# Assessing Environmental Benefits and Economic Costs of Aviation Environmental Policy Measures

by

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Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Aeronautics and Astronautics
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
September 2009

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## Abstract

Despite the recent global economic downturn, longer term growth is anticipated for aviation with an increasing environmental impact, specifically in the areas of noise, air quality, and climate change. To ensure sustainable growth for aviation, decision-makers and stake-holders need to be armed with information on balancing environmental and economic interests. The main objective of this thesis is to address key shortcomings in current decision-making practices for aviation environmental policies. This work demonstrates how the inclusion of environmental impact assessment and quantification of modeling uncertainties can enable a more comprehensive evaluation of aviation environmental policy measures. A comparison is presented between the conventional cost-effectiveness analysis and an illustrative cost-benefit analysis focused on assessing a subset of the engine $NO_x$ emissions certification stringency options under consideration for the upcoming eighth meeting of the International Civil Aviation Organization's Committee on Aviation Environmental Protection.

The Aviation environmental Portfolio Management Tool (APMT) is employed to conduct the aforementioned policy assessments. Monte Carlo methods are adopted to explicitly quantify uncertainties in the modeling process. To enable the aviation climate impact assessment required by the policy analysis, a separate component of this work focuses on advancing the climate impact modeling capabilities within APMT. Major contributions towards assessing aviation climate impacts in APMT include: improved characterization of uncertainty for $NO_x$-related effects and for aviation climate damages, introduction of a reduced-order methodology for assessing climate impacts of methane emissions from the processing of alternative jet fuels, and comparison and validation of APMT results with external sources.

This work also discusses the importance of uncertainty assessment for understanding the sensitivity of policy analysis outcomes to input and model parameter variability and identifying areas of future work. An uncertainty analysis for the APMT Climate Module is presented. Radiative forcing from short-lived effects, climate sensitivity, damage function, and discount rate are identified to be the model parameters with the greatest contribution to output variability for the Climate Module for any given aviation scenario. Key contributors to uncertainty in the difference between policy and baseline scenarios are determined by the nature of the policy. For the $NO_x$ stringency analysis, the $NO_x$ radiative forcing and associated efficacies are significant contributors to uncertainty in analysis outcomes. Information based on model uncertainty assessment is also used for distilling and communicating key analysis results to the relevant stake-holders and policy-makers through the development of the lens concept. The lens, defined as a combination of inputs and model parameters representing a particular perspective for conducting policy analysis, is applied in conducting the engine $NO_x$ stringency policy assessment.

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# Acknowledgments

The successful completion of this thesis is grounded in the support, guidance, and encouragement of many people both on the professional and personal fronts. First and foremost, I would like to express my sincere gratitude to my advisor, Prof. Ian Waitz; I have learned so much from him. He has been a great mentor over the past several years fostering my professional growth by encouraging me to shoulder increasing responsibility and always believing in my abilities. I also wish to thank Prof. Waitz for giving me the opportunity to experience first-hand how our work is received in the broader community. I would like to thank my committee members, Prof. Karen Willcox and Prof. Henry Jacoby for their guidance and critical evaluation of my work and my thesis readers Dr. Lourdes Maurice and Prof. Mort Webster for their valuable insights and recommendations.

Next, I want to acknowledge project team members I worked closely with from other organizations – Gregg Fleming and Sathya Balasubramanian from the Volpe Transportation Center, Richard Hancox and Caroline Sinclair from MVA consultancy, and Fabio Grandi from Wyle Labs. The CAEP analysis work presented in this thesis required constant coordination with the extended team and I wish to thank them for their help and for responding promptly to all my questions and requests. I would also like to thank Maryalice Locke who is the FAA project manager for APMT for her support and guidance.

Through this research, I have enjoyed working closely with many MIT colleagues. I would like to thank Karen Marais and Mina Jun for helping me learn about aviation climate impact modeling and have fun while doing that! Julien Rojo made sure that I did not fall asleep at my desk and introduced me to the world of AQ. Chris Kish helped me learn about noise impacts and I respect him for having survived GIS. Thank you Jianye Zhang and Chris Sequeira for being great lunch buddies and making the lab a fun place. I would like to thank Andrew March for dropping by every so often to make sure that I retained my sanity till the very end. Doug Allaire has not only been the assessment expert, but also a good venting companion, be it the quals or

the defense. Rhea Liem, Pearl Donohoo, Alice Fan, and Elza Brunelle-Yeung have been my lab support group, cheering me on always. I have had some very memorable times with you ranging from international travel, eccentric office decorations, and daily horoscopes to just fun dinners, shopping trips, and movies! I will miss you all lots.

I would like to thank Stephen Lukachko for many interesting and stimulating conversations on a multitude of topics and his help with the climate work. Jim Hileman and Tom Reynolds have always given me excellent technical and career advice and I wish to thank them for their help and guidance on numerous occasions. It has been a pleasure working with the rest of the MIT-PARTNER team and I would like to thank Chris Dorbian, Stephen Kuhn, Chelsea He, Russ Stratton, Phil Wolfe, and Christoph Wollersheim for all the good times we have shared.

Several other individuals at MIT have been incredibly supportive and have ensured a smooth and enjoyable graduate experience for me. Thank you Robin Palazzolo, Sue Whitehead, Jennie Leith, Marie Stuppard, and Barbara Lechner for taking such good care of us students!

On the personal front, I have found deep and enriching friendships while at MIT that have shaped my entire graduate experience. These relationships have carried me through the tough times and taught me so much. I leave here with many fond memories and I will always cherish the time we spent together. Cecilia, I had to go quite an extreme to get you to be my friend, but that White Mountains experience was absolutely worth it! Thank you for being there for me through it all. I have really enjoyed all our travels together and look forward to many more. Tzu-Ching, while you've been away for a while now, you have been a constant presence in my life, thank you for being such a great friend. Mridula and Liang, I did not have a chance to see you both as often as I would have liked to in recent times, but I will never forget our old Tang days and your help especially during the quals, thank you so much. Hui, my parents still tell me that they were so happy when they saw that I would be staying with you in our first year. Thank you for taking such good care of my during our early Tang days.

Anna has been my happiness fix, always there with her big smile! I cannot imagine having survived the past year without you, thank you so much for putting up with me, and for all those crazy conversations about anything and everything. Aruna, I don't think I will be able to enjoy a cup of tea or aloo paratha with the same excitement with anyone else; thank you for being such a great roommate! Krupa, I am so glad that we became such good friends over the past couple years, thank you for all the great times we have had together! Arvind, Karthik, and Murali, I have really enjoying hanging out with you all (not in the Murali sense), I just wish I had met you much earlier on.

Ganesh, I am very lucky to have you in my life. Thank you for being so kind, caring, and patient through good times and bad.

Finally, I would like to dedicate this work to my parents and my sister. Mom, and Dad, thank you for being my source of strength and support. None of this would have been possible without your love, encouragement, and blessings. Guddu, thank you for listening, caring, and always being there for me.

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# Chapter 1

# Introduction

## 1.1 Background

Environmental impacts of aviation have become increasingly important over the last 50 years with the rapid growth of commercial jet aviation. Aircraft noise, with the most distinctly 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 which has subsequently been updated for newer technology aircraft [1]. Emissions standards were next to follow with the implementation of ICAO Standards and Recommended Practices for aircraft emissions in the 1980s to improve air quality in the vicinity of airports. ICAO emissions standards are summarized in the Annex 16: Environmental Protection, Volume II – Aircraft Engine Emissions [2] for nitrogen oxides ($NO_x$), hydrocarbons (HC), carbon monoxide (CO) and smoke.

In response to growing concerns about aviation's impact on climate change, the ICAO recently established the Group on International Aviation and Climate Change, which is responsible for providing policy guidance to the ICAO for addressing international commercial aviation's climate change impacts [3]. The United States Federal Aviation Administration (FAA) has recently developed the Aviation Climate Change Research Initiative with participation from the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration 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 system as a part of a post-Kyoto agreement for the next commitment period starting in 2012 [5]. This new directive targets all 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 proposed a rule requiring mandatory reporting of greenhouse gas emissions from large sources including aircraft engines to collect data for informing future policy decisions with reporting to begin in 2011 [9].

While the IPCC cites a projected growth rate of about 5% [10] for aviation over the next 20-25 years, the recent global economic downturn is expected to dampen growth in the near future [11]. However, given that longer term growth is anticipated for aviation as the world economy rebounds and continues to grow [11], what are the appropriate measures to ensure that this growth balances both economic and environmental interests? Which aircraft and engine technologies, air traffic management strategies, and government policies should be employed to satisfy the growing demand, while, at the same time, reducing significant environmental impacts in absolute terms? Answering these questions requires understanding the trade-offs among technologies, operations, policies, market conditions, manufacturer and airline economics, and 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 measures where reductions in aircraft noise or emissions are weighed 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 ICAO-CAEP held in 2007 recognized the necessity for comprehensive analyses that assess the tradeoffs between noise and emissions impacts and economic costs to better inform policymaking decisions [12]. Policymakers need to be armed with information on balancing environmental and economic interests to better evaluate proposed environmental policy measures for aviation. Developing tools and metrics to assess and communicate aviation's environmental impacts is also one of the recommendations made in the Report to the U.S. Congress on aviation and the environment [13].

The main objective of this thesis is to address shortcomings in current decision-making practices and illustrate how the inclusion of environmental impact assessment can lead to different conclusions about selected environmental policy options for aviation. This work demonstrates interdependencies among the different environmental impacts of aviation and tradeoffs between environmental and economic performance through an assessment of some of the engine $NO_x$ emissions certification stringency options under consideration for the upcoming eighth meeting of the ICAO-CAEP.

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) has been employed to analyze the selected policy measures. To facilitate the climate impact assessment required by the aforementioned policy analysis, a separate component of the research effort contributes to advancing the aviation climate impact modeling capabilities within APMT. APMT Climate Module enhancements include improved characterization of uncertainties in aircraft $NO_x$-related impacts and uncertainties in estimating societal damages from climate change, a reduced-order methodology for estimating the climate impacts of the well-to-tank methane($CH_4$) emissions from processing alternative jet fuels and comparison and validation of results with external sources. 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 key results from a comprehensive policy analysis given various sources of uncertainty are also discussed.

## 1.2 Thesis Organization

This section provides a brief description of the organization and structure of the different chapters of the thesis. There are seven chapters; the contents of each chapter are outlined below.

**Chapter 2:**

Chapter 2 provides the motivation for this thesis work through a discussion of the key environmental impacts of commercial aviation and by highlighting the shortcomings in current decision-making practices. First, an overview of the different health and welfare impacts of aircraft noise and emissions is presented. Next, the chapter reviews recommended practices for economic analysis of environmental regulations and describes current practices within ICAO-CAEP for aviation-specific environmental policies. Finally, the analysis developed by ICAO-CAEP to support consideration of increased engine $NO_x$ emissions certification stringency at the sixth meeting of the CAEP is discussed to identify important shortcomings in current practices.

**Chapter 3:**

Chapter 3 discusses estimation methods for aviation environmental impacts employed within APMT. This chapter also provides a brief overview of the aviation environmental tool suite being developed by the FAA-AEE in collaboration with the National Aeronautics and Space Administration and Transport Canada.

**Chapter 4:**

A literature review of the climate change impacts of commercial aviation is presented in Chapter 4 along with a discussion of the key issues in modeling physical and monetized climate impacts. Chapter 4 also highlights the contributions of this thesis in expanding the capabilities of the APMT Climate Module. More specifically, this chapter discusses the modified $NO_x$ and damage function uncertainty characterization, the simplified modeling methodology adopted in APMT for assessing climate impacts of well-to-tank methane emissions and validation of APMT results with external sources.

**Chapter 5:**

Chapter 5 discusses the role of model assessment and quantification of uncertainties in policy analysis, and highlights the issues concerning the communication of results from such a set of analysis. An uncertainty analysis of the APMT-Impacts Climate Module that ranks inputs and model parameters based on their contributions to output variability is presented in this chapter. Chapter 5 also introduces the analysis framework designated as the *lens* concept for selecting a particular combination of input and model parameters for assessing proposed policy measures.

**Chapter 6:**

Chapter 6 is focused on the ICAO-CAEP engine $NO_x$ emissions stringency analysis with a comparison between the baseline - unregulated case and two policy scenarios. This chapter provides results that demonstrate improvements in the decision-making process in the aviation context when using the cost-benefit approach to assess the proposed policy measures as compared to the cost-effectiveness approach.

**Chapter 7:**

Finally, Chapter 7 provides a summary and key conclusions from the work described in this thesis.

## 1.3 Key Contributions

This research effort is one component of a large-scale initiative by the FAA-AEE for developing an integrated assessment capability to estimate the environmental impacts of aviation. Listed below are the contributions of this thesis work in the area of aviation-related environmental impacts and policy assessment.

- An assessment of selected aviation environmental policy measures that demonstrates an improvement in the current decision-making process by incorporating more information about both economic and environmental impacts of the policy and associated uncertainties as compared to a conventional cost-effectiveness approach. The policy analysis presented in this thesis evaluates the economic costs and environmental benefits of a subset of the engine $NO_x$ emissions certification stringency options under consideration for the next ICAO-CAEP meeting to be held in 2010.
- Development of climate modeling capabilities within APMT to enable the aforementioned and anticipated policy assessments:
  - Improved characterization of uncertainty associated with climate effects of aircraft $NO_x$ emissions
  - Improved characterization of uncertainty for estimating societal damages attributed to aviation-related climate change
  - Incorporation of a simplified methodology for assessing impacts of well-to-tank methane emissions from the processing of alternative jet fuels
  - Comparison and validation of APMT results with external sources such as the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC)

# Chapter 2

# Aviation Environmental Impacts and Current Decision-making Practices

This chapter serves as the motivation for the remainder of the thesis by summarizing key environmental impacts of aircraft activity and illustrating the shortcomings in current approaches for evaluating proposed aviation environmental policies. First, an overview of the environmental and health impacts attributed to aviation in the areas of community noise, air quality, and climate change is provided. Water quality impacts associated with airport storm-water runoff are not addressed here. Methods for estimating aviation noise and air quality impacts in both physical and monetary metrics are discussed in Chapter 3. Climate impacts of aviation are discussed in detail in Chapter 4. Second, this chapter reviews common approaches for conducting economic analysis to better inform regulatory decisions. The economic analysis developed by ICAO-CAEP for engine $NO_x$ emissions certification standards for the sixth meeting of the CAEP is discussed as an example of common practices for aviation environmental policies.

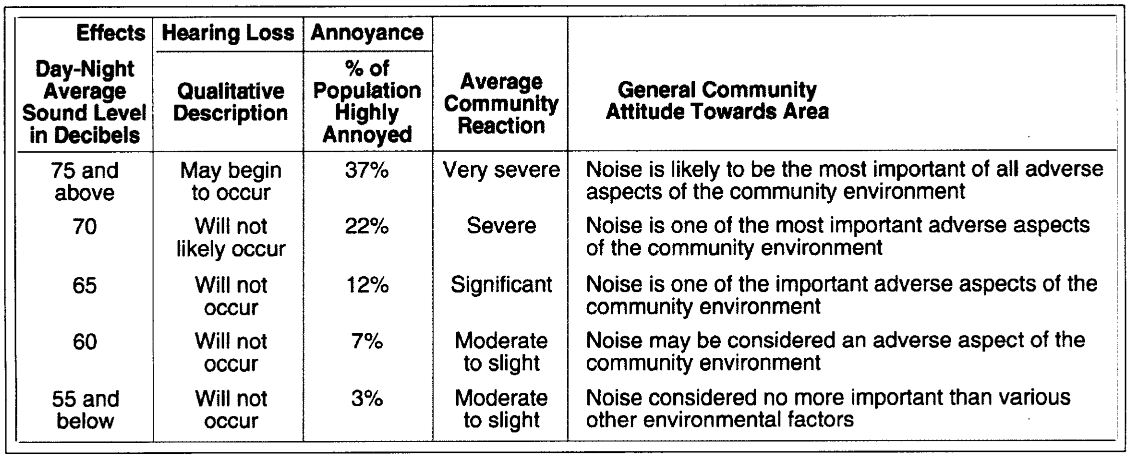
## 2.1 Aviation Environmental Impacts: an Overview

### 2.1.1 Noise Impacts

Being an easily perceived direct impact of aviation activity, aviation noise is the most significant objection of local communities to airport expansion projects [13]. While there are multiple noise sources at airports, this discussion is limited to aircraft-related noise. This section presents commonly-used noise scales and metrics first, 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 weights 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 [14].

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 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 night-time events. The A-weighted DNL is used widely for noise impact assessments [14].

Both behavioral and physiological impacts on people from long- and short-term exposure to aircraft noise have been studied extensively. Behavioral impacts include general annoyance, sleep disturbance, disruption of work performance and learning, while physiological effects range from stress-related health effects from hypertension to hormone changes and mental health effects. Attributing behavioral impacts is difficult due to the confounding effects of both acoustical factors such as time variation in noise levels and ambient noise levels and non-acoustical effects such as lifestyle, attitude to noise, income-level, etc. Community annoyance and sleep disturbance are some of the better understood behavioral impacts of aircraft noise exposure with well-defined exposure-response relationships in literature. Figure 2-1 lists the varying impacts of aircraft noise on people in residential areas for different day-night average noise exposure levels [15].



| **Effects** | **Hearing Loss** | **Annoyance** | | |
|---|---|---|---|---|
| **Day-Night Average Sound Level in Decibels** | **Qualitative Description** | **% of Population Highly Annoyed** | **Average Community Reaction** | **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 occur | 22% | Severe | Noise is one of the most important adverse aspects of the community environment |
| 65 | Will not occur | 12% | Significant | Noise is one of the important adverse aspects of the community environment |
| 60 | Will not occur | 7% | Moderate to slight | Noise may be considered an adverse aspect of the community environment |
| 55 and below | Will not occur | 3% | Moderate to slight | Noise considered no more important than various other environmental factors |

Figure 2-1: Aircraft noise effects on residential areas [15]

Data obtained from annoyance surveys have been used to derive exposure-response functions for quantifying the number of people affected by a given noise level (for instance, see [16, 17, 18, 19]. 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 is a more relevant metric for policy analysis (see [20] and [21]). Aircraft noise has been strongly 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], [23], [24], [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 [26, 15]. Hypertension has been closely linked to aircraft noise as shown by several studies, but no exposure-response functions have been estimated ([27], [28]).

### 2.1.2 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 or volatile organic compounds (VOCs), particulates, 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 [29]. Aircraft emissions of $NO_x$, CO, $SO_x$, VOCs, and particulates are of particular interest for air quality impacts in the vicinity of airports as most of them are designated as "criteria pollutants" by the US EPA and are associated with adverse health impacts. The US EPA under the Clean Air Act is required to set National Ambient Air Quality Standards for six principal pollutants which include CO, lead (Pb), nitrogen dioxide ($NO_2$), $O_3$, particulate matter (PM), and sulfur dioxide ($SO_2$). The following discussion provides a brief overview of each of the aviation pollutants linked to air quality impacts based on recent US EPA findings.

- **Nitrogen oxides ($NO_x$):**

  The atmospheric modeling community defines oxides of nitrogen ($NO_x$) as both NO and $NO_2$ which are by-products of high pressure and high temperature combustion such as in jet engines. Based on both epidemiological or observation data, and human and animal clinical studies, the recent US EPA integrated science assessment of $NO_2$ concludes that there is a positive association between short-term exposure to gaseous $NO_2$ and respiratory morbidity [30]. However, recent evidence does not clearly establish whether the association is solely due to $NO_2$ or whether $NO_2$ is a surrogate for impacts related to a different pollutant. Additionally, a concentration-response relationship between $NO_2$ 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 PM [30]. In the aviation context, ozone-related health impacts are insignificant as compared to PM impacts (less than 8%) and will not be discussed further here ([31], [32]).

- **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].

- **Sulfur oxides ($SO_x$):**

  Combustion of sulfur containing fossil fuels leads to the formation of sulfur dioxide ($SO_2$), sulfur trioxide ($SO_3$), and gas-phase sulfuric acid ($H_2SO_4$) which are referred to as sulfur oxides or $SO_x$. $SO_2$ is the dominant species with trace concentrations of $SO_3$ and $H_2SO_4$. $SO_2$ 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" [34]. 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 prevents a robust quantification of a concentration-response relationship [34].

- **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 $2.5\mu m$ [32].

Aircraft $PM_{2.5}$ emissions result from direct emissions of non-volatile PM as well as through secondary PM formation from precursor emissions of $NO_x$, $SO_x$, and hydrocarbons in the form of ammonium sulfates and ammonium nitrates [35, 32]. Aircraft PM emissions largely comprise of secondary PM from emissions of $NO_x$ and $SO_x$ with minor contributions from non-volatile PM. Figure 2-2 shows the changes in annual $PM_{2.5}$ concentrations in the US (in $g/m^3$) attributed to aircraft emissions taken from the forthcoming Energy Policy Act Study [36]. The US EPA sets the National Ambient Air Quality Standard for $PM_{2.5}$ at 15 $g/m^3$. 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 high fidelity 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 in Figure 2-2.

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 [37]. The US EPA uses the Environmental Benefits Mapping Program (BenMAP) for performing health impact analyses to evaluate incidences and costs of different health effects [38]. The Energy Policy Act Study estimates aviation-related risk of premature mortality to be 64-270 yearly deaths using BenMAP [36]. Recent work by 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 and secondary PM from hydrocarbons [39]. Several studies in literature indicate that health impacts from aircraft PM emissions outweigh impacts from other aircraft pollutant species (see [32, 39, 31]).

| | **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%** |

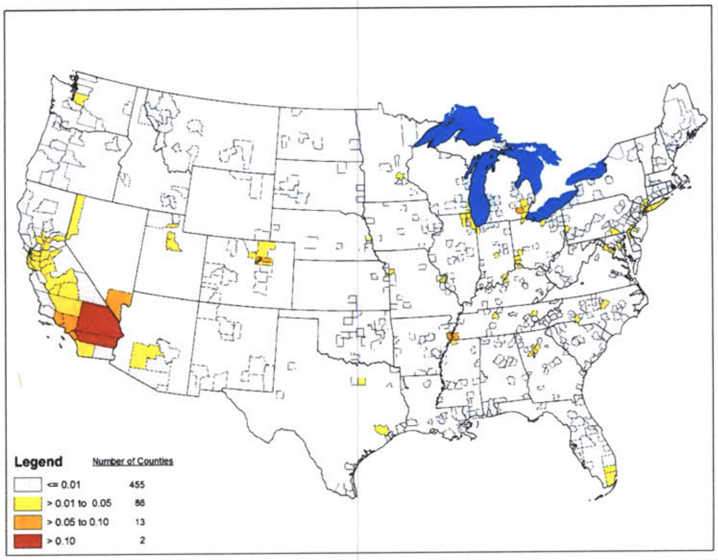


Figure 2-2: Changes in annual $PM_{2.5}$ concentrations attributed to aircraft emissions [36]

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) 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 80-90% of the total health impacts of aviation [40]. With further research, future assessments of aviation air quality impacts may need to include both landing and takeoff as well as cruise emissions to account for the full impact of aviation emissions.

### 2.1.3 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 [41]. 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" [42]. 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) [42]. 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. Chapter 4 presents a more detailed literature review of aviation climate impact assessment methods.

- **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 [41].

- **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 [41].

- **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 produce OH radicals which increase the oxidative capacity of the atmosphere; this decreases methane ($CH_4$) concentrations and has an associated primary-mode reaction that suppresses methane-related tropospheric ozone formation in the long run. $NO_x$-related radiative forcing perturbations strongly depend on seasonal variations in solar insolation and background $NO_x$ and $HO_x$ concentrations and show large spatial variations in radiative impacts [41]. The short-lived $O_3$ warming effect from $NO_x$ emissions lasts on the order of a few months while the longer-lived $NO_x$-$CH_4$-$O_3$ cooling effect has a decadal lifetime [43, 44]. At a globally-averaged scale the short-lived $NO_x$-$O_3$ and the long-lived $NO_x$-$CH_4$-$O_3$ are of roughly equal magnitude with opposite signs with a net impact close to zero; however regional variations can be significant.

- **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, 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 [41].

- **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 [41].

- **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 [41].

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 [41] are provided by Lee et al. [45], shown in Figure 2-3. Figure 2-3 identifies the main effects and indicates the uncertainties associated with each impact. $CO_2$ has a relatively well understood impact while the aviation-induced cirrus effect has the highest uncertainties. Figure 2-3 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 being low by Lee et al. [45].

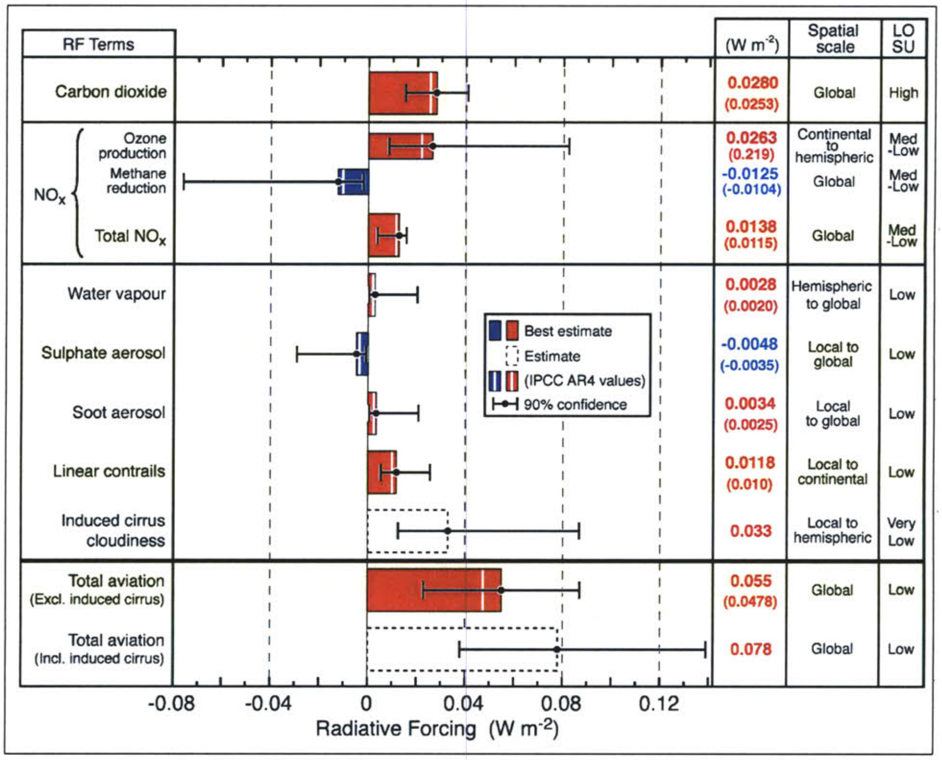


Figure 2-3: Radiative forcing from aircraft emissions in 2005 [45]

## 2.2 Current Decision-making Practices for Aviation Environmental Policies

### 2.2.1 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) [46, 47].

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 [47]. Finally, a distributional analysis is meant to address the question of who benefits and who bears the costs of the proposed policies [48].

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 [48, 49] . Although CBA is the recommended basis for assessing policy alternatives in many governments (see, for example: [50], p59; [51], p2-3; [49], p11; [52], p23; and [53], 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, some 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 in adopting the CEA approach for aviation environmental policy analysis.

### 2.2.2 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 [54]. The ICAO establishes Standards and Recommended Practices 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 [55]. Next, an overview of conventional ICAO practices for conducting economic policy analysis is presented through considering the most recent $NO_x$ stringency analysis.

The $NO_x$ 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 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 during the landing-takeoff cycle normalized by the maximum engine takeoff thrust rating. The new increased $NO_x$ stringency level is typically applicable to new engines being introduced into the fleet, but may also lead to an early retirement of non-compliant engines. Chapter 6 provides a brief overview of aircraft engine $NO_x$ emissions standards. 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) [56]. 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 stakeholder resulted in the decision to reduce certified emissions levels for new engines by 12% starting in 2008.

The CAEP/6-IP/13 analysis conducted a comprehensive costs 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. 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 2-4 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.

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. Additionally, the cost-effectiveness ranking of a policy measure does not indicate whether the net benefits of the policy measure exceed the anticipated benefits. 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" [50]. 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 nor an assessment of whether or not the \$30,000/tonne-$NO_x$ costs are justified.

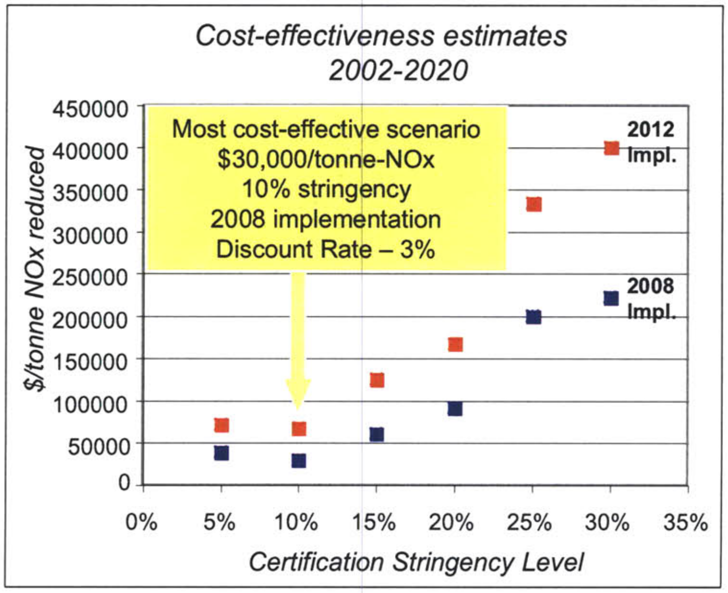


Figure 2-4: CAEP/6 FESG economic analysis [56]

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 2-5 using notional uncertainty distributions.

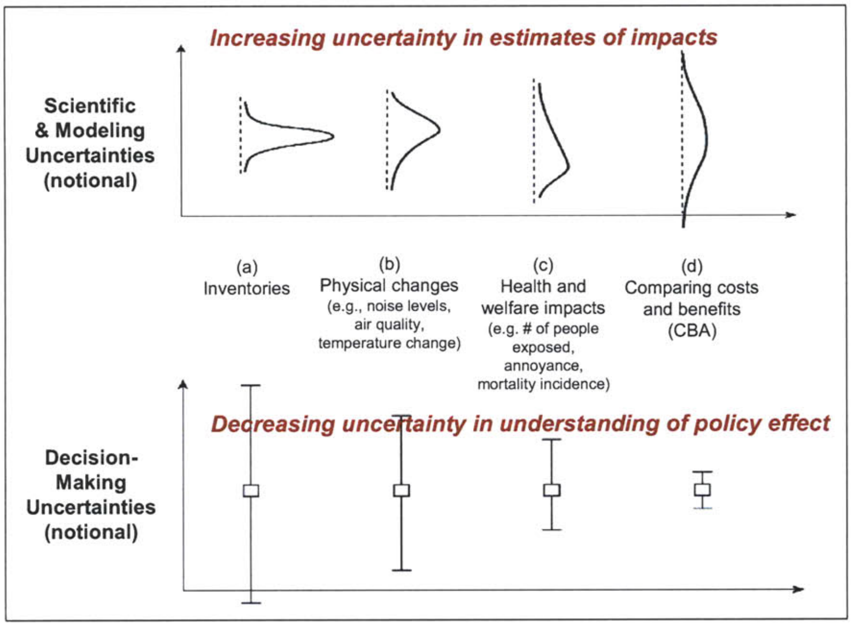


Figure 2-5: Scientific vs. policy-making perspectives on uncertainty

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 CAFÉ 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) [31, 32, 30]. 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.

Chapter 6 presents both cost-benefit and cost-effectiveness analyses for a subset of $NO_x$ stringency options that the ICAO-CAEP is considering for its eighth meeting in 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. Chapter 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 depending on the selected economic analysis approach.

# Chapter 3

# Methods for Assessing Tradeoffs between Aviation Environmental and Economic Impacts

Chapter 2 provided an overview of key aviation environmental impacts and emphasized the need for comprehensive analyses that address tradeoffs between environmental and economic objectives. There are several research initiatives that are focused on improving the understanding of aviation environmental impacts, exploring mitigative 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 the US 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. The UK government funded OMEGA program is an alliance among nine UK universities to study scientific, operational, and policy-relevant aspects of the environmental impacts of aviation [55].

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 [57]. 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 second initiative involves a joint venture by the FAA's Office of Environment and Energy (FAA-AEE), NASA, and Transport Canada through the PARTNER Center aimed at developing a comprehensive suite of tools to thoroughly assess the environmental impacts of aviation activity.

For the analysis conducted in this thesis, the Aviation environmental Portfolio Management Tool (APMT) is employed. APMT is focused on the economic analysis and environmental impact assessment functions within the FAA-NASA-Transport Canada aviation environmental tool suite. 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 chapter is devoted to an overview of the air quality, noise, and economics modeling methods within APMT while Chapter 4 explores climate modeling methods in APMT in detail. Chapter 5 addresses the challenges in uncertainty assessment and communication of results for complex models like APMT. The FAA-NASA-Transport Canada aviation environmental tool suite also consists of two other tools – the Aviation Environmental Design Tool (AEDT) and the Environmental Design Space (EDS) which are described in Appendix A. Figure 3-1 presents a schematic of the APMT, AEDT, and EDS framework.

APMT development was preceded by an extensive survey of guidance documents on current practices for environmental policy analysis. Some of the key documents consulted include *EPA Guidelines for Preparing Economic Analyses [50], OMB Circular A-4, Best Practices for Regulatory Analysis [49], UK HM Treasury Green Book on Appraisal and Evaluation in Central Government [53], UK Cabinet Office, Bet-*

*ter Regulation Executive Regulatory Impact Assessment Guidance [58], OECD The economic appraisal of environmental projects and policies – A practical guide [52], Transport Canada Guide to Benefit Cost Analysis in Transport Canada [59], WHO Air Quality Guidelines for Europe [60], Resources for the Future, Cost Benefit Analysis and Regulatory Reform: An Assessment of the Science of the Art [47], Peer Review of the Methodology of Cost-Benefit Analysis of the Clean Air for Europe Programme [61], and Clean Air for Europe (CAFÉ) Programme Methodology for the Cost-Benefit Analysis for CAFÉ Vol. 1 [62].* The survey findings have been summarized in the Requirements Document for the Aviation environmental Portfolio Management Tool [63] and were reviewed by the Transportation Research Board of the US National Academies [64]. 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.

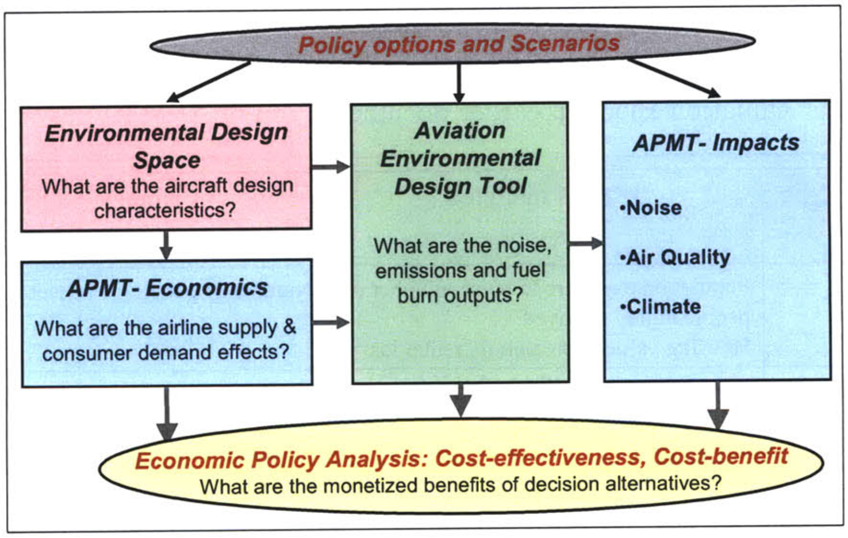
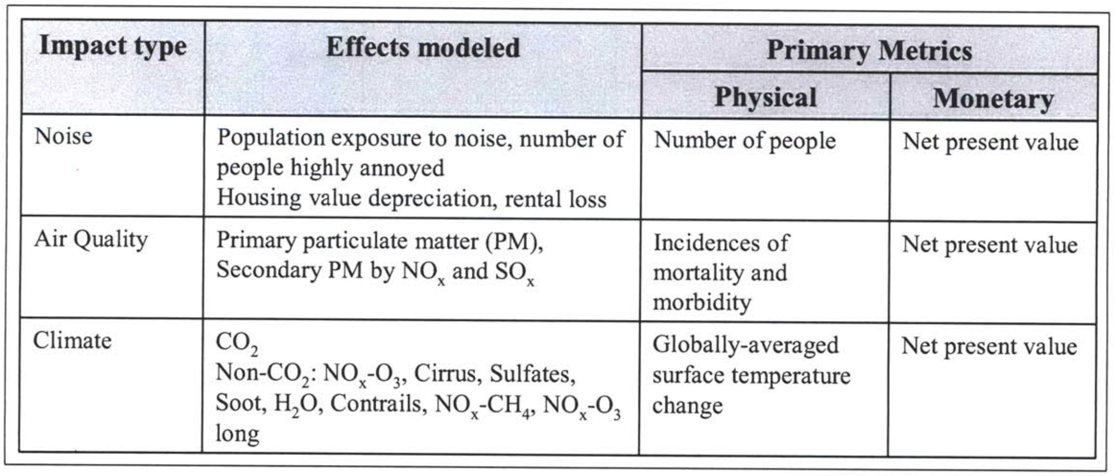


Figure 3-1: The FAA-NASA-Transport Canada Aviation Environmental Tool Suite

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 are defined as costs and environmental impacts that are not directly measured in monetary terms (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.

## 3.1 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 3-2 lists the effects modeled under each impact area and corresponding metrics. This section describes the modeling approaches utilized in the Noise and Air Quality modules; the Climate Module is discussed in Chapter 4. Note that the APMT-Impacts module was referred to as the Benefits Valuation Block in earlier documentation of APMT.



| **Impact type** | **Effects modeled** | **Primary Metrics** | |
|---|---|---|---|
| | | **Physical** | **Monetary** |
| Noise | Population exposure to noise, number of people highly annoyed<br>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 | $CO_2$<br>Non-$CO_2$: $NO_x$-$O_3$, Cirrus, Sulfates, Soot, $H_2O$, Contrails, $NO_x$-$CH_4$, $NO_x$-$O_3$ long | Globally-averaged surface temperature change | Net present value |

Figure 3-2: Overview of environmental impacts modeled in APMT

### 3.1.1 APMT-Impacts: Noise Module

Section 2.1.1 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 [65]. The APMT-Noise Module estimates global impacts of aviation noise in terms of both physical and monetary metrics for 181 airports located in 38 countries around the world. 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 computes 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. Kish [66] can be consulted for additional details.

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 the given contour. 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 [16]. 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. APMT currently uses US national average NDI values based on a meta-analysis conducted by Nelson using NDI estimates at 23 different airports in the United States and Canada [67]. These NDI values were compared by Kish to 28 other international willingness-to-pay and hedonic valuation studies and were found to represent the mean of reported responses well [66].

APMT currently applies the NDI values developed by Nelson for the United States and Canada to the rest of the world. Noise contours are superimposed on housing values from the 2000 SF3 US Census database [68]; applying the NDI gives an estimate of housing value loss.

The loss in housing value is only realized when the owner decides to sell the property and is therefore a one-time loss. Housing depreciation may vary from year to year due to changes in noise levels as well as changes in housing prices due to other factors. The losses are summed around each airport and future marginal losses are discounted to provide a net present value of housing depreciation. Only one of the studies examined by Nelson used rental prices, and too few other studies have measured the effect of aircraft noise on rents to determine how, if at all, noise reduces rent differently than the price of owner-occupied houses. Therefore, Nelson's NDI value is also used for the reduction in value of rental properties. For airports outside of the United States and the UK, detailed housing value data is not available. For countries other than the US and UK, it is necessary to develop a model that estimates house prices around an airport. Additionally, all airports outside the United States require a model to estimate rental values. Detailed descriptions of these housing price and rental value models as developed with the assistance of ICF International are available in [66].

Future updates to the APMT-Noise Module will include the capability to quantify other supplemental impact metrics such as sleep disturbance and learning impairment. The NDI approach in APMT necessitates the use of housing price data which is difficult to estimate in several parts of the world. On-going research within APMT is exploring the potential for adopting willingness-to-pay (WTP) estimates from literature that would be a function of income level, largely because income levels are more readily available for many parts of the world than are housing price data.

### 3.1.2 APMT-Impacts: Air Quality Module

The Air Quality Module within APMT-Impacts estimates the health impacts due to 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 2.1.2, 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 internal studies within APMT [see for example, [32]] and external studies such as the Clean Air for Europe Baseline Analysis [31]. 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 and their associated costs. Rojo [32], Masek [69], and Brunelle-Yeung [39] provide detailed information on the modeling methodology for the Air Quality Module (with the latest methods being those described by Brunelle-Yeung [39]).

The impact pathway within the Air Quality Module begins with aircraft emissions ($NO_x$, $SO_x$, non-volatile PM, and fuelburn) inputs for below 3000ft. The contribution of cruise emissions to air quality impacts is not presently considered and is an area of active research for APMT-Impacts. 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. 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 derived from 25 CMAQ simulations for each grid-cell; 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 [39].

The RSM computes changes in ambient $PM_{2.5}$ concentrations broken down into four different 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 ($H_2SO_4$). The RSM estimates the breakdown of 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 [39]. Note that currently the RSM does not employ the US EPA-recommended Speciated Modeled Attainment Test (SMAT) approach which seeks to reconcile PM concentrations estimated by models such as CMAQ with data from air quality monitors [39, 70]. Incorporating the SMATing process in the APMT modeling methodology is an area of on-going research and is expected to alter the apportionment of PM impacts across the different PM species modeled such as that secondary PM formation from $SO_x$ emissions makes the largest contribution to total aviation PM [39].

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 [71]) and the United States (EPA analyses using BenMAP [38]). Changes in ambient PM concentrations estimated by the RSM are related to incidences of mortality and morbidity are 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 the US Department of Transportation (DOT) [72] recommended Value of a Statistical Life (VSL) and 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 DOT recommendations and adjusted to be in 2000 US dollars [39, 72]. Rojo provides detailed information on the valuation of other health endpoints which were derived from an extensive literature survey of current U.S. and European methodologies [32].

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, incorporating health impacts of cruise emissions, and adopting the US EPA-SMATing process in the RSM.

## 3.2 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 growth or policy-related changes in the aviation market, 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, 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. Finally, airlines may change operational procedures to minimize costs in response to a policy.

The Economics Module begins by modeling the Datum year (currently set at 2006) demand, fleet and 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. 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 [73, 74]. Note that the APMT-Economics module was referred to as the Partial Equilibrium Block in previous documentation of APMT.

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 [75]. Future work entails developing modeling capabilities to address other types of policy options such as market-based measures.

# Chapter 4

# Aviation and Climate Change

While Chapter 2 provided a brief overview of the different mechanisms through which aircraft emissions directly or indirectly contribute to climate change, this chapter delves into methods for estimating aviation-related climate change impacts. First, a brief overview of aviation-specific modeling approaches in literature is provided followed by a description of the APMT-Impacts Climate Module. Next, results from the APMT Climate Module are validated through comparisons with estimates provided by the Intergovernmental Panel on Climate Change (IPCC) and other models. Finally, the key sources of uncertainty within the APMT Climate module are discussed which identify limitations and avenues for future work.

## 4.1 Overview of Aviation Climate Impact Modeling Methods

The impacts pathway for aviation-related climate change starts with emissions and culminates at societal impacts as seen in Figure 4-1 [4]. This impacts pathway is not unique to aviation effects, but is described here in the aviation context. Direct emissions of $CO_2$, $NO_x$, $H_2O$, $SO_x$, HC, and black carbon or soot from aircraft engines lead to perturbations in the planetary radiation budget through mechanisms described in Section 2.1.3. Radiative forcing from these aviation effects alters the physical climate system as measured by changes in indicators such as surface temperature, sea-level, precipitation patterns, ice or snow cover, etc. Surface temperature is a commonly-used metric for understanding changes in the physical climate system. These physical changes further result in impacts that directly or indirectly affect human as well as global biological systems and can be classified as market or non-market impacts.

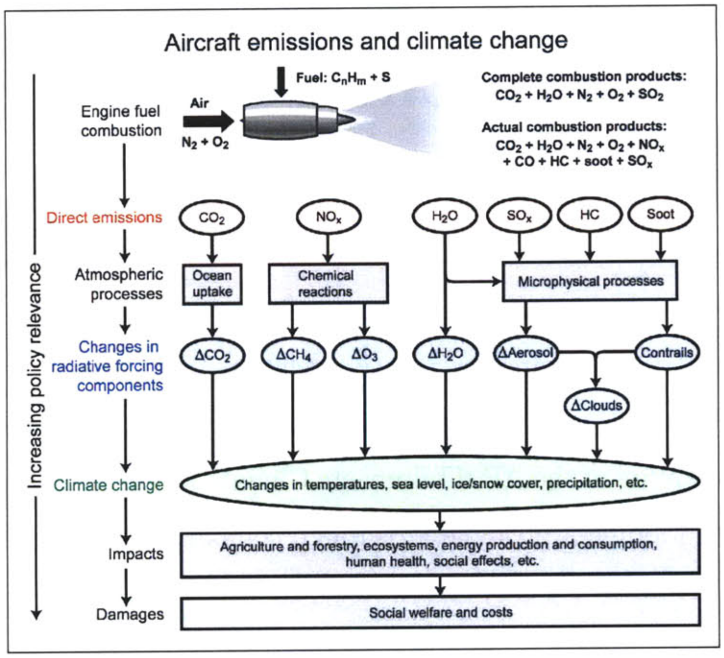


Figure 4-1: Aviation climate change impacts pathway [4]

Market impacts refer to impacts on goods or services that are typically traded in markets. Some examples of market impacts related to anthropogenic activity include agriculture, forestry, livestock, fisheries, energy production, construction, tourism, insurance, etc. Non-market impacts are impacts on biological systems or human welfare that are not typically expressed in monetary terms. Non-market impacts can include loss of human life, changes in ecosystems, species extinction, increases in risk of hunger, distributional inequity with some regions facing more severe impacts than others, and so on. Estimating non-market impacts that are more intangible in nature can involve ethical judgments which makes it harder to reach consensus on the magnitude of these impacts [10]. Finally, both market and non-market impacts can result in societal damage or welfare loss which may be quantified in monetary units. As one proceeds from emissions to estimating societal impacts, the information collected becomes increasingly relevant to the policymaking community. However, uncertainties associated with impact estimates also increase as one proceeds further down the impact pathway.

Next, an overview of methods for estimating physical climate change impacts is provided in Section 4.1.1, followed by a discussion on relating physical changes to market and non-market impacts and societal damages in Section 4.1.2.

### 4.1.1 Physical impacts

Climate models are utilized for estimating impacts of all anthropogenic activities including aviation. These models aim to capture the essential characteristics and key interactions among the different components of the climate system which include the atmosphere, oceans, terrestrial biosphere, glaciers, ice sheets, and land surface. Several different approaches can be used to model the behavior of the climate system and the questions one seeks to answer determine the selection of the appropriate method. Climate models are of varying complexity in terms of dimensionality or spatial resolution, characterization of physical processes at the sub-grid level (parametrization), and computational costs [76].

Atmosphere-ocean general circulation models (AOGCMs) are at one end of the complexity spectrum, being the most comprehensive models that aim to simulate the physical world as closely as possible with high fidelity [77]. The basic idea behind AOGCMs is to solve the equations of the atmosphere and oceans derived from conservation of mass, momentum, and energy by dividing the planet into boxes or grids over which the conservation equations are integrated. The spatial resolution of a given AOGCM is determined by the size of the grid; physical processes that occur at a smaller spatial scale relative to the grid are captured through parametrizations. The IPCC Fourth Assessment Report compares 23 different AOGCMs for their multi-decadal climate impact analyses. However, higher spatial resolution and complexity make AOGCMs computationally very expensive and unsuitable for simulations that involve century long time scales for assessing climate change into the future [42, 76].

Earth System Models of Intermediate Complexity (EMICs) are next in the hierarchy of climate models and typically comprise simplified atmospheric and/or oceanic components with a lower spatial resolution as compared to AOGCMs. EMICs are typically used for better understanding large-scale processes and feedbacks within the climate system [42]. Other types of intermediate complexity models can also be found which focus on individual components of the climate system with parametrizations to represent interactions with other components. For instance, Chemical Transport Models (CTMs) and Climate-Chemistry Models (CCMs) model atmospheric dynamics and chemistry respectively and are coupled with offline meteorological data from global climate models. CTMs and CCMs enable 2-D and 3-D computations of chemical processes in the atmosphere; however they can also require long run times depending on the scope of the model and may be unsuitable for long term, global projections.

Finally, simplified climate models lie at the other extreme on the complexity scale relative to AOGCMs. Simplified climate models tend to quantify climate impacts at a global, hemispherical, or zonally-averaged spatial scale and involve parameterizations derived from AOGCMs or CTMs. Simplified climate models are better suited for investigating future trends in climate impacts on a large spatial scale and for a range of emissions scenarios. There are several categories of simplified climate models including but not limited to upwelling-diffusion ocean models and energy balance models which are tuned to results from AOGCMs such that they can reproduce key interactions captured by the AOGCMs even at a much lower spatial resolution. The IPCC Fourth Assessment Report used a simplified climate model – Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), tuned to outputs from 19 different AOGCMs for making future projections of climate change for different emissions scenarios [42].

Reduced-order approaches for climate impact modeling are also used in integrated assessment models (IAMs) that evaluate both physical and socioeconomic impacts of anthropogenic activity on climate change. Simplified approaches used in IAMs generally produce results at the globally-averaged scale and are also tuned to more complex models. Some such approaches include systems-dynamics models, reservoir models and impulse-response functions. Systems-dynamics models characterize the climate system through stocks and flows between different components with associated feedbacks and lags [78]. Reservoir models are also very similar to the systems-dynamics models in representing flows of stock pollutants like $CO_2$ in the climate system through different reservoirs or boxes representing the atmosphere and the different layers of the oceans [79, 80]. An impulse response function (also known as Green's function) is an analytical expression representing the response of the climate system to a small perturbation (unit-delta function forcing) and is empirically derived from numerical experiments using AOGCMs. The impulse response function is expressed as a sum of exponentials that correspond to the different modes of the system response [81]. Table 4.1 lists several different simple climate models found in literature.

| **Model** | **Sector** | **Spatial Domain** | **Approach** |
|---|---|---|---|
| AirClim<br>(Grewe, 2007) | Aviation | Global, zonally-averaged | Impulse response |
| LinClim<br>(Lim et al, 2007) | Aviation | Global | Impulse response |
| Schwartz, 2009 | Aviation | Global | Impulse-response |
| OMEGA-MAGICC<br>(Meinshausen, 2009) | Aviation | Global | Modified MAGICC model |
| APMT<br>(Marais, 2008) | Aviation | Global | Impulse response |
| IPCC MAGICC<br>(IPCC AR4, 2007) | All sources | Global, regional | Tuned to 19 AOGCMs |
| C-ROADS<br>(Fiddaman, 2009) | All sources | Global | Systems-dynamics model |
| FUND<br>(Anthoff, 2008) | All sources | Global, regional | Reservoir model |
| DICE<br>(Nordhaus, 2007) | All sources | Global | Reservoir model calibrated to MAGICC |
| Berntsen, 2008 | Transportation | Global | Impulse-response |

Table 4.1: Simple climate models [82, 83, 84, 85, 86, 42, 78, 80, 87, 88]

Hasselmann et al. [89] propose a general framework not specific to aviation for $CO_2$ impacts based on impulse response models derived from carbon-cycle models and AOGCMs. Impulse response functions (IRFs) derived from carbon-cycle models are used for estimating atmospheric $CO_2$ concentration changes following emissions of $CO_2$, while IRFs derived from AOGCMs relate changes in radiative forcing to changes in climate change impacts such as surface temperature or sea-level rise [89, 90]. Sausen et al. [91] extend this approach to assessing impacts of aviation $CO_2$ and $NO_x$ (warming $O_3$ effect) emissions on globally-averaged surface temperature and sea level. Radiative forcing estimates for non-$CO_2$ effects such as $NO_x$ on $O_3$ and $CH_4$, contrails, aviation-induced cirrus, sulfates, soot, and $H_2O$ are derived from Chemical Transport Models (CTMs), Climate-Chemistry Models (CCMs) as well as from observational data [92, 41].

Given aviation's relatively small contribution to total anthropogenic radiative forcing (~2-4%), the impulse response approach has been commonly used for estimating future climate impacts of aviation activity. See Table 4.1 for aviation-specific climate models that use IRFs such as AirClim, LinClim, APMT, and work by Schwartz et al. [82, 83, 86, 84]. The AirClim model uses 3-D aircraft emissions along with pre-calculated atmospheric data from CCM E39/C to estimate global mean surface temperature changes for the $CO_2$, $H_2O$, $CH_4$, $O_3$, and contrails effects, thereby accounting for differing global impacts of aviation emissions depending on the region of emissions [82]. LinClim is another simplified climate model that assesses global radiative forcing and temperature impacts of aviation $CO_2$, $O_3$, $CH_4$, sulphate, soot and contrails effects [83]. The APMT-Impacts Climate module uses the Bern carbon-cycle impulse response function along with a simplified analytical temperature change model to provide climate impacts for aviation $CO_2$ and non-$CO_2$ effects. APMT evaluates impacts in terms of physical metrics (RF, global temperature change) as well as monetary metrics (world gross domestic product (GDP) loss and net present value of damages) [86]. Schwartz et al. [84] also use IRFs for estimating global climate change impacts of aviation $CO_2$ and non-$CO_2$ effects and include altitude dependence for effects such as $NO_x$, contrails, and cirrus. All four models – AirClim, LinClim, APMT, and Schwartz et al. [84] are extensions of the Sausen et al. framework [91]. The OMEGA-MAGICC model listed in Table 4-1 takes a different approach for estimating aviation impacts by modifying the MAGICC model to capture altitude dependent characteristics of aircraft $NO_x$ emissions [85].

### 4.1.2 Monetary Impacts

The discussion presented here is not unique to aviation-related impacts but is inclusive of all anthropogenic activities that perturb the physical state of the climate system and in turn affect societal well-being. Societal impacts include, but are not limited to impact areas such as health, agriculture, forestry, coastal land loss, loss of ecosystems, etc. Valuation of damages generally involves estimating impacts in monetary units to facilitate cost-benefit analysis as discussed in Section 2.2.1. Societal welfare loss can then be compared with the costs of avoiding climate change for decision-making purposes.

Establishing a causal relationship between climate change and societal damages is fraught with uncertainties and challenges. Uncertainties arise from two modeling aspects – assessment of climate change impacts resulting from physical changes in the climate system and valuation of these climate change impacts in monetary terms. Predicting climate change impacts involves relating changes in surface temperature or sea-level to impacts such as potential threats to vulnerable species or ecosystems, severity and frequency of storms, droughts, etc., and low-probability high-impact events that can drastically alter the climate system with catastrophic consequences (such as changes in the North Atlantic thermohaline circulation or collapse of polar ice sheets) [93]. Valuation of climate change impacts incorporates both market and non-market impacts. Impacts areas that can be related to market goods and associated prices (for instance agriculture or forestry) are in general better understood as compared to those environmental impact areas that are not traded in conventional markets. Monetization of non-market impacts has also received criticism on the grounds of morality that valuing items deemed "priceless" (e.g. human life or wilderness areas) will diminish their value [94]. However, counter-arguments presented have made a distinction between pricing and commodification. Many goods are already price without diminishing their inherent value such as pets, homes, medical care, life insurance, etc. [46].

There are two basic approaches for monetizing non-market damages from climate change: revealed preference and stated preference. Revealed preference methods infer the value people place on the environment through the choices they make. There are two main methods within the revealed preference approach: hedonics and household production. In the hedonics method the change in price of a conventional good is correlated to changes in environmental characteristics associated with that good using statistical analysis to infer the value of that environmental characteristic. The household production method assumes that consumers will purchase complementary goods to either offset damages from environmental problems or maintain benefits derived from environmental sources. Major challenges associated with the revealed preference methods are finding data that allow for isolating the environmental effect while controlling for all other factors that contribute to price changes. The hedonic approach 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 [95]. The stated preference approach on the other hand, relies on directly asking people about how they value an environmental good. Contingent valuation (CV) is the dominant method within the stated preference approach. The CV method constructs a hypothetical market for environmental goods and derives information on the value of the good through opinion polls and surveys. The stated preference methods are somewhat controversial 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 [96].

Several studies have been conducted on valuing the damages from climate change using the methods described previously with some studies focused on specific sectors while others have estimated damages aggregated across several sectors [97, 79, 98, 99, 100, 87, 101, 102]. Given that aviation-specific climate impacts are generally presented as aggregated estimates, the discussion here is limited to aggregated climate damages. For a detailed discussion on sectoral or regional vulnerabilities to damages from climate change, the reader is referred to the most recent IPCC report on impacts, adaptation, and vulnerability [10]. Aggregated damage estimates are commonly quantified as total damages expressed as a percentage of gross domestic product (GDP), or as marginal damages in the form of the social cost of pollutants. There are several estimates of damage functions that compute impacts in terms of percentage of GDP as a function of changes in global mean temperature. Aggregated impacts computed by these damage functions range from 1.5% to 3.5% of world GDP for a doubling of $CO_2$ concentrations relative to pre-industrial times [10]. The more recent Stern report estimates impacts in terms of an average reduction in per capita consumption ranging from 5–20% of global GDP depending on assumptions about non-market impacts, positive feedbacks in the climate system, and the use of equity weights for aggregating impacts to a global level [101]. Impacts can also be estimated in terms of the social cost of a pollutant which is defined as the marginal impact of one ton of emissions of the pollutant or the marginal benefit of reducing one ton of emissions of the pollutant at a given point in time. Estimates of the social cost of a pollutant are more easily applicable to a long-lived, well-mixed pollutant such as $CO_2$ with no spatial variability in terms of the magnitude of impacts. Peer-reviewed studies estimate the social cost of carbon (SCC) to have a mean value of US$43 and a standard deviation of US$83 per ton of carbon with the SCC likely to grow at a rate of 2–4% per year [10].

Differences among damage estimates in the literature arise not only due to a poor understanding of potential long term impacts of climate change and challenges associated with valuing non-market impacts, but also from varying modeling assumptions and methodologies. Two important sources of uncertainty in damage estimates include ethical issues involved with spatial and temporal aggregation of impacts [103, 10]. Spatial aggregation challenges here refers to equity issues related to summing up damages across different parts of the world. A simple sum of damages across different regions converted to one currency such as US dollars leads to differential treatment of similar impacts. Under the simple sum approach impacts in rich countries get a higher valuation than those in poor countries despite the understanding that poor countries are more vulnerable to damages from climate change. Assigning equity weights derived from a global social welfare function to impacts is one way of accounting for the geographical differences in valuation of impacts. However, the implicit choice of a welfare function for deriving equity weights is a value judgment that can lead to large differences in impact estimates found in literature [104, 103]. Climate change impacts from present day emissions can be felt for several centuries making it an inter-generational problem. Consequently, temporal aggregation of climate change impacts raises ethical questions about inter-generational equity – how can one balance costs of emissions reductions today with benefits experienced in the distant future? How does one value impacts in the distant future relative to impacts that occur in the near future? Discounting methods are used for converting future monetary impacts into present day terms and the selection of a discount rate is a topic of debate among economists. In the context of monetized climate damages, a zero discount rate equally weights damages today and in the future while a high positive discount rate lowers the value placed on impacts in the future. Varying assumptions about discounting methods are a major source of differences among damage estimates found in literature [105, 103, 87, 106, 107].

## 4.2 APMT-Impacts: Climate

As indicated in Figure 3-2, the APMT Climate Module estimates $CO_2$ and non-$CO_2$ impacts using both physical and monetary metrics. Given the need for a capability to analyze several different scenarios within the broader APMT policy analysis context, APMT uses computationally inexpensive reduced-order methods for estimating physical metrics of climate change. The APMT Climate Module adopts the impulse response modeling approach based on the work by Hasselmann et al. [89], Sausen et al. [91], Fuglestvedt et al. [108] and Shine et al. [109]. The temporal resolution of the APMT Climate Module is one year while the spatial resolution is at a highly aggregated global mean level. The aviation effects modeled include long-lived $CO_2$, and short-lived effects including the short-lived impact of $NO_x$ on ozone ($NO_x$-$O_3$ short), 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). The APMT-Impacts Climate Module described here is built upon the work presented in Marais et al. [86] and Jun [110]. Updates to the APMT-Impacts Climate Module through the work presented in this thesis include: improved characterization of uncertainties in aircraft $NO_x$-related impacts and in the damage function employed, a reduced-order methodology for estimating the climate impacts of well-to-tank methane ($CH_4$) emissions from processing alternative jet fuels comparison and validation of results with external sources. Figure 4-2 provides a schematic of the APMT-Impacts Climate Module.

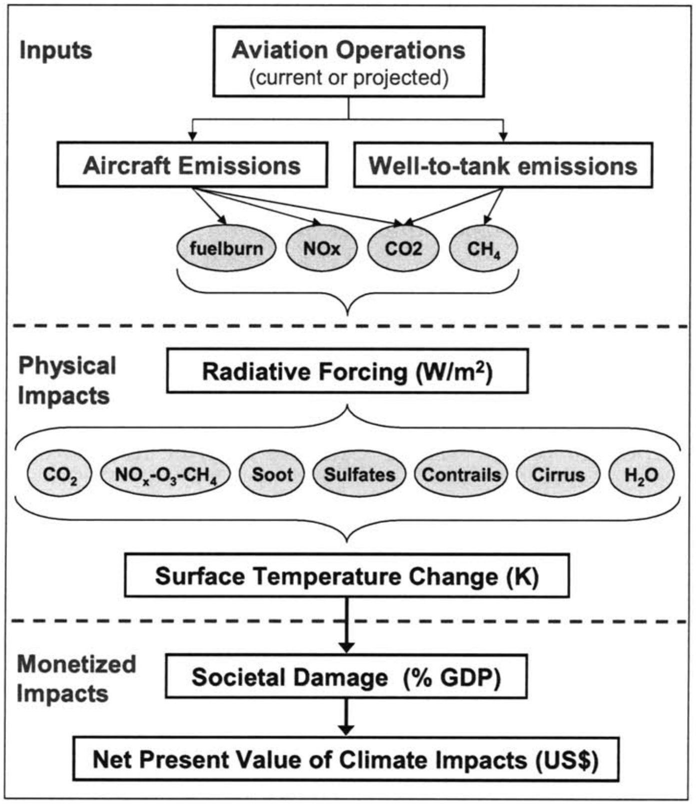


Figure 4-2: APMT-Impacts Climate Module (adapted from Marais et al. [86])

The APMT-Impacts Climate Module evaluates impacts using Monte Carlo approaches by expressing inputs and model parameters as probabilistic distributions where possible and propagating uncertainties to the outputs of the module. Section 4.2.4 provides detailed information about key inputs and model parameters for the APMT-Impacts Climate Module. Starting with fleet-level aviation emissions, APMT modeling methods 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. [92], Wild et al. [44], Stevenson et al. [43], and Hoor et al. [111]. To compute globally-averaged surface temperature change from the estimated radiative forcing, a simplified analytical model by Shine et al. [109] is used.

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. Uncertainty in damage estimates is captured by sampling uniformly between the DICE-2007 damage function, twice, and half the DICE-2007 damage function [87]. APMT uses a range of constant discount rates from 2% to 5% following the recommendations of the US Office of Management and Budget (US OMB) to estimate the net present value of future impacts [49]. The following sections describe each component of the APMT Climate Module in greater detail and provide relevant equations where necessary.

### 4.2.1 Radiative Forcing

This section presents the methodology adopted in the APMT-Impacts Climate Module for estimating the direct and indirect radiative forcing impacts associated with the different aircraft emissions as well as methane emissions from the processing of alternative jet fuels. Figure 4-3 shows the methodology for computing radiative forcing estimates for the different aviation effects considered in APMT.

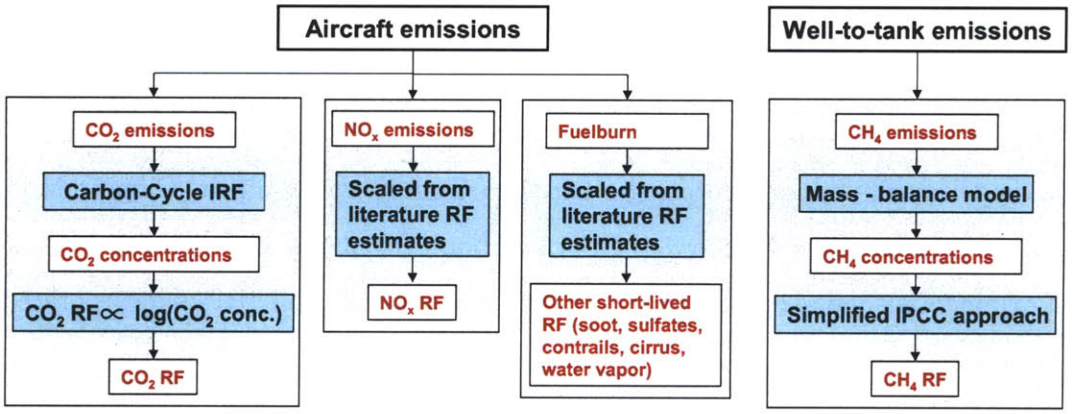


Figure 4-3: APMT-Impacts Climate Module radiative forcing

Aircraft emissions are treated as pulse emissions emitted each year during a scenario which ultimately lead to changes in mean surface temperature. Pulses of aircraft $CO_2$ and $NO_x$ emissions lead to direct and indirect radiative forcing effects related to these species. Aircraft fuel burn is used as a surrogate for other short-lived climate effects such as contrails, cirrus, water vapor, black carbon, 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. Next each of the different boxes shown in Figure 4-3 is discussed and relevant equations are provided.

#### 4.2.1.1 $CO_2$ Impacts

As shown in Figure 4-3, the APMT-Impacts Climate Module takes aircraft $CO_2$ emissions as inputs and estimates changes in atmospheric $CO_2$ concentrations through an impulse response function (IRF) fit to a more complex carbon-cycle model. The carbon-cycle describes the exchange of carbon between the terrestrial biosphere, the atmosphere and the oceans. The APMT Climate Module uses the impulse response function fit to the Bern carbon-cycle model with a background $CO_2$ concentration of

378 ppm as a nominal selection [42]. The IPCC also uses the Bern carbon-cycle IRF for estimating global warming potentials (GWPs) in their fourth assessment report [42]. APMT also provides the capability of exploring the impact of the choice of IRF on model results by incorporating other IRFs from literature in the Climate Module [89, 90, 81]. Equation 4.1 shows the Bern carbon-cycle model IRF expressed as a sum of exponentials [86, 42] while Equation 4.2 shows the how the IRF is incorporated in APMT.

$$G_C = a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i} \tag{4.1}$$

where:

$\mathrm{a}_0 = 0.217$, $\mathrm{a}_1 = 0.259$, $\mathrm{a}_2 = 0.338$, $\mathrm{a}_3 = 0.186$, and

$\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, $\tau_3 = 1.186$ years

$$\begin{aligned} \Delta X_{CO_2}(t') &= \int_{t_0}^{t'} Q_{CO_2}(t'') \cdot G_C(t' - t'')\, dt'' \\ &\approx \sum_{n=0}^{N-1} Q_{CO_2}(t_0 + n\Delta t) \cdot G_C(t' - t_0 - n\Delta t) \cdot \Delta t \\ N &= (t' - t_0)/\Delta t \end{aligned} \tag{4.2}$$

In Equation 4.2, $\Delta X_{CO_2}$ is the change in atmospheric $CO_2$ concentrations in parts per million (ppm), $Q_{CO_2}$ are $CO_2$ emissions in TgC emitted in one year, and $G_{CO_2}$ is the IRF from Equation 4.1. A conversion factor of 2123 ppm/TgC is used to compute $CO_2$ concentrations in units of ppm [89]. The time step in the computations is one year. $CO_2$ RF is based on a simplified logarithmic relationship between $CO_2$ concentrations and radiative forcing as indicated by the IPCC [42]. $CO_2$ RF is normalized such that a doubling of $CO_2$ concentrations relative to pre-industrial times gives a normalized $RF^*_{CO_2}$ of 1 as seen in Equation 4.3 [86].

$$RF^*(t') = \log_2 \left( \frac{X_{CO2(present)} + \Delta X_{CO_2}(t')}{X_{CO2(1750)}} \right) \tag{4.3}$$

where $X_{CO_2(1750)}$ is the pre-industrial atmospheric $CO_2$ concentration and is taken to be 278ppm [42]. Given the non-linearities in estimating $CO_2$-related impacts, APMT estimates climate impacts attributed to aircraft $CO_2$ emissions through a residual analysis. Impacts from aircraft $CO_2$ emissions are estimated as the difference between impacts due to all anthropogenic $CO_2$ emissions and all anthropogenic $CO_2$ minus aircraft $CO_2$ emissions [86]. Future projections of all anthropogenic $CO_2$ emissions and corresponding economic growth are obtained from the Intergovernmental Panel on Climate Change – Special Report on Emissions Scenarios (IPCC-SRES) [112].

#### 4.2.1.2 Other Short-lived Effects

For non-$CO_2$ and non-$NO_x$ effects, fuel burn is used as a surrogate to scale radiative forcing estimates from literature. The APMT-Impacts Climate Module follows the approach of Sausen et al. [91] and scales literature RF estimates with respect to fuel burn, accounts for efficacies from Hansen et al. [113] and the latest IPCC assessment report [42] and normalizes by the RF for a doubling of $CO_2$ concentrations relative to pre-industrial times [86]. Scaling contrails and cirrus effects linearly with respect to fuelburn is appropriate as a first order assumption, however, the formation of contrails and aviation-induced cirrus also depends on atmospheric conditions and engine propulsive efficiency [86]. Table 4.2 shows the reference radiative forcing for the different effects for aviation operations for year 2000 from Sausen et al. [92] and associated efficacies [113, 42].

| **Effect** | **Radiative forcing [mW/m$^2$]** | **Efficacy** |
|---|---|---|
| $H_2O$ | 2.0 | 1 |
| Sulfates | -3.5 | 0.68-1.09 |
| Soot | 2.5 | 0.62-1.29 |
| Contrails | 10.0 | 0.59-1 |
| Cirrus | 30.0 | 1 |

Table 4.2: Aviation short-lived effects radiative forcing and efficacies [92, 113, 42]

These reference RF values shown in Table 4.2 are scaled and normalized according to Equation 4.4. RF associated with these short-lived effects are assumed to persist only for the year of emissions.

$$RF^{*}_{short,j}(t') = \frac{\lambda_{short,j}}{\lambda_{CO_2}} \cdot \frac{RF^{ref}_{short,j}}{RF_{2XCO_2}} \cdot \frac{Q_{short,j}(t')}{Q^{ref}_{short,j}} \tag{4.4}$$

In Equation 4.4, the ratio $\lambda_{short,j}/\lambda_{CO_2}$ refers to the efficacy of a given effect with values listed in Table 4.2 [113, 42]. Efficacy is defined as the global temperature response per unit radiative forcing for a given species relative to that resulting from a $CO_2$ forcing. $Q^{ref}_{short,j}$ is 169 Tg and is the fuelburn associated with the Sausen et al. [92] aviation RF estimates. Finally, $RF_{2XCO_2}$ is the RF from a doubling of $CO_2$ concentrations relative to pre-industrial times is estimated to be 3.7 W/m$^2$ by the IPCC [42].

#### 4.2.1.3 $NO_x$ Impacts

$NO_x$ being a short-lived species does not have a well defined gas-cycle like the carbon cycle; APMT therefore estimates radiative forcing for $NO_x$ effects by linearly scaling RF estimates from literature with respect to $NO_x$ emissions. As shown by Köhler et al. [114], $O_3$ and $CH_4$ perturbations related to aircraft $NO_x$ emissions scale linearly with emissions provided that there are no significant changes in flight routing. To capture uncertainties arising from experimental or model differences, RF estimates from three sources – Stevenson et al. [43], Wild et al. [44] (as corrected in Stevenson et al. [43]) and Hoor et al. [111] are used.

Stevenson et al. [43] and Wild et al. [44] RF estimates are based on pulse response studies that track the transient behavior of pulses of $NO_x$ emissions emitted throughout the year or as a one year long pulse to capture seasonal variations in the $O_3$ and $CH_4$ responses. RF estimates from these two pulse experiments are provided as the integrated response of the pulse decay over 100 years. Hoor et al. [111] on the other hand provide the steady-state response associated with sustained aircraft emissions. At infinite time horizons, the steady response of a sustained perturbation approaches the integrated response of a pulse perturbation; this is also approximately true when the integration time horizon is much greater than the lifetime of the species concerned [115]. For a pulse of 1kg of a pollutant with a specific radiative forcing $RF_0$ (W/m$^2$/kg), and species lifetime of $\tau$ (years), the temporal evolution of RF (W/m$^2$/kg-year) can be expressed as shown below.

$$\begin{gathered} RF(t) = RF_0\, e^{-t/\tau} \\ \int_0^\infty RF(t)dt = RF_0\, \tau \end{gathered} \tag{4.5}$$

While for sustained emissions of 1kg/year, the system response is given by:

$$\begin{gathered} RF(t) = RF_0\, \tau\, (1 - e^{-t/\tau}) \\ \text{As } t \rightarrow \infty,\ RF(t) \rightarrow RF_0\, \tau \end{gathered} \tag{4.6}$$

In using the pulse approach in APMT where the total system response is a superposition of pulses emitted each year, the specific radiative forcing, $RF_0$ in Equation 4.5 or 4.6 is required. This information is extracted from aforementioned literature sources that use both the integrated pulse response RF estimates as well as steady state RF and is designated as the reference specific radiative forcing or $RF_0^{ref}$. For the pulse response estimates Equation 4.5 is integrated to calculate $RF_0^{ref}$ from the 100-year integrated value provided by Stevenson et al. and Wild et al. [43, 44]. For the Hoor et al. steady-state RF estimates, $RF_0^{ref}$ is calculated as the ratio of the steady-state value and the perturbation lifetime of the species. Table 4.3 lists the RF estimates and methane perturbation lifetime employed in APMT to derive specific radiative forcing $RF_0^{ref}$. Note that the values listed in Table 4.3 are normalized by emissions and indicate the 100-year integrated pulse response for Stevenson et al. and Wild et al. and steady-state values for Hoor et al. [43, 111, 44].

The short-lived $O_3$ warming RF is assumed to last only during the year of emissions, while the longer-lived cooling RF from $CH_4$ reduction and the corresponding $O_3$ reduction decay with $CH_4$ perturbation lifetime listed in Table 4.3. The $CH_4$ perturbation lifetime is different from its atmospheric lifetime owing to chemical feedbacks with the OH radical. This discussion is deferred to Section 4.2.1.4, however, it is important to note that the lifetimes listed in Table 4.3 account for the feedbacks with the OH radical and the stratospheric and soil sinks of $CH_4$. Stevenson et al. [43] provide $CH_4$ perturbation lifetime corrected for the OH feedback and the other sinks for their work as well as the work by Wild et al. [44]. The Hoor et al. [111] lifetime had to be corrected for the feedback factor and other sinks following the approach taken by the IPCC [42]:

$$
\begin{aligned}
\tau_{corrected} &= \left( \frac{1}{\tau_{Hoor} * 1.4} + \frac{1}{\tau_{soil}} + \frac{1}{\tau_{stratospheric}} \right)^{-1} \\
\tau_{Hoor} &= \tau_{base} * \text{percent change from aviation } \mathrm{NO}_x
\end{aligned}
\tag{4.7}
$$

Here the $\tau_{base}$ is 8.97 years and refers to the mean atmospheric lifetime derived from simulations conducted by Hoor et al. [111]; initial perturbation to this lifetime from aviation $NO_x$ emissions results in a mean lifetime change of 1.04% resulting in a value of 9.06 years for $\tau_{Hoor}$. Hoor et al. use the IPCC estimated factor of 1.4 to account for the long-term OH feedback in estimating their steady state RF values, which is used here to derive a $\tau_{corrected}$ value of 10.7 years [111]. $\tau_{soil}$ is assumed to be 120 years and $\tau_{stratospheric}$ is 160 years following Stevenson et al. [43].

| **Source** | **Radiative forcing [$mW/m^2/TgNO_x$-yr]** | | | **Perturbation lifetime [year]** |
|---|---|---|---|---|
| | $NO_x$-$O_3$short | $NO_x$-$CH_4$ | $NO_x$-$O_3$long | |
| Stevenson et al. (2004) | 5.06 | -4.2 | -0.95 | 11.53 |
| Hoor et al. (2009) | 7.4 | -4.3 | -1.8 | 10.7 |
| Wild et al. (2001) | 7.9 | -4.6 | -1.5 | 11.8 |

Table 4.3: Aviation $NO_x$ radiative forcing [43, 111, 44]

Having determined the specific radiative forcing for $NO_x$-related effects, $RF_0^{ref}$, from literature the approach of Sausen et al. [91] is followed by accounting for efficacies and scaling with respect to $NO_x$ emissions to produce normalized RF for

$NO_x$. The efficacy for $NO_x$-$O_3$ ranges from 0.75-1 and is assumed be 1 for $NO_x$-$CH_4$ [113, 42]. The normalized specific RF for $NO_x$-$CH_4$ is given by Equation 4.8a, which scales $RF_0^{ref}$ by the efficacy of the $NO_x$ effect and $NO_x$ emissions ($Q_{NO_x}$ in year $t'$) and normalizes by the $RF_{2XCO_2}$ similar to the approach taken for other short-lived effects. Equation 4.8b captures the temporal evolution of the normalized specific RF based on the decay time of the $NO_x$ perturbation.

$$RF^*_{0,NO_x-CH_4}(t') = \frac{\lambda_{NO_x-CH_4}}{\lambda_{CO_2}} \cdot \frac{RF^{ref}_{0,NO_x-CH_4}}{RF_{2XCO_2}} \cdot Q_{NO_x}(t') \tag{4.8a}$$

$$RF^*_{NO_x-CH_4}(t') = \int_{t_0}^{t'} RF^*_{0,NO_x-CH_4}(t'') \cdot e^{-(t'-t'')/\tau}\, dt'' \tag{4.8b}$$

While Equation 4.8 is specific to the long-lived $NO_x$-$CH_4$ effect, this approach is also employed for the long-lived $O_3$ effect which decays with the same perturbation lifetime. Equation 4.8a is also applicable in the case of the short-lived warming $NO_x$-$O_3$ effect, however, APMT assumes that the RF only lasts for the year of emissions.

#### 4.2.1.4 $CH_4$ Impacts from Well-to-tank Emissions

Well-to-tank emissions arise from fuel processing steps which include extraction, transportation to processing facility, processing or refining to the final product, and finally transportation and distribution to desired locations. Greenhouse gas emissions from the processing of fuels include $CO_2$, $CH_4$, and $N_2O$ emission with greater contribution from $CO_2$ and $CH_4$ as compared to $N_2O$ emissions [116]. $CO_2$ emissions from well-to-tank processes are treated in the same manner as aircraft $CO_2$ emissions. This section focuses on methane emissions from the processing of aviation jet fuels.

In order to enable an assessment of methane-related climate impacts of well-to-tank emissions, a new component is introduced to the APMT-Impacts Climate Module that can model changes in atmospheric methane concentrations and associated radiative forcing. Methane is a well-mixed, long-lived greenhouse gas with both direct and indirect radiative forcing impacts. Major sources of $CH_4$ include biogenic sources such as wetlands, rice agriculture, biomass burning, ruminant animals as well as industrial sources such as fossil fuel mining and processing. The largest sink for $CH_4$ is the hydroxyl free radical or OH which is photochemically produced in the atmosphere; other sinks include stratospheric and soil processes [42]. While the soil and stratospheric $CH_4$ sinks are considered fairly stable, the OH sink strongly depends on ambient $CH_4$ concentrations [117, 118, 42, 119]. As briefly discussed previously in Section 4.2.1.3, $CH_4$ global atmospheric lifetime is given by:

$$\tau_{CH_4,global} = \left(\frac{1}{\tau_{OH}} + \frac{1}{\tau_{SOIL}} + \frac{1}{\tau_{STRAT}}\right)^{-1} \tag{4.9}$$

Under steady state conditions, the IPCC estimates $\tau_{CH_4,global}$ to be 8.7 years ± 1.3 years. The atmospheric lifetime or the $e$-folding time of a species is the time required for the global atmospheric burden to decrease by a factor of $e$. For many species including $CH_4$, the atmospheric lifetime is dependent on the global atmospheric concentration of the particular species. For $CH_4$, the perturbation lifetime is defined as the lifetime for a pulse of methane emissions to decay. $CH_4$ emissions suppress OH abundance in the atmosphere which is the primary sink for $CH_4$ with a positive feedback that leads to a longer lifetime for $CH_4$ relative to the unperturbed state. Based on an ensemble of experiments, the IPCC estimates the ratio between the perturbed lifetime and unperturbed lifetime for methane to be 1.4 [42]. Emissions of other chemically reactive species, namely, CO, volatile organic compounds (VOCs), and $NO_x$ emissions also perturb the atmospheric abundance of OH radicals thereby indirectly impacting $CH_4$ lifetime. $CH_4$, CO, and VOCs all deplete the atmospheric abundance of free OH radicals, while $NO_x$ emissions lead to the formation of OH radicals [117, 118, 42, 119].

A simple mass balance approach following Wigley et al. [117] is employed that estimates changes in atmospheric $CH_4$ concentrations based on the balance between $CH_4$ sources and sinks. Equation 4.10 shows the basic mass balance between $CH_4$ sources and sinks while Equation 4.11 shows the changes in $\tau_{OH}$ from emissions of reactive species and ambient $CH_4$ concentrations [117].

$$\frac{dC}{dt} = \frac{E}{2.78} - C\left(\frac{1}{\tau_{OH}} + \frac{1}{\tau_{STRAT}} + \frac{1}{\tau_{SOIL}}\right) \tag{4.10}$$

$$\frac{d(\ln \tau_{OH})}{dt} = a\frac{d(\ln C)}{dt} + b\frac{dE(NO_x)}{dt} + c\frac{dE(CO)}{dt} + d\frac{dE(VOC)}{dt} \tag{4.11}$$

where:

a = -0.32, b = 0.0042, c = -0.000105, d = -0.000315

$C$ in Equation 4.10 is the global atmospheric concentration of $CH_4$ in ppb, $E$ (in Tg/yr) represents annual $CH_4$ emissions from both natural and anthropogenic sources, while 2.78Tg/ppb is a conversion factor. $\tau_{STRAT}$ is estimated to be 120 years while $\tau_{SOIL}$ is 160 years [117], while OH-related lifetime, $\tau_{OH}$ is inversely related to OH abundance [120]. APMT uses projections of $CH_4$, CO, VOC, $NO_x$ emissions from IPCC-SRES scenarios to estimate future concentrations of $CH_4$. Equations 4.10 and 4.11 are integrated out to future years using initial conditions for year 2000 – intital $CH_4$ abundance of 1764 ppb, $\tau_{OH}$ of 9.6 years with an average growth rate from 2000-2005 of 0.2ppb/year [42, 117]. A constant $CH_4$ emissions offset is applied to all years to balance the mass budget to match the initial conditions. Natural emissions of $CH_4$, CO, VOC, $NO_x$ are assumed to be constant such that all changes in emissions are described by the IPCC-SRES scenarios. Similar to $CO_2$ impacts, a residual method is applied to estimate impacts of aviation well-to-tank emissions.

Radiative forcing from $CH_4$ concentration changes is estimated based on a simplified expression provided by the IPCC [121] as shown in Equation 4.12.

$$\begin{aligned} \Delta F &= 0.036\left(\sqrt{M} - \sqrt{M_0}\right) - \left(f(M, N_0) - f(M_0, N_0)\right) \\ f(M,N) &= 0.47\ln[1 + 2.01 \times 10^{-5}(MN)^{0.75} + 5.31 \times 10^{-15}M(MN)^{1.52}] \end{aligned} \tag{4.12}$$

where $M$ refers to atmospheric $CH_4$ concentrations in ppb, $M_0$ and $N_0$ are the pre-industrial $CH_4$ and $N_2O$ concentrations estimated to be 715 ppb and 270 ppb respectively [42]. In addition to the direct radiative forcing effect of $CH_4$ and the OH-lifetime feedback, there are three other indirect RF impacts attributed to $CH_4$. These include RF due to $CH_4$-related changes in tropospheric ozone, increases in stratospheric water vapor, and production of $CO_2$ [42, 118]. The indirect ozone effect is the most significant and highly uncertain as depends on tropospheric OH concentrations and emissions of other reactive species. $CH_4$ oxidation also leads to the formation of water vapor in the stratosphere where water vapor has significant radiative impacts and finally $CH_4$ oxidation is also a source of $CO_2$. Given that the complex chemical processes involved with these indirect effects are beyond the scope of the APMT model fidelity, the approach adopted by the IPCC in estimating the $CH_4$ Global Warming Potential (GWP) is used. The IPCC estimates the ozone effect to be approximately 25% and the stratospheric water vapor impact is 15% of the direct and OH-lifetime $CH_4$ RF [42]. The $CO_2$ effect is not included to prevent double counting of radiative impacts attributed to $CO_2$ as it may be already included in estimating $CO_2$ impacts. The total direct and indirect RF from $CH_4$ is estimated in APMT as the RF calculated from Equation 4.12 increased by a factor of 1.4 (a 40% increase to include the tropospheric ozone and stratospheric water vapor effects).

### 4.2.2 Surface Temperature Change

Radiative forcing estimates for aviation emissions evaluated using the methodology presented in Section 4.2.1 are related to changes in globally-averaged surface temperature as the next step in the impact pathway for climate change. While impulse response functions fit to complex AOGCMs are available in literature similar to the Bern carbon-cycle IRF presented in Section 4.2.1.1, a simple analytical model is employed in the APMT-Impacts Climate Module to estimate surface temperature impacts. IRFs from literature are generally fit to particular AOGCMs and have an implicit climate sensitivity associated with the AOGCM that cannot be varied exogenously [90, 89]. Climate sensitivity is defined as the equilibrium global mean annual surface temperature change resulting from a doubling of $CO_2$ concentrations relative to pre-industrial times. Climate sensitivity is measure of the responsiveness of the global climate system to any forcing; a higher climate sensitivity value results in a greater climate response to a given forcing. Variability in climate sensitivity across models due to differences in modeling feedback processes is one of the major sources of uncertainty in determining potential future climate change.

In order to assess the importance of variability in climate sensitivity on aviation-specific climate impact estimates, the approach proposed by Shine et al. [109] is used. Other IRFs from literature are also incorporated in the Climate Module to explore the variability in results based on the method of choice for estimating temperature changes [90, 89]. This simple analytical model presented in Equation 4.13 enables us to express climate sensitivity as a random variable and propagate uncertainties to the outputs [109, 86, 110].

$$\begin{aligned} \Delta T(t) &= \frac{1}{C}\int_{t_0}^{t} \Delta F(t')\exp\left(\frac{t'-t}{\lambda^* \cdot C}\right) dt' \\ \lambda^* &= \frac{\lambda}{RF_{2\times CO_2}} \\ \Delta F(t') &= RF^*(t') \cdot RF_{2\times CO_2} \\ \tau &= \lambda^* \cdot C \end{aligned} \tag{4.13}$$

Here, $C$ is the ocean heat capacity for a global ocean mixed layer of 100 m depth ($4.2\times10^8$ J/Km$^2$). $\lambda^*$ is the climate sensitivity parameter, which is the the climate sensitivity ($\lambda$) normalized by the $RF_{2\times CO_2}$. Equation 4.13 relates the normalized radiative forcing described in Section 4.2.1 for different aviation effects to surface temperature change ($\Delta T$ (K)) by accounting for the time constant of the climate system, $\tau$ [109, 86].

### 4.2.3 Valuation

This section is focused on relating physical impacts of climate change expressed as changes in globally-averaged surface temperature change to societal impacts in monetary terms. As mentioned previously, 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 [87]. 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 [87, 79].

The DICE-2007 damage function includes both market and non-market impacts along with an estimation of impacts related to catastrophic events. Impacts sectors covered by DICE-2007 include agriculture, sea-level rise, other market impacts, health, non-market amenity impacts, human settlements and ecosystems, and catastrophic events [79]. 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) [122]. 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]. Equation 4.14 provides the DICE-2007 damage function; damages for the different aviation effects are estimated through a residual analysis given the non-linear form of the damage function.

$$\begin{aligned} D(t) &= a_1 \Delta T_{1900}^2(t) \\ D_j(t) &= D_{\Delta T_{total}}(t) - D_{\Delta T_{total}-\Delta T_j}(t) \end{aligned} \tag{4.14}$$

The coefficient $a_1$ in Equation 4.14 is 0.0028388 with units of %GDP/K$^2$. The DICE-2007 function estimates climate damages in terms of percentage of world GDP. APMT uses the simplified analytical framework of the DICE-2007 damage function with climate damages that are proportional to the square of the change in global mean temperature. However, the coefficient $a_1$ is varied in APMT-Impacts to capture uncertainties in damage estimates as presented by other damage functions found in the literature; a comparison is provided in Section 4.2.5.3.

Climate damages estimated as percentage of GDP are transformed into monetary units by multiplying through with future projections of GDP growth from IPCC-SRES scenarios. Discounting is applied to future damages to convert them to present monetary measures and sum them up to a net present value of damages. The selection of a discounting approach is topic of debate in the literature and several different discounting methods have been proposed including various types of declining discount rates (see Weitzmann [123], Groom et al. [107], the UK Treasury [53], Guo et al. [124], etc.) as well as constant discount rates. The US OMB requires that federal agencies show analyses using discount rates of 3% and 7% for near term impacts experienced by the current generation. For assessing impacts on future generations, the US OMB recommends sensitivity analyses using lower discount rates [48]. APMT uses a range of constant discount rates to estimate the net present value of climate damages as shown in Equation 4.15.

$$NPV = \sum_{t_0}^{t} \frac{Damages(t)}{(1+r)^{t-t_0}} \tag{4.15}$$

where, $r$ is the discount rate and $Damages(t)$ are monetized climate damages in the future.

### 4.2.4 Characterization of Uncertainties

Section 4.2.3 described the modeling methodology employed in the APMT-Impacts Climate Module; here the focus is on the characterization of uncertainties involved throughout the modeling process. APMT uses Monte Carlo methods to propagate uncertainties in inputs and model parameters to outputs and this requires expressing inputs and parameters as random variables when possible. Sources of uncertainty in aviation-specific climate impacts can be found along all steps in the impact pathway shown in Figure 4-1. Tables 4.3 and 4.4 list the pertinent inputs and model parameters in the APMT-Impacts Climate Module and the associated approach for characterizing uncertainty.

For further details about the different input and model parameter distributions, the reader is referred to Marais et al. [86] and Jun et al. [125]. Parametric uncertainty analysis conducted on a previous version of the APMT-Impacts Climate Module indicated that climate sensitivity and RF from short-lived effects are the biggest contributors to uncertainties in temperature change estimates, while the net present value of climate damage is most sensitive to assumptions about discount rate, damage coefficient, climate sensitivity, and RF from short-lived effects. Chapter 5 presents an uncertainty analysis conducted on the updated APMT-Impacts Climate Module described in this thesis.

| Inputs | Description | Approach to uncertainty |
|---|---|---|
| Aviation fuel burn and $CO_2$ emissions | Emissions inventories of fuel burn, and $CO_2$ | Uniform distribution [-5% to +5%] |
| Aviation $NO_x$ emissions | Emissions inventories of $NO_x$ | Uniform distribution [-10% to +10%] |
| Anthropogenic emissions | Future projections of anthropogenic $CO_2$ emissions | Select among IPCC-SRES scenarios: A1B, A2, B1, B2 |
| GDP projection | Extrapolated based on selected SRES scenario | Select among IPCC-SRES scenarios: A1B, A2, B1, B2 |

Table 4.4: APMT-Impacts Climate Module inputs

### 4.2.5 Validation of Results

This section presents comparisons of results from the APMT-Impacts Climate Module with external sources as a validation exercise for the Climate Module. First, the impacts of long-lived species – $CO_2$ and $CH_4$ from APMT are compared with the IPCC MAGICC model. Next, this section provides Global Warming Potentials (GWPs) for $NO_x$-related impacts, followed by an assessment of APMT climate damage estimates through a comparison with other damage functions from literature. Other aviation short-lived effects modeled by APMT are set by modeling assumptions and Equation 4.4 to replicate RF values from Sausen et al. [92] and therefore are not assessed independently.

#### 4.2.5.1 Comparison with the IPCC MAGICC Model

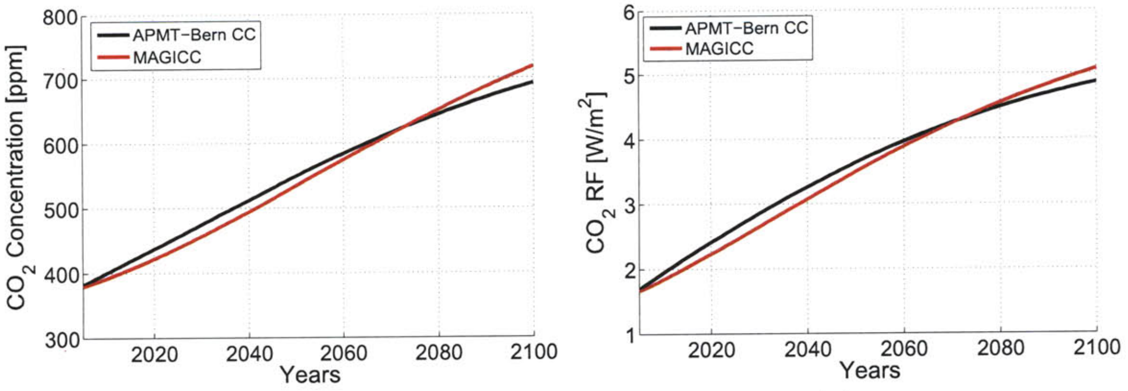
The Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) is a simplified climate model tuned to the outputs of more complex models and has been used in make future projections of climate change in the most recent IPCC report [42, 126]. First, a comparison of the $CO_2$ concentration and RF estimates from APMT with results from the MAGICC model version 5.3.v2 is provided

| **Model parameters** | **Description** | **Approach to uncertainty** |
|---|---|---|
| Carbon cycle model choice | Impulse response functions capturing main features of a complex carbon cycle model | Select between different IRFs fit to carbon cycle models |
| Temperature response model choice | Approach for estimating surface temperature change | Select between different IRFs fit to GCMs or the simplified analytical model |
| Climate sensitivity | Climate sensitivity for $CO_2$ doubling relative to 1750 levels, taken from IPCC (2007) | Triangular distribution<br>[mode = 2.0K, range = 3.0 - 4.5K] |
| RF for doubling $CO_2$ | Radiative forcing from a doubling of $CO_2$ concentrations relative to pre-industrial times taken from IPCC (2007) | Triangular distribution:<br>[mode = 3.7, range = 3.5 - 4.2] $W/m^2$ |
| RF value for short-lived non-$CO_2$ effects | Radiative forcing for [$H_2O$; sulfate; soot; contrails; Cirrus] from Sausen et al. (2005) | Triangular distribution: mode, range<br>[ 2, 0-6; -3.5, -10-0; 2.5, 0-10; 10, 0-30; 30, 0-80] $mW/m^2$ |
| Efficacies for non-$CO\text{-}_2$ effects | Efficacies for [$H_2O$; sulfate; soot; contrails; Cirrus] from Hansen et al.(2005), IPCC (2007) | Uniform distribution:<br>[1; 0.68-1.09; 0.62-1.29; 0.59-1; 1] |
| RF for $NO_x$-$CH_4$, $NO_x$-long-term $O_3$, and $NO_x$-short-term $O_3$ | Radiative forcing for $NO_x$-related impacts | Uniform discrete distribution:<br>[Stevenson et al. 2004, Hoor et al. 2009 and Wild et al. 2001] |
| Reference temperature change since pre-industrial times | Reference temperature change in damage function from IPCC TAR | Triangular distribution:<br>[mode = 0.4K, range = 0.6 - 0.8K] |
| Damage function | Climate damages in terms of percentage of GDP | Uniform discrete distribution:<br>[DICE-2007, ½ DICE-2007, 2XDICE-2007] |
| Discount rate | Discount future impacts to present monetary terms | Assess for different values of discount rate |

Table 4.5: APMT-Impacts Climate Module parameters, adapted from [86]

and then a similar comparison is conducted for $CH_4$ impacts. While APMT uses the Bern carbon-cycle impulse response function to estimate $CO_2$ concentration changes, the MAGICC carbon-cycle model is tuned to results from the Coupled Carbon-Cycle Climate Model Intercomparison Project ($C^4$MIP) [42, 127]. Figures 4-4a and 4-4b show APMT and MAGICC results for IPCC SRES scenario A1B.

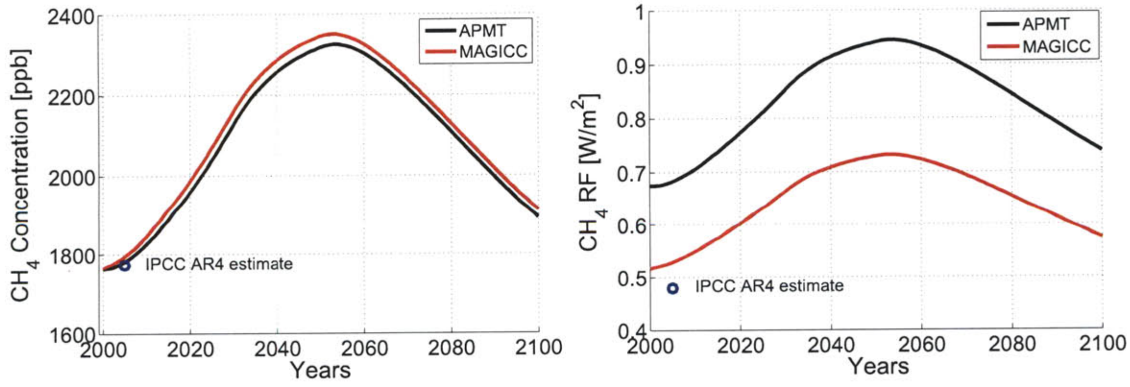
Both sets of results from Figure 4-4 show APMT results to be in good agreement with the MAGICC $CO_2$ results for the IPCC-SRES A1B scenario. The APMT results are obtained with inputs and parameters set at mid-range values, while the MAGICC results are for default settings of the model. Minor difference between these two sets of results can be attributed to inter-model differences and the inclusion of climate feedbacks in the MAGICC model whereas the APMT Bern carbon-cycle IRF assumes a fixed background $CO_2$ concentration of 378 ppm [126, 42]. Next, $CH_4$ concentration



(a) (b)

Figure 4-4: Comparison of $CO_2$ results from APMT and MAGICC (a) $CO_2$ Concentrations [ppm], (b) $CO_2$ radiative forcing [W/m$^2$]

and radiative forcing results from APMT are compared with those from MAGICC. Both models follow the simplified mass balance approach of Wigley et al. [117] and therefore APMT results are anticipated to be in good agreement with the MAGICC results. Figures 4-5a and 4-5b show the $CH_4$ concentrations and RF for IPCC-SRES scenario A1B respectively.



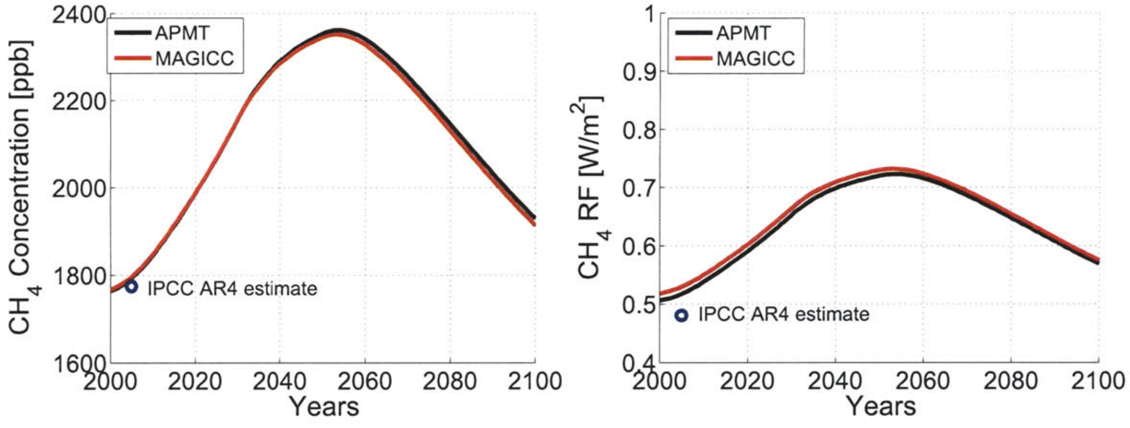
(a) (b)

Figure 4-5: Comparison of $CH_4$ results from APMT and MAGICC (a) $CH_4$ Concentrations [ppb], (b) $CH_4$ radiative forcing [W/m$^2$]

The general trends of results from APMT and MAGICC compare well and the discrepancies can be explained by differences in modeling assumptions; the blue circle indicates the latest IPCC estimate for year 2005. The $CH_4$ concentration results from APMT and MAGICC are similar in magnitude with differences arising from assumptions about the initial atmospheric $CH_4$ growth rate which is used to balance the $CH_4$ mass budget and integrate the mass balance equation (Equation 4.10) out to future years. The MAGICC model uses a previous growth rate estimate of 3.5ppb/yr, while APMT uses the most recent IPCC estimate of 0.2ppb/year over the period 2000-2005 [126, 42]. The difference in RF estimates are much larger due to the differences in which direct and indirect components of $CH_4$ RF are included in these results. The IPCC AR4 estimate indicated by the blue circle only includes the direct radiative forcing from $CH_4$, the MAGICC estimate includes the direct effect, the OH-lifetime feedback and the stratospheric water vapor effect, while the APMT values include all direct and indirect RF effects of $CH_4$ except $CO_2$ production. Note that the MAGICC model approximates the stratospheric water vapor effect as being 5% of the direct and the OH-lifetime feedback effects summed based on information from the IPCC Third Assessment Report [126, 121]. APMT models indirect $CH_4$ forcing effects based on the more recent IPCC Fourth Assessment Report as described in Section 4.2.1.4. Figure 4-6 compares APMT $CH_4$ and MAGICC results with the APMT modeling assumptions aligned with MAGICC assumptions thereby diminishing differences in results from the two models. In summary, both sets of comparisons for $CO_2$ and $CH_4$ results indicate that APMT results agree well with those estimated by the MAGICC model.

#### 4.2.5.2 Global Warming Potentials for $NO_x$

In this section APMT estimates of Global Warming Potentials (GWPs) for $NO_x$ effects are compared with those provided by the IPCC [42] and work presented by Fuglestvedt et al. [115] which use the same aviation-specific $NO_x$ studies as APMT. These studies include the work by Stevenson et al. [43] and Wild et al. [44] discussed previously in Section 4.2.1.3. GWPs are defined as an index that quantifies the time-integrated global mean radiative forcing of a pulse of 1kg of a species relative to that of 1 kg of a reference gas which is typically selected to be $CO_2$. GWPs are intended



(a)

(b)

Figure 4-6: Comparison of $CH_4$ results from APMT and MAGICC with similar assumptions (a) $CH_4$ Concentrations [ppb], (b) $CH_4$ radiative forcing [W/m$^2$]

to be used as an equivalency metric across different greenhouse gases to quantify the tradeoffs involved in multi-component climate change abatement strategies [42].

| **Study** | **Aviation $NO_x$ GWP - 100 years** | | |
|---|---|---|---|
| | **IPCC (2007)** | **Fuglestvedt et al. (2008)** | **APMT** |
| Stevenson et al. (2004) | -3 | -2 | -5 |
| Wild et al. (2001) | 130 | 71 | 93 |

Table 4.6: Aviation $NO_x$ Global Warming Potentials [42, 115]

While GWPs have already been used in the Kyoto Protocol to compare climate impacts of long-lived greenhouse gases such as $CH_4$, $N_2O$, HFCs, $SF_6$, PFCs with those from $CO_2$, several studies have also pointed out key inadequacies with the GWP concept. Some criticisms include the dependence of the GWP metric on the choice of time horizon for integration, the differences in temporal trends of climate impacts for two GWP-equivalent species, evaluation of impacts relative to a fixed background, etc. (see [108, 128, 42] for a detailed discussion). GWPs for short-lived species like $NO_x$ are highly uncertain as compared to long-lived greenhouse gases as the short-lived impacts vary with time and place of emissions [129, 42]. Here an estimate of aviation $NO_x$ GWP is provided as a means of comparing model performance with external sources. Table 4.6 lists GWPs from the IPCC [42], Fuglestvedt et al. [115] and APMT.

The differences between APMT and other literature estimates are largely explained by the methodology for computing $CO_2$ impacts. The IPCC and Fuglestvedt estimates follow the conventional definition of GWPs and compute $CO_2$ impacts with a constant radiative efficiency ($1.82 W/m^2/kgCO_2$) corresponding to a constant background concentration for $CO_2$ of 378ppm. While the Bern carbon-cyle IRF parameters in APMT are also tuned to a constant background concentration of 378 ppm, $CO_2$ RF is computed as a function of changing atmospheric concentrations. Since $CO_2$ RF has a logarithmic dependence on $CO_2$ concentrations, APMT estimates have a declining $CO_2$ radiative efficiency as background concentrations grow in the future. When APMT GWPs are computed with a fixed $CO_2$ radiative efficiency, results are found to be within 5% for the Fuglestvedt et al. estimates using Wild et al. RF values and within 50% of the Stevenson et al. estimates [115, 43, 44]. The differences with Stevenson et al. results are amplified given that they are very close to zero. The APMT results identically match the IPCC GWPs for Stevenson et al. when the $CO_2$ methodological differences are accounted for [42, 43]. Both APMT and Fuglestvedt et al. [115] results for Wild et al. [44] differ from the IPCC estimates even with a constant radiative efficiency as the IPCC uses RF values from the original Wild et al. [44] study, while the other two use corrected Wild et al. results presented in Stevenson et al. [43].

#### 4.2.5.3 Comparison with Other Damage Functions

This section compares the APMT valuation approach based on the DICE-2007 damage function [87] with other literature estimates. As discussed previously in Section 4.2.3, the DICE-2007 damage function estimates both market and non-market impacts as well as impacts related to catastrophic events. DICE along with other damage functions in literature express societal damages as a function of changes in mean surface temperature. Figure 4-7 taken from the most recent IPCC report [10] compares results from a previous version of the DICE model (DICE-99) [79] with those from the other damage functions including the Model for Evaluating Regional and Global Effects of GHG reduction policies (MERGE) [130], the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) [80], and the Policy Analysis of the Greenhouse Effect (PAGE2002) model used in the Stern Review [101]. Differences in damage estimates arise from varying assumptions about market and non-market impacts, catastrophic events, discounting methods, equity weights, climate system feedbacks and so on [10].

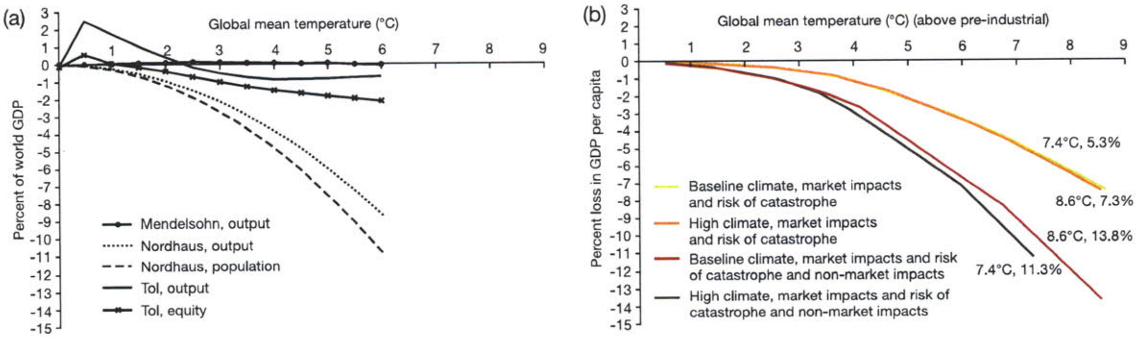


Figure 4-7: Damage estimates from literature [10]

Figure 4-8 shows the temperature dependence for the latest version of the DICE-2007 damage function described in Section 4.2.3. Also plotted along with the original DICE-2007 damage function are the half and twice the damage estimates relative to DICE-2007. APMT captures uncertainties in damage function estimates by sampling uniformly between the three different damage estimates shown in Figure 4-8. This band of damage estimates shown in Figure 4-8 is representative of the behavior of other damage functions and encompasses the range of estimates presented in Figure 4-7. The shaded area in Figure 4-8 indicates the range of damage estimates from the literature presented by the IPCC and provided in Figure 4-7.

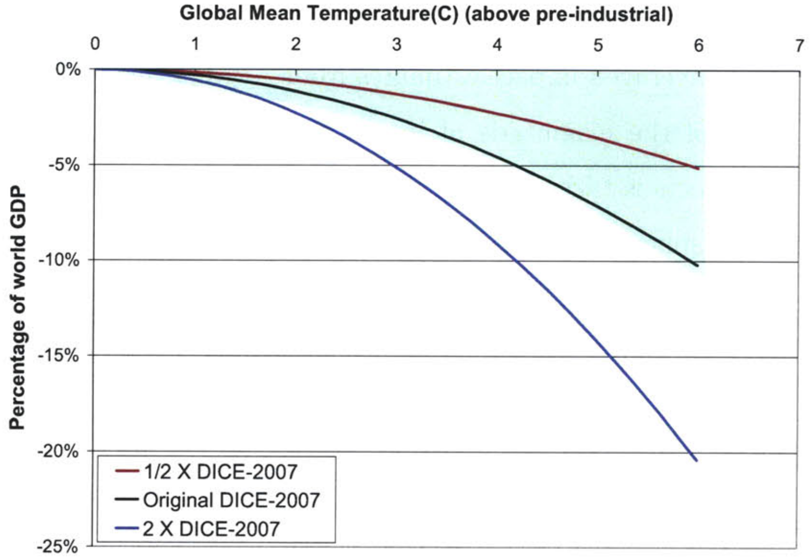


Figure 4-8: DICE-2007 implementation in APMT

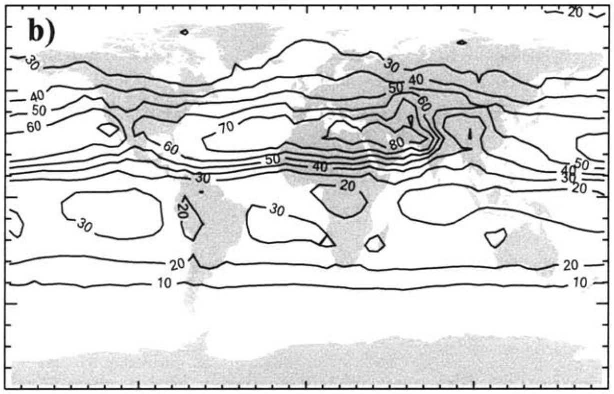
### 4.2.6 Limitations

This section focuses on a discussion of some key limitations of the APMT-Impacts Climate Module which sheds light on current gaps in functionality and identifies future areas of research. Listed below are some of major limitations of the APMT-Impacts Climate Module:

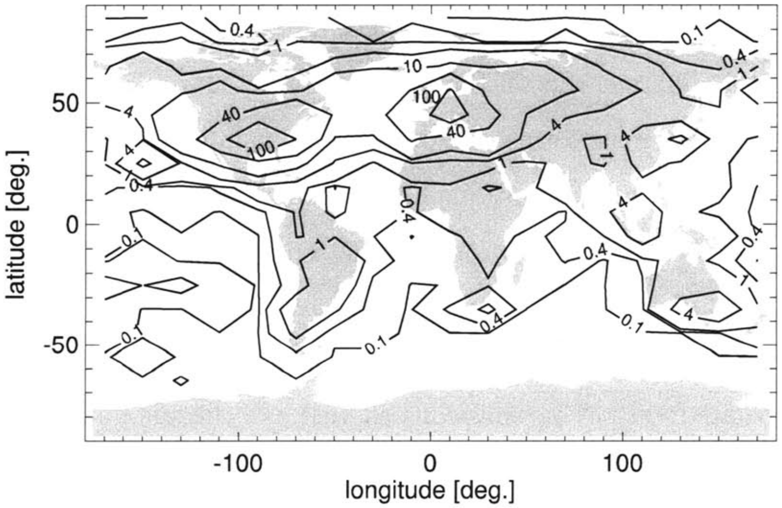
**Spatial resolution:** APMT currently estimates aviation-specific impacts at a globally-averaged spatial scale. However, this does not capture the spatially heterogeneous nature of aviation effects such as contrails, cirrus, black carbon, sulfates, and the short-lived $NO_x$-$O_3$ effect. All these effects are short-lived with residence times on the order of days to weeks and therefore are strongly felt in the region of emissions. Globally-averaged result do not capture the potential large regional variations in impacts from short-lived species. APMT is constrained to globally-averaged metrics given the high uncertainties in and lack of literature estimates for regional radiative forcing impacts from aviation. While there are several studies in literature that assess the impacts of regional perturbations of aviation emissions on global impacts (see [131, 114, 82]), there are virtually no robust estimates of regional variations of aviation climate impacts.

Using globally averaged impact estimates from APMT, this work presents a first order assessment of the magnitude of impacts when spatial heterogeneity of aviation short-lived effects is taken into consideration. Given greater aviation activity in the northern hemisphere, aviation short-lived effects have a stronger impact in the northern hemisphere as compared to the southern hemisphere. This is shown in Figures 4-9a and 4-9b for radiative forcing from the warming $NO_x$-$O_3$ effect and contrails respectively [131, 114]. Assuming globally-uniform impacts from short-lived effects does not capture the spatial variation shown in Figure 4-9 and may underestimate impacts from aviation. This is can be seen in the case of $NO_x$-related impacts. As described earlier, the short-lived, regional, $NO_x$-$O_3$ warming RF roughly balances the longer-lived, globally-uniform, $NO_x$-$CH_4$-$O_3$ cooling RF when integrated globally and over the full time horizon of impacts [43, 44, 111]. This indicates a negligible impact from $NO_x$ effects, however, spatial and temporal heterogeneity of aviation $NO_x$ impacts may lead to warming in the northern hemisphere and cooling in the southern hemisphere.

An upper bound conservative estimate of total aviation impacts can therefore be made by estimating impacts only in the northern hemisphere and assuming that all the short-lived effects of aviation are confined to the northern hemisphere. Aviation short-lived RF in the northern hemisphere can be estimated by scaling the globally-averaged APMT estimates by a factor of 2 based on area weighting (assuming no short-lived impacts in southern hemisphere). Longer-lived $CO_2$ and $NO_x$-$CH_4$-$O_3$ RF for the northern hemisphere would be identical to APMT RF estimates as they are globally uniform effects. Given current modeling limitations within APMT, this estimation of physical impacts in the northern hemisphere is intended to illustrate the difference in impact estimates when spatially heterogeneity is accounted for. Damage estimates in the northern hemisphere can be estimated by using global damage functions. This is a fair first order approximation given that the northern hemisphere has greater land mass, population, and economic activity as compared to the southern hemisphere. A detailed regional assessment of aviation climate impacts using more complex climate models with greater spatial resolution and regional damage functions would be necessary to model more accurate estimates of spatial variations in aviation impacts. The fidelity and modeling complexity required by a regional analysis is beyond the scope of this work and for the purposes of this thesis illustrative results are presented in Chapter 6 for the case where only impacts in the northern hemisphere are considered.



(a) $NO_x$-$O_3$ RF ($mW/m^2$) [114]



(b) Contrails RF ($mW/m^2$) [131]

Figure 4-9: Global distribution of $O_3$ and contrails annual mean radiative forcing from air traffic in 2002

**Climate feedbacks:** The use of impulse response functions and a simple analytical climate model in APMT does not enable an assessment of the impact of feedbacks within the climate system which may enhance or mitigate the climate impacts associated with aviation emissions. The impulse response coefficients are fit to complex climate models assuming a fixed atmosphere and do not capture changes in chemical or dynamic processes from future climate change. Some of these feedbacks are better understood as compared to other – for instance, the $C^4$MIP Project indicates a positive feedback (of uncertain magnitude) within the coupled climate-carbon cycle system with future increases in atmospheric $CO_2$ concentrations leading to changes in oceanic and biological uptakes of carbon and in turn leading to higher atmospheric $CO_2$ concentrations [42]. However, feedbacks associated with other short-lived species are poorly understood in terms of uncertainties with respect to both the sign and the magnitude of the feedbacks [42].

**Independent treatment of aviation effects:** Presently, different aviation effects within APMT are treated as being independent of each other. All $NO_x$-related impacts scale with aviation $NO_x$ emissions, short-lived impacts with fuel burn, $CO_2$ impacts with $CO_2$ emissions in APMT. While this approach provides a first-order estimate of the major impacts of each effect, it does not capture potential interactions among the different effects. Some of these interactions include contributions of aerosol particles to cirrus formation, impacts of sulfates and water-ice particles on tropospheric ozone, etc. which are highly uncertain in magnitude [41].

**Changes in future flight operations:** Impacts are estimated with the implicit assumption that future operational changes involve no significant changes in flight routes and are only linear increases in operations and consequently in emissions. Impacts associated with $NO_x$ emissions as well as contrails and cirrus are strongly dependent on flight routes and current RF estimates cannot be linearly scaled if large deviations from present day flight routing are to be expected [131, 114]. Similarly the APMT-Impacts Climate Module currently does not provide the capability for estimating impacts of a future supersonic fleet with stratospheric flight altitudes. There are some important differences in the behavior of aircraft emissions in the stratosphere as compared to the UTLS region where subsonic aircraft fly, for instance, water vapor is significant greenhouse gas in the stratosphere while its direct radiative impacts in troposphere are negligible [41].

### 4.2.7 Future Work

Future work for the APMT-Impacts Climate Module should focus on addressing current gaps in functionality highlighted in the previous section. These future work tasks can be separated into short-term and long-term goals for APMT development. Assessing regional climate impacts of aviation emissions and incorporating climate feedbacks into the Climate Module are developmental issues with high uncertainty and can be labeled as long-term research tasks that are driven by advances in climate science. On the other hand, incorporating altitude dependence of $NO_x$ and contrails/cirrus effects can be a near term research item based on recent studies [131, 114]. Comparisons of APMT results with those from a complex AOGCM can be conducted to improve characterization of uncertainties as well as test the robustness of the assumption of independence of effects. Finally, routine updates to the Module can be expected as improved IRFs and radiative forcing estimates become available in the literature.

# Chapter 5

# Uncertainty Assessment and Communication of Results

The previous chapters identified major environmental impacts attributed to aviation and indicated key shortcomings in current decision-making practices, namely, lack of impact assessment or evaluation of environmental tradeoffs, and limited treatment of uncertainties. Chapters 3 and 4 discussed methods for conducting a more comprehensive aviation environmental and economic impact analysis; this Chapter addresses the treatment of uncertainties 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 chapter does not delve into decision theory or formal methods for evaluating optimal policies.

There is a substantial body of literature that addresses challenges associated with using 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 [132, 133, 134, 135]. 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 [133]. Among other challenges in their experience with the EU Water Framework Directive, Brugnach et al. [134] 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 place a strong emphasis on both 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 for reducing uncertainties in the outputs and expanding modeling capabilities.

APMT assessment involves separate quantitative and qualitative procedures for APMT-Economics and the three APMT-Impacts modules [136]. Quantitative methods include formal parametric sensitivity studies and uncertainty analyses, and capability demonstrator and sample problems. Capability demonstrator problems were used when the tool components being tested were still under development. Sample problems were used with components that were relatively well developed and need limited changes to be able to fully address the problem. Qualitative assessment methods such as external reviews by experts in the respective modeling domains are also 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 scope 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 [75].

The final step in the policy analysis process is the distillation and communication of key 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 match their preferences. 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 [136]. The fundamental tool for conducting uncertainty analysis in APMT is the Monte Carlo simulation. 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 cannot be 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 [136]. 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. Running several computational trials with inputs and model parameters defined as random variables is the defining characteristic of Monte Carlo methods [137]. 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 reduces uncertainties in outputs as many modeling uncertainties are common to both scenarios. In estimating policy impacts, a paired sampling approach is 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 5-1 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 or spread 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 spread in the policy impact results.

Monte Carlo methods are also used to conduct global and local sensitivity analysis; the reader is referred to [136] for details on the sensitivity analysis approaches. The assessment process is conducted following a double-loop approach (see [136, 138] 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 [139, 140]. 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 [39, 66, 136, 110, 141] for more details).

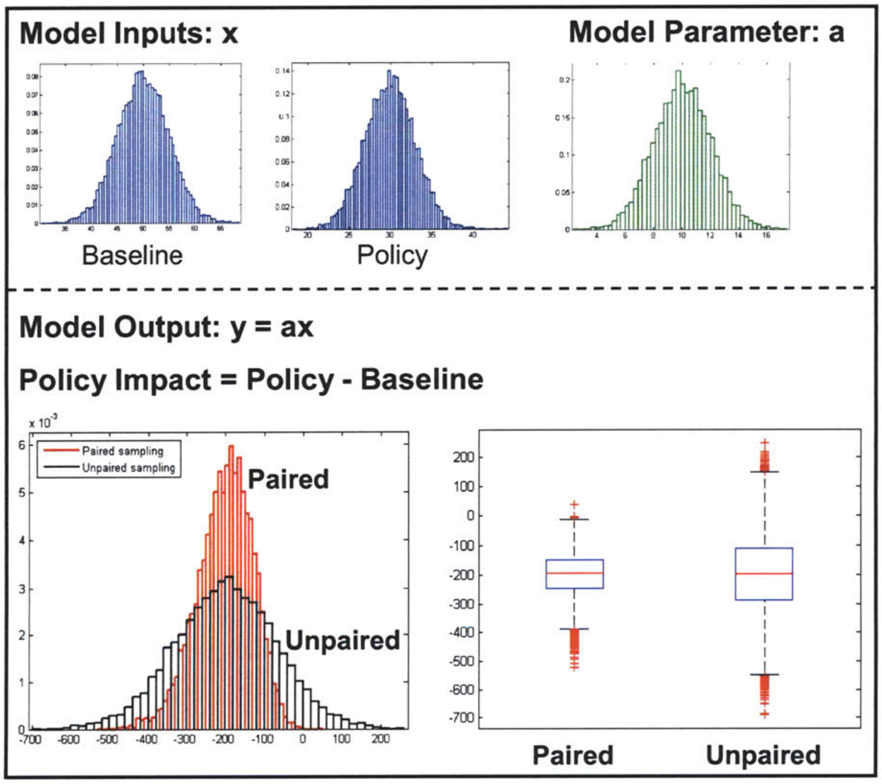


Figure 5-1: Paired sampling for Monte Carlo analysis

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, choice of a carbon-cycle impulse response function, etc. 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 modeling 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 which arise from lack of scientific understanding versus those which are inherently dependent on user preferences. Epistemic uncertainties that fall into the scientific and valuation categories can be expected to reduce in the future as the state of knowledge improves. However, uncertainties in parameters that are policymaker choices can only be addressed by evaluating policies using different parameter values as further research is not expected to shed light on reducing uncertainties; some examples of such parameters include discount rate and future anthropogenic growth scenarios. The next section presents the GSA and LSA for the APMT-Impacts Climate Module and classifies inputs and model parameters into the uncertainty categories described above.

## 5.2 Uncertainty Analysis for the APMT-Impacts Climate Module

### 5.2.1 Global Sensitivity Analysis

Chapter 4 provides a detailed description of the APMT Climate Module with key inputs and model parameters listed in Tables 4.4 and 4.5. The inner-loop GSA 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 5.1 and are presented graphically in Figure 5-2. The total sensitivity index (TSI) is estimated following the mean-subtracted alternative GSA approach presented in [110, 142]. 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.

TSI are presented in Table 5.1 and Figure 5-2 for temperature change and net present value of damages from aviation climate impacts. While Table 5.1 lists TSI for all model parameters include in the GSA, Figure 5-2 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 Chapter 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 Chapter 6).

| **Model Parameter** | **Temperature Change** | | **Net Present Value** | |
|---|---|---|---|---|
| | Baseline | Policy Impact | Baseline | Policy Impact |
| Fuelburn and $CO_2$ emissions multiplier | 0.018 | 0.001 | 0.003 | 0.0004 |
| $NO_x$ emissions multiplier | 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 effects | 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** |

Table 5.1: Global sensitivity analysis for the APMT-Impacts Climate Module – total sensitivity indices for model parameters with probability distributions

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 rank 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 Chapter 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 5.1 and Figure 5-2 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.

### 5.2.2 Local Sensitivity Analysis

The outer-loop LSA is focused on other model parameters within the APMT Climate Module that are selected as distinct values from a range of potential options. These include the carbon-cycle impulse response function, the temperature response approach, scenarios of future anthropogenic growth, and discount rate. Variability in outputs arising from these model parameter choices cannot be apportioned through

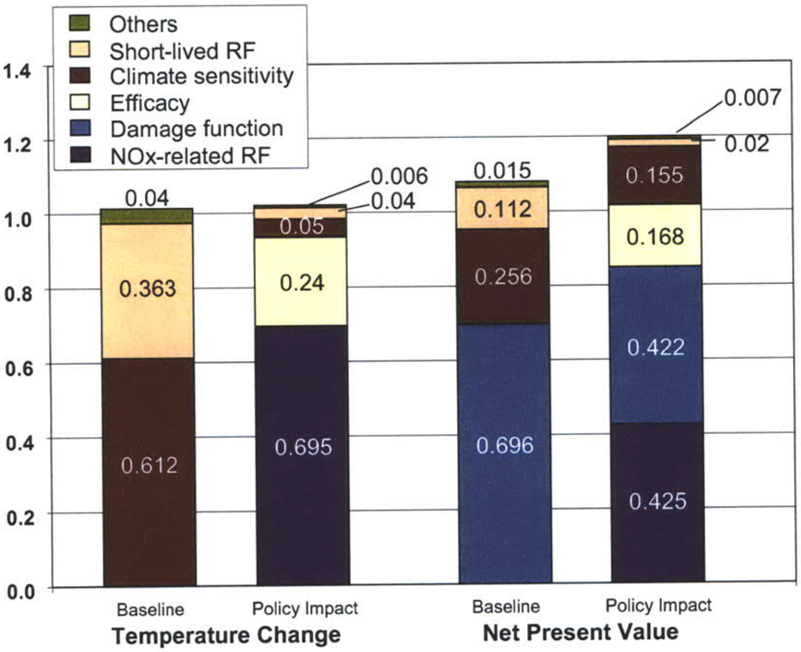


Figure 5-2: Global sensitivity analysis for the APMT-Impacts Climate Module – total sensitivity indices for key model parameters

a GSA, therefore a local sensitivity analysis is conducted to quantify changes in the outputs when each of these parameters are perturbed from the nominal selection. Key probabilistic parameters identified by the GSA are also included in the LSA to provide a comparison with the deterministic parameters.

Figure 5-3 shows LSA results for the APMT-Impacts Climate Module through a tornado chart. The selected output is the net present value of climate damages and is indicated by the x-axis. The vertical line designated as the nominal case represents results with model parameters set at their nominal values listed in Table 5.2. Each of the horizontal bars indicates the variability in NPV when the corresponding model parameter is perturbed from its nominal value while fixing all other model parameters at their nominal values. The perturbed model parameter values are provided in Figure 5-3 with the low and high $NO_x$ and short-lived RF values corresponding to the low and high assumptions described in Chapter 6 (see Table 6.6). Note that model parameters not listed in Figure 5-3 are treated as being probabilistic and are sampled from their respective distributions. Figure 5-3 shows the discount rate to have the largest contribution to NPV variability. Climate sensitivity, damage function, and RF from short-lived effects are the next set of model parameters that influence NPV variability with approximately comparable magnitudes. Following these parameters are the temperature response approach, the anthropogenic growth scenario, the carbon cycle IRF, and the $NO_x$ related RF values in terms of their impact on NPV uncertainty.

| **Model Parameter** | **Nominal values** |
|---|---|
| Discount rate | 3% |
| Damage function | DICE 2007 |
| Anthropogenic growth scenario | IPCC SRES A1B |
| Temperature response approach | Shine et al. 2005 |
| Carbon cycle IRF | Bern carbon cycle coefficients |
| Climate sensitivity | 3K |
| RF for $NO_x$ effects | Hoor et al. 2009 |
| RF value for short-lived effects<br>[$H_2O$; sulfate; soot; contrails; cirrus] | Sausen et al. 2005<br>[ 2; -3.5; 2.5; 10; 30] $mW/m^2$ |

Table 5.2: Local sensitivity analysis nominal model parameters

The model parameters examined in Figure 5-3 are also grouped into the uncertainty categories described in Section 5.1, namely, valuation, scenario, and scientific and modeling uncertainties. Discount rate, which is typically is policy-maker choice and damage function with its associated ecological and economic uncertainties fall within the valuation category. Anthropogenic growth scenarios which estimate future economic activity and corresponding $CO_2$ emissions belong to the scenario uncertainty category. Finally, the scientific and modeling uncertainty category comprises the temperature response approach, carbon cycle IRF, climate sensitivity, $NO_x$-related RF, and RF from short-lived effects. The modeling and scientific uncertainties can further be separated into uncertainties that are common to global climate change impact modeling versus those that pertain specifically to aviation. This classification of uncertainties can also aid in setting research priorities for reducing uncertainties in output estimates. While scientific and modeling uncertainties as well as damage function related uncertainty can be reduced with further research, uncertainties related to the discount rate choice and future anthropogenic growth are based on alternative projections of the future and ethical judgment and do not depend on the current state of scientific or economic knowledge.

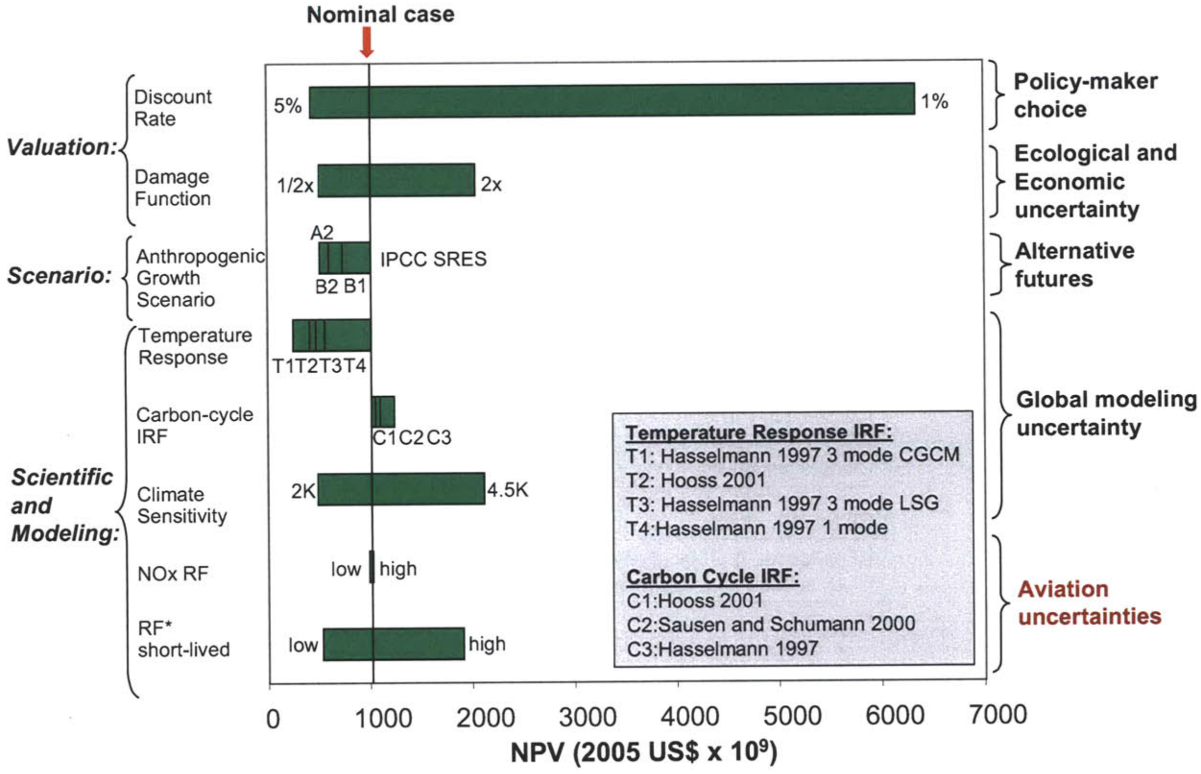


Figure 5-3: Local sensitivity analysis for the APMT-Impacts Climate Module

## 5.3 Communication of Results

Given the complex nature of APMT with several inputs and model parameters that are highly 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. A strong emphasis is placed on relaying three different kinds of information for any policy analysis: quantified environmental and economic impacts, uncertainties in these impact estimates, and the inputs and model parameters that provided these set of 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 data accumulated through multiple Monte Carlo runs. For all components of APMT assessment results indicate five to six inputs and model parameters to which the respective outputs are most sensitive. Based on this condensed information, the APMT decision-making framework specifically targeted toward policymakers or other stakeholders is developed. This framework enables an interactive application of APMT to aid decision-making, where the 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 has to do with 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 in to the decision-making process. Section 5.3.2 delves further into the selection of timescales for policy analysis.

### 5.3.1 Decision-making Framework – Lens

As mentioned previously, there are about five to six influential parameters for each APMT module, which determine the magnitude of the estimated impacts and associated uncertainties. These influential parameters are derived from global and local sensitivity analysis conducted separately for each module that ranks parameters in terms of their contribution to output variability [39, 66, 136, 110, 141]. Impacts can be represented in physical or monetary metrics, with the monetary metrics having a few more parameters in addition to the parameters necessary to compute physical metrics such as valuation parameters and discount rate. Depending on the user preferences for each of these inputs and model parameters, 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 helpful if the analysis options are synthesized into a set of pre-defined combinations of inputs and assumptions. These combinations of inputs and model parameters each describe a particular point of view or perspective on conducting the policy analysis. Each of these combinations is designated as a *lens* as it symbolizes a particular viewpoint through which one can assess a given policy option. A similar approach has been used by the IPCC in their Special Report on Emissions Scenarios (IPCC-SRES) in formulating future anthropogenic growth scenarios which represent different storylines or perspectives about key factors that determine future growth trajectories [112]. The IPCC-SRES narrative storyline approach takes into account demographic, social, economic, technological, and environmental factors that determine future anthropogenic emissions and economic growth with each storyline based on internally consistent assumptions. The lens concept introduced here also groups inputs and model parameters into specific combinations that define the analysis perspective. Some example lenses include a lens with mid-range environmental impacts and economic impacts; one with conservative or worst-case environmental impacts and mid-range economic impacts or vice-versa; one focused on short or long-term environmental impacts; or one that adopts a conservative perspective on 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 or what if scenarios.

Figure 5-4 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 5.3

provides a short description of the different inputs graphically represented in Figure 5-4. 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 5-4; only those inputs and model parameters critical to output variability are presented here. Chapter 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.

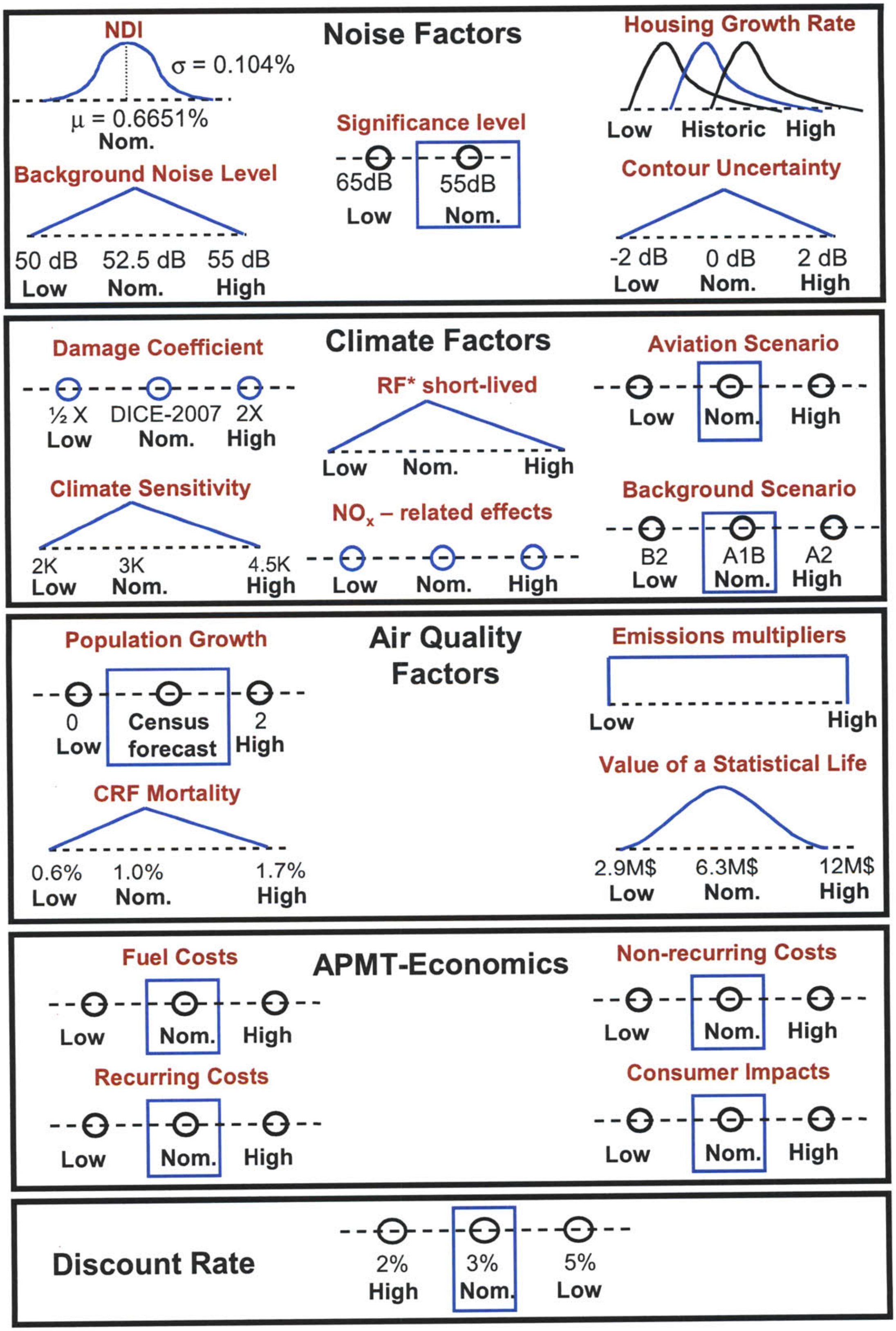


Figure 5-4: Mid-range lens

| 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 multipliers | Multipliers to capture uncertainty in fuelburn; SOx; NOx; 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 |

Table 5.3: APMT lens inputs and model parameters

### 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 influences the current fleet mix. The second timescale is the impacts time period over which the impacts of the different environmental effects attributed to the activity of the current fleet persist. As illustrated in Figure 5-5, in order to evaluate the impacts of a proposed policy measure relative to a baseline scenario, aviation activity is modeled for the duration of the policy influence time period where the policy impacts are expected to be significant. This does not imply that aviation activity ceases after the policy impact time period; as shown in Figure 5-5, aviation continues, but the policy is assumed to no longer influence the fleet mix.

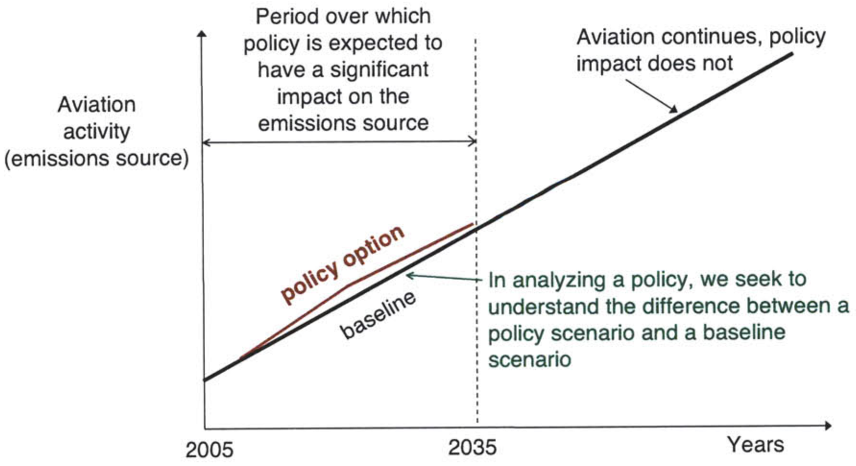


Figure 5-5: Timescales in policy analysis

The policy influence time period may or may not coincide with the impacts time period depending on the nature of the environmental effects considered. For example, climate change impacts include short-lived and long-lived effects as described in Chapter 2. A policy that aims to decrease the long-lived $CO_2$ emissions may modify fleet characteristics for 30-40 years. However, the emissions from the fleet during the policy influence time period may persist in the atmosphere for a significantly longer time period due to the long atmospheric residence time of $CO_2$ (on the order of centuries). In this case the environmental impacts of $CO_2$ emissions are not fully realized in the 30-40 year span and continue well beyond the policy influence period.

Distinctions between the timescales discussed previously 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. For the policy analysis presented in Chapter 6, costs and benefits aggregated over the full 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.

# Chapter 6

# $NO_x$ Stringency Policy Analysis

As described in Chapter 2, $NO_x$ emissions include both NO and $NO_2$ and are a byproduct of combustion at high temperatures and high pressures such as in jet engines. $NO_x$ emissions are of concern for both air quality and climate impacts. 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 [71]. 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 $CH_4$ concentrations. The $NO_x$-related $CH_4$ reduction is a long-lived effect with a e-folding time of order of a decade ([43, 111, 44]) and also has an associated $O_3$ reduction effect. This long-lived $NO_x$-$CH_4$-$O_3$ effect has a cooling impact that to a large extent counter-balances the short-lived warming $O_3$ effect when integrated globally.

ICAO has regulated aircraft $NO_x$ emissions from the 1980s to improve air quality in the vicinity of airports with increasingly stringent standards over the years. The ICAO $NO_x$ emissions standards only apply to engines with a thrust rating of greater than 26.7kN. Figure 6-1 provides an overview of the increasingly stringent CAEP standards for engine $NO_x$ emissions for engines with a high thrust rating (greater than 89kN)[143]. The standards control the engine $NO_x$ characteristic or $D_p/F_{oo}$, 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. 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 percent as compared to CAEP/4 for engines manufactured after December 2007 [144]. 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 ($F_{oo}$), with an allowance for engines with higher OPR values to emit more $NO_x$.

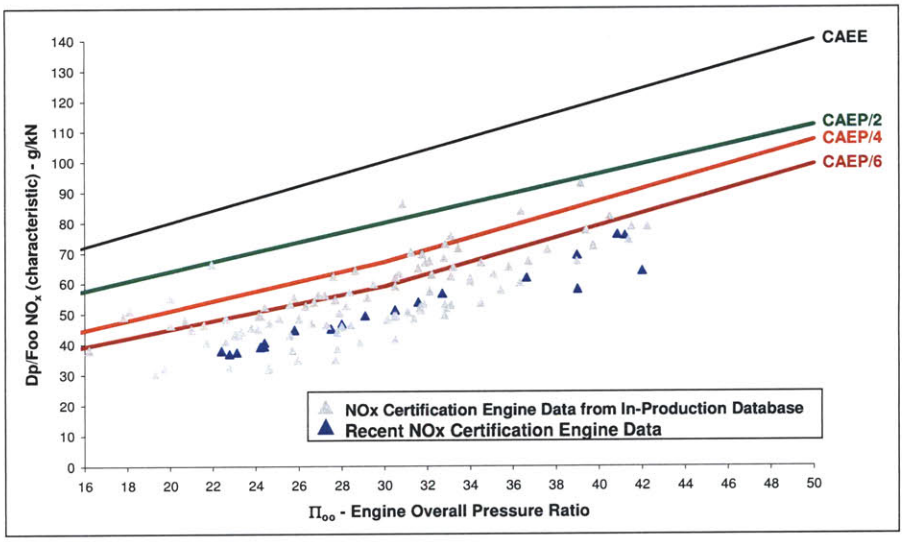


Figure 6-1: ICAO-CAEP $NO_x$ stringency standards [143]

As discussed in Section 2.2, 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 2.2.2 found the 10% stringency level implemented in 2008 to be most cost-effective option, however, negotiations with stakeholders lead to an agreement over a stringency increase of 12% relative to CAEP/4 standards as the new CAEP/6 standard [144]. 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 [56]. The ICAO-CAEP will hold its eighth meeting in 2010 and will revisit engine $NO_x$ emissions stringency standards as a part of its work program. This chapter analyzes a subset of engine $NO_x$ emissions stringency options being considered for the CAEP/8. 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 Chapters 3 and 4, this chapter illustrates how the inclusion of health and welfare impacts through a cost-benefit analysis is a substantial improvement 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 has been 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 [55].
- $NO_x$ stringency analysis derived from several different models as compared to the CAEP/6 analysis which solely used the FAA Emission and Dispersion Modeling System 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 [145].
- 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 key 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. This information is then used by the FESG to develop future fleet and traffic forecasts and fleet retirement curves. 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 thesis. For additional details on the databases and assumptions used in the CAEP/8 $NO_x$ stringency analysis, the reader is referred to [145].

### 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 under consideration are shown in Table 6.1 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 6.1 also indicates the slope of the stringency limit when plotting $D_p/F_{oo}$ as a function of the overall engine pressure ratio for the large engines. The analysis presented in this chapter includes both small and large engines.

Environmental and economic results provided by the MODTF and the 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 using a cubic spline fit such that the policy and no stringency cases have identical noise and emissions inventories till the policy implementation year. For the purposes of this chapter, the most stringent scenario from the ten options listed in Table 6.1 is selected. The analysis presented later in this chapter compares the environmental benefits and economic costs of Scenario 10 relative to the no stringency case for both implementation years. Scenario 10 involves a 20% increase in stringency for all engines relative to CAEP/6 standards. Next, the FESG modeling process and assumptions for developing the future traffic and fleet forecast underlying the stringency options are discussed [145].

| **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 |

Table 6.1: CAEP/8 $NO_x$ stringency scenarios [145]

### 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, 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 the 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 [146].

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 [146].

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 [146].

It is important to note that the FESG fleet and traffic forecast used for the CAEP/8 $NO_x$ stringency analysis conducted in this thesis does not reflect the recent global economic downturn which is expected to dampen air traffic growth in the near future [11]. This FESG forecast was developed prior to the economic downturn in 2008 and was not revised to account for recent changes for the purposes for the $NO_x$ stringency analysis. However, the anticipated decline in growth does not impact the cost-benefit analysis methodologies presented in this thesis.

### 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 year 2006. The COD consists of detailed operations data for year 2006 based on information from EUROCONTROL's Enhanced Traffic Flight Management System, the FAA's Enhanced Traffic Management System and the International Offical 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 [145].

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 Procedure for the Calculation of Airplane Noise in the Vicinity of Airports, AIR-1845 [147] and the European Civil Aviation Conference Document 29 [14] in its methodologies. AEDT/MAGENTA provides results in the form of population exposure to and noise contours for 55, 60, and 65 dB DNL noise levels for 210 airports worldwide.

Emissions modeling is broken down 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 and full mission emissions are provided by the AEDT/System for assessing Aviation's Global Emissions. 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. A brief description of the AEDT tool can be found in Appendix A. 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 [145].

While emissions and noise data are provided on a global basis, for the analysis presented in Section 6.3 US-centric results are utilized given 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 [145]:

1. 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.

2. 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.

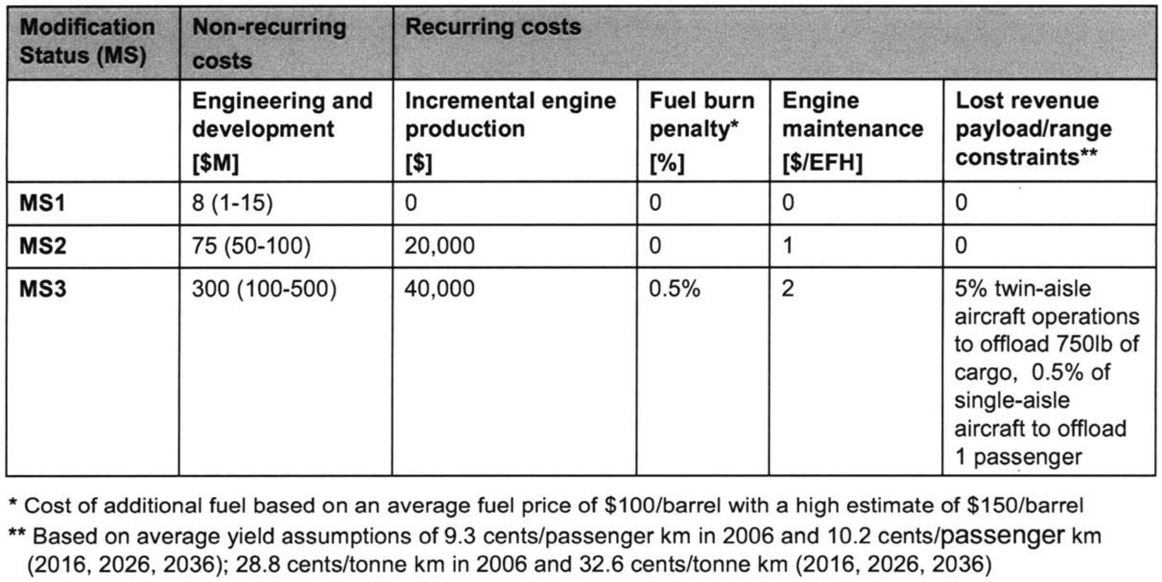
3. MS3 – New Technology Applying Combustor from Research Programs

   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 atleast 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 6.4.2 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 any double-counting in the economic analysis.

Table 6.2 lists the different cost categories by the different MS levels [148] 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 presented in this thesis are shown in Table 6.2. The FESG also plans to include additional costs impacts such as costs from having additional spare engines, and loss in fleet value for affected engines in their $NO_x$ stringency cost-effectiveness analysis for CAEP/8. 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. However, at the time of this analysis, those data were not available and were therefore not included in the cost estimates.



| **Modification Status (MS)** | **Non-recurring costs** | **Recurring costs** | | | |
|---|---|---|---|---|---|
| | **Engineering and development [\$M]** | **Incremental engine production [\$]** | **Fuel burn penalty* [%]** | **Engine maintenance [\$/EFH]** | **Lost revenue payload/range constraints**** |
| **MS1** | 8 (1-15) | 0 | 0 | 0 | 0 |
| **MS2** | 75 (50-100) | 20,000 | 0 | 1 | 0 |
| **MS3** | 300 (100-500) | 40,000 | 0.5% | 2 | 5% twin-aisle aircraft operations to offload 750lb of cargo, 0.5% of single-aisle aircraft to offload 1 passenger |

* Cost of additional fuel based on an average fuel price of \$100/barrel with a high estimate of \$150/barrel

** Based on average yield assumptions of 9.3 cents/passenger km in 2006 and 10.2 cents/passenger km (2016, 2026, 2036); 28.8 cents/tonne km in 2006 and 32.6 cents/tonne km (2016, 2026, 2036)

Table 6.2: Costs of CAEP/8 $NO_x$ stringency options [148]

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 6.2 and a range provided in parentheses [148].

2. **Recurring costs**

   There are four different cost categories included under recurring costs as shown in Table 6.2. 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). Increased maintenance costs for the modified engines with increased complexity are listed as costs per engine flight hour in Table 6.2. 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 [148].

## 6.2 APMT Modeling Assumptions

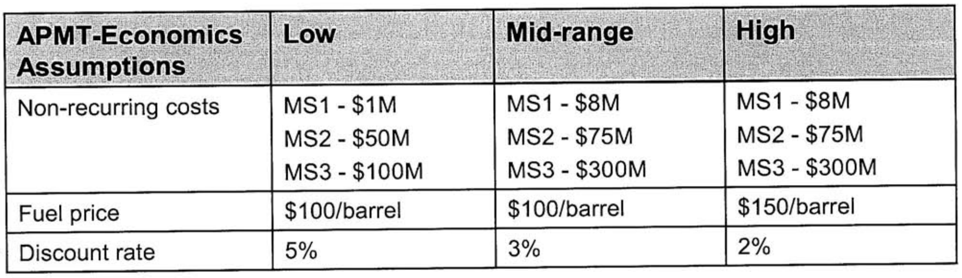
Section 6.1 discussed modeling assumptions upstream of APMT within the CAEP analysis groups; here a description of modeling assumptions within APMT-Economics and APMT-Impacts is provided. The APMT $NO_x$ stringency analysis presented in this thesis is limited to US-related impacts given the geographic 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 economic 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 investigating the uncertainties in the CAEP/8 modeling process described in Section 6.1 is constrained by 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 Chapter 5.

This section describes the lenses selected for conducting a cost-benefit analysis using the APMT model (see Chapter 5 for a discussion on the lens concept). Three different lenses capturing low, mid-range, and high impact estimates are presented for both APMT-Impacts and APMT-Economics, where low, mid-range, and high input and model parameter assumptions in each impact category are grouped together. Also presented is an illustrative lens that makes first order estimates of air quality and climate impacts not currently modeled using detailed methods in APMT. The lenses selected for the purposes of the CAEP/8 $NO_x$ stringency analysis serve as sample lenses that limit the results discussion to a few analysis perspectives and highlight the main features of the approach. However, one can envision several different lenses for conducting any given policy assessment, for instance, lenses can be defined based on different combinations of low, mid-range, and high assumptions for the impact areas.

### 6.2.1 APMT-Economics

The APMT-Economics results presented in Section 6.4 have been provided by MVA Consultancy, UK. Inputs to the APMT-Economics Module include operations data from the AEDT Fleet and Operations Module and technology response and cost assumptions from the CAEP Working Groups. As mentioned earlier in Section 6.1.1, this chapter analyzes Scenario 10 from the CAEP/8 scenarios for both 2012 and 2016 implementation years. The analysis presented here is focused on US-related impacts where US-related is defined as flight operations having the US as a destination or origin point. Table 6.3 lists the key assumptions for APMT-Economics for the low, mid-range, and high lenses. Only those assumptions that differ among lenses are shown in Table 6.3; the remaining cost assumptions are set as defined in Table 6.2. Sections 6.4.2 and 6.4.3 explore the variability in outputs attributed to the APMT-Economics lens assumptions from Table 6.3.

The mid-range lens uses central cost assumptions shown in Table 6.2 with a discount rate of 3%. The low lens uses low range non-recurring engineering and development cost assumptions with a discount rate of 5%, while the high lens corresponds to a higher fuel price and a 2% discount rate. Estimated costs are expressed as changes in producer and consumer surplus attributed to the implementation of the policy measure relative to the no stringency case. Changes in producer surplus include policy costs borne by manufacturers and airlines, while changes in consumer surplus measure policy costs borne by consumers. Producer surplus for manufacturers includes non-recurring engineering and development costs; producer surplus for airlines incorporates recurring costs associated with revenue loss from changes in the payload-range capability. The other recurring cost categories listed in Table 6.2, namely, the engine production costs, fuel costs, and engine maintenance costs are passed on from manufacturers to operators through engine price changes and from airline operators to passengers through airfare changes. APMT-Economics assumes that 100% of these three recurring cost categories are passed on to consumers. Furthermore, this analysis also assumes that air travel demand is completely inelastic such that passengers continue to travel despite fare changes with no impacts on demand. This assumption is reasonable for cases where fare increases are minor as in this analysis.



| APMT-Economics Assumptions | Low | Mid-range | High |
|---|---|---|---|
| Non-recurring costs | MS1 - \$1M<br>MS2 - \$50M<br>MS3 - \$100M | MS1 - \$8M<br>MS2 - \$75M<br>MS3 - \$300M | MS1 - \$8M<br>MS2 - \$75M<br>MS3 - \$300M |
| Fuel price | \$100/barrel | \$100/barrel | \$150/barrel |
| Discount rate | 5% | 3% | 2% |

Table 6.3: APMT-Economics CAEP/8 $NO_x$ stringency assumptions

### 6.2.2 APMT-Impacts

This section describes the high, mid-range, and low lenses within APMT-Impacts. Tables 6.4, 6.5, and 6.6 show the lens assumptions for the Noise, Air Quality, and

Climate Modules respectively. The illustrative lens analyzes the $NO_x$ stringency options assuming conservative upper bound estimates for air quality and climate impacts. More specifically, the illustrative lens seeks to capture effects currently not modeled in APMT with detailed methods which include air quality health impacts from cruise emissions and spatial heterogeneity of aviation climate impacts. Air quality health impacts of cruise emissions are approximated by scaling the results provided by Barrett et al. [40]. The spatial heterogeneity of short-lived climate effects of aircraft emissions is accounted for by considering aviation impacts only in the northern hemisphere as described in Chapter 4. For details on the selection of key parameters for the different lenses see Chapter 5. Chapters 3 and 4 provide relevant information on the inputs and model parameters for the APMT-Impacts Modules.

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.

| Noise Assumptions | Low | Mid-range | High |
|---|---|---|---|
| Noise Depreciation Index (NDI) | 0.56% (mean - std) | Normal distribution<br>mean = 0.6651%, std = 0.104% | 0.77% (mean + std) |
| Background noise level | 55 dB | Triangular distribution<br>(mode = 52.5, range = 50-55) dB | 50 dB |
| Housing growth rate | Historic distribution (mean shift -2%) | Historic distribution | Historic distribution (mean shift +2%) |
| Significance level | 65 dB | 55 dB | 55 dB |
| Contour uncertainty | -2 dB | Triangular distribution<br>(mode = 0, range = -2 to 2) dB | 2 dB |
| Discount rate | 5% | 3% | 2% |

Table 6.4: APMT-Impacts Noise assumptions for the CAEP/8 $NO_x$ stringency analysis

| **Air Quality Assumptions** | **Low** | **Mid-range** | **High** |
|---|---|---|---|
| Population growth | No growth | US Census estimate | 2 x US Census estimate |
| Emissions multipliers<br>1. Fuel burn<br>2. SOx<br>3. NOx<br>4. Non-volatile PM | 1. 0.92<br>2. 0.0066 (5th percentile)<br>3. 0.83<br>4. 0.52 | 1. Uniform [0.92 1.12]<br>2. Weibull [mean = 0.0627, std = 1.2683]<br>3. Uniform [0.83 1.23]<br>4. Uniform [0.52 2.06] | 1. 1.12<br>2. 0.154 (95th percentile)<br>3. 1.23<br>4. 2.06 |
| Adult premature mortality CRF | 0.6 | Triangular distribution<br>(mode = 1, range = 0.6-1.7) | 1.7 |
| Value of a statistical life | $2.9 M (US 2000)<br>90% CI lower | Lognormal distribution (US 2000)<br>mean= $6.3M, std = $2.8M | $12 M (US 2000)<br>90% CI upper |
| Discount rate | 5% | 3% | 2% |

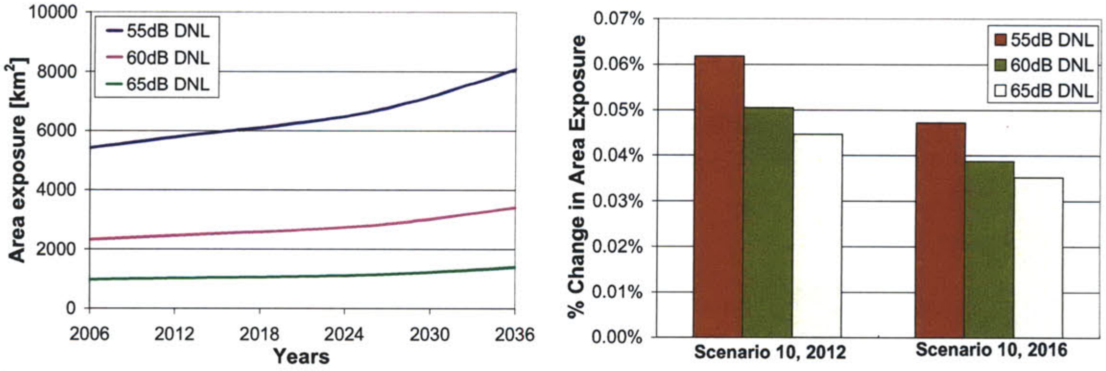
Table 6.5: APMT-Impacts Air Quality assumptions for the CAEP/8 $NO_x$ stringency analysis

| **Climate Assumptions** | **Low** | **Mid-range** | **High** |
|---|---|---|---|
| Climate sensitivity | 2K | Triangular distribution (mode, range)<br>[3.0, 2.0-4.5] K | 4.5K |
| NOx-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, 0] mW/m$^2$ | Triangular distribution (mode, range)<br>[30 (0 - 50), -3.5 (-10 - 0), 2.5 (0 - 10), 2.0 (0 - 6.0), 10 (0 - 30)] mW/m$^2$ | [50, 80, -10, 10, 6, 30] mW/m$^2$ |
| Background scenario | IPCC SRES A1B | IPCC SRES A1B | IPCC SRES A1B |
| Aviation scenario | CAEP/8 scenario | CAEP/8 scenario | CAEP/8 scenario |
| Damage coefficient | ½ x DICE-2007 | Discrete uniform distribution (DICE-2007, 2 x DICE 2007, ½ DICE-2007) | 2 x DICE-2007 |
| Discount rate | 5% | 3% | 2% |

Table 6.6: APMT-Impacts Climate assumptions for the CAEP/8 $NO_x$ stringency analysis

## 6.3 AEDT Noise and Emission Inputs

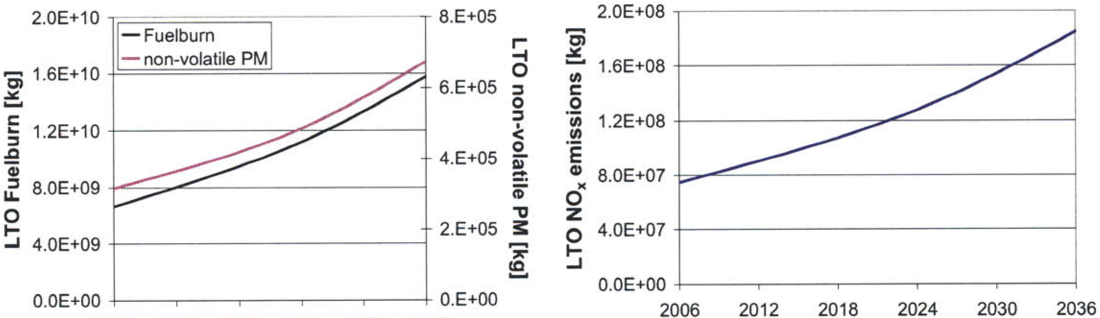
AEDT noise inputs for this analysis are noise contours around 91 US airports expressed in terms of the average day-night noise level at the 55dB, 60dB, and 65dB levels. These US airports are a part of 185 AEDT/MAGENTA Shell-1 airports worldwide that account for 91% of total global noise exposure (102 of the Shell-1 airports are located in North America). [149]. Figure 6-2a shows the growth in total area exposure to aircraft noise at three noise levels from 2006-2036 for the unconstrained baseline case. Figure 6-2b 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 6-2a 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 6-2b. As expected, the Scenario 10 option implemented in 2012 is seen to have a greater noise penalty as compared to the 2016 implementation option.



(a) Baseline yearly area exposure to aircraft noise (b) %Δ area exposure to aircraft noise summed over 30 years

Figure 6-2: AEDT noise inputs for the $NO_x$ stringency analysis

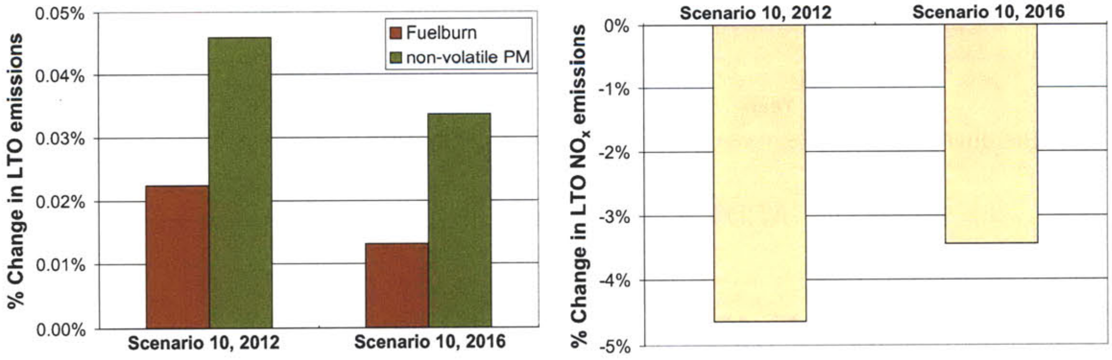
AEDT inputs to the APMT-Impacts Air Quality Module include fuel burn and emissions of $NO_x$, $SO_x$, and non-volatile PM below 3000 feet for the landing and takeoff flight segments. Growth in future emissions for the baseline case is shown in Figures 6-3a and 6-3b while Figures 6-4a and 6-4b show changes in total landing and takeoff (LTO) emissions for Scenario 10 relative to the baseline summed over the policy period. Air quality emissions inputs for 313 US airports are incorporated in this analysis. Similar to trends in aircraft noise, LTO emissions are seen to grow in the future for the baseline case. Fuel burn, non-volatile PM, $SO_x$ emissions are greater for Scenario 10 relative to the baseline as a result of the MS3 fuel burn penalty. $SO_x$ emissions scale directly with fuel burn with an emissions index (EI) of 1.1712 g/kg fuel burn based on a fuel sulfur content of 600ppm. Reductions in $NO_x$ emissions and increases in fuel burn and other emissions are greater for the policy option implemented in 2012.



(a) Baseline yearly LTO fuel burn and non-volatile PM

(b) Baseline yearly LTO $NO_x$ emissions

Figure 6-3: AEDT baseline air quality inputs for the $NO_x$ stringency analysis



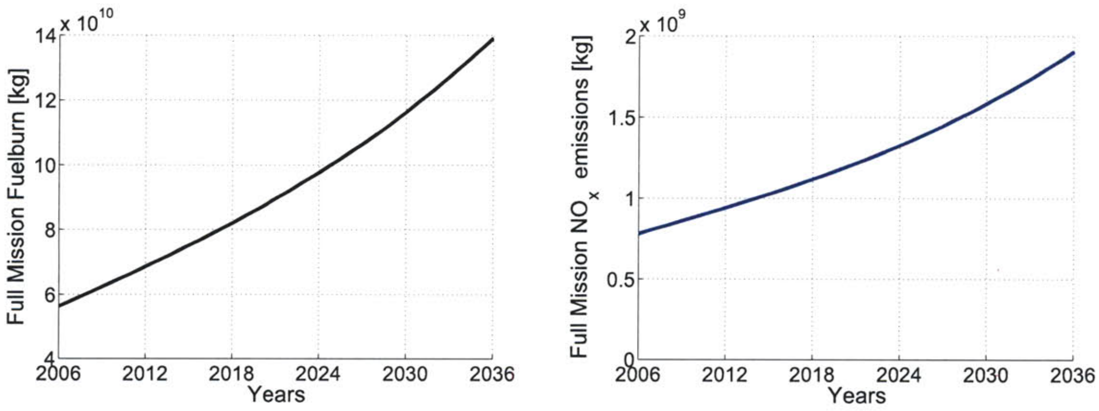
(a) %Δ LTO fuel burn and non-volatile PM

(b) %Δ LTO $NO_x$

Figure 6-4: AEDT policy air quality inputs for the $NO_x$ stringency analysis summed over 30 years

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

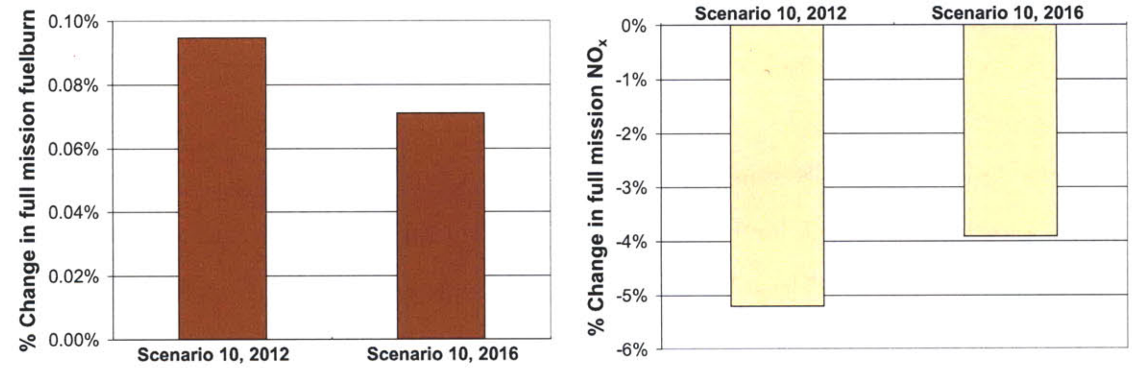
3155g/kg fuel burn and are not present here. Figure 6-5a and 6-5b show the temporal trends in full mission fuel burn and $NO_x$ respectively for the baseline scenario reflecting growth in operations. AEDT results for full mission emissions are provided for North America and US emissions have been scaled from AEDT results assuming that US operations account for roughly 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 [150]. Figures 6-6a and 6-6b show the differences in Scenario 10 emissions relative to the baseline case. The MS3 fuel penalty drives fuel burn increases in Scenario 10 while increased engine $NO_x$ stringency lowers $NO_x$ emissions.



(a) Baseline yearly full mission fuel burn

(b) Baseline yearly full mission $NO_x$

Figure 6-5: AEDT baseline climate inputs for the $NO_x$ stringency analysis



(a) %Δ full mission fuel burn

(b) %Δ full mission NO$_x$ emissions

Figure 6-6: AEDT policy climate inputs for the NO$_x$ stringency analysis summed over 30 years

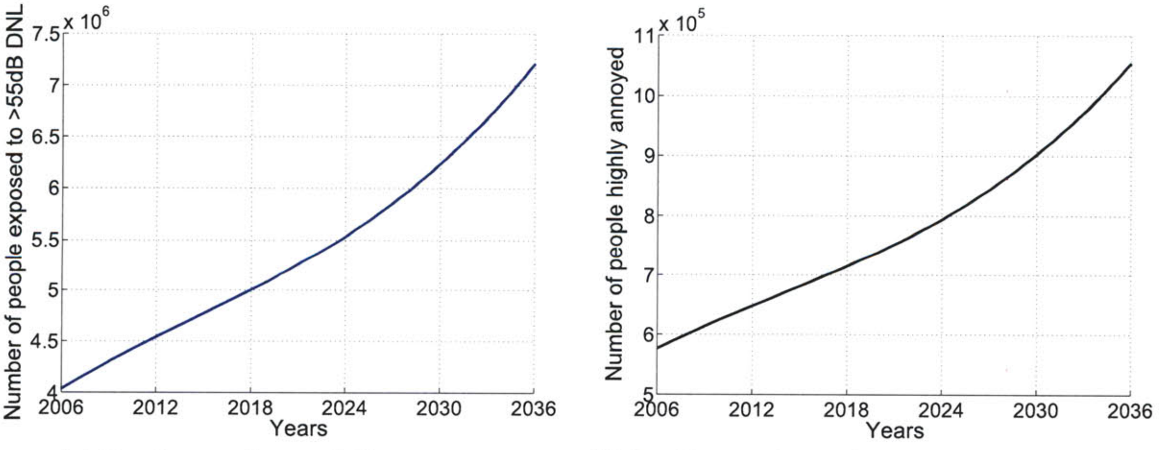
## 6.4 Results

The goal of the policy analysis presented in this section is to examine the environmental benefits and economic costs of Scenario 10 options relative to the baseline no stringency case. First the baseline temporal trends in noise, air quality, and climate impacts in physical metrics are presented in Section 6.4.1. 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 Scenario 10 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 Baseline Results

The baseline results provided are for the mid-range lens assumptions and model parameters presented in Section 6.2.2. First this section presents physical impacts of noise in terms of number of people exposed to noise levels of 55dB DNL and above and number of people highly annoyed. Figures 6-7a and 6-7b show temporal trends in baseline physical impacts. 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 and highly annoyed by aircraft noise.

Baseline air quality impacts expressed in terms of incidences of premature mortality attributed to exposure to aircraft particulate matter emissions are shown in Figure 6-8. Only the incidences of premature mortality attributed to particulate matter are presented as they constitute more than 95% of the total monetized air quality health impacts [32]. 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 elemental carbon or soot, sulfates, and organics. Note that the apportionment determined by the APMT-Impacts Air Quality Module does not include the EPA-SMATing process or particle-bound water as discussed in Chapter 3 and this may significantly alter the distribution of impacts across the different species placing more emphasis on sulfates as compared to nitrates [39].



(a) Baseline yearly population exposure (b) Baseline yearly number of people highly annoyed

Figure 6-7: $NO_x$ stringency - baseline yearly noise physical impacts

Figure 6-9 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 $NO_x$-$O_3$ 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 6-9 persist for several centuries past the last of the scenario.

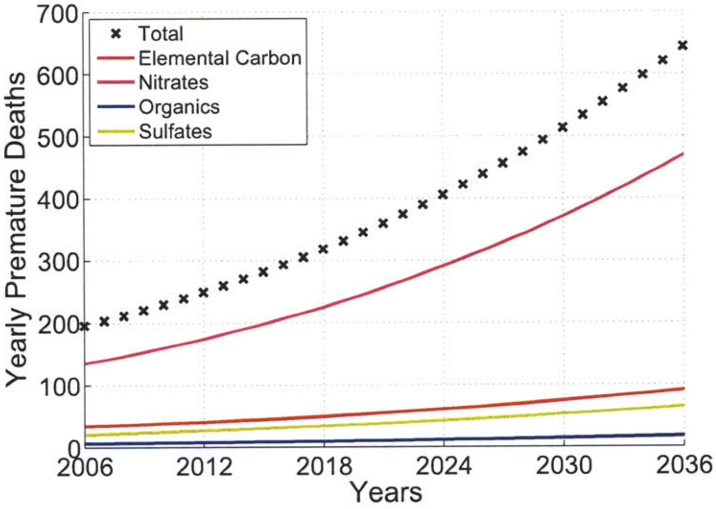


Figure 6-8: $NO_x$ stringency - baseline yearly air quality physical impacts

Figures 6-7 through 6-9 indicate that growth in operations will lead to increasing environmental impacts in the future in the absence of any mitigative environmental policies. As seen in Section 6.3, implementation of the $NO_x$ stringency Scenario 10 options leads to decreases in $NO_x$ emissions, and increases in fuel burn and area exposure to aircraft noise. The next section examines how these changes in fleet noise and emissions performance relate to changes in noise, air quality, and climate impacts. However, it is not possible to directly compare aviation-related noise, air quality, and climate impacts given the disparate nature of impacts and different timescales involved. This motivates the need for adopting a common metric to enable a comparison not only of all the environmental benefits of a policy measure but also of the economic costs incurred by producers, operators, and consumers. The next section presents an aggregated cost-benefit analysis comparing the environmental benefits and economic costs of Scenario 10 options relative to the baseline case using monetization methods described in Chapters 3 and 4.

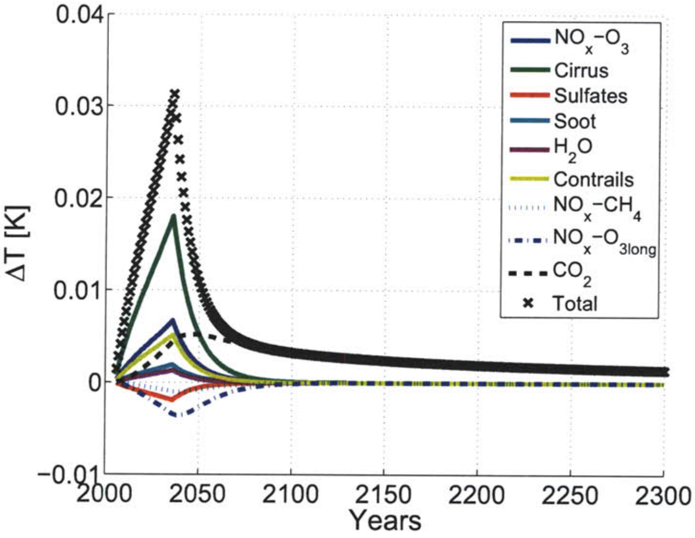


Figure 6-9: $NO_x$ stringency - baseline yearly climate physical impacts

### 6.4.2 Cost-Benefit Analysis

The results presented here employ the mid-range lens assumptions presented in Sections 6.2.1 and 6.2.2 for both environmental and economic impact assessment. Monetized environmental impacts along with industry impacts in terms of producer and consumer surplus for the mid-range lens are shown in Figure 6-10. The results in Figure 6-10 represent the difference between Scenario 10 and the baseline case. The net impact for monetized results is calculated by summing the three environmental impacts: noise, air quality, and climate, with the two economic impacts: consumer and producer surplus. The uncertainties for the environmental impacts are estimated through Monte Carlo methods. Details on the treatment of uncertainties in the different APMT modules can be found Chapter 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 and standard deviation of the net impact. The height of the bars indicates the mean value and the error bars represent one standard deviation. Note that Figure 6-10 presents policy minus baseline results and therefore a positive change is considered detrimental while a negative change is seen as being beneficial. The two different bar colors correspond to the two options within Scenario 10 – one with implementation in year 2012 and the second option with an implementation year of 2016.

The MS3 noise penalty leads to increased area exposure and correspondingly population exposure for the stringency option as shown in Figure 6-2a. However, as seen in Figure 6-10, the housing and rental value impacts are minor when compared to air quality and climate impacts. The primary environmental tradeoff in implementing the $NO_x$ stringency scenario under consideration is between reduced air quality and increased climate impacts. Reductions in air quality impacts are from lower $NO_x$ emissions and therefore lower nitrates formation. Higher climate impacts are a result of the MS3 fuel burn penalty that leads to increased warming from $CO_2$ and short-lived climate effects. While there are reductions in full mission $NO_x$ emissions for Scenario 10, there are no reductions in climate impacts since at the globally-averaged scale the warming $NO_x$-$O_3$ effect roughly balances the $NO_x$-$CH_4$-$O_3$ cooling effect. Consequently, the increased warming from higher fuel burn for Scenario 10 outweighs the $NO_x$ climate effects leading to detrimental climate impacts.

Economic costs are separated into producer surplus changes for manufacturers and airlines and consumer surplus impacts with a positive change indicating detrimental changes or increased costs. Manufacturer producer surplus changes arise from non-recurring engineering and development costs for producing engines that comply with the increased $NO_x$ stringency for Scenario 10. The airlines producer surplus changes or increased costs are from revenue loss resulting from operations with decreased payload-range capability as described in Section 6.1.5. Finally, other recurring costs such as incremental manufacturing costs, fuel costs, and engine maintenance costs are passed on to consumers through fare increases and are expressed as changes in consumer surplus. For mid-range assumptions, Figure 6-10 shows that stringency costs are split approximately evenly between consumer impacts and total producer impacts.

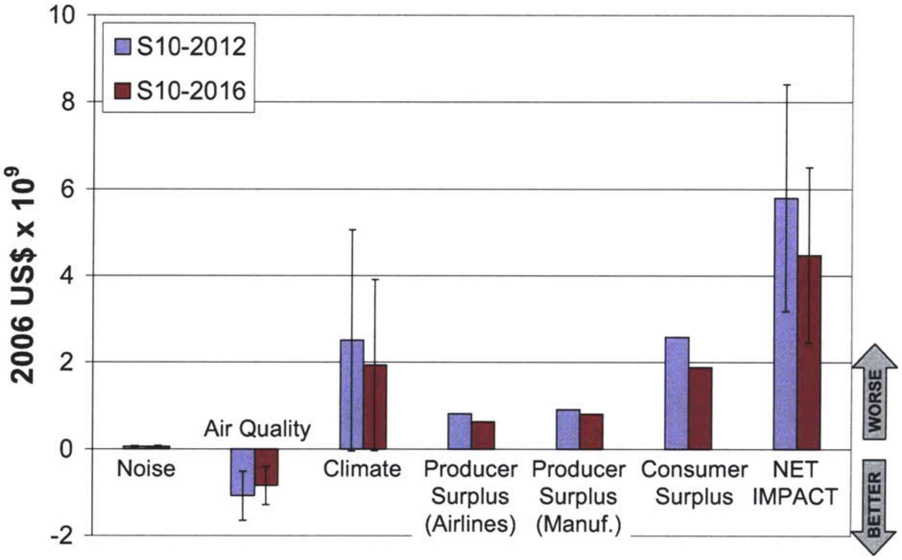


Figure 6-10: $NO_x$ stringency Scenario 10 minus Baseline impacts, mid-range lens assumptions

Figure 6-10 indicates that for mid-range inputs and model parameters, implementation of the Scenario 10 options 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 the Scenario 10 option relative to the baseline case. Scenario 10 implemented in 2012 has a mean net impact of roughly \$6 billion (US 2006), while an implementation year of 2016 has an impact of approximately \$4.5 billion (US 2006). The results indicate that the impacts of the 2012 implementation option are more detrimental relative to the 2016 option with greater than 99% probability. This assessment is based on the output distributions of the two policy impact results assuming statistical independence. Note that these conclusions are based on results from the mid-range lens; the next section explores the sensitivity of 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 two aspects – variability in results depending on selection of inputs and model parameters within APMT and from effects not currently captured by APMT. The first source of variability is explored using the low and high lenses described in Section 6.2. The second source of variability is expressed by making first order estimates of important effects described in the literature but not captured by detailed models in APMT; this assessment also identifies areas of future work for APMT.

Figure 6-11 presents results for the low lens while Figure 6-12 shows results for the high lens. Similar to the mid-range lens results presented in the previous section, net impacts for both the low and high lens assumptions indicate detrimental impacts associated with the implementation of the Scenario 10 options relative to the baseline case. However, the magnitude of the net impact varies significantly and the contributions of the different environmental and economic impact areas are also different in comparison to the mid-range lens. Note also, the one-sigma uncertainty bounds on the low and high lenses are narrower in comparison to that of the mid-range lens as some inputs are fixed at their low or high bounds as opposed to being sampled from a distribution. For instance as shown in Table 6.6, climate sensitivity is fixed as 2K for the low lens and at 4.5K for the high lens, but is sampled from a triangular distribution for the mid-range lens.

The low lens assumptions lead to air quality and climate impacts of opposite but comparable magnitudes; noise impacts are approximately three orders of magnitude lower and are therefore not visible in Figure 6-11. Consumer surplus impacts dominate the total economic impacts for the low lens since the low lens assumptions involve lower engineering and development costs for the manufacturers, but retain all other assumptions from the mid-range lens. Overall, incremental economic costs of Scenario 10 are seen to make a greater contribution to the net policy impact as compared to environmental impacts. Lower impact estimates for all impact categories for the low lens arise not only from using lower-bound estimates of input parameters but also from a higher discount rate of 5% which reduces the monetized value of future impacts. The net impact of Scenario 10, implemented in 2012 is seen to be approximately \$2.4 billion (US 2006) while that of implementation year 2016 is \$1.8 billion (US 2006). The net policy impact of the 2012 implementation option is greater than that of the 2016 implementation with greater than 99% probability.

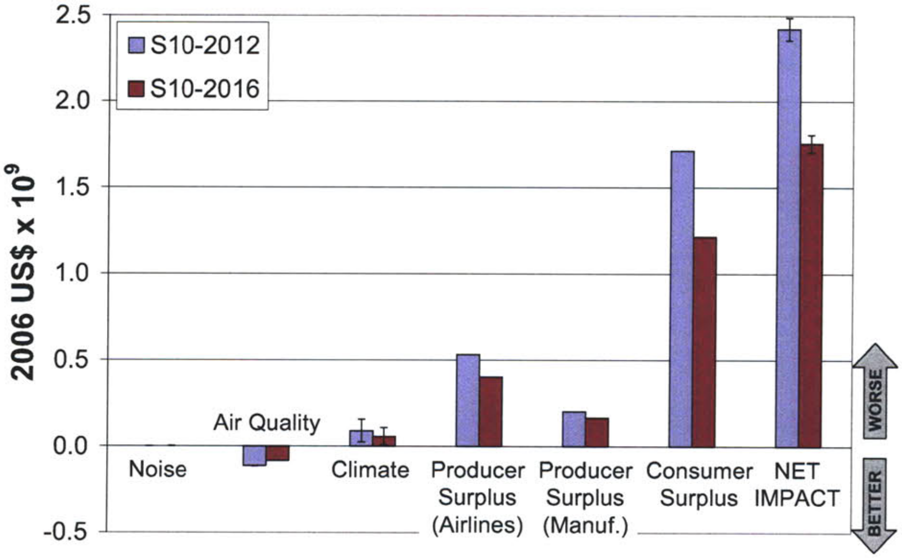


Figure 6-11: $NO_x$ stringency Scenario 10 minus Baseline impacts, low lens assumptions

The high lens results shown in Figure 6-12 also indicatesS net detrimental impacts of approximately \$21 billion (US 2006) and \$17.5 billion (US 2006) associated with implementing Scenario 10 options in years 2012 and 2016 respectively. Again the policy impact of the 2012 option is seen to be greater than that of the 2016 option with greater than 99% probability. Environmental impact categories are seen to make a large contribution to the net impacts of the policy options. The net impacts are largely driven by high-end assumptions about climate impacts and the use of a low discount rate which places greater value on future impacts relative to the mid-range lens. Economic costs are borne mostly by consumers as the high fuel price assumption for the high lens results in recurring airline costs that passed on through fare changes. Airlines also face increased costs through greater losses in revenue for operations with reduced payload-range capability.

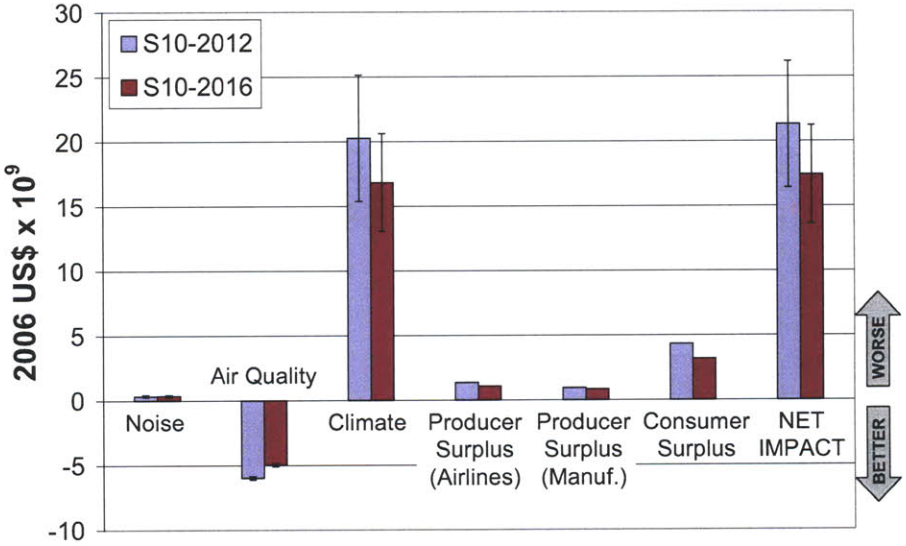


Figure 6-12: $NO_x$ stringency Scenario 10 minus Baseline impacts, high lens assumptions

The final lens results presented in Figure 6-13 are meant to be illustrative of the magnitude of key effects not currently accounted for by detailed models in APMT-Impacts for air quality and climate. As such, they represent simplified first order estimates and should be interpreted as conservative upper bound estimates for air quality and climate impacts. All other impact categories, namely, noise and economic costs are based on the mid-range lens assumptions. Air quality impacts include both LTO and cruise emissions and are determined by scaling the mid-range lens impact estimate by a factor of 4. This scaling is based on an upper bound estimate of aviation premature mortality effects by Barrett et al. [40] for US health impacts resulting from LTO and cruise emissions from US operations. Climate impacts are presented for a simplifying assumption of limiting the impacts of short-lived effects from US operations to regions of maximum aviation activity, that is, the north hemisphere. Chapter 4 provides a detailed discussion of this simplifying assumption which allows for an estimation of non-uniform hemispherical effects of aviation activity. This estimate is obtained by scaling the short-lived effects by a factor of 2 to account for area weighting. Since APMT-Impacts provides globally-averaged impacts, by assuming that all short-lived effects are confined to the north hemisphere, a first order estimate of north hemisphere impacts can be made by multiplying the globally-averaged results by 2. This is a highly simplified estimation of the heterogeneity of aviation climate impacts; however, it provides a means for exploring the importance of the assumption of spatial homogeneity currently employed in APMT. As mentioned previously, globally-averaged impact estimates do not capture the greater warming effect experienced in the north hemisphere as shown by several studies [114, 131].

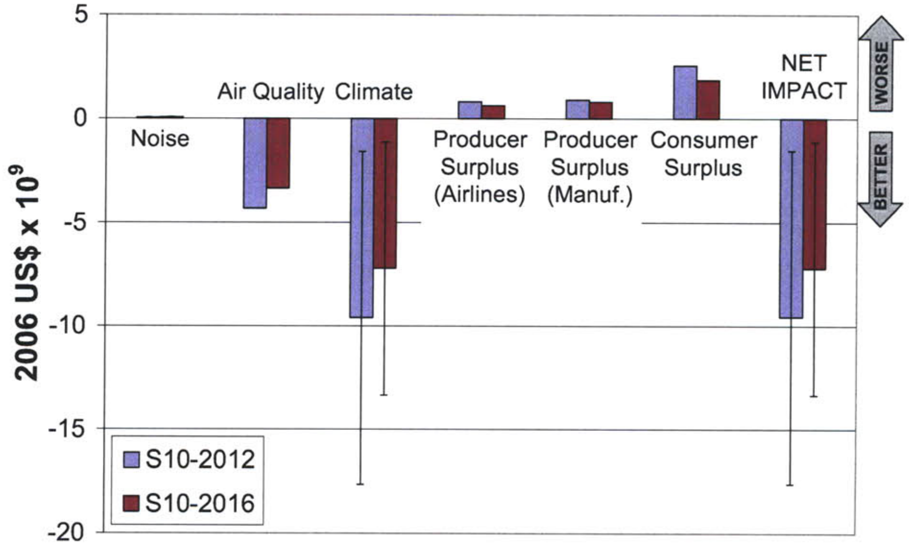


Figure 6-13: $NO_x$ stringency Scenario 10 minus Baseline impacts, mid-range lens with conservative upper bound assumptions for air quality and climate impacts

Figure 6-13 indicates that these upper bound conservative estimates for air quality and climate impacts significantly alter the results of the policy analysis. Most notably, the net impact of implementing Scenario 10 options relative to the baseline are seen to be beneficial. Results indicate that the impacts of the 2012 option are more beneficial relative to the 2016 option with greater than 90% probability. Reductions in air quality impacts upon the incorporation of cruise emissions impacts fall in the range between mid-range and high lens estimates provided in the previous section. Climate impacts in the north hemisphere show a net reduction from the reduction of $NO_x$ emissions despite the MS3 fuel penalty. If only the AQ cruise emissions impacts are considered keeping all other impact categories at the mid-range level, the $NO_x$ stringency policy options would still indicate a net detrimental impact. On the other hand, if conservative climate impacts are considered while maintaining all other impacts as mid-range, the net impact of the Scenario 10 options is seen to be beneficial. These illustrative set of assumptions highlight the importance of addressing key model limitations within APMT.

Two of these limitations, namely, air quality impacts of cruise emissions and spatial heterogeneity are explored through this illustrative lens. Another effect currently not included in APMT methods that may impact the outcome of this analysis is the EPA-SMATing process which may alter the distribution of mortality impacts across PM species. As discussed in Chapter 2, the US EPA-SMATing process shifts the distribution of impacts such that a large fraction of impacts are attributed to sulfates; this may lower the benefits realized from increased $NO_x$ stringency. Second, inclusion of health costs associated with increased population exposure to noise may increase monetized impacts of noise from the MS3 noise penalty. Finally, the FESG is expected to include additional costs such as costs from having additional spare engines, and loss in fleet value for affected engines in their $NO_x$ stringency cost-effectiveness analysis for CAEP/8, which will increase the costs estimates presented here.

| **APMT-Impacts Assumptions** | **Implementation Year** | **Noise (2006 US\$x$10^9$)** | | **Air Quality (2006 US\$x$10^9$)** | | **Climate (2006 US\$x$10^9$)** | |
|---|---|---|---|---|---|---|---|
| | | **mean** | **std** | **mean** | **std** | **mean** | **std** |
| Low | 2012 | -3.6E-04 | 3.6E-04 | -0.11 | 1.1E-03 | 0.09 | 0.07 |
| | 2016 | 8.8E-05 | 3.7E-04 | -0.08 | 8.2E-04 | 0.06 | 0.05 |
| Mid-range | 2012 | 0.05 | 0.02 | -1.1 | 0.57 | 2.5 | 2.6 |
| | 2016 | 0.06 | 0.02 | -0.8 | 0.44 | 1.9 | 2.0 |
| High | 2012 | 0.33 | 0.09 | -6.0 | 0.13 | 20 | 4.9 |
| | 2016 | 0.34 | 0.08 | -5.0 | 0.10 | 17 | 3.8 |
| Illustrative air quality and climate impacts | 2012 | 0.05 | 0.02 | -4.3 | 0 | -9.6 | 8.0 |
| | 2016 | 0.06 | 0.02 | -3.4 | 0 | -7.2 | 6.1 |

Table 6.7: APMT-Impacts results for the CAEP/8 $NO_x$ stringency analysis

The lenses described in this section and associated results are summarized in the tables presented below. First, Table 6.7 provides noise, air quality, and climate impacts and uncertainties for the low, mid-range, high, and illustrative lenses described previously. Next, Table 6.8 lists low, mid-range, and high estimates of changes in producer and consumer surplus from implementing the policy scenarios. Finally, Table 6.9 provides the net cost-benefit impacts of the two policy scenarios under consideration along with uncertainty estimates.

| APMT-Economics Assumptions | Implementation Year | Producer Surplus (Airlines) | Producer Surplus (Manufacturer) | Consumer Surplus |
|---|---|---|---|---|
| | | | (2006 US$x10$^9$) | |
| Low | 2012 | 0.53 | 0.20 | 1.7 |
| | 2016 | 0.40 | 0.17 | 1.2 |
| Mid-range | 2012 | 0.82 | 0.91 | 2.6 |
| | 2016 | 0.63 | 0.81 | 1.9 |
| High | 2012 | 1.4 | 0.95 | 4.4 |
| | 2016 | 1.1 | 0.88 | 3.2 |

Table 6.8: APMT-Economics results for the CAEP/8 $NO_x$ stringency analysis

| APMT-Impacts Assumptions | APMT-Economics Assumptions | Implementation Year | Cost-Benefit Net Impacts (2006 US$x10$^9$) | |
|---|---|---|---|---|
| | | | mean | std |
| Low | Low | 2012 | 5.8 | 2.6 |
| | | 2016 | 4.5 | 2.0 |
| Mid-range | Mid-range | 2012 | 21 | 4.9 |
| | | 2016 | 17 | 3.8 |
| High | High | 2012 | 2.4 | 0.1 |
| | | 2016 | 1.8 | 0.1 |
| Illustrative air quality and climate impacts | Mid-range | 2012 | -9.6 | 8.0 |
| | | 2016 | -7.2 | 6.1 |

Table 6.9: APMT cost-benefit results for the CAEP/8 $NO_x$ stringency analysis

### 6.4.3 Cost-Effectiveness Analysis

This section shifts the presentation of results from a economic costs and environmental benefits framework to the conventional CAEP approach of cost-effectiveness analysis.

Cost-effectiveness results are provided for the low, mid-range, and high cost assumptions listed in Table 6.3. 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. This ratio is provided in Figure 6-14 for both Scenario 10 policy options. The cost-effectiveness results for the low, mid-range, and high analysis assumptions are also listed in Table 6.10.

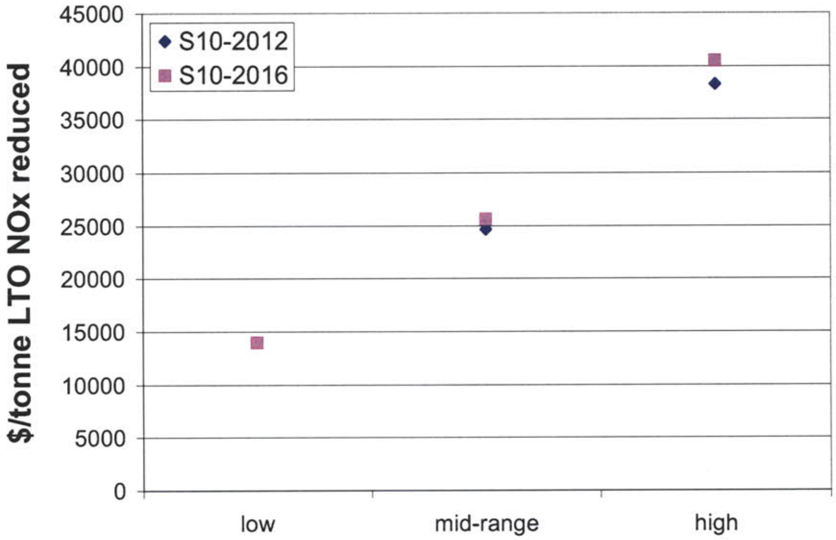


Figure 6-14: NO$_x$ stringency Scenario 10 cost-effectiveness results

| APMT-Economics Assumptions | Implementation Year | Net costs | Change in LTO NO$_x$ | Cost-effectiveness |
|---|---|---|---|---|
| | | (2006 US$x10$^9$) | (tonnes) | (2006 US$/tonne NO$_x$) |
| Low | 2012 | 2.4 | -130000 | 14000 |
| | 2016 | 1.8 | -175000 | 14000 |
| Mid-range | 2012 | 4.3 | -175000 | 25000 |
| | 2016 | 3.3 | -130000 | 26000 |
| High | 2012 | 6.7 | -175000 | 38000 |
| | 2016 | 5.3 | -175000 | 40000 |

Table 6.10: APMT cost-effectiveness results for the CAEP/8 NO$_x$ stringency analysis

The 2012 implementation year option is seen to be marginally more cost-effective than the 2016 option for high and mid-range cost assumptions. The two options are indistinguishable under low cost assumptions. Based on this information the Scenario 10 option implemented in 2012 appears to the policy of choice. However, this analysis conveys no information about health and welfare impacts of reductions in $NO_x$ emissions and if the costs incurred are justified in terms of expected environmental benefits. The cost-effectiveness analysis also does not provide a distributional breakdown of economic costs across producers, operators, and consumers. When cost-benefit results from Section 6.4.2 are examined, neither options seem desirable given net detrimental impacts relative to the baseline case for all three lenses. Therefore, 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 as compared to measuring benefits in terms of changes in $NO_x$ emissions. The cost-benefit analysis despite the uncertainties in impact estimates relays more relevant information about the potential impacts of the $NO_x$ stringency options in terms of different environmental and economic impact categories and therefore provides a more comprehensive assessment of the policy options under consideration.

## 6.5 Key Policy Insights

Having provided both cost-benefit and cost-effectiveness assessments of the CAEP/8 $NO_x$ stringency Scenario 10 options, this chapter concludes with reflections on key policy and analysis insights. First, it should be noted that only two of the 20 CAEP/8 $NO_x$ stringency scenarios are considered in the analysis presented in this chapter, so one should not interpret the conclusions presented here as the conclusions for CAEP/8 policy decisions. Rather, the intention is to highlight the benefits and challenges of moving from a cost-effectiveness framework to a cost-benefit framework, and the two CAEP/8 scenarios analyzed are meant to serve as an illustrative example. Also, the FESG forecast underlying the CAEP/8 $NO_x$ stringency scenarios analyzed in this chapter does not reflect the decline in aviation activity following the recent global economic downturn; however, changes to the FESG forecast are not expected to affect the cost-benefit analysis methodologies presented here. The following discussion first presents conclusions on the economic costs and environmental benefits of the policy scenarios as evaluated through the analysis presented in this chapter. Second, the key differences between the cost-benefit and cost-effectiveness analysis are discussed.

Economic cost and environmental benefit evaluation in Section 6.4.2 indicates that for low, mid-range, and high lens assumptions the stringency scenario shows detrimental net impacts relative to the baseline case. Reductions in air quality impacts from LTO $NO_x$ reductions are outweighed by other environmental impacts and economic costs. The magnitude of net impacts and distribution across impact categories varies by lens assumptions. For the low, mid-range, and high lenses the net impact of the 2012 stringency option is greater than that of the 2016 option with greater than 99% probability. These results are strongly driven by CAEP assumptions about noise and fuel burn penalties and costs incurred by manufacturers, operators, and consumers. Section 6.4.2 also presents an illustrative analysis that makes first order conservative upper bound estimates of health impacts of cruise emissions and spatially heterogeneous aviation climate impacts from short-lived effects. This illustrative lens demonstrates that based on a conservative first order analysis, the stringency scenario may result in air quality and climate benefits that outweigh the noise penalty and economic costs leading to a net beneficial impact of the policy scenarios. The main purpose behind this illustrative lens presentation is to highlight areas of modeling limitations within APMT that have significant impacts on the policy analysis outcomes. The cost-effectiveness analysis presented in Section 6.4.3 shows that for all lens assumptions, Scenario 10 implemented in 2012 is more cost-effective. The cost-effective analysis identifies the policy scenario which achieves LTO $NO_x$ reductions for least costs.

As discussed in Chapter 2, while the cost-effectiveness approach allows for a selection among different policies based on a measure of which policy achieves a given objective for the least cost, it does not assess whether the costs incurred are justified in light of the benefits expected. In the case of the $NO_x$ stringency analysis reductions in LTO $NO_x$ alone are not a sufficient measure of benefits expected given the complex mechanisms through which $NO_x$ emissions lead to both air quality and climate impacts. The cost-effectiveness analysis also does not directly take into consideration tradeoffs with noise and climate impacts as a decision criterion. The MS3 fuel burn tradeoff is indirectly accounted for by incorporating increased fuel costs in the cost-effectiveness analysis but the environmental impacts of increased fuel burn are not considered. Ranking policies based on cost-effectiveness would result in the selection of the Scenario 10 option implemented in 2012 as the policy of choice. However, the cost-benefit assessment for low, mid-range, and high lens assumptions indicates that neither policy options result in net beneficial impacts. Thus, the decision outcome regarding the same policy scenarios differs depending on the analysis approach taken. The cost-benefit analysis presents a more comprehensive assessment of the given policy by identifying the different impact categories for the given policy. The results of this chapter indicate that a cost-effectiveness approach alone does not provide all the relevant information essential for understanding the potential environmental and economic impacts of policy measures.

The trends in uncertainties in impact estimates observed through this analysis also correspond to the discussion provided in Section 2.2.2 through Figure 2-5. Uncertainties in impact estimates are seen to grow as one proceeds from looking at differences between baseline and policy emissions inventories or noise contours to changes in environmental and economic impacts. However, uncertainties in understanding environmental and economic effects associated with the different scenarios decrease when one considers both physical and monetized impact estimates as opposed to only looking at inventory-level results. This work shows that incorporating information about economic costs and environmental benefits will improve the decision-making process for aviation environmental policies by providing more complete information to policymakers and other stake-holders. In some cases, the 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.

# Chapter 7

# Conclusions and Future Work

The primary focus of this work was to identify key shortcomings in current decision-making practices for aviation environmental polices and 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. A separate component of this work contributed to advancing aviation climate impact modeling capabilities within APMT. An uncertainty analysis for the APMT-Impacts Climate Module was presented and issues in communicating key results and uncertainties from a complex policy analysis tool were also discussed. This chapter offers concluding thoughts based on the work presented in this thesis and identifies opportunities for future work.

## 7.1 Summary and Conclusions

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 the 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 major shortcomings of the CAEP cost-effectiveness analysis approach. As demonstrated by the CAEP/6 $NO_x$ stringency analysis, CEA does not reveal whether anticipated benefits from the policy exceed the costs incurred.

In practice, the CEA approach is often preferred 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 upcoming eighth meeting of ICAO-CAEP in 2010 was presented to demonstrate the CBA approach and provide a comparison between CBA and CEA outcomes. While the FESG forecast used for modeling future aviation activity for the CAEP/8 $NO_x$ stringency analysis did not reflect the recent global economic downturn, the cost-benefit modeling methodologies presented in this thesis are not affected by changes in the aviation forecast. 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 thesis.

A separate component of this thesis focused on advancing aviation climate impact assessment methods within APMT. Major contributions towards assessing aviation climate impacts in APMT include: improved characterization of uncertainty for

$NO_x$-related effects and for aviation climate damages, introduction of a reduced-order methodology for assessing climate impacts of methane emissions from the processing of alternative jet fuels, and comparison and validation of APMT results with external sources. APMT validation exercises focused on $CO_2$ and $CH_4$ impacts, $NO_x$ global warming potentials, and damage estimates and indicated that APMT results are in agreement with other climate impact assessments in the literature. An uncertainty assessment of the updated APMT-Impacts Climate Module was also presented as a part of this thesis. Climate sensitivity and RF from short-lived effects were found to be the most significant contributors to uncertainty in temperature change estimates based on a global sensitivity analysis for the baseline case. Global and local sensitivity analysis indicated that the net present value of baseline climate damages was most sensitive to assumptions about the discount rate, damage function, climate sensitivity, and RF from short-lived effects. For the policy impact of the Scenario 10 $NO_x$ stringency option implemented in 2012, the $NO_x$ RF and related efficacies were also significant contributors to uncertainty in both temperature change and NPV of climate damages along with other key model parameters.

This work 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. More specifically, three sample lenses estimating low, mid-range, and high impacts were defined for the purposes of this analysis. The environmental benefits and economic costs associated with the CAEP/8 Scenario 10 options relative to the baseline case were analyzed for the US. The Scenario 10 policy scenarios represent a 20% increase in $NO_x$ stringency relative to CAEP/6 standards with two different implementation years – 2012 and 2016. Both policy and baseline scenarios were modeled for 30 years of aviation activity extending over the period from 2006 to 2036. The $NO_x$ stringency Scenario 10 involved reductions in LTO and full mission $NO_x$ mission with an associated fuel burn and noise penalty. Environmental impacts were modeled using APMT-Impacts in physical and monetary impacts. Economic costs were modeled as changes in producer surplus for manufacturers and airlines and in consumer surplus resulting from increased costs for complying with the increased stringency levels.

CBA results for all three lenses indicated that reductions in air quality impacts from lower Scenario 10 $NO_x$ emissions were outweighed by detrimental effects in other environmental and economic impact categories leading to net detrimental impacts from the policy relative to the baseline. Net impacts of the policy scenario were estimated by summing impacts in all categories and results were presented with uncertainty bounds. Mean net impacts for the 2012 implementation year ranged from approximately \$2.4 – \$21 billion (US 2006) while those for the 2016 implementation ranged from roughly \$1.8 – \$17.5 billion (US 2006). The 2012 implementation option showed greater net impacts as compared to the 2016 option for the low, mid-range, and high lenses with greater than 99% probability. Here a positive impact indicated a detrimental effect while a negative impact referred to a beneficial effect. The CBA was also conducted for an illustrative lens that made first order estimates of physical effects not captured by detailed models in APMT. These physical effects included air quality impacts of cruise emissions and spatial heterogeneity of short-lived climate impacts. Incorporation of these effects led to a net beneficial impact from the increased $NO_x$ stringency. The illustrative lens was primarily used to demonstrate the significance of current modeling limitations within APMT and identify areas of future work.

CBA results for Scenario 10 options were also compared with CEA results. CEA results identified the 2012 implementation policy to be more cost effective as compared to the 2016 option. While the CEA ranked one policy option to be more cost-effective, it does not take into consideration any environmental tradeoffs or health and welfare impacts of the $NO_x$ reductions and therefore does not indicate whether the costs incurred are justified in terms of benefits anticipated. The CBA assessed both environmental and economic impact categories and evaluated both policy options as having a net detrimental impact. Thus, the decision outcome regarding the same policy scenarios differed depending on the analysis approach taken. The CEA and CBA comparison presented in this thesis demonstrates the CBA approach to be more comprehensive and an improvement over the conventional CEA approach adopted for aviation environmental policies. Note that the CBA and CEA results are also strongly driven by CAEP/8 assumptions about technology response by engine manufacturers, cost of technology, and fuel burn and noise penalties. Results presented here represent a small subset of the CAEP/8 $NO_x$ stringency scenarios and should not be used for policy-making purposes. The next section discusses areas of future work as identified by this research.

## 7.2 Future Work

Three broad areas of future work have been identified here associated with APMT development, communication of results to decision-makers, and improvements to the cost-benefit analysis approach presented here. The policy analysis presented in this thesis identified some key modeling limitations within APMT. Areas of future work for the APMT Noise Module include estimating other supplemental impact metrics such as sleep disturbance and learning impairment, and adopting willingness-to-pay measures to quantify monetary impacts of aircraft noise. Future work for the Air Quality Module incorporates expanding the geographical scope of the model beyond the US, assessing health impacts of cruise emissions, and adopting the US EPA-SMATing process within the Air Quality Module. For the Climate Module, short-term research areas include incorporating altitude dependence for $NO_x$ and contrails effects and conducting comparisons with more complex climate models to improve characterization of uncertainties as well as test the robustness of the assumption of independence of effects. An important long-term research area for the APMT Climate module would involve implementing modeling approaches that enable a regional assessment of aviation climate impacts. For APMT-Economics, future developmental work involves expanding model capabilities to evaluate other categories of policy options including market-based measures.

The lens concept was introduced to facilitate communication of APMT results to decision-makers while enabling transparency into the inputs and model parameters that drive key outcomes for a given policy analysis. However, experience thus far in implementing the lenses for APMT analysis has indicated that the level of detail provided through the lenses may need to distilled further to improve communication with users unfamiliar with APMT. An important area of further research would be to investigate how cost-benefit information from APMT is received by users and incorporated in decision-making processes. This research into the applicability of APMT for decision-making purposes will provide valuable feedback for improving communication approaches for APMT.

The applicability of a cost-benefit approach was demonstrated here for a stringency policy, however, the same approach can also be employed for other categories of policy measures including operational and market-based measures. It is important to note that the policy under consideration may demand analysis of additional elements not covered by the cost-benefit analysis presented here. For instance, a policy introducing alternative jet fuels will require an estimation of infrastructure and processing costs of alternative fuels and environmental impacts of the well-to-tank emissions from processing the new fuels in addition to considering aircraft level impacts. Similarly, assessing market-based measures such as the EU ETS will require an expansion of the scope of the APMT economic analysis to include impacts on sectors other than the aviation industry. Finally, another aspect of future work for advancing the CBA approach presented here is to consider the distributional aspects of the costs and benefits of a proposed policy measure across stake-holders, which relates back to developing regional modeling capability in APMT.

# Appendix A

# The FAA-NASA-Transport Canada Aviation Environmental Tool Suite

The FAA-NASA-Transport Canada Aviation Environmental Tool Suite consists of two other tools – the Aviation Environmental Design Tool (AEDT) and the Environmental Design Space (EDS) in addition to the Economics and Impacts Modules of the Aviation environmental Portfolio Management Tool. Here the AEDT and EDS are described as they interface with APMT in the broader context of conducting comprehensive policy analyses.

Modeling approaches and assessment efforts vary across the different modules of the tool suite as they entail different modeling domains. AEDT provides APMT with noise and emissions inventories while EDS conducts detailed aircraft and engine analyses, providing technology and cost tradeoffs. APMT is also capable of accepting inputs from other emissions and noise inventory tools, and also of accepting alternative aircraft and engine technology assumptions (in place of those provided by EDS). Integrating APMT, AEDT and EDS enables aviation-related environmental impact assessment at the global, regional, and local-airport spatial scales.

The flow of information within the tool suite is as follows. The APMT-Economics module produces future fleet and operations scenarios and associated costs and revenues in the aviation market for cases with and without policy intervention. It takes inputs from the Forecasting and Economic Sub-Group (FESG) within CAEP on future demand and capacity requirements, and from EDS or industry sources on the nature of available future replacement aircraft. It provides detailed flight schedules to AEDT based on different policy and market scenarios and fleet information. AEDT then computes noise and emissions inventories at the local and global levels based on inputs from APMT-Economics. Alternatively, APMT-Economics can use external forecasts of future aviation activity and compute the costs incurred by the producers, operators and consumers. The APMT-Impacts module uses noise and emissions inventory data from AEDT to calculate environmental impacts in physical and monetary metrics. This process is conducted for the baseline, unregulated scenario, as well as for the scenario with a proposed policy measure. The difference between these two cases gives the marginal impacts of a policy scenario relative to the baseline case for aviation activity.

The modular framework of the EDS-AEDT-APMT tool suite enables independent, stand-alone functionality for the three tools and sub-modules within the tools. Depending on user needs, APMT-Economics and APMT-Impacts can be decoupled from each other and simulations can be conducted that provide economic or environmental impacts separately. For instance, as noted above, APMT-Impacts is capable of accepting emissions and noise inventories generated by external tools other than AEDT. A modular setup also facilitates updates to all sub-modules as more information becomes available without affecting the overall tool architecture. Next, a brief description of the AEDT and EDS tools is provided.

## A.1 Aviation Environmental Design Tool

The Aviation Environmental Design Tool (AEDT) aims to provide an integrated aviation noise and emissions estimation capability at the local and global levels for the international fleet. AEDT provides the capability for estimating emissions not only from aircraft but also from other airport sources such ground support equipment, on-road vehicles and stationary sources using publicly available and internationally recognized methods. Common modules and databases within AEDT enable the assessment of interdependencies between emissions and noise effects by integrating existing tools. The existing tools include the Integrated Noise Model (INM), the Emissions and Dispersion Modeling System for local noise and emissions analysis respectively and the Model for Assessing Global Exposure from Noise of Transport Airplanes and the System for assessing Aviation's Global Emissions for global noise and emissions analysis respectively [151, 152, 153]. These legacy tools are in the process of being integrated into a set of five main modules that forecast fleet operations and conduct noise, emissions and performance calculations – the Fleet and Operations Module, the Aircraft Acoustics Module, the Aircraft Emissions Module, the Aircraft Performance Module and the Emissions Dispersion Module. These modules interface with a common set of databases including the Airports, Fleet, Movements, and the FESG Retirements-Replacements-Growth databases.

The AEDT models aircraft emissions including carbon dioxide ($CO_2$), water vapor ($H_2O$), sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), total hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) for all flight segments. $CO_2$, $H_2O$, and $SO_x$ are scaled relative to fuel flow using constant emissions indices while $NO_x$, CO, and HC are calculated using the Boeing Fuel Flow Method 2 (BFFM2) [154]. PM below 3000 ft is calculated using the First Order Approximation version 3 (FOA3) [155] while PM above 3000 ft is calculated using constant emissions indices. Noise computation in AEDT includes exposure-based, maximum noise level, and time-above specified noise level metrics based on INM version 7 methods. The AEDT System Architecture document [156] provides further information on the AEDT framework and component modules, while the AEDT $NO_x$ Demonstration Analysis report [157] illustrates how the modules and databases work together through a sample analysis.

## A.2 Environmental Design Space

Aircraft and engine level design trade-offs are estimated by the Environmental Design Space (EDS) tool using non-proprietary methods. EDS estimates source noise, emissions, performance, and vehicle cost characteristics for existing and future aircraft.

EDS captures future aircraft technology trends either by considering new aircraft designs or by incorporating new technology on existing aircraft based on extensive input from industry experts. AEDT receives input on vehicle characteristics such as performance, noise and emissions from EDS while APMT-Economics receives information on vehicle cost parameters and performance. EDS provides estimates for existing vehicles as well as on potential future replacement aircraft. Alternatively, AEDT and APMT can use data directly provided by external sources such as the FESG or industry. EDS consists of five different modules for aircraft and engine performance and design analysis; the CMPGEN module, the Numerical Propulsion Systems Simulator (version 1.6.4), the Weight Analysis of Turbine Engines module, the FLight OPtimization System and the Aircraft NOise Prediction Program. Additional details on EDS methodology and capabilities can be found in [158].

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