to the baseline no stringency case. We begin in Section 6.4.1 by showing baseline trends in noise, air quality, and climate impacts in physical metrics. Section 6.4.2 discusses key results from an aggregated cost benefit analysis and examines the sensitivity of analysis outcomes to variability in inputs and model parameters. Section 6.4.3 evaluates the stringency options from the perspective of a conventional cost-effectiveness analysis. Finally, Section 6.5 presents key policy insights based on results from the cost-benefit and cost-effectiveness analysis. The analysis is conducted using Monte Carlo methods and the results represent the mean of several thousand Monte Carlo runs.

6.4.1 APMT-Impacts Results

The baseline results provided in this Section are for the mid-range lens model parameters presented in Section 6.2.1, and for a 3% discount rate. Later we discuss results for other lenses. First this Section presents physical impacts of noise in terms of number of people exposed to noise levels of 55dB DNL, as shown in Figure 24. Growth in future operations leads to increases in area exposure to aircraft noise as shown in Section 6.3 and consequently to increases in number of people exposed to aircraft noise.

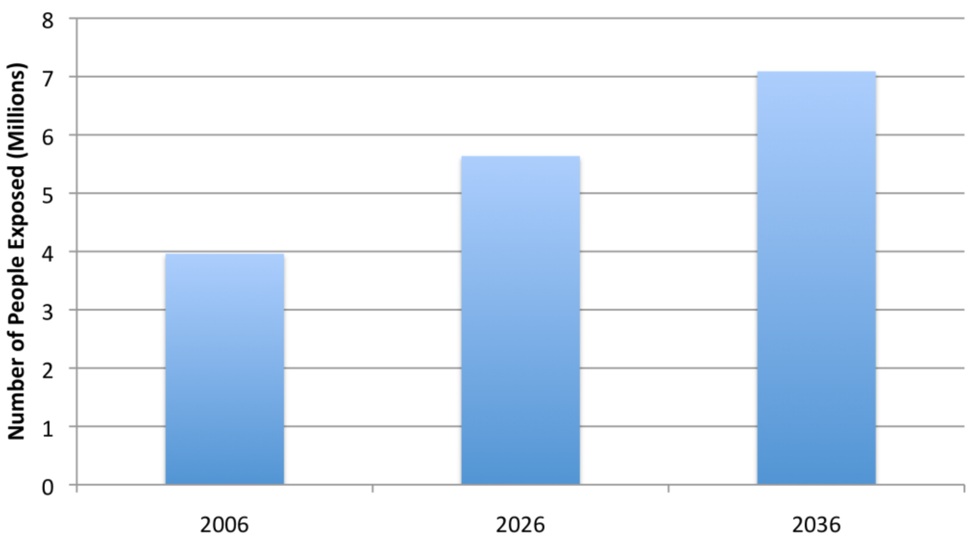

Figure 24: Baseline Number of People Exposed to >55 dB DNL

Baseline air quality impacts expressed in terms of yearly incidences of premature deaths attributed to exposure to aircraft particulate matter emissions are shown in Figure 25 and Figure 26. Figure 25 shows premature deaths due to separate emissions species for the baseline case and Figure 26 shows the change between stringency and baseline premature deaths. Only the incidences of premature deaths attributed to particulate matter are presented as they constitute more than 95% of the total monetized air quality health impacts [38]. These impacts are due to aircraft emissions below 3000 feet and do not account for impacts of cruise PM emissions. Impacts are apportioned to the different aircraft emissions species contributing to changes in ambient particulate matter concentrations. Nitrates are seen to dominate the total impacts with smaller contributions from sulfates, soot (labeled EC, elemental carbon), and organics.

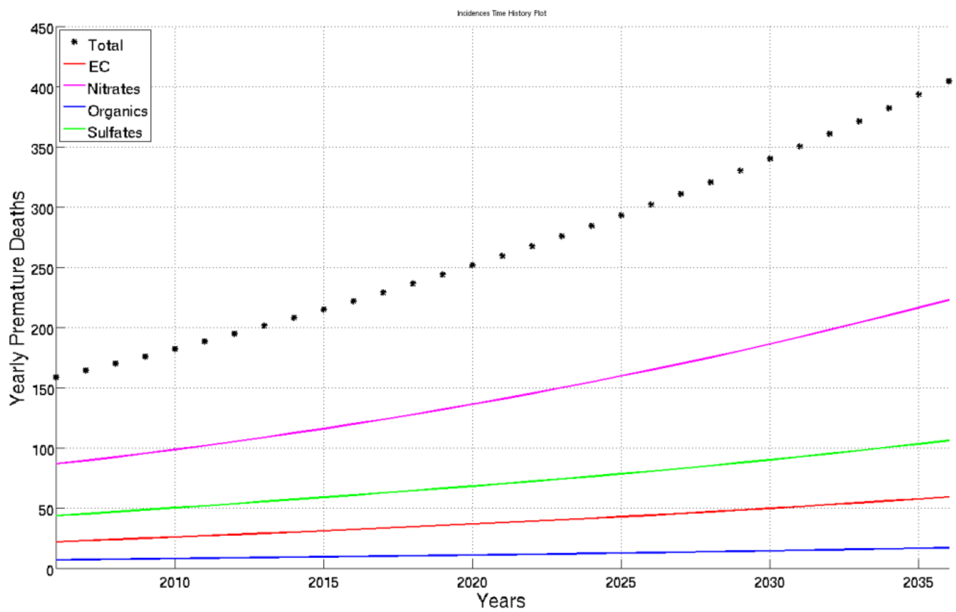

Figure 25: Baseline Yearly Air Quality Physical Impacts

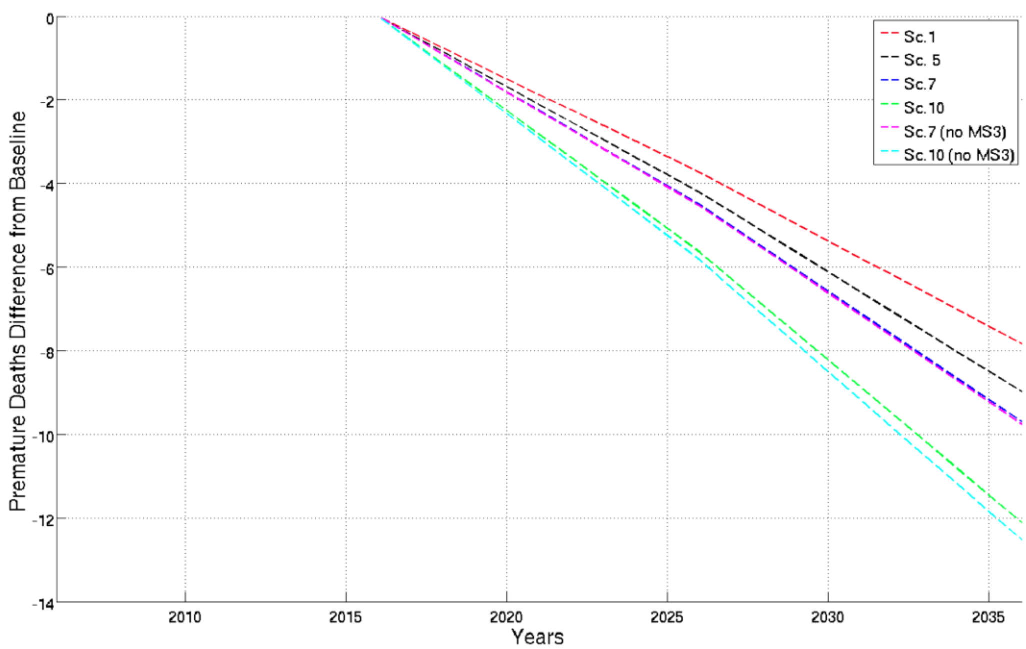

Figure 26: NO_X Select Stringencies - Baseline Yearly Total Air Quality Physical Impacts

Figure 27 presents baseline climate impacts in terms of changes in globally-averaged surface temperature. Aviation accounts for roughly 2-3% of all anthropogenic greenhouse gas emissions, which explains the relatively small magnitude of the temperature change attributed to aviation. Longer-lived aviation-related climate impacts such as the warming CO_2 effect and the cooling effects of NO_X-CH_4 and NO_X-O_3-long continue well beyond year 2036 - the last year for which aviation emissions are modeled. Short-lived effects including NO_X-O3 short, cirrus, sulfates, soot, H_2O and contrails decay within 20 years after the 30 year scenario. For noise and air quality impacts, the duration over which the selected policy influences the fleet mix (2006-2036 in this case) coincides with the time period over which the impacts persist. However, climate impacts as seen in Figure 27 persist for several centuries past the last of the scenario.

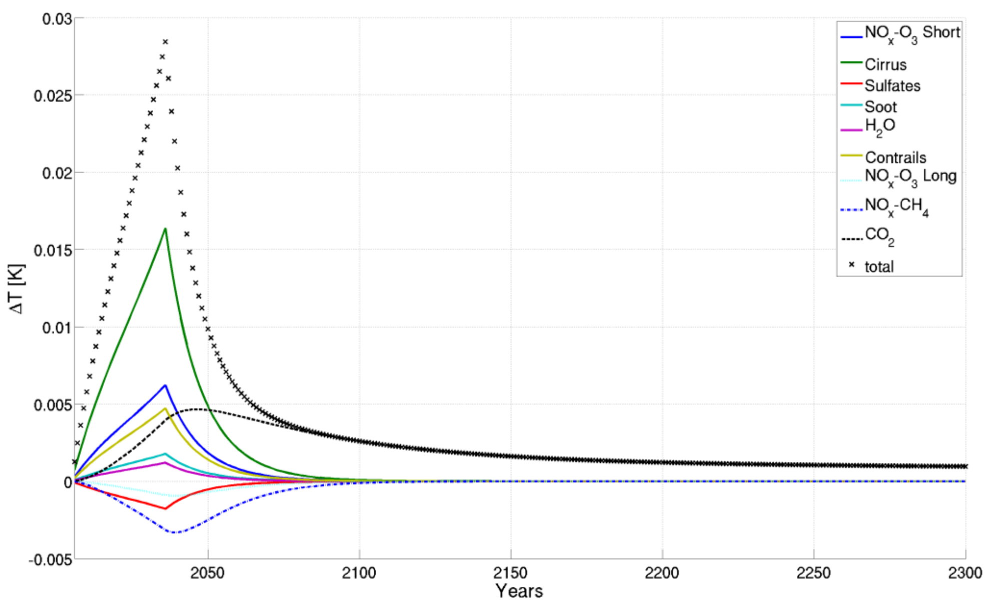

Figure 27: Baseline Component Climate Yearly Physical Impacts

Figure 28 shows the climate impacts by component for stringency 10 (with MS3) minus baseline. It can be seen from this figure that NO_X reduction effects, both short term cooling and long term warming effects, contribute the largest components to the overall change in surface temperature. This result is consistent with the very small percent changes in fuel burn relative to the percent changes in NO_X for all of the stringency levels. The significance of the NO_X climate impact assumptions in determining the climate response are further explored using the low- and high- NO_X lenses presented in Section 6.4.2.1.

Figure 29 shows the climate impacts for the different stringencies studied. The high and low peaks caused by the NO_X components are also visible here.

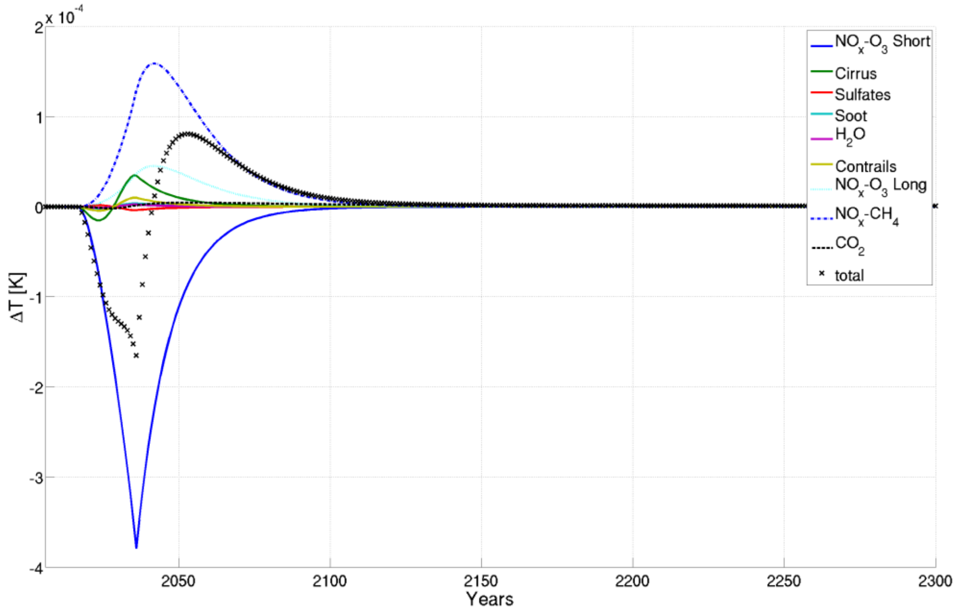

Figure 28: NO_X Stringency 10 MS3 Minus Baseline Component Climate Yearly Physical Impacts

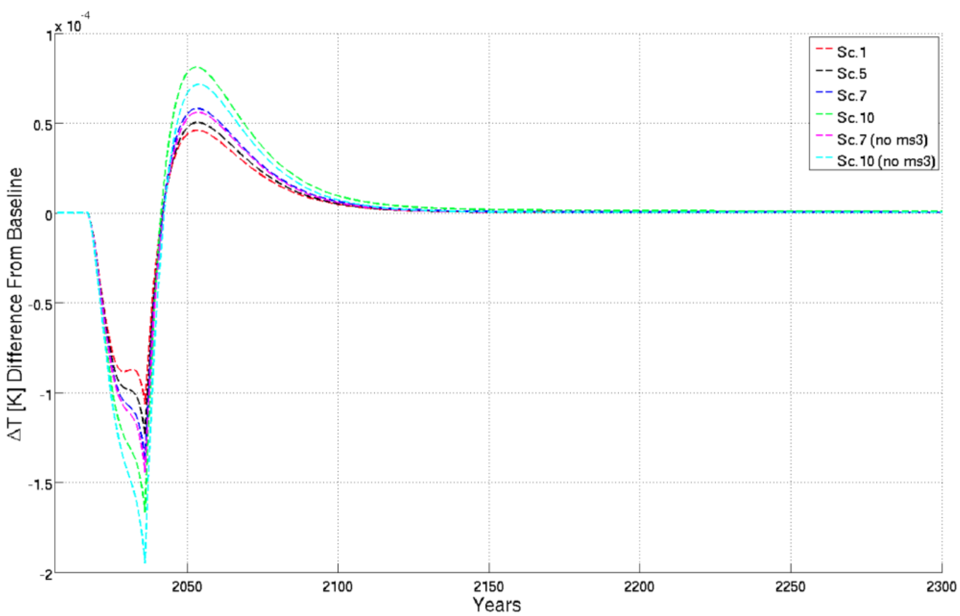

Figure 29: NO_X Select Stringencies Minus Baseline Climate Yearly Physical Impacts

Results presented in this Section indicate that growth in operations will lead to increasing environmental impacts in the future in the absence of new environmental policies. It can also be seen that different stringency levels lead to different environmental impacts. As seen in Section 6.3, implementation of the NO_X stringency leads to decreases in NO_X emissions, and for higher stringency levels, to increases in fuel burn and area exposure to aircraft noise. The next Section presents an aggregated cost-benefit analysis comparing the environmental benefits and economic costs of selected stringency options relative to the baseline case using monetization methods described in Section 4.

6.4.2 Cost-Benefit Analysis

The results presented here employ the mid-range lens assumptions presented in Section 6.2.1 and a 3% discount rate. The percent change in physical impacts is shown in Figure 30 for the stringency options we considered: stringencies 1, 5, 7, and 10 (the latter two with and without the MS3 fuel burn penalty). Although we did not analyze all of the stringency options, we anticipate results for stringencies 2-4 to fall between those for stringencies 1 and 5; results for stringency 6 to be similar to those for stringency 7, and results for stringencies 8 and 9 to be similar to those for stringency 10.

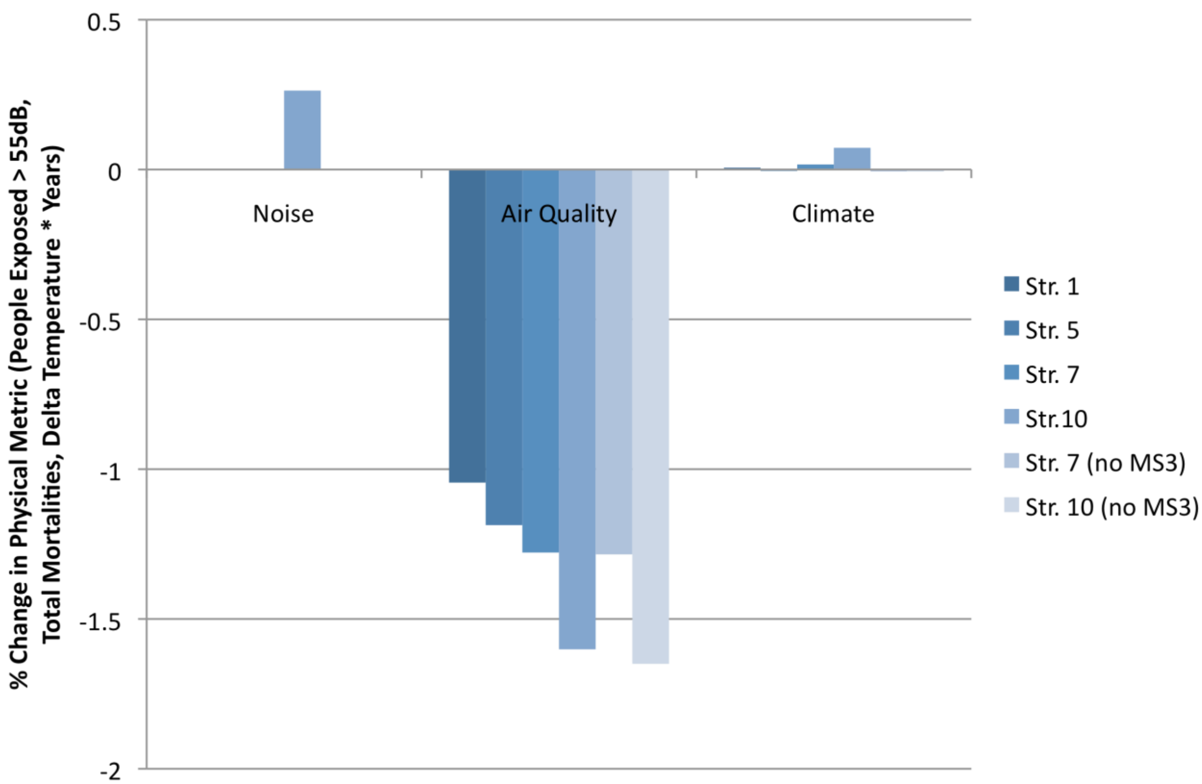

Figure 30: % Change in APMT Physical Metrics

The MS3 noise penalty leads to increased area exposure and corresponding population exposure. Reductions in air quality impacts result from lower NO_X emissions and therefore lower PM formation (largely a reduction of nitrate PM, but there is a bounce back effect with some corresponding increase in sulfate PM). Higher climate impacts are a result of the MS3 fuel burn penalty that leads to increased warming from CO_2 dominating the largely counter-balancing effects of NO_X on climate; at a globally-averaged scale the warming NO_X-O3 effect roughly balances the NO_X-CH4 NO_X-O3 cooling effects as shown in Figure 27. Consequently, the increased warming from higher fuel burn outweighs the NO_X climate effects leading to detrimental climate impacts.

An example of monetized environmental impacts along with industry impacts is shown in Figure 31. The results in Figure 31 represent the difference between Scenario 10 (2016 implementation) with the MS3 fuel burn penalty and the baseline case. The net impact for monetized results is calculated by summing the three environmental impacts: noise, air quality, and climate, and comparing to the FESG economic impacts (where we have taken 27% of the FESG costs as an estimate of the US operations based on analyses conducted with APMT-Economics). The uncertainties in the costs are estimated by taking the high and low cost estimates from FESG. The uncertainties in the environmental impacts are estimated through Monte Carlo methods. (Details on the treatment of uncertainties in the different APMT modules were presented in Section 5.) While all these impacts and associated uncertainties have common assumptions and are not entirely independent of each other, for a first order estimate it is assumed that they are statistically independent effects. All of the mean impacts are summed to get the net impact and all their variances are summed to get the variance. The height of the bars indicates the mean value and the error bars represent the 10th and 90th percentile values. Note that Figure 31 presents policy minus baseline results and therefore a positive change is considered detrimental while a negative change is beneficial.

Figure 32 shows the net cost-benefit results for each stringency option analyzed minus the baseline scenario. For this analysis stringency 10 MS3 noise impacts were used to calculate the net impact for all stringencies since we only have noise impacts for this one policy scenario (note that the noise impacts are small relative to the other impacts in all cases, so this assumption does not change any of the conclusions). It can be seen from this figure that all stringencies incur net costs relative to the baseline (although the mean changes for stringencies 1 and 5 are smaller than the estimated uncertainties).

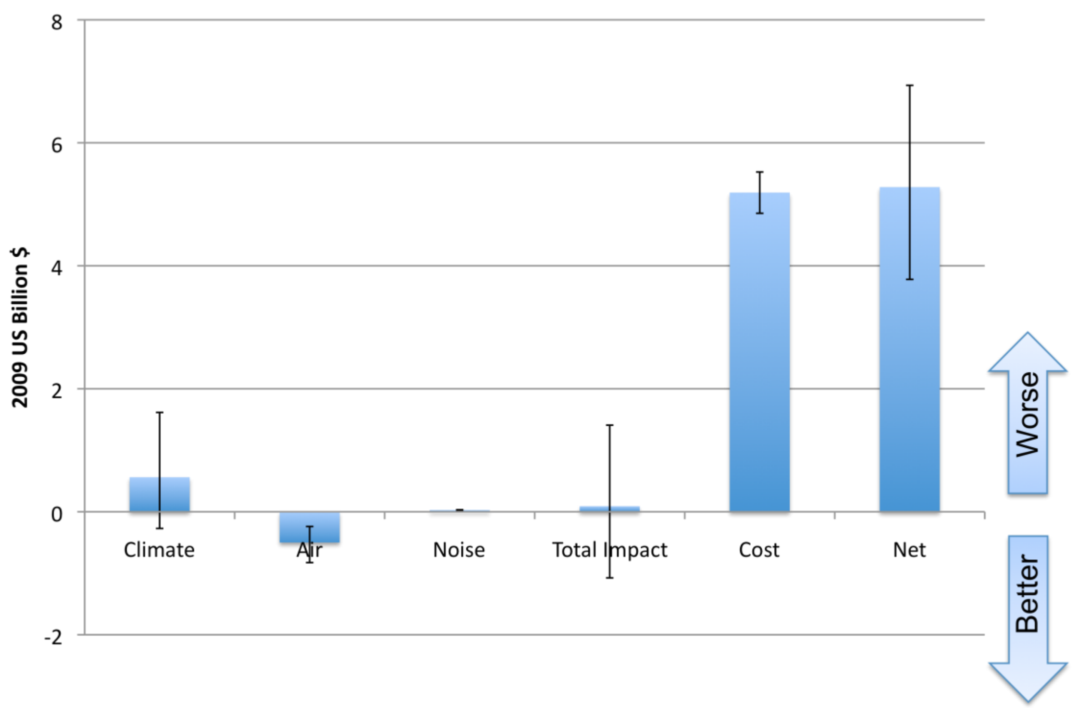

Figure 31: NO_X Stringency Scenario 10 MS3 minus Baseline Impacts and Cost Benefit

(mid lens, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

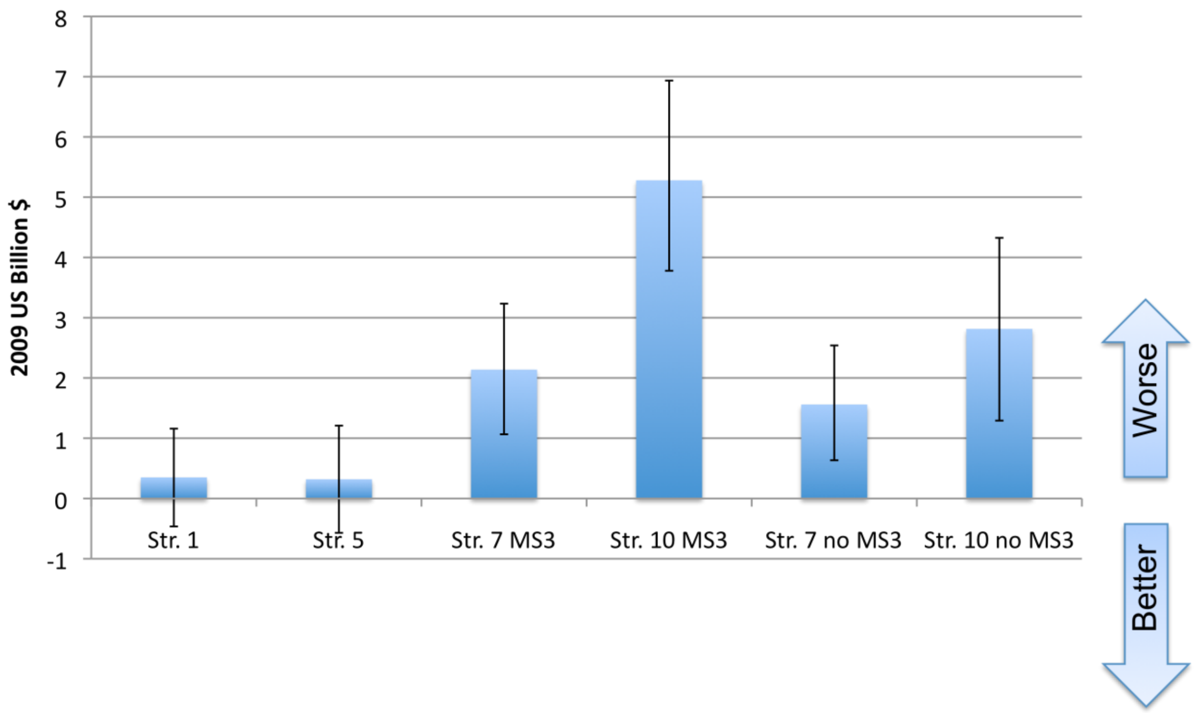

Figure 32: NO_X Select Stringencies minus Baseline Impacts

(Stringency 10 MS3 noise impacts used for all stringencies, mid lens, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

The analysis described in this Section and associated results are summarized in Table 10 and Table 11 below. Table 10 provides APMT noise, air quality, and climate impacts for each stringency case analyzed. Table 11 shows the total APMT impacts, the FESG costs (US-only), and the net impact for each stringency analyzed.

Table 10: APMT Impacts for Noise, Air Quality, and Climate

APMT-Impacts Assumptions	Scenario	Noise (2009 US $Billion)		Air Quality (2009 US $Billion)		Climate (2009 US $Billion)	
		mean	10-90%	mean	10-90%	mean	10-90%
Midrange Lens 3% Discount Rate	1			-0.33	-0.54 -0.16	0.11	-0.46 0.72
	5			-0.37	-0.61 -0.18	0.08	-0.52 0.74
	7 MS3			-0.40	-0.66 -0.19	0.18	-0.50 0.94
	10 MS3	0.03	0.02 0.03	-0.50	-1.12 -0.34	0.56	-0.27 1.62
	7 (no MS3)			-0.40	-0.66 -0.19	0.08	-0.46 0.72
	10 (no MS3)			-0.52	-0.85 -0.25	0.05	-0.80 0.95

Table 11: Cost Benefit Summary

APMT-Impacts Assumptions	Scenario	Total Impact (2009 US $Billion)		Cost (2009 US $Billion)		Net Cost Benefit (2009 US $Billion)	
		mean	10-90%	mean	range	mean	10-90%
Midrange Lens 3% Discount Rate	1	-0.19	-0.98 0.59	0.54	0.52 0.57	0.35	-0.46 1.16
	5	-0.27	-1.12 0.59	0.58	0.55 0.62	0.32	-0.57 1.21
	7 MS3	-0.19	-1.14 0.78	2.33	2.21 2.45	2.14	1.07 3.23
	10 MS3	0.09	-1.08 1.41	5.19	4.85 5.53	5.28	3.78 6.94
	7 (no MS3)	-0.30	-1.10 0.56	1.86	1.74 1.98	1.56	0.63 2.54
	10 (no MS3)	-.044	-1.63 0.73	3.26	2.92 3.59	2.81	1.29 4.33

Figure 31 indicates that for mid-range inputs and model parameters and a 3% discount rate, the implementation of the Scenario 10 leads to detrimental effects in all impact areas with the exception of air quality. Reductions in air quality impacts are outweighed by detrimental impacts in other areas leading to a net detrimental impact of over $5 billion for stringency 10 relative to the baseline case. Furthermore, Figure 32 shows that all stringencies analyzed result in a net detrimental impact for the mid-range lens and a 3% discount rate. The next Section explores the sensitivity of the cost-benefit results to variability in inputs and model parameters through different lenses.

6.4.2.1 Lens Analysis

The sensitivity analysis presented here focuses on variability in results depending on selection of inputs and model parameters within APMT-Impacts. This is explored using the lenses described in Section 6.2 and a range of discount rates.

Figure 33 shows the impacts for stringency 10 MS3 minus baseline using the low, mid, and high lenses and a 3% discount rate. It can be seen from the figure that low and mid lens assumptions lead to similar net results (largely because the environmental benefits are dominated by the much larger industry costs), while the high lens assumptions lead a much greater detriment. Even though the magnitude of net impacts varies per lens, all lenses result in a net detriment.

Figure 34 shows the impact for stringency 10 MS3 minus baseline using the mid range lens assumptions and discount rates of 2%, 3%, and 5%. The net impacts decrease with an increasing discount rate, however, the overall impact is still detrimental for all discount rates analyzed.

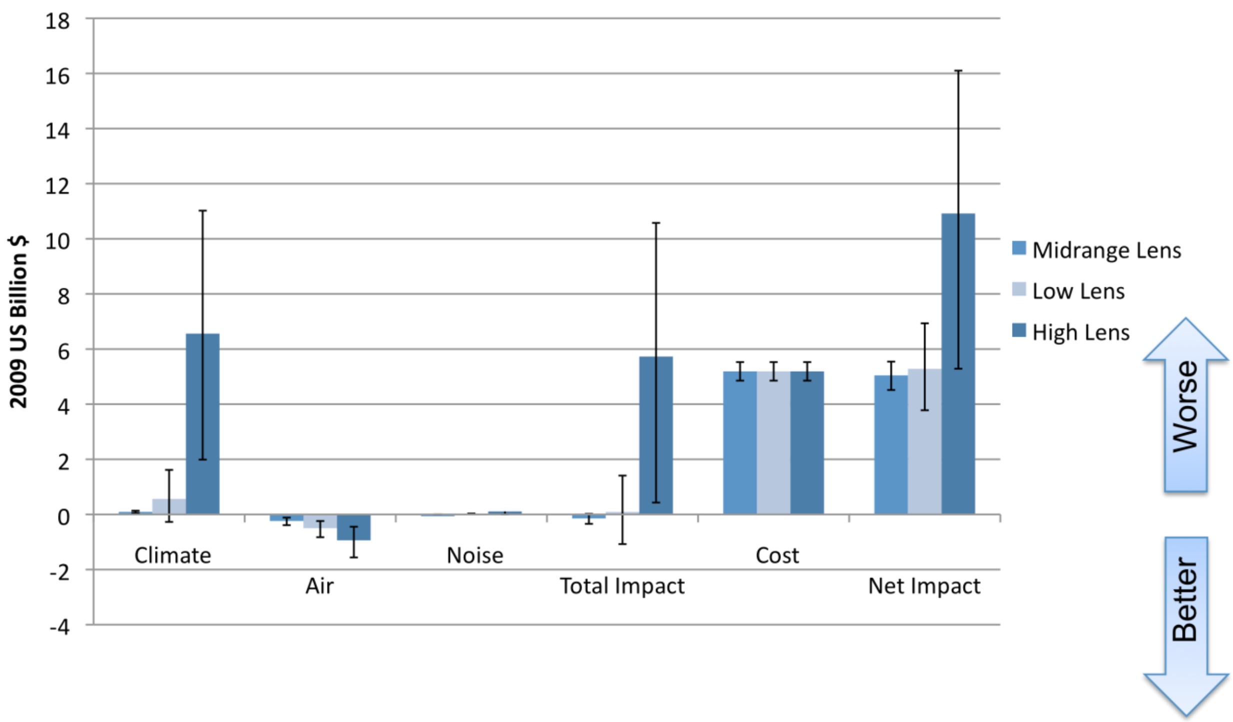

Figure 33: NO_X Stringency 10 MS3 minus Baseline Impacts and Cost Benefit per discount rate

(all lenses, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

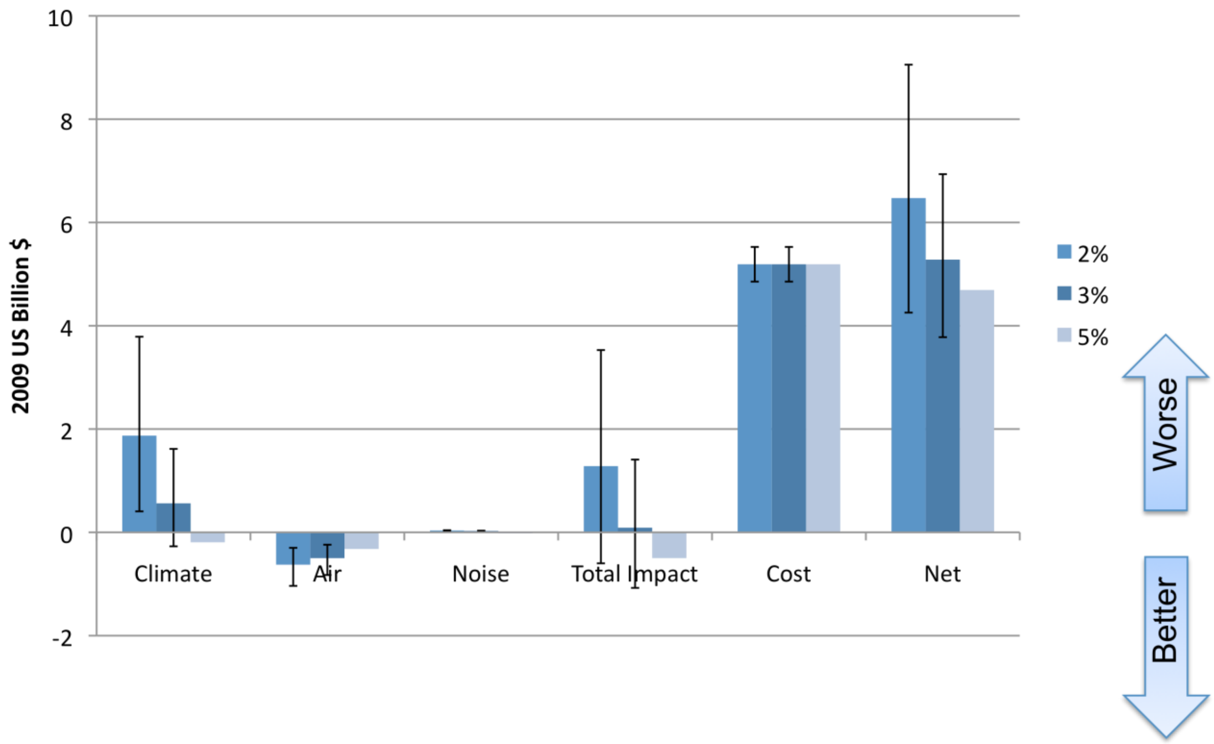

Figure 34: NO_X Stringency 10 MS3 Impacts minus Baseline per discount rate

(mid lens, all discount rates, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

Figure 35 shows the cost and benefit impacts for stringency 10 MS3 minus the baseline scenario using the mid lens assumptions, but with a low and high NO_X settings for climate impacts. This analysis was done to better understand the implications of uncertainties in the NO_X impacts on climate as discussed in Section 6.4.1. Again, although for the high NO_X setting, the NO_X climate impacts roughly balance the CO_2/fuel burn penalty leading to a net environmental benefit (because of the air quality benefits), the sum of the benefits does not outweigh the FESG cost estimates.

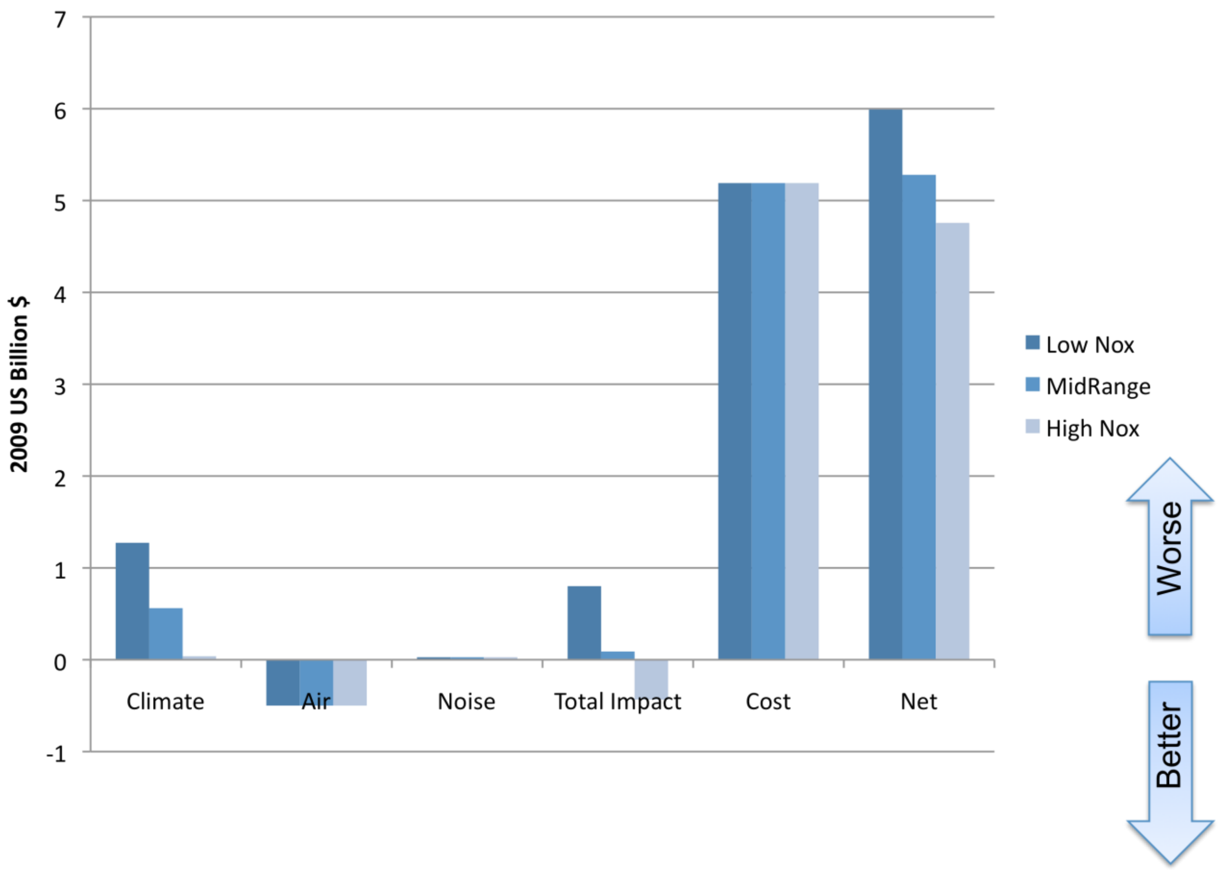

Figure 35: NO_X Stringency 10 MS3 Impacts minus Baseline with low and high NO_X assumptions

(mid lens, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

The lenses described in this Section and associated results are summarized in Table 12 below. The table provides noise, air quality, and climate impacts along with uncertainties for the low, mid-range, high, lenses described previously for Stringency 10 MS3. The table also includes climate impacts for the mid-range lens with low and high NO_x assumptions.

Table 12: Lens Analysis of Stringency 10 MS3

<table>
<tr><th rowspan="2">APMT-Impacts Assumptions</th><th rowspan="2">Scenario</th><th colspan="2">Noise
(2009 US $Billion)</th><th colspan="2">Air Quality
(2009 US $Billion)</th><th colspan="2">Climate
(2009 US $Billion)</th></tr>
<tr><th>mean</th><th>10-90%</th><th>mean</th><th>10-90%</th><th>mean</th><th>10-90%</th></tr>
<tr><td>Low Lens</td><td rowspan="5">10 MS3</td><td>0.00</td><td></td><td>-0.24</td><td>-0.39
-0.12</td><td>0.09</td><td>0.05
0.14</td></tr>
<tr><td>Midrange Lens, Low NOx</td><td rowspan="3">0.03</td><td rowspan="3">0.02
0.03</td><td rowspan="3">-0.50</td><td rowspan="3">-1.12
-0.34</td><td>1.27</td><td>0.35
2.71</td></tr>
<tr><td>Midrange Lens</td><td>0.56</td><td>-0.27
1.62</td></tr>
<tr><td>Midrange Lens, High NOx</td><td>0.04</td><td>-0.77
0.92</td></tr>
<tr><td>High Lens</td><td>0.11</td><td></td><td>-0.94</td><td>-1.56
-0.45</td><td>6.56</td><td>1.99
11.02</td></tr>
</table>

As described in Sections 4.1.2 and 6.2.1, we also made a first estimate of the influence that considering cruise emissions impacts on surface air quality may have on the results. This was done by scaling the midrange lens results using information from the Barrett et al. [43] study—leading to about a factor of 5 increase in the air quality benefits attributable to NO_x emissions reduction. We caution that such impacts are still the subject of scientific study and carry substantial uncertainty. Nonetheless, it is certain there are some additional impacts on surface air quality due to emissions above 3000 feet, and thus we present this as a sensitivity study. When this preliminary estimate of the surface impacts of emissions above 3000 feet is included several of the policies become cost-beneficial as shown in Figure 36. This highlights the need for greater understanding of these impacts. We also anticipate that other modelling uncertainties such as insufficient resolution of impacts local to airports, not accounting for population growth, and not accounting for changes in background concentrations, cause our baseline air quality impact calculations to be underestimates. Thus, notwithstanding the uncertainty in cruise emissions impacts, their inclusion here also can be viewed as a surrogate sensitivity analysis for assessing the potential influence of other unquantified surface air quality-related modelling limitations and uncertainties.

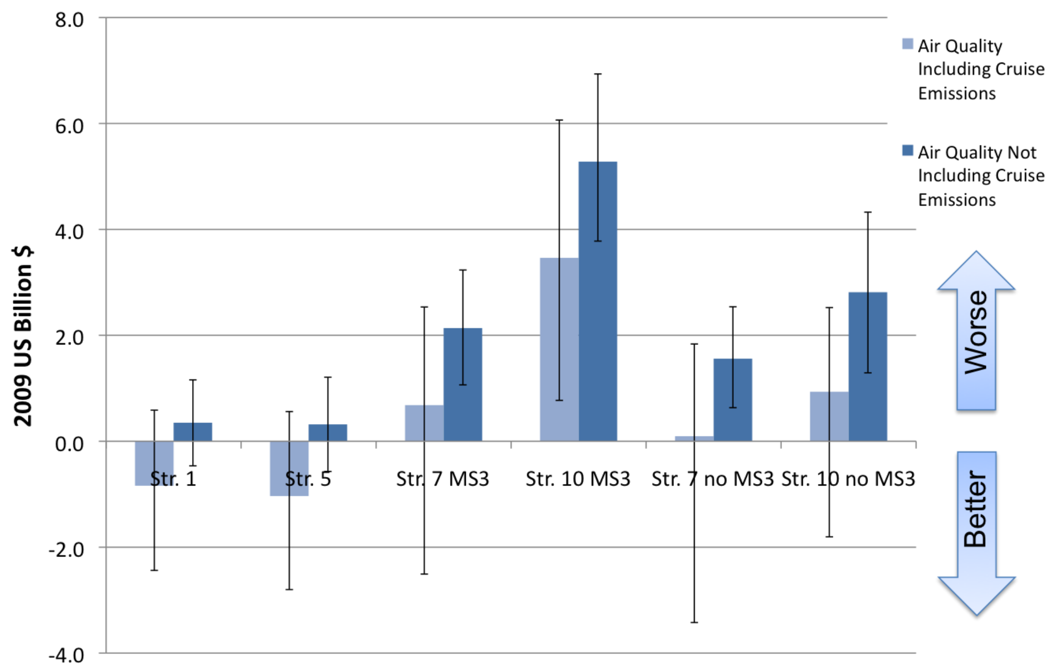

Figure 36: NOx Select Stringencies minus Baseline with and without estimated cruise emissions impacts on surface air quality.

(mid lens, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

Due to the uncertainty associated with the industry cost estimates provided by FESG a lens study for costs was also conducted. The three lenses selected used mid-range environmental assumptions with 0% of FESG costs, 50% of FESG costs, and 100% of FESG costs. The results are shown in Figure 37. It can be seen that for the 0% cost assumption uncertainties in the input data and modeling methods are larger than the estimated changes—signaling that for all stringency levels with mid-range environmental assumptions the modest changes in emissions inventories lead to small, often counterbalancing, changes in environmental impacts. For all other cost assumptions (50% and 100%) the policies are not cost-beneficial at levels of Stringency 7 and 10, and not resolvable at lower stringencies (1 and 5).

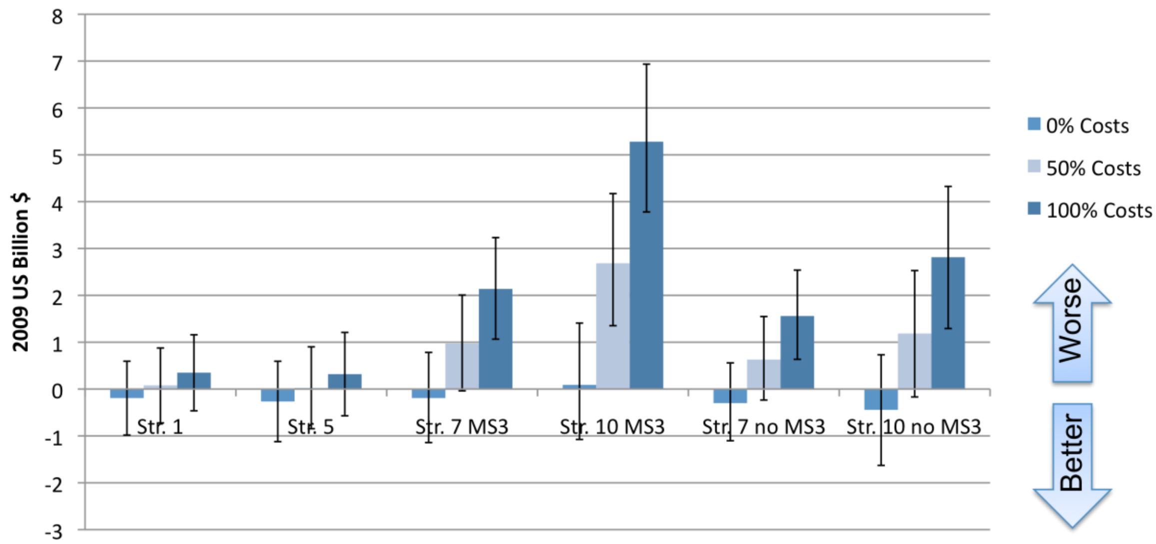

Figure 37: NOx Select Stringencies minus Baseline with 0%, 50%, and 100% Cost Assumptions

(mid lens, 3% discount rate, 2016 implementation, large engines and combined engines for noise, cost data with lost resale value)

6.4.3 Cost-Effectiveness Analysis

This section contrasts the cost-benefit framework we have adopted thus far with the conventional CAEP approach of cost-effectiveness analysis. Cost-effectiveness for a given policy option is measured by the ratio of total costs, in this case the sum of producer and consumer surplus, and the total reduction in LTO NO_X over the 30-year policy period. Cost-effectiveness results for selected stringencies, 2016 implementation date, large engines, and a 3% discount rate are shown Figure 38. FESG calculated costs using both a low and high set of assumptions and both are shown in the figure.

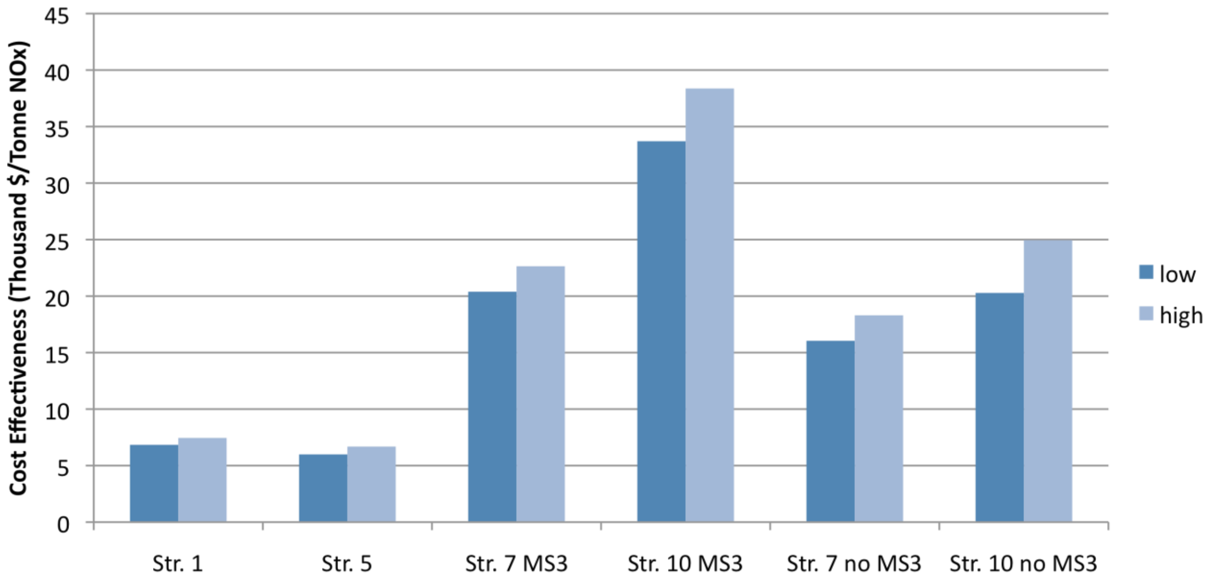

Figure 38: NO_X Stringency Cost-Effectiveness Results

(large engines only, 3% discount rate, 2016 implementation, 2009$)

Based on Figure 38, stringency 1 is the most cost-effective choice for a new policy. However, this analysis conveys no information about health and welfare impacts of reductions in NO_X emissions, and no information about whether the costs incurred are justified in terms of expected environmental benefits. When cost-benefit results from Section 6.4.2 are examined, it is shown that for the midrange assumptions (and most of the sensitivity analyses presented) no stringency option is estimated to be desirable relative to the baseline case. Indeed, it is only with the inclusion of a first estimate of cruise emissions impacts (which carry substantial uncertainty and have not been considered in prior ICAO deliberations) that some of the policies are estimated to be cost-beneficial. Notably, we have not presented all combinations of assumptions and scenarios and one may wish to consider additional viewpoints. Nonetheless, it is clear that different conclusions may be drawn about the same policy options depending on whether benefits and interdependencies are estimated in terms of health and welfare impacts versus changes in NO_X emissions inventories. The cost-benefit analysis relays important information about the potential impacts of the NO_X stringency options and the uncertainties in these impacts. In some cases, more complete information can make the “best” policy choice less obvious, but that is a direct outcome of the scientific and economic uncertainties of the underlying impacts. Clearly articulating the range of possible outcomes of a policy choice is in itself a valuable contribution of the cost-benefit analysis.

7. SUMMARY AND CONCLUSIONS

The primary focus of this paper was to demonstrate how the inclusion of environmental impact assessment and quantification of modeling uncertainties can enable a more comprehensive evaluation of policy measures. The Aviation environmental Portfolio Management Tool (APMT) was employed to conduct an illustrative analysis of a subset of engine NO_X stringency policy options under consideration for the eighth meeting of the ICAO-CAEP. This section offers concluding thoughts based on the work presented in this paper and identifies opportunities for future work.

While cost-benefit analysis (CBA) is the recommended practice for conducting economic analysis of proposed policy measures, including environmental policies, by several regulatory agencies around the world, the ICAO-CAEP has conventionally adopted a cost-effectiveness analysis (CEA) approach for aviation environmental policies. Shortcomings of the cost-effectiveness analysis approach as identified both within and outside of ICAO were highlighted through a discussion of the most recent CAEP/6 engine NO_X emissions certification Standards for the sixth meeting of the CAEP. Lack of estimation of health and welfare impacts of proposed policy measures and of tradeoffs among different environmental impacts, and limited treatment of modeling uncertainties were some of the shortcomings of the CAEP cost-effectiveness analysis approach. CEA does not reveal whether anticipated benefits from the policy exceed the costs incurred.

In practice, the CEA approach is often adopted over the CBA approach given the greater modeling uncertainties associated with environmental impact assessment. Here, a distinction was made between modeling and decision-making perspectives on uncertainty. While modeling uncertainties grow as one proceeds down the impact pathway toward impact metrics of increasing relevance to decision-makers, decision-making uncertainty decreases as one gains a better understanding of the ultimate impacts of the policy on human health and welfare. This work proposed improvements in current decision-making practices for aviation environmental policies through the inclusion of environmental impact assessment and explicit quantification of uncertainties. An illustrative analysis of a subset of engine NO_X stringency policy options under consideration for the eighth meeting of ICAO-CAEP in 2010 was presented to demonstrate the CBA approach and provide a comparison between CBA and CEA outcomes. This CAEP/8 NO_X stringency analysis was conducted by employing APMT, which is a component of the FAA-NASA-Transport Canada aviation environmental tool suite. An overview of key environmental impacts of aviation and a description of modeling methods adopted in APMT were also included in this paper.

This paper also discussed the importance of uncertainty assessment for gaining a better understanding of the variability in outputs, identifying areas of future work as well as for communicating results from a complex policy analysis tool such as APMT. The qualitative and quantitative methods for uncertainty assessment adopted within APMT were described. Modeling uncertainties arising from different aspects of the policy analysis process were grouped into categories including scenarios, modeling and scientific uncertainties, valuation assumptions, and behavioral assumptions to help identify areas of focus for future research. Outcomes of the formal parametric uncertainty assessments conducted for each of the APMT modules were used to develop the lens concept. The lens, defined as a combination of inputs and assumptions representing a particular perspective for conducting policy analysis, was introduced to facilitate distillation of policy analysis results from APMT.

An application of the lens framework was provided through the aforementioned cost-benefit and cost-effectiveness analysis of selected CAEP/8 NO_X stringency options. Several different lenses reflecting economic, scientific and modeling uncertainties were presented. The environmental benefits and economic costs associated with the CAEP/8 NO_X stringency options were analyzed for the US. All policy and baseline scenarios were modeled for 30 years of aviation activity extending over the period from 2006 to 2036. The NO_X stringency scenarios involved reductions in LTO and full mission NO_X emissions with associated fuel burn penalties for two of the stringencies. Environmental impacts were modeled using APMT-Impacts in physical and monetary impacts. Economic costs calculated by FESG and used for the CAEP/8 analysis were used.

All of the policies lead to changes in emissions inventories that are smaller than the change in certification stringency since aircraft in the existing fleet may be used for 20-30 years and new technology (lower NO_x) aircraft are only introduced to satisfy growth and retirements. NO_X reductions range from -5% to -8% compared to the baseline by 2036 (with the percent change in integrated emissions over the 30-year policy analysis period being about half of this). Changes in fuel burn inventories relative to the baseline are below 0.05% for all stringencies until the MS3 fuel penalty is added to the -20% stringencies cases, at which point the maximum change by 2036 is 0.15%. As a result, the climate costs of the CO_2 emissions changes are typically smaller than other costs and benefits. Depending on the literature sources used, the impacts from changes in NO_x on climate can be more prominent. Nonetheless, the warming and cooling effects of NO_x reductions may counterbalance one another to some extent and may also be counterbalanced by the changes in CO_2 emissions. Noise changes were not a significant influence on the analysis of costs and benefits.

There was no combination of assumptions, sensitivity studies, or methods in which the APMT analysis found the -20% stringency scenarios to provide benefits that appreciably exceed costs (i.e., by more than the uncertainties in scientific understanding and modeling methods). Stringencies 1 and 5 were found to be cost-beneficial only when a first (very uncertain) estimate of the impacts of cruise emissions on surface air quality was included in the analysis. Although we note that other modeling limitations and uncertainties related to airport-local effects, future background changes, and population growth are also likely to lead underestimates of the air quality benefits of NOx reductions; thus the inclusion of cruise emissions impacts also can be viewed as a surrogate sensitivity analysis to explore the influence of these other unquantified modeling limitations. These modeling limitations and uncertainties were not included because they are just now being established in the literature and/or the methods are still under development to incorporate them more formally. Stringency 7 also becomes cost-beneficial when the anticipated air quality modeling limitations and uncertainties are considered if the costs incurred to implement the NO_x reductions are considered to be half of the FESG provided costs for implementing the possible new NO_x Standards. Although we did not analyze all of the stringency options, we anticipate results for stringencies 2-4 to fall between those for stringencies 1 and 5; results for stringency 6 to be similar to those for stringency 7, and results for stringencies 8 and 9 to be similar to those for stringency 10.

While we have not presented all combinations of assumptions and scenarios, it is clear that different conclusions may be drawn about the same policy options depending on whether benefits and interdependencies are estimated in terms of health and welfare impacts versus changes in NO_X emissions inventories. Despite the uncertainties in impact estimates, the analysis provides important information about the potential impacts of the NO_X stringency options and the uncertainties in these impacts. In some cases, more complete information can make the “best” policy choice less obvious, but this is a direct outcome of the scientific and economic uncertainties of the underlying impacts. Clearly articulating the range of possible outcomes of a policy choice is in itself a valuable contribution of such an analysis.

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9. REFERENCES

[1] "Annex 16: Environmental Protection Volume I: Aircraft Noise, 4th Edition," ICAO 2005
[2] "Annex 16: Environmental Protection Volume II: Aircraft Engine Emissions," ICAO 2006
[3] "Summary of Discussions – Day 3," ICAO Group on International Aviation and Climate Change (GIACC), Montréal February 2008.
[4] Brasseur, G. P., (coordinating lead author), et al., "Aviation Climate Change Research Initiative: A Report on the Way Forward Based on the Review of Research Gaps and Priorities," 2008.
[5] "Proposal for a Directive of the European Parliament and Council amending Directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community," ed: Commission of the European Communities, December 2006.
[6] European Commission, "Commission notice pursuant to Article 18a(3)(a) of Directive 2003/87/EC," ed, 2009.
[7] European Commission, "Commission Decision amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for emissions and tonne-kilometre data from aviation activities," ed, April 16, 2009.
[8] U.S. EPA, "Advance Notice of Proposed Rulemaking - Regulating Greenhouse Gas Emissions under the Clean Air Act," vol. 73, ed.: Federal Register, 2008, pp. 44353-44520.
[9] U.S. EPA, "Mandatory Reporting of Greenhouse Gases, Final Rule" vol. 74, ed.: Federal Register, October 30, 2009. http://www.epa.gov/climatechange/emissions/ghgrulemaking.html
[10] Metz, B., et al., Climate change 2007 : mitigation of climate change : contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge ; New York: Cambridge University Press, 2007.
[11] "Transition to a More Comprehensive Approach for Assessing and Addressing Aviation Environmental Impacts," ICAO, Montréal February 2007.
[12] Waitz, I., J. Townsend, J. Cutcher-Gershenfeld, E. M. Greitzer and J. L. Kerrebrock, "Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions," December, 2004.
[13] ECAC, "ECAC.CEAC Doc 29: Report on Standard Method of Computing Noise Contours Around Civil Airports," 2005.
[14] FICON, "Federal Agency Review Of Selected Airport Noise Analysis Issues," 1992.
[15] Fidell, S., and L. Silvati, "Parsimonious Alternative to Regression Analysis for Characterizing Prevalence Rates of Aircraft Noise Annoyance," Noise Control Engineering Journal, vol. 52, pp. 56-68, 2004.
[16] Miedema, H. M. E., and H. Vos, "Exposure-response relationships for transportation noise," The Journal of the Acoustical Society of America, vol. 104, pp. 3432-3445, 1998.
[17] Miedema, H. M. E., and C. G. M. Oudshoorn, "Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals," Environmental Health Perspectives, vol. 109, pp. 409-416, 2001.
[18] Fidell, S., D. Barber, and T. J. Schultz, "Updating a dosage--effect relationship for the prevalence of annoyance due to general transportation noise," The Journal of the Acoustical Society of America, vol. 89, pp. 221-233, 1991.
[19] Finegold, L.S., C.S. Harris, and H.E. von Gierke, "Community Annoyance and Sleep Disturbance: Updated Criteria for Assessing the Impacts of General Transportation Noise on People," Noise Control Engineering Journal, vol. 42, 1994.
[20] Anderson, G. S., and N. P. Miller, "Alternative Analysis of Sleep-Awakening Data," Noise Control Engineering Journal, vol. 55, pp. 224-245, 2007.
[21] Passchier-Vermeer, W., "Night-Time Noise Events and Awakening," 2003.

[22] Stansfeld, S. A., and M. P. Matheson, "Noise pollution: non-auditory effects on health," British Medical Bulletin, vol. 68, pp. 243-257, 2003.
[23] Clark, C., R. Martin, E. van Kempen, T. Alfred, J. Head, H. W. Davies, M. M. Haines, Isabel L. Barrio, M. Matheson and S. A. Stansfeld, "Exposure-Effect Relations between Aircraft and Road Traffic Noise Exposure at School and Reading Comprehension: The RANCH Project," American Journal of Epidemiology, vol. 163, pp. 27-37, 2006.
[24] Hygge, S., G.W. Evans, and M. Bullinger, "A Prospective Study of Some Effects of Aircraft Noise on Cognitive Performance in Schoolchildren," Psychological Science, vol. 13, pp. 469-474, 2002.
[25] Stansfeld, S., B.Berglund, C.Clark, I.Lopez-Barrio, P.Fischer, E.Öhrström, M.Haines, J.Head, S.Hygge, I.van Kamp, "Aircraft and road traffic noise and children's cognition and health: a cross-national study," The Lancet, vol. 365, pp. 1942-1949, 2005.
[26] Health Council of the Netherlands: Committee on the Health Impact of Large Airports, “Public health impact of large airports,” The Hague: Health Council of the Netherlands, 1999/14E, ISBN: 90-5549-279-5H., 1999.
[27] Babisch, W., "Transportation Noise and Cardiovascular Risk: Updated Review and Synthesis of Epidemiological Studies Indicate that the Evidence has Increased," Noise & Health, vol. 8, 2006.
[28] Jarup, L., W. Babisch, D. Houthuijs, G. Pershagen, K. Katsouyanni, E. Cadum, M.-L. Dudley, P. Savigny, I. Seiffert, W. Swart, O. Breugelmans, G. Bluhm, J. Selander, A. Haralabidis, K. Dimakopoulou, P. Sourtzi, M/ Velonakis, and F. Vigna-Taglianti, "Hypertension and Exposure to Noise near Airports - the HYENA study," Environmental Health Perspectives, vol. 116, pp. 329-33, 2008.
[29] Nelson, J. P., "Meta-Analysis of Airport Noise and Hedonic Property Values," Journal of Transport Economics and Policy, vol. 38, pp. 1-27, 2004.
[30] Kolstad, C. D., Environmental Economics. NY: Oxford University Press, 2000.
[31] Kish, C. "An Estimate of the Global Impact of Commercial Aviation Noise," S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, June, 2008.
[32] FAA Office of Environment and Energy, "Aviation & Emissions: A Primer," www.faa.gov/regulations_policies/policy_guidance/envir.../ae**primer**.pdf, 2005.
[33] U. S. EPA, "Air Quality Criteria for Carbon Monoxide," 2000.
[34] U. S. EPA, "Air Quality Criteria for Particulate Matter," 2004.
[35] U. S. EPA, "Integrated Science Assessment for Oxides of Nitrogen — Health Criteria," 2008.
[36] U. S. EPA, "Integrated Science Assessment for Sulfur Oxides – Health Criteria," 2008.
[37] Watkiss, P., S. Pye, and M. Holland, "Baseline Scenarios for Service Contract for carrying out cost-benefits analysis of air quality related issues, in particular in the clean air for Europe (CAFE) program," AEA Technology Environment, 2005.
[38] Rojo, J. J., "Future trends in local air quality impacts of aviation," S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2007.
[39] Greco, S.L., A. M. Wilson, J. D. Spengler, and J. I. Levy, "Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States," Atmospheric Environment, vol. 41, pp. 1011-1025, 2007.
[40] Brunelle-Yeung, E. "The Impacts of Aviation Emissions on Human Health through Changes in Air Quality and UV Irradiance," Masters of Science Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2009.
[41] Ratliff, G., C. Sequeira, I. Waitz, M. Ohsfeldt, T. Thrasher, M. Graham, and T. Thompson, "Aircraft Impacts on Local and Regional Air Quality in the United States: PARTNER Project 15 final report," PARTNER-COE-2009-002, October 2009. http://web.mit.edu/aeroastro/partner/reports/proj15/proj15finalreport.pdf

[42] BenMAP, "BenMAP: Environmental Benefits Mapping and Analysis Program," US EPA - Office of Air Quality Planning and Standards, http://www.epa.gov/air/benmap/, 2005.
[43] Barrett, S. R. H., R. E. Britter, and I. A. Waitz, "Global Mortality Attributable to Aircraft Cruise Emissions," Environmental Science and Technology, forthcoming. Also Barrett, S. R. H. "The Air Quality Impacts of Aviation", Ph.D. Thesis, University of Cambridge, 2009.
[44] J. E. Penner, et al., "Aviation and the global atmosphere : a special report of IPCC Working Groups I and III in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer," Cambridge University Press, 1999.
[45] S. Solomon, et al., "Climate Change 2007: the physical science basis: contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change," Cambridge University Press, 2007.
[46] Stevenson, D. S., R. M. Doherty, M. G. Sanderson, W. J. Collins, C. E. Johnson, and R. G. Derwent, "Radiative forcing from aircraft NO_X emissions: Mechanisms and seasonal dependence," Journal of Geophysical Research, vol. 109, 2004.
[47] Wild, O., M. J. Prather, and H. Akimoto, "Indirect long-term global radiative cooling from NO_X emissions," Geophysical Research Letters, vol. 28, pp. 1719–1722, 2001.
[48] Lee, D. S. , D. W. Fahey, P. M. Forster, P. J. Newton, R. C.N. Wit, L. L. Lim, B. Owen, and R. Sausen, "Aviation and global climate change in the 21st century," Atmospheric Environment, Volume 43, Issues 22-23, Pages 3520-3537, July 2009.
[49] Revesz, R., and M. Livermore, "Retaking Rationality: How Cost Benefit Analysis Can Better Protect the Environment and Our Health," Oxford University Press, 2007.
[50] Kopp, R.J., A.J. Kuprick, and M. Toman, "Cost-Benefit Analysis and Regulatory Reform: An Assessment of the Science and the Art," Resources for the Future Discussion Paper, No. 97-19, 1997.
[51] "Economic Analysis of Federal Regulations, Executive Order 12866," U.S. Executive Branch, The White House, 1994.
[52] "Regulatory Analysis, Circular A-4," U. S. Office of Management and Budget, 09/17/2003.
[53] "Guidelines for Preparing Economic Analyses," U. S. Environmental Protection Agency (EPA), 2000.
[54] "Economic Analysis of Investment and Regulatory Decisions," Federal Aviation Administration (FAA) Office of Aviation Policy and Plans (APO), 1998.
[55] "The economic appraisal of environmental projects and policies - A practical guide," Organisation for Economic Co-operation and Development (OECD), 1995.
[56] "The Green Book. Appraisal and Evaluation in Central Government.," UK HM Treasury, 2003.
[57] ICAO, "Convention on International Civil Aviation, Ninth Edition," 2006.
[58] "ICAO Environmental Report 2007," ICAO 2007.
[59] Newton, P., "Long Term Technology Goals for CAEP/7," International Civil Aviation Organization (ICAO) - Seventh Meeting of the Committee on Aviation Environmental Protection, 2007.
[60] ICAO CAEP, "CAEP/6 Final Report - Agenda Item 1, CAEP/6–WP/57," ICAO - CAEP, Sixth Meeting, Montreal, Canada, 2004.
[61] "Economic Analysis of NO_X Emissions Stringency Options," ICAO CAEP Forecasting and Economic Analysis Support Group (FESG), Montréal, February, 2004.
[62] Reynolds, T., S. Barrett, L. Dray, A. Evans, M. Köhler, M. Vera-Morales, A. Schäfer, Z. Wadud, R. Britter, H. Hallam, and R. Hunsley "Modelling Environmental & Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Project," AIAA-2007-7751, presented at the AIAA Aviation Technology, Integration and Operations Conference, Belfast, 18-20 September 2007.
[63] "Regulatory Impact Assessment Guidance," UK Cabinet Office, Better Regulation Executive (UK BRE), 2005.
[64] "Guide to Benefit Cost Analysis in Transport Canada, TP11875E," Transport Canada, 1998.

[65] "Air Quality Guidelines for Europe, WHO Regional Publications, European Series, No. 91.," ed: World Health Organization (WHO), 2000.

[66] Krupnick, A., B. Ostro, and K. Bull, "Peer Review of the Methodology of Cost- Benefit Analysis of the Clean Air for Europe Programme," 2004.

[67] "Methodology for the Cost-Benefit Analysis for CAFÉ Vol. 1, 2 , and 3.," Clean Air for Europe (CAFÉ) Programme, 2005.

[68] Waitz, I., S. Lukachko, Y. Go, P. Hollingsworth, K. Harback, and F. Morser, "Requirements Document for the Aviation Environmental Portfolio Management Tool," Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER), June, 2006.

[69] "LETTER REPORT: Workshop #3, FAA Aviation Environmental Design Tool (AEDT) and Aviation Portfolio Management Tool (APMT)," www.**faa**.gov/about/office_org/headquarters.../**workshop3**_2005.pdf, Transportation Research Board (TRB), 2005.

[70] Wadud, Z. "A Systematic Review of Literature on the Valuation of Local Environmental Externalities of Aviation," OMEGA Report, 2009.

[71] He, Q., C. Wollersheim, M. Locke, and I. Waitz, "Estimation of the Global Impact of Aviation-Related Noise Using an Income-Based Approach," Transport Policy (in review)

[72] Sequeira, C.J., "An Assessment of the Health Implications of Aviation Emissions Regulations," S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2008.

[73] Masek, T., "A Response Surface Model of the Air Quality Impacts of Aviation," Masters of Science Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, June, 2008.

[74] Byun, D. W., and J. K. S. Ching, "Science algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) Modeling System," U. S. EPA Office of Research and Development, Ed., ed, 1999.

[75] Byun, D. W., and K. Schere, "Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System," Appl. Mech. Rev, vol. 59, pp. 51-77, 2006.

[76] U. S. EPA, "EPA procedures for estimating future $PM_{2.5}$ values for the CAIR final rule by application of the (revised) speciated modeled attainment test (SMAT)," 2006.

[77] "ExternE - Externalities of Energy: Methodology 2005 Update, EUR 21951 EN," European Commission, 2005.

[78] U. S. DOT, "Revised Departmental Guidance: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses. Memorandum to Secretarial Officers, Modal Administrators; Re: Treatment of the Economic Value of a Statistical Life in Departmental Analyses," Office of the Secretary of Transportation, Washington, D.C.2008.

[79] Hasselmann, K., S. Hasselmann, R. Giering, V. Ocana and H. V. Storch, "Sensitivity Study of Optimal CO_2 Emission Paths Using a Simplified Structural Integrated Assessment Model (SIAM)," Climatic Change, vol. 37, pp. 345 - 386, 1997.

[80] Sausen, R., and U. Schumann, "Estimates of the Climate Response to Aircraft CO_2 and NO_X Emissions Scenarios," Climatic Change, vol. 44, pp. 27-58, Jan 2000.

[81] Fuglestvedt, J.S., T. Berntsen, O. Godal, R. Sausen, K. P. Shine and T. Skodvin, "Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices," Climatic Change, vol. 58, pp. 267 - 331, Jun 2003.

[82] Shine, K. P., J. S. Fuglestvedt, K. Hailemariam and N. Stuber, "Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases," Climatic Change, vol. 68, pp. 281 - 302, Feb 2005.

[83] Marais, K., S. P. Lukachko, M. Jun, A. Mahashabde, and I. A. Waitz, "Assessing the impact of aviation on climate," Meteorologische Zeitschrift, vol. 17, pp. 157-172, 2008.

[84] Jun M., and A. Mahashabde, "APMT Assessment Report: Benefits Valuation Block – Climate Module," 2008.
[85] R. Sausen, I. Isaksen, V. Grewe, D. Hauglustaine, D. S. Lee, G. Myhre, M. Köhler, U. Schumann, F. Stordal, C. Zerefos, "Aviation radiative forcing in 2000: An update on IPCC (1999)," Meteorologische Zeitschrift, vol. 14, pp. 555-561, 2005.
[86] P. Hoor, J. Borken-Kleefeld, D. Caro, O. Dessens, O. Endresen, M. Gauss, V. Grewe, D. Hauglustaine, I. S. A. Isaksen, P. J¨ockel, J. Lelieveld, G. Myhre, E. Meijer, D. Olivie, M. Prather, C. Schnadt Poberaj, K. P. Shine, J. Staehelin, Q. Tang, J. van Aardenne, P. van Velthoven, and R. Sausen, "The impact of traffic emissions on atmospheric ozone and OH: results from QUANTIFY," Atmospheric Chemistry and Physics, vol. 9, pp. 3113-3136, 2009.
[87] Hansen, J., et al., "Efficacy of climate forcings," Journal of Geophysical Research Atmospheres, vol. 110, 2005.
[88] Nordhaus, W. D., A Question of Balance: Weighing the Options on Global Warming Policies. New Haven, Yale University Press, 2008.
[89] Nordhaus, W. D., and J. Boyer, Warming the world: economic models of global warming. Cambridge, Mass.: MIT Press, 2000.
[90] Schneider, S., and J. Lane, "Integrated Assessment Modeling of Global Climate Change: Much Has Been Learned—Still a Long and Bumpy Road Ahead," Integrated Assessment, vol. 5, pp. 41–75, 2005.
[91] Hancox, R., et al., "Aviation Environmental Portfolio Management Tool (APMT): Partial Equilibrium Block Algorithm Design Document (ADD), Report for Federal Aviation Administration," MVA Consultancy2009.
[92] Hancox, R., and C. Sinclair, "Analysis of Aviation & Fuel Price Scenarios for U.S. Participation in the ICAO Group on International Aviation and Climate Change," MVA Consultancy2009.
[93] "APMT Progress," ICAO CAEP/7; CAEP/7-IP/25; February 2007.
[94] Webster, M., "Communicating Climate Change Uncertainty to Policy-Makers and the Public," Climatic Change, vol. 61, pp. 1-8, 2003.
[95] van Asselt, M., and J. Rotmans, "Uncertainty in perspective," Global Environmental Change, vol. 6, pp. 121-157, 1996.
[96] Brugnach, M., A. Tagg, F. Keil, and W. J. de Lange, "Uncertainty Matters: Computer Models at the Science–Policy Interface," Water Resources Management, vol. 21, pp. 1075-1090, 2007.
[97] Morgan, M. G., and M. Henrion, Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis. NY: Cambridge University Press, 1990.
[98] Allaire, D. L., "Uncertainty Assessment of Complex Models with Application to Aviation Environmental Systems," Ph.D. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2009.
[99] Sobol, I.M., A primer for the Monte Carlo method. Boca Raton, CRC Press, 1994.
[100] Helton, J. C., "Conceptual and computational basis for the quantification of margins and uncertainty. Sandia National Laboratories Technical Report, in draft, SAND2009-XXXX," ed, 2009.
[101] Homma, T., and A. Saltelli, "Important measures in global sensitivity analysis of nonlinear models," Reliability Engineering and System Safety, vol. 52, pp. 1-17, 1996.
[102] Sobol, I. M., "Theorems and examples on high dimensional model representation," Reliability Engineering and System Safety, vol. 79, pp. 187-193, 2003.
[103] Jun, M., "Uncertainty Analysis of an Aviation Climate Model and an Aircraft Price Model for Assessment of Environmental Effects," S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2007.
[104] Tipton, C., et al., "Aviation Environmental Portfolio Management Tool (APMT): Partial Equilibrium Block Assessment, Report for FAA," MVA Consultancy; 2008.
[105] Sobol, I. M., "Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates," Mathematics and Computers in Simulation, vol. 55, pp. 271-280, 2001.

[106] ICAO CAEP MODTF, "MODTF NO_X Stringency Assessment, CAEP8_MODTF_WP04" 2009.
[107] ICAO CAEP FESG, "FESG CAEP/8 Traffic and Fleet Forecasts, CAEP-SG/20082-IP/02," ICAO CAEP, Steering Group Meeting; 2008.
[108] SAE A-21, "Procedure for the Computation of Airplane Noise in the Vicinity of Airports," Society of Automotive Engineers, Committee A-21, Aircraft Noise, Warrendale, PA; March 1986.
[109] CSSI, "Emissions and Dispersion Modeling System (EDMS) User's Manual Version 5.0," Prepared for Federal Aviation Administration Office of Environment and Energy; 2007
[110] Roof, C., "Aviation Environmental Design Tool (AEDT) System Architecture, Prepared for FAA Office of Environment and Energy," 2007.
[111] Kim, B.,"System for assessing Aviation's Global Emissions (SAGE) Version 1.5 Technical Manual," 2005
[112] Hancox, R., "Personal communication on forthcoming CAEP/8-FESG NO_X Stringency Economic Analysis," 2009
[113] "NO_X Stringency Assumptions," ICAO CAEP FESG 2007.
[114] Mahashabde, A., "Assessing the Environmental Benefit and Economic Cost of Aviation Environmental Policy Measures," PhD Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, 2009.
[115] Stevenson, D. S., R. M. Doherty, R. M., M. G. Sanderson, W. J. Collins, C. E. Johnson, R. G. Derwent, "Radiative forcing from aircraft NOX emissions: Mechanisms and seasonal dependence," Journal of Geophysical Research, vol. 109, 2004.
[116] Nakicenovic, N., "Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change," ed, 2000.
[117] US EPA, "Technical Support Document on Benefits of Reducing GHG Emissions," 2 June 2008.
[118] U. S. FAA Environmental Tool Suite Frequently Asked Questions; Available: http://www.faa.gov/about/office_org/headquarters_offices/aep/models/toolsfaq/index.cfm?print=go#magenta , 2009.
[119] Balasubramanian, S., personal correspondence, Volpe National Transportation Systems Center, 2009
[120] Olmstead, J. R., et al., "Integrated Noise Model (INM) Version 6.0 Technical Manual," 2002.
[121] DuBois, D., and et al., "Fuel Flow Method for Estimating Aircraft Emissions," Society of Automotive Engineers, Inc., Warrendale, Pa2006.
[122] Ratliff, G. L, "Preliminary Assessment of the Impact of Commercial Aircraft on Local Air Quality in the U.S.," Masters of Science Thesis, Department of Aeronautics and Astronautics and Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA, June, 2007.
[123] Thrasher, T., "NO_X Demonstration Analysis Round 3," 2006
[124] Kirby, M., et al., "EDS Algorithm Description Document," 2008.

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