An Assessment of Environmental Impacts of a NextGen Implementation Scenario and its Implications on Policy-making

by

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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Master of Science in Aeronautics and Astronautics at the

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Abstract

With demand for aviation projected to grow by 5% per year over the next 20 to 25 years, policy makers must not only consider ways to ensure that the air transportation system can accommodate significant growth, but also how their policy decisions will affect the environment. Because environmental issues are becoming increasingly apparent, the sustainability of policy measures will likely constrain responses to this potential increase in aviation demand. Policy makers will need to consider various trade-offs that come with policy decisions, and find ways to balance the demands of the air transport system with the need to reduce the environmental impact of aviation. This thesis assesses the environmental impacts of implementing a policy scenario, which employs both operational and technological improvements to the air transport system. The impacts are presented in both physical and monetary metrics using the Aviation environmental Portfolio Management Tool, to allow for a comparison of trade-offs among different environmental effects. This thesis discusses the limitations of this particular scenario, while also providing an overview of policy-making models, and the observed weaknesses in current policy-making processed involving technical data. In particular, it identifies the mismatch between needs of those involved in the policy-making process, and the information provided by analysts, which can be an obstacle to developing credible and objective support for a policy proposal. It finally provides suggested methods for improving the relationship between different groups involved in developing policy to allow for better informed decision-making, and a more fluid policy-making process.

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Chapter 1

Introduction

1.1 Background

In the last 35 years, the United States has seen a six-fold increase in the use of aviation for transportation purposes. Although fuel efficiency within this period has increased by 60%, and the number of people exposed to aircraft noise levels has decreased, the impact of aviation on the environment is expected to rise, with the projected 5% per year growth rate of aviation over the next 20-25 years [1] [2]. Preliminary analysis from the Committee on Aviation Environmental Protection (CAEP), within International Civil Aviation Organization (ICAO), an agency within the United Nations, estimates that global aviation fuel burn will rise from 190 mega tonnes (Mt) in 2006 to a likely range of 730 to 880 Mt in 2050 [3]. Likewise, without accounting for alternative fuels, carbon dioxide (CO₂) from aviation, which currently constitutes about 2% of the world’s CO₂, is expected to rise from 600 Mt in 2006 to a likely range of (2,300 to 2,800 Mt) in 2050 [3][4]. Within the US, to prepare for the expected growth in demand, which could severely strain the current air transport system and the environment, federal agencies are working together through the Joint Planning and Development Office (JPDO) to develop a nationally integrated plan to sustainably transform the US air transport system through improvements to operational procedures and aircraft technology. These plans will manifest themselves through the Next Generation Air Transport System.
Aviation’s effect on the environment has been a growing concern over the past 50 years both internationally, and in the US. Regulations governing aviation-related impacts on the environment began in the 1960’s through aircraft noise standards set by the ICAO and the US Federal Aviation Administration (FAA). Both organizations developed noise standards concurrently, with ICAO’s publication of Annex 16: Environmental Protection, Volume I - International Noise Standards, and the US FAA’s Federal Aviation Regulation (FAR) Part 36 [5] [6]. Standards for regulating aircraft emissions affecting air quality around airports were then set by ICAO Standards and Recommended Practices (SARPs) for aircraft emissions in the 1980s. Annex 16: Environmental Protection, Volume II - Aircraft Engine Emissions describes ICAO’s emissions standards for nitrogen oxides (NOx), hydrocarbons (HC), carbon monoxide (CO) and smoke [7]. To address concerns regarding the impact of aviation on climate, the ICAO established the Group on International Aviation and Climate Change (GIACC) in 2007. GIACC is tasked with developing plans and providing policy guidance for addressing aviation-related climate impacts [8]. In 2008, the European Commission amended a directive for greenhouse gas emissions allowance tradings to include emissions from aviation activities. This directive applies to flights arriving to and departing from European Union member states, and is to be fully implemented by 2012 [9].

Within the US, the Environmental Protection Agency (EPA) sets emissions standards for aircraft engines through the Clean Air Act (CAA), which was first established in the 1970s. The US FAA has the authority to enforce these standards and certify engines under the CAA [10]. Emissions standards set by ICAO have served as the basis of the US FAAs aircraft engine performance certification standards, which are established through EPA regulations [11]. To help bridge gaps in scientific understanding and address uncertainties in climate research, the FAA has established Aviation Climate Change Research Initiative (ACCRI), which will also support NextGen in achieving its environmental goals. Other organizations participating in ACCRI include the National Aeronautics and Space Administration
(NASA), the National Oceanic and Atmospheric Administration (NOAA), and the US EPA [12]. To inform future policy decision making, the EPA has also mandated that emissions data be collected from all heavy-duty engines, including those of aircraft, by 2011 [13].

1.2 Motivation

The challenge of sustainably transforming the air transport system, involves considering various operational and technological improvements, weighing the benefits and costs of these scenarios, and making decisions based on results that have ranges of uncertainty. Trade-offs within the environmental scope of the analysis add to the complexity of this decision-making process, which is also dependent on a range of other political factors. To assist policy makers in the decision-making process related to the environmental impacts of aviation, the Aviation environmental Portfolio Management Tool (APMT) is being developed as part of the aviation environmental tool suite of the Federal Aviation Administrations Office of Environment and Energy (FAA-AEE) [14]. APMT is used to assess environmental scenarios related to aviation in terms of both monetary and physical metrics, and to help policy makers evaluate the trade-offs between different environmental impacts. However, even with tools such as APMT, questions still remain as to how policy makers systematically manage and process this complex and large amount of information to make policy decisions. What are the limitations of the current policy-making process? What can be done to improve the process?

This thesis has two primary objectives. The first is to provide an assessment of environmental impacts under a particular NextGen implementation scenario. The second is to use this assessment and observations from the development of other environmental policies, to identify challenges and opportunities associated with the use of environmental impact assessments for aviation policy-making.
1.3 Thesis Organization

This thesis is composed of seven chapters, with a more detailed description of the content and structure described below.

Chapter 2
Chapter 2 provides an overview of current decision-making methods in developing aviation environmental policies, as well as the rules and regulations behind these methods. As motivation for the assessment of the NextGen scenario, Chapter 2 describes the goals and investment levels of the NextGen program, and discusses the environmental impacts of aviation on noise, air quality, and climate.

Chapter 3
Chapter 3 discusses the methods used in evaluating the monetary and physical environmental impacts of aviation. In particular, it describes the methods and the specific assumptions used in APMT for analyzing the NextGen scenario.

Chapter 4
The methods and assumptions used to generate the NextGen scenario are discussed in Chapter 4. The results of the scenario analysis, using methods from Chapter 3, are then presented and discussed. The final section highlights the observed reactions of those involved in the policy-making process to these results, which will provide motivation for the following chapters that analyze the formulation of policy that is based on technical information.

Chapter 5
To better understand the different methods of generating policy, Chapter 5 summarizes the methods and assumptions behind three policy-making models: the rational model, incrementalism, and the agenda building model. The observations from the NextGen policy-making process, along with other recent environmental policy-making developments are then related to these models to underscore the
framework for viewing the development of environmental policy.

Chapter 6
Chapter 6 focuses on the dynamics between different groups in their collaboration to formulate environmental policy. In particular, it describes the language barrier observed between those involved in the policy-making process and technical analysts due to the different roles that these groups assign to different communication tools. The issues with the NextGen policy scenario analysis that have been made clearer through the frameworks in Chapter 5, are also described, along with suggested methods of improving and smoothing the collaboration in developing environmental policy.

Chapter 7
Chapter 7 provides concluding remarks of this thesis, and highlights areas of further research.

1.4 Key Contributions

The contributions of this thesis are based on the application of APMT in assessing the sustainability of a particular NextGen scenario, as described below.

- An assessment of the environmental impacts of the implementation of a particular NextGen scenario, with a summary of the observed reactions to the results of this analysis, and the shortcomings of the NextGen scenario. To address these shortcomings, this thesis also provides a reanalysis of the scenario with assumptions that are more applicable to the objectives of the NextGen scenario.

- An application of frameworks for understanding the NextGen policy-making process, and for highlighting the weaknesses of the processes. This thesis comments on the observed relationship between policy makers and analysts.
It also defines the source of difficulties in the collaboration process between these groups, which can potentially hinder the policy-making process, as well as weaken the credibility of a policy.

- The development of suggested solutions to address these observed difficulties in developing policy, to make the policy-making process more fluid and systematic.
Chapter 2

Literature Review

This chapter discusses current decision-making methods used in formulating aviation environmental policies, and provides motivation for the following chapters which elaborate on these methods. Section 2.1 summarizes current practices used to evaluate environmental policy scenarios; section 2.2 reviews the current rules and regulations relevant to analyzing environmental policy scenarios and their application to aviation environmental policy; section 2.3 provides an overview of the Next Generation Air Transportation System (NextGen), and elaborates on the purpose, investment levels, and the application of environmental analysis to NextGen. The final section summarizes the environmental impacts of aviation on noise around airports, air quality, and climate.

2.1 Current Decision-making Practices for Aviation Environmental Policies

Environmental problems arise due to the lack of explicit valuation of resources, which individuals and firms consume without necessarily considering or fully accounting for the potential suboptimal effects of their usage. In making environmental policy decisions, environmental or resource economics can be useful, as it allows for an assessment of how people value the environment. This is necessary in
addressing resource and environmental problems, and correcting for the incentives that lead to the misusage of resources.

Environmental economics is a useful decision-making tool that provides methods of valuing various trade-offs between environmental and economic objectives. Trade-offs can arise, for instance, with new engine technology, which might reduce aircraft emissions, but lead to an increase in noise levels around airports. To facilitate the decision-making process, it is thus necessary to quantify these environmental objectives to allow for a direct comparison of trade-offs. Cost Benefit Analysis (CBA), Cost Effectiveness Analysis (CEA), and Distributional Analysis are common practices in achieving this.

CBA involves a comparison between the related costs and benefits of a policy measure, which are usually monetized. Ratios of benefits to costs are another method of expressing the results of CBA. It should be noted, however, that using these ratios to rank different options can lead to ambiguous results [14]. Cost effectiveness analysis, on the other hand, is appropriate when the benefits of candidate scenarios or policy measures are similar. In this case, implementation costs of the scenarios are compared, and the policy measure with the lowest cost is chosen. However, CEA can be misleading if there is a non-linear relationship between the physical intermediate benefits which are typically assessed, such as changes in emissions levels, and the ultimate health and welfare benefits [14]. Moreover, the most cost-effective option may be cost inefficient, as the costs may outweigh the benefits. 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 [15]. In many cases, it is also necessary to determine which sector of society is bearing the costs or the benefits of a policy measure. Distributional analysis would thus be needed to evaluate who is being affected.

Conducting analysis for aviation environmental regulation typically involves emissions inventories, which contain the amount of pollutants emitted in a given time period and area. Economic environmental analysis, using methods such as CBA, allows for policymakers to move a step beyond emissions inventories when
making policy decisions, and to consider more thoroughly the possible impacts of a particular policy on the environment. Cost benefit analysis, nonetheless, has often been criticized when applied to environmental policy, due to the monetization of environmental impacts, such as premature mortalities, health problems associated with air quality, damage to eco-systems from global warming, etc. Ethical questions arise as to whether or not dollar values should be assigned to non-market factors, such as human life or eco-systems. The US EPA, FAA, US Department of Agriculture, and the US Food and Drug Administration all employ some form of the value of statistical life (VSL) in conducting CBA, as it provides a way to compare governmental programs and regulations that involve the allocation of scarce resources for life-saving activities [16]. The VSL specifically allows for benefits from life-saving activities to be compared with the cost of the program. It should also be noted that the VSL used in environmental policy analysis is not assigned to any particular individual and is not based on any particular occurrence of mortality. It can thus be thought of as "a convenient way to summarize the value of small reductions in mortality risk" [16]. Moreover, if the value of a statistical life is not factored into environmental regulatory analysis, it is possible that an undesirably low number of lives would be saved from the policy being considered.

2.2 Rules and Regulations for Assessing Environmental Policy

Within the United States, it is required that benefits and costs be evaluated for all regulatory measures issued by federal agencies, as directed by executive orders and directives of the Office of Management and Budget (OMB)[17]. Although decisions no longer need to be made based on benefits outweighing costs, as originally required by Executive Order (EO) 12291, both quantitative and qualitative costs and benefits should be accounted for according to EO 12866 [18]. This EO requires a statement of the purpose for the proposed action is required, as well
as an examination of alternative approaches, and their associated distributional effects according to EO 12866[15]. To more thoroughly assess regulatory measures, the OMB specifies that both CBA and CEA should be conducted in rulemaking pertaining to health and safety [19].

The EPA continues to be the main governmental agency conducting environmental analysis for federal regulations within the United States. Much of the analysis is conducted under specific pieces of legislations such as the Clean Air Act (CAA). The same requirements mandated by executive orders and the OMB that apply to all federal agencies that conduct economic analysis for regulatory measures, also apply to the EPA. In 2000, the EPA established its own guidelines that are in accordance with executive orders and the OMB, which discuss in greater detail the procedure for conducting CBA, and other environmental economic practices [15].

2.2.1 Aviation Environmental Economic Analysis

The Office of Environment and Energy (FAA-AEE), within the Federal Aviation Administration, has been responsible for the development of several tools to assess environmental impacts of aviation, such as the Emissions and Dispersion Modeling System (EDMS), Model for Assessing Global Exposure to Noise from Transport Aircraft (MAGENTA), Integrated Noise Model (INM), System for Assessing Aviations Global Emissions (SAGE), and Screening Model for Airport Air Quality (SMAAQ). The FAA-AEE is also responsible for developing, recommending, and coordinating aviation policy within the US relating to the environment and energy [14].

The FAA is part of the Joint Planning and Development Office, which seeks to revamp the air traffic control system to accommodate the projected increase in demand, through The Next Generation Air Transportation System (NextGen). Although most of the analysis for NextGen does not incorporate economic analysis, some of the work does relate to the impacts of operational and technological improvement on the environment and the economy. The work presented in this thesis
is a component of the broader NextGen analysis effort.

2.3 The Next Generation Air Transport System

The Next Generation Air Transport System is a congressionally mandated program managed by JPDO to modernize the US air transportation system. Specifically, it is responsible for increasing capacity and reliability, improving safety and security, while also minimizing environmental impact [20]. This is in accordance with the Vision 100 Century of Aviation Reauthorization Act, which has allowed for the formation of JPDO, and hence the NextGen program [21]. NextGen improvements will manifest themselves through transformations from ground-based navigation and surveillance to space-based navigation and integrated surveillance, video radio control to digital data exchange, and through other mechanisms, such as digital communications, layered adaptive security, weather integrated into decision-making, advanced automation of Air Traffic Management, and net-centric information access for operations. NextGen is targeting a 40% to 60% increase in airport capacity by 2025 [20]. Because NextGen will involve large-scale changes to accommodate the anticipated increase in demand for air transport, the environment will inevitably play a significant role in terms of determining the feasibility of NextGen implementation options. In creating possible scenarios for NextGen, environmental targets are also taken into consideration. For instance, future individual aircraft, with new airframes, engines, and air traffic control, are anticipated to allow for a reduction in the number of people exposed to greater than 65 dB noise by 1% per year, a 30% to 40% decrease in fuel burn per flight, and a 60% to 75% reduction in landing and take-off NOx emissions per flight. Delays attributed to weather conditions are also planned to be reduced through NextGen improvements [22].

Since NextGen will require a large-scale transformation of the air transportation system, industry players who would be affected by these changes are also involved. The NextGen Institute serves as a mechanism for industry involvement, allowing industry to work with JPDO to define, develop, and implement NextGen [20].
Implementing NextGen by 2025 requires investments in areas of research, engineering, development, Air Traffic Organization capital appropriations, and avionics. It is estimated that for the first five years, the NextGen program will cost $4.6 billion. Long term estimates of cost are $8-10 billion in the next 10 years, and $15-22 billion in the end-state or through 2025. Avionics costs may also amount to $14-20 billion [20].

2.4 Environmental Impacts of Aviation

The structure and content in the following sections follow closely to that of Mahashabde [2] and the CAEP/8 NO\textsubscript{x} Stringency Cost-Benefit Analysis Demonstration using APMT-Impacts [23].

2.4.1 Noise Impacts

Since noise from aviation is the most easily perceived effect of aviation, complaints in local communities due to aircraft noise are more common than those of emissions or other environmental effects. Noise due to aviation primarily affects communities in close proximity to airports, with impacts that include annoyance, sleep deprivation, hypertension, etc. [24] Although noise around airports result from various sources, this section focuses on noise due only to aircraft, since airborne flight operations, which include landing and take-off, dominate the noise exposure around airports [25]. This section will first discuss common noise scales and metrics, and then provide a more detailed description of the impacts of aircraft-related noise.

Noise levels are usually expressed in units of decibels, and can applied in both single-event or cumulative metrics. Single-event metrics correspond to noise effects from a single aircraft movement, and are thus appropriate for measuring impacts such as sleep-awakenings [24]. These metrics include Maximum A-weighted Sound Level, Sound Exposure Level (SEL), and effective perceived noise level (EPNL). The A-weighted scale weights frequencies based on the frequency
response of the human ear, and is the more commonly used scale in noise assessments and in producing noise exposure area maps or contours. The sound exposure level is defined as the total noise energy for a single event. EPNL, which is the tone-corrected perceived noise level, takes the instantaneous perceived noise level, which is a pure tone that can be perceived by humans, and corrects for spectral irregularity using a tone correction factor [6].

Cumulative noise metrics aggregate or apply a time average to all single events from aircraft operations, and thus are more representative of airport activity than single-event metrics. These metrics include the equivalent sound level and the day-night average sound level (DNL). The equivalent sound level describes a constant sound level over a period of time that produces an equivalent amount of energy as the time-varying sound level during the given period of time. The DNL is the A-weighted equivalent sound level over a period of 24 hours, with 10 dB added during nighttime to account for increased sensitivity of people to noise at night. Since cumulative noise metrics aggregate noise events over a period of time, they are useful when evaluating long-term exposure to aircraft noise [24].

The impacts of short-term and long-term aircraft noise exposure, based on extensive studies, are found to include behavioral and physiological effects. Behavioral impacts consist of general annoyance, sleep disturbance, disruption of work performance and learning. Physiological impacts of aircraft noise include stress-related health effects, which range from hypertension, which has the strongest link to noise, to hormone changes, as well as mental health effects. Although evidence that aircraft noise causes annoyance, sleep disturbance, learning disruptions, and cardiovascular diseases is well documented, little evidence exists of environmental noise causing hormonal changes or psychiatric disorders [24].

2.4.2 Air Quality Impacts

Aircraft emissions affecting air quality are typically measured from operations below 3,000 feet, and include carbon dioxide (CO₂), which accounts for 70% of aircraft
emissions; water vapor (H₂O); nitrogen oxides (NOₓ); carbon monoxide (CO); sulfur oxides (SO₂); unburned hydrocarbons or volatile organic compounds (VOCs); particulates; and other trace compounds. H₂O makes up about 30% of aircraft emissions, and other species only about 1% of total emissions [11]. Under the Clean Air Act, the US EPA sets National Ambient Air Quality Standards (NAAQS) for six principal pollutants. These include CO, lead (Pb), nitrogen dioxide (NO₂), O₃, particulate matter (PM), and sulfur dioxide (SO₂). These pollutants are of interest because they are associated with adverse health impacts.

**Nitrous Oxides (NOₓ)**

NOₓ refers to NO or NO₂. NO₂ is linked to respiratory morbidity by the recent US EPA integrated science assessment of NO₂. However, it is not clearly understood if the link between NOₓ and respiratory morbidity is due solely to NO₂, or if NO₂ merely acts as a surrogate for impacts related to a different pollutant. NOₓ with other compounds can serve as a precursor to ozone. The formation of ambient PM through NOₓ as a precursor for other organic and inorganic oxidized nitrogen compounds, poses more significant health risks, which are described in more detail below.[26]

**Carbon Monoxide (CO)**

CO emissions are produced from incomplete combustion of fossil fuels. Health impacts caused by short-term and long-term exposure to CO include cardiovascular morbidity, central nervous system effects, birth outcomes and developmental effects, respiratory morbidity, and mortality. CO has the strongest causal relationship with cardiovascular morbidity. Other health effects are based on a suggestive causal relationship with CO; although there is inadequate evidence of CO-induced respiratory morbidity or mortality for long-term exposure [27].

**Sulfur Oxides (SO₂)**

Sulfur Oxides are produced through the combustion of sulfur-containing fuels,
and include sulfur dioxide (SO$_2$), sulfur trioxide (SO$_3$), and gas-phase sulfuric acid (H$_2$SO$_4$). The EPA has determined that short term exposure of 5 minutes to 24 hours of SO$_2$ is linked to a series of adverse respiratory effects including bronchoconstriction and increased asthma symptoms. An EPA Integrated Assessment concluded that sufficient evidence exists supporting the "causal relationship between respiratory morbidity and short-term exposure to SO$_2$" [28]. Among the sulfur oxides, SO$_2$ is the source of the greatest concern in terms of causing serious health impacts. Other gaseous SO$_2$ components exist in smaller concentrations in the atmosphere. Since the formation of SO$_2$ also leads to the formation of other SO$_x$ species, SO$_2$ is used as an indicator by the EPA for the larger group of gaseous sulfur oxides. The reaction of SO$_2$ and other compounds in the atmosphere, leads to the formation of particulate matter, which also causes serious health impacts. These particles can penetrate deeply into the lungs, causing or worsening respiratory diseases, such as emphysema and bronchitis, and possibly aggravating existing heart disease. These effects can lead to increased hospital admissions and premature mortalities [28].

**Particulate Matter (PM)**

Fine particles or particulate matter emissions (PM$_{2.5}$) from aircraft have a diameter of less than 2.5 μm, and are produced as direct emissions in the form of non-volatile PM, and through secondary PM formation. Secondary PM makes up the larger portion of aircraft-sourced PM, and is the result of precursor emissions, which include NO$_x$, SO$_x$, and hydrocarbons in the form of ammonium sulfates and ammonium nitrates [2]. The US EPA, under the Clean Air Act currently maintains the National Ambient Air Quality Standard for PM2.5 at 15 μg/m$^3$ [29]. The EPA uses the high fidelity Community Multiscale Air Quality (CMAQ) simulation system to model changes in ambient PM2.5 as part of its regulatory analysis of impacts. PM impacts are largely regional, with aircraft emissions contributing to a less than 0.1% increase in annual PM concentrations. This result was based on the Energy Policy Act study on emissions below 3,000 ft, at 325 US commercial airports or 95% of US operations that have filed flight plans, from June 2005 to May 2006.
Exposure to PM$_{2.5}$ can lead to serious health problems, as these particles can enter a person's lungs. These problems may include increased respiratory symptoms, decreased lung function, aggravated asthma, chronic bronchitis, heart attacks, and premature mortality in those with heart or lung disease [29]. The EPA models health impacts using the Environmental Benefits Mapping Program (BenMAP) [31]. The Energy Policy Act study, using BenMAP, estimates that PM from aviation leads to 64 to 270 annual premature deaths [32]. Several studies suggest that the health impacts of PM are more significant than those of other aircraft pollutants. Although most analyses of air quality impacts of aviation pollutants are measured from take-off and landing of aircraft, studies are also showing that cruise emissions may contribute significantly to health impacts [33]. Future assessment of aviation related air quality health impacts may need to incorporate emissions from all stages of flight to have a complete analysis of impacts [2].

### 2.4.3 Climate Impacts

Assessments of climate impacts from aviation generally are based on emissions from all stages of flight. The discussion in this section pertains to commercial subsonic aviation, which is comprised of aircraft that fly typically at an altitude of 9 to 13 km, or in the upper troposphere and lower stratosphere. According to the Intergovernmental Panel on Climate Change (IPCC), emissions from aircraft and other anthropogenic sources affect climate through changes in radiative forcing (RF), as these pollutants modify the atmospheric composition of gases and aerosols [34]. Radiative forcing refers to changes in the radiative balance of the earth’s climate system due to anthropogenic activities. It is specifically defined by the IPCC as a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system [34]. Three types of processes that affect the atmospheric balance include the emission of “radiatively active substances,” such as CO$_2$; the emission of species that react with these “radiatively
active substances,” such as NO, which affects ozone concentration; and the emission of substances that allow for the formation of aerosol particles or clouds [35]. Aviation-related climate impacts vary spatially and in time. The following is a discussion of aircraft emissions that affect climate. It should be noted that the current level of understanding of the effects of these emissions varies.

**Carbon Dioxide (CO₂)**
CO₂ has a net warming effect through a positive radiative forcing, with impacts that are spatially homogeneous and that last on the order of centuries [35].

**Water Vapor (H₂O)**
H₂O also has a net warming effect, with impacts that last on the order of days. H₂O emissions from subsonic aircraft in the troposphere and lower stratosphere do not have a large effect relative to other aviation emissions, unlike those that would be emitted by supersonic aircraft at higher cruise altitudes [35].

**Nitrogen Oxides (NOₓ)**
NO and N₂O, collectively known as NOₓ, have two effects on the atmosphere. In the upper troposphere and lower stratosphere, an increase in NOₓ can lead to a rise in ozone (O₃), which has a warming effect. NOₓ also produces OH radicals that lead to greater oxidative capacity of the atmosphere. This causes the destruction of CH₄, which decreases ozone, both leading to a cooling effect. The effect of NOₓ on the atmosphere is strongly dependent on background concentrations of NOₓ and HOₓ, which includes OH and HO₂, and seasonal variation of insolation [35]. These effects vary spatially and temporally, as the short-lived warming effect from the production of O₃ from NOₓ lasts on the order of a few months, while that of the reduction of O₃ from lower CH₄ concentrations lasts for decades [2]. Although when globally averaged, these counterbalancing effects amount to a net impact of almost zero radiative forcing. Regionally, however, there is a strong variation in the effects of NOₓ on RF [2].
Sulfate Aerosols and Particulate Matter
Atmospheric reactions with aerosols have a cooling effect, as they involve the reduction of NO\textsubscript{x} and HO\textsubscript{x}, which can cause a decrease in ozone. A cooling effect is also generated through reflective properties of sulfate aerosols with sunlight. On the other hand, particulate matter which is comprised of soot or black carbon has a warming effect through its absorption of sunlight.

Indirect effects of aerosols from aircraft emissions on naturally occurring clouds are still the subject of scientific study due complexities associated with processes such as ice-cloud nucleation and the alteration of microphysical properties of cirrus clouds. Given present knowledge, these uncertainties are considered to be significant [35].

Carbon Monoxide (CO) and Volatile Organic Compounds (VOCs)
Aviation CO emissions and VOCs from unburned hydrocarbons are found to have a negligible effect on climate. The low impact of CO is also due to the small amount of CO emitted in the atmosphere by aircraft compared to other sources of CO [35].

Contrails and Induced Cirrus
Contrails are visible line clouds that form behind aircraft during flight due to water vapour emissions. Persistent contrails can develop into artificially induced cirrus clouds that are comprised of ice crystals, with properties that are dependent on the physics of ice particle nucleation. The mechanism through which ice formation occurs is highly dependent on relative humidity and temperature. Both contrails and aviation-induced cirrus produce a net warming effect in the atmosphere, with the effect from contrails persisting for hours, and that of cirrus lasting from hours to days [35].
Chapter 3

Methods for Assessing Trade-offs Among Aviation Environmental and Economic Impacts

Much of the text in this chapter paraphrases the work of Mahashabde [2] and the CAEP/8 NOx Stringency Cost-Benefit Analysis Demonstration using APMT-Impacts [23]. To better understand the impacts of aviation on the environment, and to facilitate decision-making, research tools are being developed largely by two major research groups: 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 for Excellence is comprised of members of academia, and is supported by the US Federal Aviation Administration, the National Aeronautics and Space Administration, and Transport Canada. OMEGA, which is funded by the UK government, is made up of nine UK universities, with the purpose of studying scientific, operational, and policy-related measures of the environmental effects of aviation [36]. Currently two major research initiatives, led by Cambridge University (UK) and a joint venture of the FAA’s Office of Environment and Energy (FAA-AEE), NASA, and Transport Canada through the PARTNER Center, are underway to develop tools to assess trade-offs between the environmental impacts...
of aviation. Cambridge University's Aviation Integrated Modeling (AIM) project is developing the capability to perform policy assessment that would account for the economic and environmental impacts of aviation [37]. AIM specifically incorporates "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" [2]. The second research initiative involves the development of the Aviation environmental Portfolio Management Tool (APMT) suite through the PARTNER Center. APMT allows for a comprehensive evaluation of aviation's environmental impacts, through the ability to assess trade-offs between noise, air quality, and climate impacts using economic analysis and environmental impact assessment. It is developed with the purpose of better informing decision makers "by providing the capability to assess different policy measures in terms of their implementation costs, environmental benefits, and associated uncertainties"[2]. APMT is based on an extensive survey of documents that provide guidance for environmental policy analysis. These key documents include EPA Guidelines for Preparing Economic Analyses [15], OMB Circular A-4, Best Practices for Regulatory Analysis [19], UK HM Treasury Green Book on Appraisal and Evaluation in Central Government [38], UK Cabinet Office, Better Regulation Executive Regulatory Impact Assessment Guidance [39], OECD The economic appraisal of environmental projects and policies - A practical guide [40], Transport Canada Guide to Benefit Cost Analysis in Transport Canada [41], WHO Air Quality Guidelines for Europe [42], Resources for the Future, Cost Benefit Analysis and Regulatory Reform: An Assessment of the Science of the Art [43], Peer Review of the Methodology of Cost-Benefit Analysis of the Clean Air for Europe Programme [44], and Clean Air for Europe (CAFÉ) Programme Methodology for the Cost-Benefit Analysis for CAFE Vol. 1 [45]. The Requirements Document for APMT summarizes the findings from the survey, and was reviewed by the Transportation Research Board of the US National Academies [14]. APMT was used to generate the environmental impact analyses in this thesis. This chapter will discuss in more detail the modelling methods used in APMT.
APMT is comprised of the Economics and Impacts modules as shown below in Figure 3-1. The Economics module models the economics of the aviation industry, and outputs an economic cost. The Impacts module models the environmental impacts of aviation, and has the capabilities of providing comprehensive cost-effectiveness and cost benefit analyses. In this thesis, only the APMT-Impacts module will be discussed since it is the part of APMT applied to the analysis described in the following chapters. For more information about APMT-Economics, please refer to [46].

![Aviation Environmental Tools Suite](image)

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

### 3.1 APMT Impacts

APMT Impacts evaluates the environmental impacts of aviation through physical and socio-economic metrics using noise contours and emissions inventories as inputs. Uncertainties in parameters used to model impacts are accounted for probabilistically through Monte Carlo methods. APMT is comprised of Noise, Air Quality, and Climate modules, and is discussed in more detail in the following
sections. Table 3.1 shows the effects modeled, and the monetary and physical metrics calculated within each module.

Table 3.1: APMT-Effects noise assumptions for NextGen scenario analysis

<table>
<thead>
<tr>
<th>Impact Type</th>
<th>Effects Modeled</th>
<th>Physical</th>
<th>Monetary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise</td>
<td>Population exposure to noise, number of people annoyed, housing value depreciation, rental loss</td>
<td>Number of people</td>
<td>Net present value</td>
</tr>
<tr>
<td>Air Quality</td>
<td>Primary particulate matter (PM) Secondary PM by NOx and SOx</td>
<td>Incidences of mortality and morbidity</td>
<td>Net present value</td>
</tr>
<tr>
<td>Climate</td>
<td>CO2, Non-CO2: NOx-O3, Cirrus, Sulfates, Soot, H2O, Contrails, NOx-CH4, NOx-O3long</td>
<td>Globally averaged surface temperature change</td>
<td>Net present value</td>
</tr>
</tbody>
</table>

3.1.1 APMT Impacts: Noise Module

The APMT-Noise Module estimates the physiological impacts of aviation noise for 178 airports in 38 countries plus Taiwan, which comprises about 90% of the estimated noise due to aviation [23]. It takes noise contours in units of day-night average sounds level (dB DNL) around airports as inputs, and overlays them onto population data around each airport. Outputs include the population exposed to a specified noise level, which is calculated by simply counting the number of people within the noise contours, as well as welfare and health impacts, which are represented by housing value and rental depreciation due to aviation noise. Current work by He et al., builds upon this hedonic method to estimate health and welfare impacts through a person's annual willingness to pay (WTP) for a reduction in noise [23].

Noise levels are related to housing value and rental loss through the use of a noise depreciation index (NDI) and hedonic pricing analysis from literature. The
NDI is defined as the percentage loss in housing value from an increase in a decibel unit of noise exposure. Through a meta-analysis of 60 hedonic studies of housing value depreciation, and with city-level income and housing data, He et al. derived a relationship between personal income and WTP through a statistical analysis [23].

The WTP method to characterize health and welfare impacts of noise is an improvement from the hedonic method, since income data is more readily available than housing data in many parts of the world.

3.1.2 APMT Impacts: Air Quality

The APMT-Air Quality Module estimates health impacts for US aviation activities below 3,000 ft., which includes the take-off and landing portion of flight. It begins with aircraft emissions (NO$_x$, SO$_x$, non-volatile PM, and fuelburn) as inputs, and estimates air quality impacts in terms of physical metrics, such as the incidence of premature mortality, and monetary metrics. Monetized impacts are derived based on the cost associated with premature adult mortality, infant mortality, chronic bronchitis, respiratory and cardiovascular hospital admissions, emergency visits for asthma, and minor restricted activity days [2].

Aircraft emissions (primarily soot, aerosols formed from NO$_x$, SO$_x$, and gaseous hydrocarbon emissions) below 3,000 ft. are converted to concentrations of PM$_{2.5}$ within the air quality module using a response surface model (RSM) which is based on 25 Community Multiscale Air Quality (CMAQ) simulations. CMAQ is a high fidelity air quality modelling tool being developed by US EPA Atmospheric Model Development Branch (AMDB) for research and regulatory analysis [47]. The RSM applies a statistical linear regression to the 25 CMAQ simulations to account for the complex chemistry of each grid cell at a lower computational cost than that of CMAQ, and with a root-mean-square prediction error of about 3.5% for total PM$_{2.5}$ [48]. Both the RSM and CMAQ have a spatial grid resolution of 36x36km over the continental US. Although this resolution is commonly used regulatory impact
assessments, it may underestimate local health impacts around airports from air quality by a factor of two. The RSM is designed to evaluate air quality impacts from emissions at a national level, by aggregating effects across grid cells. Since the RSM has a root-mean-squared average error of approximately 3.5%, the model serves as a valid surrogate for CMAQ simulations for national level assessments [48].

PM$_{2.5}$ concentrations can be divided into four different groups of species: 1. elemental carbon (non-volatile primary PM), 2. organic PM (from volatile organic PM or VOCs), 3. ammonium-nitrate (NH$_4$NO$_3$) and 4. ammonium-sulfate ((NH$_4$)$_2$SO$_4$) and sulfuric acid (H$_2$SO$_4$). Impacts from PM are attributed to aircraft emissions in the following manner: 70% due to NO$_x$ emissions, 14% from non-volatile PM, 12% from SO$_x$ emissions, and another 4% from PM formation from hydrocarbons [48]. In compliance with US EPA guidance, which prescribes reconciling air quality monitoring data with outputs from simulation models, the RSM uses the Speciated Modeled Attainment Test (SMAT), which is also used by the US EPA for the Clean Air Interstate Rule (CAIR) proposal modeling [49]. Results using the SMAT approach are adjusted in terms of the apportionment of PM impacts across different PM species, resulting in secondary PM formation from SO$_x$ providing a larger contribution to total aviation PM.

The health impact analysis of the RSM is based on the review of the best practices for air quality policy in both Europe (ExternE program) and the United States (EPA analyses using BenMAP)[50][31]. To estimate the incidences of mortality and morbidity, the RSM uses grid-level population data and linear concentration response functions (CRFs) from epidemiological studies relating to population exposure to PM. Since CRFs are not differentiated based on PM species, equal toxicity is applied to the different PM species. Health impacts are then monetized using the Value of a Statistical Life (VSL), willingness-to-pay (WTP), and cost-of-illness (COI) from literature. The RSM currently uses the US EPA recommended VSL of 6.3 million US $2000, with a standard deviation of 2.8 million US $2000 [48][51]. More detailed information regarding the valuation of other health endpoints can
be found in Rojo [52].

Several limitations exist that are currently being addressed as part of on-going research. The RSM, for instance, does not account for aviation emissions from sources other than the aircraft. Regarding spatial limitations, only health impacts from landing and take-off emissions are evaluated. Incorporating impacts from cruise emissions is part of plans for future development of the air quality module. Further, a fixed background scenario is assumed.

3.1.3 APMT Impacts: Climate

The APMT-Climate Module estimates global impacts, such as temperature change, and health and welfare impacts, from aviation emissions during all stages of flight. Aircraft emissions include long-lived CO$_2$ effects, as well as short-lived impacts of NO$_x$ on ozone (NO$_x$-O$_3$ short), the production of cirrus, sulfates, soot, H$_2$O, and contrails. As described in section 2.4.3, long-lived CO$_2$ can last on the order of centuries, while short-lived effects persist only during the year in which the pollutant is emitted.

The module treats aircraft emissions scenarios as pulses emitted each year, and applies an impulse response function from complex carbon cycle models to calculate concentrations of these emissions. Pulses of CO$_2$ and NO$_x$ result in direct and indirect longer-lived radiative forcing, which decay according to their e-folding times. Short-lived effects, such as contrails, induced cirrus cloudiness, water vapor, soot, and sulfates, are assumed to last only during the year of emissions. Radiative forcing from CO$_2$ concentrations is estimated using a logarithmic relationship as specified by the IPCC. RF for non-CO$_2$ concentrations is based on a scaling to RF estimates from Sausen et al. [53], Wild et al. [54], Stevenson et al. [55], and Hoor et al. [56]. Radiative forcing is then related to global mean temperature change using the temperature response function from Shine et al. [57]. Although this approach results in lower fidelity modelling of temperature change than that from detailed general circulation models, it has the advantage accounting for uncertainties asso-
ciated with climate sensitivity. To calculate temperature change of non-CO$_2$ effects, efficacy values, which are defined as the temperature response per unit of radiative forcing relative to the response from forcing of CO$_2$, is set to values recently provided from Hansen et al. [58] and the IPCC [34].

Health, ecological, and welfare impacts of climate change are represented monetarily through the use of a damage function, which relates temperature change to percent changes in world GDP, ultimately allowing for the estimation of the net present value of damages. The damage function currently employed by APMT is from the Dynamic Integrated model of Climate and the Economy (DICE-2007) [59]. DICE-2007 is an integrated assessment model that relates economic growth with environmental constraints to allow for policy scenario analysis of optimal growth trajectories. The APMT-Climate Module uses only the damage function approach within the DICE-2007 model. Although DICE-2007 has been criticized for its simplified assumptions by not accounting for non-market damages, including loss of natural beauty or the extinction of species, estimating non-market damages is an area of contention among the broader environmental impact assessment community [2]. DICE-2007 accounts for uncertainty in the damage distribution by sampling a Gaussian distribution [59].

Limitations of the climate module are currently being addressed as part of ongoing research. The module is being developed to account for regional variability in short-lived effects due to aviation, in addition to modeling at a global resolution. APMT also does not explicitly account for feedbacks in the climate system which can have a positive or negative effect on climate change due to aviation emissions, and considers effects independently. The interactions of physical and chemical mechanisms are thus not included. In addition, the module assumes that there are no significant changes to flight routes within the operational improvements of aviation scenarios. Future areas of research include the incorporation of altitude dependence of NO$_x$ and contrails/cirrus effects, as well as a comparison of the results from the APMT-Climate Module to those of other complex atmosphere-ocean coupled general circulation models (AOGCM), to improve the accounting of
uncertainties, and to test the robustness of APMT assumptions [2]. For comparisons of APMT to the DICE and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) models, see Appendices A and B of this thesis.

3.2 Communicating Uncertainty

Several parameters within the Noise, Air Quality, and Climate impact modules are considered to be most influential to the magnitude of resulting impact estimates based on a global sensitivity analysis that was conducted for each module. These parameters, however, carry uncertainty, which can be represented through different probability distributions. To account for the possible range of parameters used to model noise, air quality, and climate impacts, a pre-determined set of parameters and inputs are defined within the framework of lenses. A lens is a set of assumptions that allows one to view environmental impacts through a particular point-of-view or perspective. Lenses in APMT typically include low, mid-range, and high lenses. A low lens can be thought of as containing a "best-case" set of assumptions, in which parameters are set to the lowest value in an uncertainty distribution. In the mid-range case, the parameter distributions are sampled using Monte Carlo methods. A high lens involves a conservative set of assumptions, in which parameters are set to the highest value in an uncertainty distribution. However, a multitude of lenses can be created based on different combinations of these parameters.

Table 3.2 describes the parameters shown in Figure 3-2, which provides an illustrative example of a lens with mid-range assumptions. The probability distributions of parameters, which are sampled using Monte Carlo methods, are represented in the figure through the blue lines in the shape of the distributions. Parameters without distributions, are shown as discrete choices, with blue boxes selecting a particular choice.
Table 3.2: Lens with Mid-Range Assumptions for Environmental Impacts

<table>
<thead>
<tr>
<th><strong>APMT-Impacts: Noise</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Depreciation Index (NDI)</td>
<td>Index relating housing price change to noise level changes</td>
</tr>
<tr>
<td>Background noise level</td>
<td>Noise level above which aircraft noise affects housing value</td>
</tr>
<tr>
<td>Contour uncertainty</td>
<td>Uncertainty in the magnitude of noise contours</td>
</tr>
<tr>
<td>Income coefficient, interaction term, and intercept</td>
<td>Income parameters that relate personal income to willingness to pay for noise reduction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>APMT-Impacts: Air Quality</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population growth</td>
<td>Growth in population in the future</td>
</tr>
<tr>
<td>Emissions uncertainty</td>
<td>Estimate of uncertainty in fuel burn; SO$_x$; NO$_x$; nvPM</td>
</tr>
<tr>
<td>Adult premature mortality CRF</td>
<td>Concentration response function relating PM exposure to mortality</td>
</tr>
<tr>
<td>Value of a statistical life</td>
<td>Value of statistical life used for estimating monetary impacts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>APMT-Impacts: Climate</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate sensitivity</td>
<td>Climate sensitivity for CO$_2$ doubling relative to 1750 levels</td>
</tr>
<tr>
<td>NOx-related effects</td>
<td>Uncertainty for aviation-NO$_x$ RF</td>
</tr>
<tr>
<td>Short-lived effects RF</td>
<td>Uncertainty for other aviation effects RF - cirrus, sulfates, soot, H$_2$O, contrails</td>
</tr>
<tr>
<td>Anthropogenic growth scenario</td>
<td>Anthropogenic CO$_2$ emissions and GDP growth scenario</td>
</tr>
<tr>
<td>Aviation scenario</td>
<td>Aviation growth scenario</td>
</tr>
<tr>
<td>Damage coefficient</td>
<td>Uncertainty in estimating societal damages</td>
</tr>
</tbody>
</table>
Figure 3-2: Lens with Mid-Range Assumptions for Environmental Impacts
Chapter 4

NextGen Environmental Analysis

In the next 25 years, US air traffic is expected to increase by 5% per year [60]. To ensure that the air traffic control system will be able to sustainably accommodate this projected growth, the Next Generation Air Transportation System is tasked with transforming the air traffic control system by leveraging new technology and operational procedures. The Joint Planning and Divisions Office is charged with developing and implementing policy related to NextGen, and is comprised of members from Federal Aviation Administration, NASA, the Department of Transportation (DOT), Defense (DOD), Homeland Security, Commerce, and the Office of Science and Technology Policy (OSTP). This chapter will provide a first assessment of the environmental impacts of a preliminary NextGen implementation scenario, the sensitivity of these results to different assumptions, as well as analyze the challenges observed in producing and presenting the results.

4.1 Scenario Background

The process of formulating the NextGen environmental policy scenario, begins with the Senior Policy Committee (SPC), which is composed of senior representatives from five federal agencies, and which develops goals and provides policy guidance for the integrated plan for NextGen. The JPDO Board, composed of one senior executive from each agency, then reviews JPDO's operating plan and mate-
rial to be presented to the SPC. JPDO Divisions, under the JPDO Board, are charged with overseeing research and development of NextGen, among other responsibilities [61]. The IPSA division, within JPDO, is responsible for coordinating, refining, and developing metrics and targets that are in line with NextGen initiatives [21]. IPSA thus performs analysis on future operations by developing aviation scenarios with operations and technology improvements, to assess the sustainability of the NextGen program and the ability of air traffic control system to respond to these policy changes. Metrics relating to capacity and the environment are currently being calculated, while others relating to other divisions of JPDO (Global Leadership, Safety, National Defense, and Security) have not yet been developed [21]. Analysts within the PARTNER group responsible for the development of APMT, then determine the environmental impact metrics, which are shown in the following sections, based on the NextGen scenario inputs provided by IPSA. JPDO can thus be defined as being comprised of the SPC, the JPDO Board, JPDO Divisions, and JPDO working groups, which are made up of government officials and industry representatives specializing in developing the specific capabilities of NextGen [62].

For this analysis, the IPSA group provided the Baseline Most and the NextGen N+1 policy scenario for the years 2006, 2025, and 2050 [63]. Baseline Most refers to the baseline scenario in which no operational or technological improvements are made. Demand for the baseline scenario in 2006 is taken from traffic levels on the 23rd of July in 2006. For 2025 and 2050, the projected demand is based on FAA's Terminal Area Forecasts, and set to a level that can be handled by current operational procedures with minimal delays. The NextGen N+1 scenario refers to the policy scenario in which some of the NextGen operational procedures are implemented, along with technological improvements, which include aircraft engine technologies updated to NASA N+1 and Continuous, Lower Energy, Emissions, and Noise (CLEEN) programs starting in 2016 [22]. The CLEEN program is being developed by the US FAA, and focuses on increasing aircraft fuel efficiency, reducing aviation-related noise, reducing aircraft emissions, and advancing the use of alternative fuels for aviation [64]. The table below shows goals for the NextGen
program that are defined as the "corners of the trade space."

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>Unconventional</td>
</tr>
<tr>
<td></td>
<td>Tube and Wing</td>
<td>Hybrid Wing Body</td>
</tr>
<tr>
<td>Noise</td>
<td>-32 dB (cum below Stage 4)</td>
<td>-42 dB (cum below Stage 4)</td>
</tr>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
</tr>
<tr>
<td>Performance</td>
<td>-33%**</td>
<td>-40%**</td>
</tr>
<tr>
<td>Aircraft Fuel Burn</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-1: NextGen corners of trade-space from technology improvements for NASA's Subsonic Fixed Wing Program

By 2025, the NextGen scenario assumes that all operational improvements are implemented, and that aircraft are fully equipped [21]. Stakeholders for this scenario include overall society/passenger, commercial airlines, air navigation service provider (Federal Government/FAA), airports, and high performance general aviation. However, it does not include cargo, military, or other general aviation categories [21].

In modeling future scenarios of increased demand in the air traffic control system, the key elements of the NextGen scenario include traffic demand and capacity. Future demand for this policy scenario are also based on detailed flight schedules provided by the FAA’s Air Traffic Organization’s Policy Office, using the FAA’s Terminal Area Forecasts. Flight schedules are extrapolated from 2006 to a future year of 2050. This projection of demand is then trimmed to a level that can be accommodated by the capacity constraints set by the NextGen implementation scenario. These trimmed schedules are simulated through NASA’s Airspace Concept Evaluation System (ACES), producing emissions inventories for environmental impacts modeling using APMT [22].

To address the projected growth in demand and the potential delays that come with this demand, the NextGen scenario focuses on growth in capacity by increasing the "projected throughput," or the number of daily flights that can be accom-
dated by the air transport system [21]. Capacity growth modeled by the NextGen scenario is determined by improvements of operational capabilities and technology, as well as fleet composition. The operational improvements accounted for in the NextGen scenario include increased airport and en route capacity. Growth in airport capacity is the result of new runways at ten major airports, independent parallel and/or converging approaches, increased predictability at the outer marker, and reduced wake-based longitudinal separation restrictions during both departures and arrivals at 35 major airports [22]. Increased en route capacity is provided by improved collaborative pre-flight and in-flight rerouting, trajectory-based management through trajectory digital exchange, and by dynamic airspace reconfiguration [22]. Additional operational improvements, which are modeled as modifications to terminal area trajectories, include Continuous Descent Arrival (CDA) and Required Navigational Performance (RNP). In modeling future fleet composition, fleet evolution in the NextGen scenario considers factors that affect the environment, such as aircraft type, size, and engine characteristics. The aircraft chosen for the NextGen schedule are based on the 2007-2035 U.S. fleet forecast. No fleet evolution was assumed for flights from international carriers and general aviation operations [22].

4.2 Noise and Emissions Modeling

Several assumptions are made in forecasting future fuel consumption, emissions, and noise. Noise contours are based on noise-power-distance (NPD) curves, and are generated for 34 Continental United States (CONUS) Office of Emergency Preparedness (OEP) airports. A 70-80% noise improvement is applied to departure NPD curves, and 20-30% to arrival curves for single and dual aisle aircraft for the NextGen scenarios. This application of noise improvement is based on the assumption that new technology will have a greater affect on noise from departures than from arrivals, as current technology already reduces noise from arrivals. Since environmental impacts are sensitive to terminal-area traffic patterns around
airports, which currently cannot be simulated through NASA's Airspace Concept Evaluation System, high-fidelity, data-driven augmentation is used for the 34 airports to identify these traffic patterns. For NextGen scenarios, 100% of flights are assumed to use RNP and CDA after 2025, allowing for a measurement of the maximum benefit that would accrue with these technologies. Noise contours for the 34 CONUS OEP airports were generated based on the population exposed to noise, with population data taken from the 2000 US census. The sound exposure level, which is a time-integrated expression of sound energy, is first calculated from the FAA database of noise-power-distance curves specific to different aircraft/engine types, and is determined for each population centroid of each segment of each trajectory modeled. The day-night average sound level is then determined from the SEL at each population location due to all flights, using the high-fidelity area trajectories which are input into the Noise Integrated Routing System (NIRS) [22].

Improvements in fuel efficiency are modeled by ICAO's Emissions and Dispersion Modeling System (EDMS) and Eurocontrol Base of Aircraft Data (BADA) fuel-flow rates. Emissions, such as NOx and SOx, were also modeled using EDMS [22]. Climate impacts include CO2 for the full mission, which is scaled directly from fuel burn using an emissions index of 3,155 gCO2/kg of fuel burn. Below 3,000 feet, NOx and SOx are used to assess air quality impacts. Air quality emissions are separated by altitude with take-off at 1,000 feet above ground level, climb at 1,000 to 3,000 feet, and approach values from 3,000 feet to touchdown.

4.3 APMT Modeling Assumptions

In modeling noise, air quality, and climate impacts using cost-benefit analysis, uncertainty in modeling parameters is addressed using the low, mid-range, and high lens assumptions within APMT. Providing a range of environmental impacts based on the probability distributions of these parameters gives more dimensions to the decision-making process than simply considering impacts based on the central values of these parameters, as it presents the decision maker with a range of possible
outcomes. The mid-range lens involves Monte Carlo samples from probability distributions of specified parameters, whereas the low and high lenses deterministically choose the lowest and highest values of several of these distributions, as discussed in Chapter 3. Noise and air quality impacts are modeled from 2006 to 2050; climate impacts are modeled for 800 years starting from 2006 to account for the long-lived effects of CO₂, although effects after a couple hundred years are negligible after discounting is applied to monetary results. The following tables show the assumptions used in APMT to calculate the physical and monetary impacts on noise, air quality, and climate.

Table 4.1: APMT-Impacts noise assumptions for NextGen scenario analysis

<table>
<thead>
<tr>
<th>Noise Impacts Assumptions</th>
<th>Low</th>
<th>Mid-range</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income coefficient Approximated normal distribution</td>
<td>0.0013</td>
<td>Mean = 0.0143</td>
<td>0.0272</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD = 0.0079</td>
<td></td>
</tr>
<tr>
<td>Income Interaction Term Approximated normal distribution</td>
<td>0.0154</td>
<td>Mean = 0.0170</td>
<td>0.0154</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD = 0.0094</td>
<td></td>
</tr>
<tr>
<td>Income Intercept Approximated normal distribution</td>
<td>-30.3440</td>
<td>Mean = -37.5292</td>
<td>-30.0440</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD = 207.8134</td>
<td></td>
</tr>
<tr>
<td>Background noise level</td>
<td>55 dB</td>
<td>Triangular distribution (mode = 52.5, range = 50-55) dB</td>
<td>50 dB</td>
</tr>
<tr>
<td>Income growth rate</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Significance level</td>
<td>65 dB</td>
<td>Background noise level</td>
<td>50 dB</td>
</tr>
<tr>
<td>Contour uncertainty</td>
<td>-2 dB</td>
<td>Triangular distribution (mode = 0, range = -2 to +2) dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Population growth rate</td>
<td>No growth</td>
<td>No growth</td>
<td>No growth</td>
</tr>
<tr>
<td>Discount rate</td>
<td>5.0%</td>
<td>3.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
Table 4.2: APMT-Impacts air quality assumptions for NextGen scenario analysis

<table>
<thead>
<tr>
<th>Air Quality Impacts Assumptions</th>
<th>Low</th>
<th>Mid-range</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population growth</td>
<td>No growth</td>
<td>No growth</td>
<td>No growth</td>
</tr>
<tr>
<td>Emissions multipliers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Fuel Burn</td>
<td>1. 0.92</td>
<td>1. Uniform [0.92 1.12]</td>
<td>1. 1.12</td>
</tr>
<tr>
<td>2. SO(_2) (ppm FSC)</td>
<td>2. 0.0066 (5th percentile)</td>
<td>2. Weibull [mean = 0.0627, std = 1.2683]</td>
<td>2. 0.154 (95th percentile)</td>
</tr>
<tr>
<td>3. NO(_x)</td>
<td>3. 0.83</td>
<td>3. Uniform [0.83 1.23]</td>
<td>3. 1.23</td>
</tr>
<tr>
<td>4. Non-volatile PM</td>
<td>4. 0.52</td>
<td>4. Uniform [0.52 2.06]</td>
<td>4. 2.06</td>
</tr>
<tr>
<td>Adult premature mortality CRF</td>
<td>0.6</td>
<td>Triangular distribution (mode = 1, range = 0.6-1.7)</td>
<td>1.7</td>
</tr>
<tr>
<td>Value of a statistical life</td>
<td>$2.9$ M (US 2000) 90% CI lower</td>
<td>Lognormal distribution (US 2000) mean = $6.3$M, std = $2.8$M</td>
<td>$12$ M (US 2000) 90% CI upper</td>
</tr>
<tr>
<td>Background emissions</td>
<td>NEI 2001</td>
<td>NEI 2001</td>
<td>NEI 2001</td>
</tr>
<tr>
<td>Discount rate</td>
<td>5.0%</td>
<td>3.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
Table 4.3: APMT-Impacts climate assumptions for NextGen scenario analysis

<table>
<thead>
<tr>
<th>Climate Impacts Assumptions</th>
<th>Low</th>
<th>Mid-range</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthropogenic CO₂ emissions scenario</td>
<td>IPCC SRES B2</td>
<td>IPCC SRES A2</td>
<td>IPCC SRES A1B</td>
</tr>
<tr>
<td>Short-lived effects RF [Cirrus, Sulfates, Soot, H₂O, Contrails]</td>
<td>[0, 0, 0, 0, 0] mW/m²</td>
<td>Beta distribution (alpha, beta, range) [2.14, 2.49 (0, 80)], [2.58, 2.17 (-10 - 0)], [1.87, 2.56 (0 - 10)], [2.10, 2.58 (0 - 6)], [2.05, 2.57 (0-30)] mW/m²</td>
<td>[80, -10, 10, 6, 30] mW/m²</td>
</tr>
<tr>
<td>Climate sensitivity</td>
<td>2K</td>
<td>Beta distribution (alpha=2.17, beta=2.41) to generate [mean=3K, range 2.0-4.5K]</td>
<td>4.5K</td>
</tr>
<tr>
<td>NOₓ-related effects</td>
<td>Stevenson et al.</td>
<td>Discrete uniform distribution (Stevenson et al., Derwent et al., Wild et al.)</td>
<td>Wild et al.</td>
</tr>
<tr>
<td>Damage coefficient</td>
<td>5th percentile of DICE-2007 (deterministic)</td>
<td>DICE-2007 (normal distribution)</td>
<td>95th percentile of DICE-2007 (deterministic)</td>
</tr>
<tr>
<td>Discount rate</td>
<td>5.0%</td>
<td>3.0%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

4.4 Noise and Emissions Inputs

Noise and emissions inputs are limited to effects from aircraft, and do not account for other sources of noise and emissions around the airports. Noise contours for 34 CONUS OEP airports were provided for both the NextGen N+1 and Baseline Most scenarios for 2006, 2025, and 2050. Figure 4-2 shows the population exposed to noise levels at 55 dB DNL and above for both the Baseline Most and NextGen N+1 scenarios, with population data taken from the 2000 US Census. The kink in 2025 is from the linear interpolation between provided data years of 2006, 2025,
and 2050.

The increase in the number of people exposed to 55 dB DNL and above for the baseline case, is due to the increase in operations with no technology or operational improvements. This leads to greater area exposure to aviation-related noise. The decrease in the population exposed to 55 dB DNL and above in the NextGen N+1 scenario can be attributed to operational improvements with new CDA and RNP procedures. These changes in operations lead to the smaller area around the 34 CONUS OEP airports exposed to 55 dB DNL and above for the NextGen N+1 scenario relative to the baseline, as shown in Figures 4-3a and 4-3b. Figure 4-3b shows that the area exposed in the NextGen N+1 scenario is 25% less than that of the baseline in 2025, and almost 45% less in 2050.
Air quality and climate APMT inputs include fuel burn and emissions for the Baseline Most and NextGen N+1 scenarios for the years 2006, 2025, and 2050. Air quality inventories include fuel burn and emissions below 3,000 ft, and are depicted in the following figures. Figure 4-4 shows an improvement in fuel consumption below 3,000 ft of the NextGen N+1 scenario when compared to the Baseline Most scenario.

Figures 4-5a and 4-5b show the difference in NO\textsubscript{x} and SO\textsubscript{x} emissions of the NextGen N+1 scenario relative to the baseline. NextGen N+1 has a 30% reduction NO\textsubscript{x} in 2050, and only an 8% decrease in 2050 when compared to the Baseline Most scenario.
Climate inputs provided by IPSA included full mission fuel burn. CO₂ emissions are then scaled from fuel burn using emissions indices. Figure 4-6 shows that despite improvements in fuel efficiency, the fuel consumed for the NextGen N+1 scenario for the full mission is higher than that of the Baseline Most. This can be attributed to the increase in the number of flights by 13% and 19% from the baseline, and distance traveled by 16% and 28% for 2025 and 2050 respectively. These increases are based on the assumption that NextGen will allow for significant increases in capacity.
4.5 Results

The objective of the policy analysis presented in this section is to provide an assessment of the environmental impacts of the NextGen N+1 scenario relative to the baseline, and observations of the reactions of those involved in the policy-making process of NextGen to these results. Section 4.5.1 shows the baseline temporal trends; section 4.5.2 discusses the aggregated environmental impacts; section 4.5.3 provides observed reactions to the presentation of these results; and section 4.5.4 discusses an alternative method for evaluating climate impacts due to NextGen N+1 implementation scenario.

4.5.1 Baseline Temporal Trends

The following results represent the temporal physical impacts of the Baseline Most scenario with the mid-range lens assumptions and parameters shown in Section 4.3. Figure 4-7 below shows the physical noise impacts in terms of population exposed to 55 dB DNL and above.

![Graph of population exposed to > 55 dB DNL](image)

Figure 4-7: Baseline population exposed to ≥ 55 dB DNL

Air quality baseline impacts shown in Figure 4-8 are represented by yearly incidence of premature mortality due to exposure to aircraft emissions below 3,000
This metric is used because premature mortalities due to particulate matter account for 95% of total monetized air quality health impacts [23]. From Figure 4-8, nitrates dominate in their effect on premature mortality. Similar to noise, air quality impacts have a duration of 45 years, which is the length of time specified for the NextGen scenarios.

![Figure 4-8: Baseline incidence of physical impacts from air quality](image)

Global mean temperature change, shown in Figure 4-9, is representative of baseline physical climate impacts, and is based on full mission emissions. The temporal temperature changes in Figure 4-9 are apportioned by contributing emission. Since CO₂ has a lifetime of hundreds of years, the warming effect of CO₂ on temperature continues past that of other emissions. The cooling effects of NOₓ-CH₄ and NOₓ-O₃ also last well past the last year of aviation scenario. Short-lived effects, on the other hand, such as NOₓ-O₃ short, cirrus, sulfates, soot, H₂O, and contrails, decay within a two decades after the 45 year aviation scenario.
4.5.2 Aggregated Environmental Impacts

The results presented in this section represent a cost-benefit analysis of the NextGen scenarios relative to the baseline, using different lens assumptions. The impacts of noise, air quality, and climate are monetized in 2009 dollars, with Monte Carlo sampling done for each year from parameters shown in Section 4.3. The means of these samples are then summed over the affected time period. The results of this cost-benefit analysis are shown in Figure 4-10. Since the impacts of NextGen are calculated as policy minus baseline, a positive value represents a detriment or a cost, and a negative value is an improvement or benefit. The height of the bars in Figure 4-10 reflect the sum of the mean yearly impacts. The uncertainty bars in Figure 4-10 represent the 10% to 90% confidence interval above and below the mean.
The NextGen scenario is shown to have an improvement in noise impacts relative to that of the baseline, as the decrease in the area exposed to 55 dB and above, leads to a benefit of $7 billion. Since, fuel burn and emissions below 3,000 ft in the NextGen scenario decreases over time relative to the baseline for air quality, Figure 4-10 shows a benefit $4 billion for air quality impacts. In contrast, fuel burn in the NextGen scenario for climate increased relative to the baseline. This results in a cost $32 billion for climate impacts. Since climate costs are higher than those of air quality and noise combined, the NextGen scenario leads to a net detriment of $21 billion.

Given the uncertainty associated with the parameters used in calculating impacts shown in Figure 4-10, it is also necessary to consider the possible range of these impacts by evaluating the net present value, using the low and high lens assumption shown in Section 4.3. The low and high lens assumptions are made by taking the values that lead to the lowest and highest impacts, respectively, of the parameters shown in the lens diagrams.
Figures 4-11 and 4-12 show that noise impacts range from -$0.01 billion with low lens assumptions to -$29 billion with high lens assumptions. Air quality impacts lie between -$0.39 billion to -$21 billion, and climate, between $0.41 billion to $695 billion.

The large variation of these impacts can be attributed to the range of parameters shown in Tables 4.1 to 4.3. For instance the discount rates used, with 5% for the
low lens, 3% for the mid-range lens, and 2% for the high lens, can contribute significantly to the range of results. A high discount rate implies that one values the future costs and benefits less than the present, and thus leads to a smaller monetized value, especially for impacts that occur far in the future. The discount rate is the dominant parameter leading to the higher cost, by several orders of magnitude, for the climate's high lens assumptions relative to that of the mid-range.

4.5.3 Observed Reactions of Policymakers

The IPSA results from Section 4.5.2 were presented to the Office of Management and Budget (OMB), and to several groups within JPDO, such as the Department of Transportation (DOT), the Federal Aviation Administration (FAA), the JPDO Environmental Working Group (EWG), National Aeronautics and Space Administration (NASA), and the Office of Science Technology and Policy (OSTP).

Different reactions to the results by IPSA analysts and policymakers in JPDO were expressed depending on to whom the results were presented. When making the business case to OMB, IPSA analysts preferred that noise impacts due to 55 dB DNL and above be shown, rather than 65 dB DNL and above. By choosing a lower DNL, more benefits would be accrued from noise, which would strengthen the business case, by bringing down the total environmental costs of the program. After the results were briefed to JPDO's Environmental Working Group and different agencies represented in the JPDO Board, questions arose regarding the origination of numbers that were presented, and how to interpret the charts within the briefing. Some senior level members within these agencies felt that too much detail was being shown, and that too many resources were spent in conducting this analysis. Since these results were to be soon presented to the DOT and OSTP, concern was also expressed as to the magnitude of the costs of the impacts. The climate cost for the lens with conservative assumptions, for instance, was considered to be unexpectedly high. As a result, there were some suggestions that this number
should not be presented. Ultimately, it was decided that all of the results would be shown, with additional calculations for climate, which are described in detail in the following section. After briefing OSTP, IPSA also questioned whether the 5% discount rate for the low lens assumptions was too low, and that perhaps a 7% discount rate should be used, which would further decrease the impacts from the low lens. There is currently no consensus in literature as to a fixed range of discount rates that should be used.

4.5.4 Reanalysis of IPSA

Since the climate costs shown in the previous section were based on an overly simplified assumption in which all operational efficiency improvements led to greater capacity than that of the baseline (which may be considered inconsistent with a future where environmental considerations are a dominating concern), a second analysis was conducted in which a reduced number of flights was assumed so that the operational efficiencies instead contributed to greater fuel burn reduction. The NextGen scenario was thus modified such that the number of flights for the policy scenario matched that of the baseline. With fewer flights for the alternative policy scenario, climate costs were expected to be lower. The fuel burn from the reanalyzed scenario is shown in Figure 4-13. The reduction in the number of flights has allowed for the fuel burn in the policy case to be less than that of the baseline.
The following chart shows the climate impacts expressed in 2009$ for the low, mid-range, and high lens assumptions. The blue bars represent the impacts from the original NextGen scenario in Figure 4-14. The red bars reflect the results from the reanalysis of the climate impacts of NextGen. The uncertainty bars again represent the 10% and 90% confidence interval. As expected, the reanalysis of NextGen, which entailed fewer flights for the policy scenario than the those of the original policy scenario, provides a net benefit for climate, unlike the original scenario, as the costs for the policy are less than that of the baseline. Figure 4-14 also shows that the magnitudes of the benefits in the reanalyzed scenario, and costs in the original scenario, are similar. This indicates that the increase in the number of flights by 13% and 19% in the original NextGen scenario from the baseline in 2025 and 2050 respectively, has a significant impact on the effect of the policy scenario on climate.
Figure 4-14: A comparison of the mid-range policy minus baseline NPV for the original NextGen scenario and the modified number of flights NextGen scenario.

The environmental impacts analysis for both the original and modified policy scenario for NextGen shows the significant influence of climate estimates on the overall policy analysis. This has led to a more careful comparison of APMT climate methods to other methods in literature, which can be found in Appendices A and B of this thesis.
Chapter 5
Observations Applied to Policy Models

To better understand the analysis and policy-making process used in the NextGen analysis, observations from the analysis are viewed from the perspective of different policy models, such as rationalism, incrementalism, and agenda building. These models provide a framework to understand the factors involved in forming and implementing policy decisions, and in viewing the analysis process from which policy is based. The following sections provide a brief description of each model, as well as an assessment of the applicability of each model to the analysis process of NextGen and other environmental policies.

5.1 The Rational Model

The rational model describes a decision-making process in which policy makers base their decisions solely on logical and sound information. Policy makers in this model operate according to a "rational, comprehensive process" [65]. Goals, along with levels of achievement of these goals, are first defined clearly, and all alternatives are considered and compared systematically. Costs and benefits of these comparisons would then be weighed. The final decision would be chosen based on its ability to fulfill the specified goals at the lowest cost [65].
This model is typically difficult to apply to the actual policy-making process because it requires policy makers to consider more alternatives than are necessarily possible. It is also impossible for one to systematically compare all of the alternatives simultaneously in one's mind. Moreover, goals, or even the problem at hand, are not usually defined precisely in the beginning of the policy-making process. Rather, they are defined or modified during the process to better support or justify a position. The rational model assumes that the policy-making process is accomplished in an orderly manner of stages. Although actual policy-making may involve different processes, they may not be followed sequentially or in regular patterns. These processes instead can "develop independently; they are logically coequal, and none necessarily precedes the other chronologically" [65]. It may not, however, be fair to characterize the policy-making process as irrational, as the process may simply be as orderly as humanly possible.

The rational model may not be the most appropriate method of categorizing the policy-making process of NextGen. First, the initial goals of the NextGen scenario were not clearly defined. The NextGen scenarios were specified as to "enable substantial traffic growth, while still attaining improved environmental performance and sustainability" [22]. Achieving the goals shown in Figure 4-1 is considered to be "very optimistic" or "unlikely."

Moreover, scenarios were modified, as the number of flights for the NextGen scenario was adjusted to match the baseline rather than increase from the baseline. Also, a thorough evaluation of alternatives was not performed, as Gawdiak states that "JPDO has only begun to explore and provide information on potential alternative portfolios and implementation of NextGen" [21]. Other issues also reflect incomplete information, as the benefits estimated from the NextGen scenario did not account for all specified operational improvements; sensitivity analysis was not included; the incremental costs of operations and maintenance is unknown; and as safety and security costs were not included in the portfolio analysis [21]. JPDO can thus be described using Kingdon's definition of an organization, which is a "loose collection of ideas [rather than] a coherent structure; it discovers prefer-
ences through action more than it acts on the basis of preference” [65]. The rational model also may not be applicable to the NextGen analysis, as it does not account for the possibility of bias in affecting policy decisions. Some people found the climate costs to be surprisingly high, and discussed whether such results should be used for presenting the business case. Bias therefore existed through expectations regarding the magnitude of the results. Also, to enhance the environmental benefits of the NextGen scenario, some analysts preferred that the significance level for noise impacts be lower, which would further decrease the number of people exposed to the aviation-related noise. Senior members of one agency, who may have had negative views of environmental analysis for NextGen, felt that too many resources had been used in producing the analysis, and that too much detail was presented.

However, aspects of NextGen may be characterized as following the rational model, as the policy scenario does involve stages for implementing technological improvements and significant changes to current operational procedures. The current target for NextGen requires that these changes be made to the US National Airspace System (NAS) by 2025. However, it remains to be seen if NextGen will actually be implemented within this timeframe, or if further adjustments will be made to the policy scenario before it is put in place.

5.2 Incrementalism

Incrementalism is widely accepted among scholars as most applicable to the American policy-making process. Incrementalism assumes that only some of the possible alternatives for addressing a problem are considered, due to limits on information, capabilities, time, and the desire to reach consensus. Also, the alternatives being considered will differ only slightly from an existing policy. In considering these alternatives, a limited number of consequences of these possible policy changes are evaluated. To make the problem at hand more manageable, the problem may be redefined or adjusted accordingly [65].
With regard to environmental policy, it is rare that radical policy alternatives are given serious consideration. Policy is typically made incrementally because it is also easier to support and implement policy that is only a slight departure from existing policy. It is also practically impossible to simultaneously consider many alternatives and their consequences.

In the case of the NextGen analysis, only one NextGen policy scenario was analyzed for the business case. Other alternatives have not yet been considered, and results were presented by the IPSA group to policy makers within federal agencies without the IPSA group having complete understanding of how the results were generated. The limitation of considering only one scenario is also noted by Gawdiak as he states that, "within the tradespace of possibilities for the NextGen system, there are too many variables and embedded assumptions for the assessment of one alternative or one particular stakeholder to constitute a complete and accurate assessment of potential value" [21]. This confirms the challenge policy makers face in dealing with limits in resources and the inability to simultaneously consider large amounts of information. These reduce the ability of policy makers to consider all possible alternatives, and to fully grasp the details of the analysis process. Also, after the IPSA group acknowledged that the policy scenario for climate impacts was based on an overly simplified assumption that an improvement in fuel efficiency would allow for climate benefits, despite growth in capacity, a second NextGen scenario was considered for the evaluation of climate impacts. The process of developing the NextGen scenario is thus reflective of the incrementalism approach.

However, the NextGen scenario itself can be considered a "radical policy alternative," since it will involve large-scale changes to operational procedures and to aircraft technology. Thus, the manner in which the policy scenario is adjusted and implemented in the future will determine how closely NextGen follows the incremental model.
5.3 Agenda Building

Agenda building describes a decision-making process in which policy decisions are made as a result of competition, opportunities, and issues. Trigger events must exist for new or innovative policy to be considered, as policy makers must choose from among a myriad of different policies on which to focus their attention. Kingdon describes agenda building as being comprised of three process: problem recognition, policy proposal development, and the political stream. The processes operate independently of each other, as solutions can be made without all three processes occurring, and as participants can be involved in any of these three streams. During critical times, these streams may come together, forming a strong impetus for a policy decision. In this case, a problem is defined which urgently requires a solution, and the political climate is inducive to implementing the proposed solution. The following sections describe the agenda building processes in more detail, and discuss the application of agenda building in formulating environmental policy.

5.3.1 Problem Recognition

The first stream, problem recognition, involves creating an awareness of existing problems to attract the attention of people in and around the government. Indicators, or quantitative metrics to reflect the problem, can be a powerful communication tool to accomplishing this. Examples of this in environmental analysis include showing the effects of aircraft pollutants on premature mortalities, temperature change, the monetary cost of this temperature change, etc. For problems to receive proper attention or for a proposal to move up on governmental agenda, however, a push is also needed, such as “a crisis or disaster that comes along to call attention to the problem, a powerful symbol that catches on, or the personal experience of a policy maker” [65].

An example of problem recognition applied to environmental policy includes the recently announced decision that the EPA will regulate greenhouse gas (GHGs) emissions. The agency has determined that CO₂ and other greenhouse gases
(GHGs) are pollutants that endanger public health and welfare (e.g. through climate change impacts), and is beginning to take steps to regulate them. This follows the 2007 Supreme Court ruling in Massachusetts v. EPA, which ordered the agency to review the possible threat GHGs place on public health and welfare, and to potentially regulate these pollutants under the Clean Air Act (CAA) [66]. This is also in compliance with Executive Order 13432, which states that the EPA, Department of Transportation, and the Department of Energy are responsible for protecting the environment with respect to greenhouse gas emissions from motor vehicles, non-road vehicles, and non-road engines, in a manner consistent with sound science, analysis of benefits and costs, public safety, and economic growth, [67]. The EPAs regulation of GHGs could have far reaching implications for transportation, manufacturing, and power generation, as these sectors are responsible for emitting significant quantities of these pollutants. The proposed endangerment findings states, In both magnitude and probability, climate change is an enormous problem. The greenhouse gases that are responsible for it endanger public health and welfare within the meaning of the Clean Air Act, [68]. The mandate for the EPA to regulate CO₂ emissions comes at a time of increasing environmental awareness through changes in the presidential administration, increasing scientific understanding of climate change, the development of more fuel-efficient modes of transportation, etc. These events serve as an impetus for the current US EPA mandate.

NextGen scenario was also based on problem recognition, as it was developed because of the projected increase in air traffic, and the idea that the current air traffic system is not equipped to handle this projected rise. The indicator used to bring urgency to this problem are current flight delays at airports within the US, which are becoming an increasingly significant source of complaints for the air transport system. Furthermore, since an increase in operations to accommodate this demand could be taxing for the environment, there is a need to accomplish the NextGen goals sustainably. Since the climate results of the NextGen analysis were found to be unexpectedly high in cost, the environmental aspect of the NextGen program became more prominent and drew greater attention from the groups
within JPDO. The quantitative analysis of the NextGen scenario thus provided “indicators,” which helped to increase awareness and support for a sustainable NextGen program.

5.3.2 The Development of Policy Proposals

The second stream, the creation and refining of policy proposals, is accomplished through a community of policy specialists who have their own political interests. To promote their proposals, logical arguments supporting a proposal can have a powerful effect on the possible selection of a proposal, and may provide more weight to a proposal than would the use of only lobbying or mobilization of the numbers of people. In addition, “technical feasibility” is important, as a policy must be without inconsistencies, and must be able to be implemented in a practical manner. It may also be necessary to “soften” the policy communities and the larger public, which may be “intertia-bound and resistant to major changes” by getting them accustomed to new ideas [65]. Then, when an important opportunity arises, the proposal is pushed with the path already cleared, and the stakeholders “softened.” For a proposal to survive in a policy community, the values of that policy must be compatible with that of the community. Political culture and ideology are prominent guides of American policy, as certain policies that are embraced in other cultures, such as nationalized railroads and “public ownership and operation of sizable portions of the housing stock,” are not even considered as possibilities in the U.S. [65]. One value that is important to policy makers in deciding the fate of a proposal is efficiency or cost-effectiveness. It is important that a policy provide the most benefits for the lowest cost.

The NextGen scenario was modified to make the scenario more consistent with reality. Initially, the scenario was based on the simplifying assumption that improvements in fuel efficiency would allow for a reduction of emissions, and thus positive benefits in climate impacts, without considering the effect of increasing capacity by 13% and 19% in 2025 and 2050 respectively. The fuel efficiency metric
used in this calculation did not consider aircraft size or capacity, and thus did not measure the efficiency of the system in moving people/cargo. The growth in capacity for the NextGen scenario was also determined with the assumption of unconstrained resources to implement NextGen, and without the constraint of the potential environmental impacts of this increase. In formulating a policy, both of these factors would need to be taken into account since they would have a significant effect on the feasibility of a policy. When IPSA realized the assumptions made to allow for the increase in the number of flights were not necessarily consistent with a future where environmental constraints were paramount, and possibly reduced the feasibility of the NextGen program, a second scenario was tested such that the projected number of flights in the NextGen scenario matched that of the baseline. As a result of this modification, the NextGen scenario provided environmental benefits rather than costs.

5.3.3 The Political Stream

The third stream is comprised of elements such as "swings of national mood, vagaries of public opinion, election results, changes of administration, and shifts in partisan or ideological distributions in Congress." [65]. These are integral parts of the process of policy-making, as they define the lines along which stakeholders think. Kingdon states that a change in climate of stakeholders "makes some proposals viable that would not have been viable before, and renders other proposals simply dead in the water" [65]. In addition, organized political forces can have an impact on a policy proposal. If all interest groups support a particular proposal, a strong impetus exists to push decision makers in that direction. If, however, there is a conflict between different interest groups regarding a proposal, the decision-makers may attempt to adjust the proposal to appease the different groups. This may have the effect of reducing the possibility of change or innovation from this proposed policy. If decision makers perceive that more groups are against the proposal, the cost of accepting it increases. Thus, political bias, in which support
for a particular interest group influences the perception of a particular policy, can play a large role in affecting policy decisions. Changes within the government can also have an impact on policy-making. There is a history of dramatic turnovers in policy agendas due to changes in governmental actors.

Transitioning from former President Bush’s administration, which did not sign the Kyoto Protocol, to that of President Obama’s, which advocates environmental awareness and protection, has allowed for the US EPA to move forward with the decision to regulate GHGs, and for more focus to be placed on the sustainability aspect of the NextGen scenarios. The current national mood of environmental protection, is also fueled by greater public awareness of the adverse environmental effects of current US energy consumption, and the development and push by the Obama administration for more fuel efficient vehicles. Political bias was exhibited through the NextGen scenario analysis, as many participants within JPDO desired environmental impact results that would support the business case for the NextGen program. This led to discussions among some analysts regarding the use of a lower significance level for noise impacts, whether or not to show the range of climate costs, and subsequently the reanalysis of the climate impacts of the NextGen scenario. Bias against NextGen was also apparent through some members, who felt that too many resources have been spent in conducting the NextGen environmental impact analysis, and that the level of detail presented was unnecessary.
Chapter 6

The Relationship between Policy and Science

Collaboration with policy makers and IPSA analysts in producing the NextGen analysis not only allows for a closer look at the policy-making process, but also provides insight into the dynamic relationship between policy and science. This chapter will comment on the observed relationship between two groups, JPDO, which includes, among others, policy makers and IPSA analysts, as described in Chapter 4, and PARTNER analysts. The following sections will discuss challenges in making policy decisions based on technical analysis, and provide suggested methods for improving the overall process.

6.1 The Language Barrier between Policy Makers and Analysts

6.1.1 The Role of Ambiguity, Symbols, and Technical Details

In developing and promoting ideas of a policy, policy makers rely on generalizability to facilitate communication of policy ideas to a broadly based community. This is important because a policy idea must be easily understood in order for it to
build a strong support base. Thus, to convey ideas to constituents, ambiguity and symbols are common tools that help people relate to issues and to draw them in as participants [69]. The need for environmental analysis of the NextGen program, for instance, is conveyed through the symbol or idea of the current air transportation system being unable to accommodate the future demand for air transportation, which is becoming more apparent through the increasing flight delays seen at US airports. Since aviation is becoming an increasingly popular and relatively convenient mode of transport, the idea that this mode may no longer be readily available, which is becoming more plausible based on growing incidence of delays, would be a daunting thought to a large portion of the population that take advantage of these services. Thus, although policy makers may disagree as to the best method to transform the air transport system, the idea that air transport may no longer be a convenient source of transportation, has the power to bring together different groups for the common purpose of addressing this potential problem. This idea is also articulated by Stone, as she describes the role of symbols as providing a "vehicle through which diverse motivations, expectations, and values are synchronized to make collective action possible" [69].

Ambiguity and symbols do not serve well in the scientific community, which bases results on attention to detail, and a comprehensive understanding of the implications of applied assumptions. The interpretation of science is intended to remain "constant, unambiguous, and unaffected by the identity of an observer" and thus may not be compatible with the form through which policy makers communicate [69]. Moreover, to prevent misinterpretation of technical results, which could have a significant impact on a policy, and to ensure that the policy considered is practical and has strong evidentiary support, analysts prefer to provide as much detail and background as possible to help policy makers understand the assumptions behind the results. APMT, for example, which was used for the NextGen Analysis in Chapter 4, is designed to analyze various trade-offs of multiple policy scenarios with different lens assumptions. However, technical details of a policy analysis may either confuse or risk losing the attention of po-
tential advocates for a particular policy. They moreover do not leave room for interpretation, which may be necessary in negotiation, as it allows for opponents to agree or claim victory on a resolution. Policy makers thus have the difficult task of balancing the provided technical information with the need for generalization to build support for a policy.

6.1.2 The Role of Numbers

Numbers play a metaphorical role in policy-making, as they are used to "select one feature of something, assert a likeness on the basis of that feature, and ignore all other features" [69]. Numbers allow for policy makers to categorize features that share certain characteristics, and to discount others that do not fit the criteria. For example, the noise impact analysis of the NextGen scenario, in Chapter 4, accounted for the number of people exposed to DNL of 55 dB or greater. However, people are also affected by aviation-related noise at DNL of 45 dB or greater. Although annoyance to noise occurs at noise levels lower than 55 dB DNL, few studies provide economic estimates of noise impacts below 50 dB for aircraft noise, and risks of certain noise-related health effects also begin at this level [24]. Counting the number of people exposed to aircraft noise in this way is a form of categorization that does not necessarily capture all parts of aviation-related noise impacts.

The magnitude of numbers can also have an effect on how technical results are interpreted. High cost can serve as a "double-edged sword," as it could signify high quality or wastefulness. In the case of the NextGen analysis, the high climate costs from the conservative lens brought the environmental aspect of NextGen into a more prominent position. Numbers in this case added authority to the need for a sustainable solution to the projected increase in air transportation demand. However, it also revealed that the initial assumptions of the NextGen scenario may not be realistic, and may require further assessment. In addition, numbers in policy-making are political tools that call for action, as measurements are not made unless change is desired. They also allow for negotiation as they provide
a method of quantifying seemingly intangible qualities, and comparing costs and benefits. The NextGen analysis, for instance, includes the monetization of health and welfare impacts for climate, noise, and air quality. Thus, impacts that seem incomparable, such as premature mortalities and the number of people exposed to certain noise levels, can be directly compared.

In technical analysis, numbers are used to provide an objective comparison among different scenarios. Analysts thus prefer to provide a comprehensive and exhaustive amount of quantitative data in order to ensure that the data is as objective as possible. This again presents policy makers with the challenge of sorting through these results to decide which information is most helpful in supporting or communicating ideas of a policy. This challenge is made more difficult by the fact that since policy makers are not directly involved in the analysis, or may not be trained in producing the analysis, they may not be technically skilled enough to understand the implications of the exhaustive set of data. They may thus not appreciate the role and importance in the uncertainty of assumptions behind the analysis as much as the analysts.

6.2 Discussion

The difficulties in communicating between policy makers and analysts stem from the different roles that these groups assign to symbols, ambiguity, technical details, and numbers, as described above. Analysts tend to ascribe to the rational model described in Chapter 5.1. Those more directly involved in the policy-making process, on the other hand, consider other complex qualitative factors that currently cannot be accounted for in impact assessment tools, such as APMT. Neither approach in policy-making is necessarily better than the other, as both take important factors into consideration. It may be that the optimal solution is somewhere in between these two approaches. Also, because policy-making and quantitative analysis are both integral parts of the process of generating environmental policy, it is necessary for both policy makers and analysts to work together in a more collaborative and
fluid manner. The following section discusses areas of improvement observed in the NextGen analysis as highlighted by the policy models described in Chapter 5, and the general dynamics between science and policy described in the previous sections. Suggested methods of improvements to these issues are discussed in section 6.3.

6.2.1 Problems that Arise from Policy Models

Incrementalism and the agenda building model are frameworks for understanding the process of developing policy for NextGen and were described in Chapter 5. In applying these models to the NextGen analysis, potential problems in the analysis process are revealed.

Incrementalism, as discussed in further detail in Chapter 5.2, describes a policy process in which policy develops incrementally, as radical changes are not usually considered. It is also assumed that policy makers are unable to consider all of the scenario options and assumptions when making a decision. The NextGen analysis reflected this as only one policy scenario was considered initially. However, this could be due to the preliminary nature of the analysis, as this was the "first time a quantitative cost/benefit and risk analysis has been aligned and conducted on a significant subset of the capabilities in the NextGen Integrated Work Plan (IWP)" [21]. Through briefings of the NextGen analysis to other governmental departments, it was also apparent that lens assumptions, and the assumption that all NextGen efficiency improvements would go towards increasing the number of flights (with potential negative impacts on climate), were not fully understood by those within JPDO. This may also be due to having too much information to process, a language barrier between JPDO and PARTNER analysts due to the discrepancy between the needs of those within JPDO for generalizations, and the detailed technical information provided by PARTNER analysts. In conducting the environmental analysis of NextGen, it is observed that the more high level perspective an organization has within the analysis process, the more the generalized result is preferred. This
may explain why some did not consider or fully comprehend all of the information provided by PARTNER analysts.

The agenda building model, as described in Chapter 5.3, also reveals potential issues in developing policy for NextGen. The model, for instance, assumes that trigger events are needed in order for a policy to develop. In the case of NextGen, because of the difficulties in carefully considering all of the information provided, some did not fully grasp the assumptions and processes behind the analysis. It was only after these results were briefed to other governmental organizations, that some felt compelled to understand in more detail the implications of the results. Thus, without this “trigger event,” the assumptions and processes described in Chapter 4 would not have been properly considered. The danger in this is that a policy would have been created without fully recognizing the potential environmental impacts of this policy. In addition, there is a risk that results are adjusted or reanalyzed in the last minute, which can reduce the quality of the analysis. In the NextGen case, once it was clear that the simplifying assumption for capacity growth was unrealistic, results for a new scenario, in which the number of flights of the policy scenario matched that of the baseline, were quickly generated and presented.

The agenda building model also incorporates the influence of the political environment on policy development. Biases can affect how results are presented or interpreted. In the NextGen analysis, the climate impacts from the conservative lens were considered to be higher than expected. There were some discussions as to how or if these results should be shown, since it could detract from the business case. In the end it was decided that the range for climate impacts should be presented, but that an additional policy scenario should be developed such that the number of flights for the policy scenario matched that of the baseline. Because the results of the NextGen analysis did not meet all expectations, and because it could detract from the NextGen business case, the unexpected results received more scrutiny. Bias in this case is based on expectations of how the answer should look, and support for the NextGen program. When the NextGen analysis was briefed to other governmental organizations, some criticized the amount of detail provided,
and the resources spent in producing this analysis. Negative views of the analysis in this case, may reflect their negative bias towards the NextGen program, which again can affect how or if results are to be presented. This can therefore detract from a more objective form of policy-making.

6.3 Suggestions

To improve the collaboration between JPDO and analysts within PARTNER, which would strengthen the environmental policy-making process, this section outlines possible ways of addressing the issues presented in Section 6.2. The language barrier described in Section 6.1 between policy makers and analysts, for instance, can be reduced through more interaction and cooperation between JPDO and analysts within PARTNER and IPSA. Policy makers and analysts within JPDO should become more involved in producing the technical results developed by PARTNER analysts to better understand their underlying assumptions and implications, and to reduce misinterpretation of the results. In addition, PARTNER analysts should become more involved in the broader policy analysis process. This could, for instance, entail that a member of the PARTNER group work with IPSA analysts to define environmental scenario assumptions, and that this member be present when the final results of the analysis are presented to policy makers. This will help PARTNER analysts to become better acquainted with the needs of policy makers and the scenario itself, and ensure that important assumptions and factors are incorporated into the analysis and presented correctly, thus helping to reduce the language barrier. If analysts were more involved in creating scenarios for NextGen, it is likely that the initial simplifying assumption made for the climate impact analysis would have been addressed in the beginning of the analysis process.

In producing the NextGen analysis, difficulties also existed in ensuring that the inputs were correct. Increased quality control should be implemented to improve the efficiency and quality of the analysis. Fuel burn over the policy years, for example, should be plotted to compare the trajectories between the policy and
baseline scenario. In addition, the emissions that scale with fuel burn should also be checked to ensure that the correct emissions indices factor are applied, and that the trajectories of these emissions correspond with the stated assumptions. To ensure that noise contours are consistent with scenario assumptions, the sizes of the contours through the policy years should be compared, and checked against scenario assumptions.

To reduce personal or political biases from affecting policy decisions, policymakers and analysts developing policy scenarios, to the extent possible, should explicitly state their biases or expectations prior to analysis. This will allow for a more objective use of results for decision-making, as those involved in developing and analyzing policies will be more aware of the biases that may influence decisions.

In addition, to ensure that the quantitative results remain as objective as possible, IPSA and PARTNER analysts should first agree upon a template of the information they would like to present, along with a set of lens assumptions.
Chapter 7

Conclusion and Future Work

Many challenges exist in preparing the air transport system to sustainably accommodate the projected increase in demand. Addressing this challenge will require closer collaboration between analysts and policy makers to account for the impacts of policy scenarios affecting the environment. The thesis focused on the evaluation of the environmental impacts of an implementation scenario for the Next Generation Air Transportation System (NextGen) using the Aviation environmental Portfolio Management Tool (APMT), as well observations made during the policy analysis. In addition, different policy-making frameworks were analyzed in the context of this analysis, to highlight some of the limitations in the process.

7.1 Summary and Conclusions

The NextGen scenario analyzed for this thesis includes improvements in both operational procedures and aircraft technology. The emissions and noise contour inputs were evaluated through APMT using different lens assumptions. This analysis results in benefits for air quality and noise exposure around airports, but a detriment to climate, since the number of flights were allowed to grow significantly. Since climate impacts were larger than that of air quality and noise, the particular scenario led to a net detriment to the environment. With high lens assumptions, policy makers and IPSA analysts found the climate costs of
$695 billion to be unexpectedly high, which compelled us to re-assess the initial assumptions regarding capacity growth. This led to the introduction of a second scenario, such that the number of flights for the policy scenario matched that of the baseline. The alternative NextGen scenario was, as a result, found to provide climate benefits ranging from $0.44 billion to $744 billion for the low to high lens assumptions respectively. This highlights how sensitive the environmental impact results of the analysis are to assumptions about the number of flights in the future air transportation system.

Three policy models were considered in this thesis: the rational model, incrementalism, and agenda building. Based on observations of the NextGen policy-making and analysis process, the latter two models are felt to be more applicable. Incrementalism assumes that policy makers are unable to consider all possible options and information to make decisions. Because of this limitation, and limited resources, policy that is generated is usually only a slight departure from that which already exists. The NextGen analysis reflected this as only one scenario was evaluated initially, and since some recipients of the information had difficulty in grasping certain concepts and assumptions behind the analysis. Modifications to the scenario to improve its feasibility are also representative of incrementalism, and are exhibited through the reduction in the number of flights for the alternative NextGen scenario when calculating climate impacts. However, because the NextGen program can be considered to be a radical change from the current capabilities of the air transport system, it will depend on how NextGen is implemented to determine to what extent does incrementalism apply to the policy scenario. The agenda building model is based on three streams, which include problem recognition, the development of policy proposals, and the political stream. The NextGen scenario involved problem recognition, as the policy is based on the projected growth in the demand for aviation, delays seen in the current air transportation system, and the risks associated with the inability of the current air transport system to manage this rise. To increase awareness for a problem, indicators are used to communicate the level of urgency and support needed to address the problem. Indicators in
the NextGen environmental scenario included the physical and monetary environmental impacts of aviation. The policy proposal development stream assumes that logic, feasibility, and consistancy are important for the acceptance of a proposal. An alternative scenario was considered that may be a more realistic representation of a future where environmental constraints are significant. The political stream is also reflected by the NextGen policy scenario, as bias may have affected the reactions of some to the presented results, and as increasing environmental awareness has helped generate more urgency and support for the environmental aspect of the NextGen program.

A language barrier between JPDO and PARTNER analysts was also a component observed in the NextGen policy-making process and analysis, as policy makers depend on ambiguity, generalizations, and symbols to communicate, while analysts tend to communicate through technical details. Numbers also serve different roles between both groups. Policy makers may use numbers to be political tools, while analysts use numbers to objectively present results. These discrepancies can make it difficult for policy makers and analysts to achieve their objectives. Too much technical information can make it difficult for policy makers to filter the necessary information to support a policy. Information can thus be misinterpreted and used irresponsibly, which can defeat the objective of analysts in providing the large amount of information. To improve the process and narrow the divide between policy makers and analysts, JPDO and PARTNER analysts should collaborate more closely in developing the policy scenarios and in producing the analysis. To reduce the risk of bias affecting the policy analysis process, policy makers and analysts should state their biases and expectations prior to viewing the results of the analysis.

7.2 Future Work

Two areas of future work that are identified in this thesis are the further development of APMT, and the implementation of the suggestions in Chapter 6 to better
the relationship between JPDO and PARTNER analysts. Future work for APMT will include improving the capabilities of the APMT Noise Module to estimate supplemental metrics, such as sleep awakenings and learning impairment; the APMT Air Quality Module to increase its geographical scope beyond the US, and to include aviation-related air quality impacts above 3,000 ft; the APMT Climate Module to incorporate altitude dependence of NOx and contrail effects, and to allow for regional assessment of aviation-related climate impacts.

Because of the complexities involved in assessing policy based on technical information, future work in this area will involve implementing suggested methods for addressing this, and further observation as to how the relationship between policy makers and analysts is affected. In analyzing more policy scenarios in the future, careful observation will also be needed to better characterize the policy-making process, to be able to more effectively bridge the gap between different groups responsible for developing and analyzing policy.
Appendix A

APMT-DICE Model Comparison

A.1 Objective

The objective of this chapter is to compare the climate damages produced using the Aviation environmental Portfolio Management Tool (APMT) with that of the Dynamic Integrated model of Climate and the Economy (DICE-2007), and to identify areas in the calculation process that would lead to differences in results.

A.2 Approach

To understand the sources of the difference in climate damages calculated using APMT and DICE-2007, we attempt to replicate the results produced by the DICE model using APMT with DICE assumptions. Particularly, we calculate the damages over a 590-year period with the DICE background scenario. Climate sensitivities are varied between 2K and 3K to assess the sensitivity of the results to this parameter.

A.3 Analysis

Figure A-1 shows the total CO₂ emissions from the DICE 2007 background scenario. In this figure, APMT_DICE_2K and APMT_DICE_3K refer to the CO₂ emissions that were calculated using APMT with the DICE-2007 background scenario and climate...
sensitivities of 2K and 3K; DICE_2007 refers to data taken directly from the DICE model. The chart shows that the background CO₂ emissions used in APMT match closely to that of DICE.

![Graph showing CO₂ emissions from DICE-2007 background scenario](image)

**Figure A-1:** CO₂ emissions from DICE-2007 background scenario

Impulse response functions derived from carbon cycle models are then used to convert emissions of CO₂ into concentrations. Figure A-2 shows that the concentrations produced from the Bern Carbon Cycle model closely match that from DICE's three reservoir model calibrated to MAGICC when comparing the APMT.DICE and DICE_2007 curves [59]. Slight differences in concentration can be attributed to the climate feedbacks included in MAGICC, while the Bern Carbon Cycle impulse response function assumes a constant background CO₂ concentration of 378 ppm [2].

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Figure A-2: \(\text{CO}_2\) concentration (ppm) calculated using the APMT and DICE-2007 model

Figure A-3, which shows the radiative forcing (RF) due to \(\text{CO}_2\), indicates that although APMT and DICE-2007 use different methods for calculating RF, there is also little difference in the resulting RF. In particular, APMT uses a simplified logarithmic relationship between \(\text{CO}_2\) concentration and radiative forcing, in accordance with the IPCC [34]. DICE-2007 again calibrates its parameters for RF to match that of MAGICC [59].
Figure A-3: Radiative forcing from CO₂ (watts per square meter) calculated using the APMT and DICE-2007 model.

Figure 4 compares the atmospheric temperatures produced using APMT and the DICE-2007 model for climate sensitivities of 2K and 3K. The DICE-2007 model calculates temperature using a 3K climate sensitivity, but deviates from APMT_DICE_3K because of differences in the temperature response model [59]. Specifically, APMT uses an impulse response function from Shine et al. (2005), while DICE uses a reservoir model with parameters calibrated to follow the same temperature trajectory as that of the MAGICC model simulations [59].
Figure A-4: Atmospheric temperature change above preindustrial level using APMT and DICE-2007

The climate damages in percent GDP are shown on Figure A-5. The damages from the DICE model are between the damages calculated using APMT for climate sensitivities of 2K and 3K. Since APMT.DICE.2K and APMT.DICE.3K use the DICE damage function, the differences in damage can again be attributed to the temperature response function.

Figure A-5: Climate damages in percent GDP using APMT and DICE-2007
Figure A-6 shows the damages discounted using a declining Ramsey discount rate. The damages from DICE between 2005 and 2055 fall below APMT.DICE.2K and closer to APMT.DICE.3K for subsequent years. To compare the relative magnitudes of these damages, the average cost of CO$_2$ is calculated by integrating the damages for each curve and dividing by the total CO$_2$ emitted. This calculation yields $7.49 per ton CO$_2$ for APMT.DICE.3K, $4.51 per ton CO$_2$ for APMT.DICE.2K, and $5.51 for DICE2007. Thus, the damages from APMT compare well with that of the DICE-2007 model.

![Figure A-6: Climate damages in billions of dollars per year using APMT and DICE-2007](image)

### A.4 Conclusion

To determine the source of the differences in the climate damages from APMT and DICE-2007, DICE assumptions were used in APMT to calculate damages, and a comparison of the outputs was made with DICE-2007 outputs at each step within the process. Although both models were set with the DICE-2007 background scenario and damage function, differences were mainly apparent when comparing the atmospheric temperatures calculated from both models. This is primarily due to the different temperature response functions used in APMT and DICE; APMT
calculates temperature using an impulse response function from Shine et al. (2005) and DICE-2007 uses a reservoir model with parameters calibrated to temperature trajectory of MAGICC. Although both models also use different methods to calculate CO$_2$ concentrations and radiative forcing, little deviation was found in the concentrations and RF produced from APMT and DICE-2007.
Appendix B

APMT-FUND Model Comparison

B.1 Objective

The objective of this chapter is to compare the climate damages produced using the Aviation environmental Portfolio Management Tool (APMT), and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model, and to identify areas in the calculation process that would lead to differences in results. In addition, this comparison will assess the assumptions behind the social cost of carbon (SCC) from the EPA's "Technical Support Document on Benefits of Reducing GHG Emissions," which was calculated using the FUND 3.3 model.

B.2 Approach

To understand the sources of the difference in climate damages produced using APMT with FUND and APMT inputs, we deterministically calculate the surface temperature change over a 300-year period, with the climate sensitivity ($\lambda$) set to 2.5K, and pre-industrial CO$_2$ concentrations set to 275 ppm. This is done with the SRES A1b scenario in APMT and in the FUND model. The DICE-2007 damage function is then applied to these temperature profiles to calculate monetary damages due to temperature change. To better understand the FUND model, we have also begun correspondence with one of the developers of FUND.
B.3 Analysis

B.3.1 Temperature Profiles

Since the FUND model does not explicitly use CO$_2$ emissions as inputs, but instead calculates them using the Kaya Identity, we are currently unable to directly view the CO$_2$ emissions used in FUND [70]. However, the global mean surface temperature change can be extracted from FUND, as shown in Figure B-1, and is thus a starting point for comparing the FUND 3.3 and APMT models. In Figure B-1, APMT SRES A1B and FUND SRES A1B refer to atmospheric temperature change above the preindustrial level, using the SRES A1B background scenarios in APMT and FUND respectively. These curves represent temperature change due only to CO$_2$ emissions.\(^2\)

![Figure B-1: Temperature profiles of the SRES A1B scenario calculated using APMT and FUND 3.3](image)

The APMT SRES A1B temperature profile is shown to be greater than that of

\(^1\)The Kaya Identity is a scheme that is used to determine future CO$_2$ emissions. It multiplies population growth, GDP per capita, emissions per unit energy, and energy consumption of production to yield total CO$_2$ emissions. [http://www.grida.no/publications/other/ipcc_sr/?src=/Climate/ipcc_emission/038.htm](http://www.grida.no/publications/other/ipcc_sr/?src=/Climate/ipcc_emission/038.htm)

\(^2\)In FUND, CH$_4$ and N$_2$O emissions are set to 0, as are the GDP per capita and population growth used for calculating SF$_6$.\(^3\)
FUND SRES A1B for earlier years, and then converges towards FUND SRES A1B for later years. To explain the differences between the temperature profiles, it is necessary to compare the concentration response functions, radiative forcing functions, and temperature response functions used in each model. To calculate CO$_2$ concentrations, FUND uses a five-box model from Maier-Reimer and Hasselmann (1987), with parameters from Hammitt et al. (1992) [70]. For this comparison APMT uses a concentration response function set to Hasselmann (1997), which is fit to Meier-Reimer and Hasselmann (1987). These carbon concentration response functions of FUND and APMT, are based on an impulse response function, $G_C(t')$, as shown below [2][71]. In equation B.1, $\Delta X_{CO2}(t)$ corresponds to the change in atmospheric CO$_2$ concentrations over a time period of $\Delta t$, which is one year. $Q_{CO2}(t'')$ refers to the mass of CO$_2$ emitted during one year of anthropogenic activity.

$$G_C(t') = \sum_{j=1}^{n_j} \alpha_j e^{-t'/\tau_j}$$  \hspace{1cm} (B.1)

$$\Delta X_{CO2}(t') = \int_0^{t'} Q_{CO2}(t'') \cdot G_C(t' - t'') dt''$$

$$\approx \sum_{n=0}^{N-1} Q_{CO2}(t_0 + n\Delta t) \cdot G_C(t' - t_0 - n\Delta t) \cdot \Delta t$$

$$N = \frac{t' - t_0}{\Delta t}$$

The following table lists the $\alpha$ coefficients, which represent the fraction of emissions within each "box" of the carbon cycle model, and the $\tau$ coefficients, which are the lifetime of the emissions in years, from the impulse response functions. Figure B-2 shows the carbon concentration curves based on parameters in Table B.1. Based on this information below, there is close correspondence between the concentration response models of both APMT and FUND.
### Table B.1: Concentration Models

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha$ [ppbv/TgC] and $\tau$ [years]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUND Maier-Reimer and Hasselmann (1987)</td>
<td>$\alpha$</td>
<td>$0.13$</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>$\propto$</td>
</tr>
<tr>
<td></td>
<td>Total carbon [GT(C)] = $2.123 \cdot$ Total Carbon [ppm]</td>
<td></td>
</tr>
<tr>
<td>APMT Hasselmann et al. (1993)</td>
<td>$\alpha$</td>
<td>$0.142$</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>$\propto$</td>
</tr>
<tr>
<td></td>
<td>Total carbon [GT(C)] = $2.123 \cdot$ Total Carbon [ppm]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parameters from Hammitt et al. (1992)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Original inorganic 3 d ocean carbon cycle model of Maier-Reimer and Hasselmann (1987).</td>
<td></td>
</tr>
</tbody>
</table>

Figure B-2: CO$_2$ concentration curves for the FUND and APMT models.

APMT calculates radiative forcing (RF) due to CO$_2$ as shown below, using a logarithmic relationship between CO$_2$ concentrations and RF as specified by the IPCC [34]. CO$_{2,275}$, which represents the preindustrial CO$_2$ concentration, is set to 275 ppm for this calculation in APMT to match FUND parameters. The radiative
forcing due to a doubling of CO₂ is specified as 3.7 W/m² based on estimates by the IPCC [34].

\[ \Delta F = 3.7 \log_2 \left( \frac{\text{CO}_2}{\text{CO}_{2,1750}} \right) \]  

(B.2)

Since the RF for the doubling of CO₂ can also be represented as 5.35ln(2), the expression from equation B.2 from APMT can be rearranged to match that in the FUND model for the RF due to CO₂, as shown in equation B.3.

\[ \Delta F = 5.35 \ln \left( \frac{\text{CO}_2}{\text{CO}_{2,1750}} \right) \]  

(B.3)

However, in calculating RF, the complete expression used in FUND is the following, with parameters taken from Ramaswamy et al. (2001) [70].

\[ \begin{align*}
RF_t &= 5.35 \ln \left( \frac{\text{CO}_2}{275} \right) + 0.036 \left( \sqrt{\text{CH}_4} - \sqrt{790} \right) + 0.012 \left( \sqrt{\text{N}_2\text{O}} - \sqrt{285} \right) \\
&\quad - 0.47 \ln \left( 1 + 2.01 \cdot 10^{-5} \text{CH}_4^{0.75} \text{CO}_{2,1750}^{0.75} + 5.31 \cdot 10^{-15} \text{CH}_4^{2.52} \text{CO}_{2,1750}^{1.52} \right) \\
&\quad - 0.47 \ln \left( 1 + 2.01 \cdot 10^{-5} \text{N}_2\text{O}^{0.75} \text{CO}_{2,1750}^{0.75} + 5.31 \cdot 10^{-15} \text{N}_2\text{O}^{2.52} \text{CO}_{2,1750}^{1.52} \right) \\
&\quad + 0.00052 (\text{SF}_6 - 0.04) - 0.03 \frac{\text{SO}_2}{14.6} - 0.08 \frac{\ln(1 + 0.04)}{\ln(1 + 0.04)} \\
&\quad - 0.03 - 0.08 \frac{\ln(1 + 0.04)}{\ln(1 + 0.04)} \\
\end{align*} \]  

(B.4)

The temperature response functions of APMT and FUND can be derived from the following equation, where \( C \) is the ocean heat capacity for the global ocean mixed layer, \( \Delta T \) is the global mean surface temperature change, \( \Delta F \) is the global mean radiative forcing, and \( \lambda^* \) is the climate sensitivity normalized by the radiative forcing for a doubling of CO₂ equivalents [57].

\[ \begin{align*}
C \frac{\Delta T(t)}{dt} &= \Delta F(t) - \frac{\Delta T(t)}{\lambda^*} \\
\end{align*} \]  

(B.5)

APMT uses the general solution of equation B.6 from Shine et al. 2005, shown

---

Note that in current documentation and papers that are based on the FUND model, the equation for \( RF_t \) is incorrect. The correct form is shown here, based on the IPCC 2001, Working Group I: The Scientific Basis, and is corroborated by Richard Tol and David Anthoff.
below, to compute global mean temperature change [2].

\[ \Delta T(t) = \frac{1}{C} \int_0^t \Delta F(t') \exp \left( \frac{t' - t}{\lambda C} \right) dt' \]  
(B.6)

FUND on the other hand uses a forward difference of equation B.5, to calculate temperature change each year. Equation B.7 shows the general form of the forward difference calculation.

\[ \Delta T_{t+1} = \left( 1 - \frac{1}{\lambda C} \right) \Delta T_t + \frac{\Delta F}{C} \]  
(B.7)

FUND’s temperature response function assumes an e-folding time of 50 years, and a global mean temperature rise of 2.5K for a doubling of CO₂ equivalents [70].45 The RF for a doubling of CO₂ is given by 5.35ln(2), and \( \Delta F \) in equations B.6 and B.7 are equivalent to the RF, in equation B.4.6 These parameters, which are based on the calibration of temperature to the IS92a scenario of Kattenberg et al. (1996), yield the following temperature response function in FUND, which follows a similar pattern to that in equation B.7 [70].

\[ T_t = \left( 1 - \frac{1}{50} \right) T_{t-1} + \frac{1}{50} \frac{2.5}{5.35ln2} RF_t \]  
(B.8)

Since the temperature response functions of APMT and FUND are derived from equation B.5, both functions can be also be defined according to the \( \alpha \) and \( \tau \) coefficients from the impulse response function, \( G_\tau(t) \). The global mean temperature change at time \( t \) is represented by \( \Delta T_{CO₂} \), and is based on \( RF_{CO₂} \), which is the radiative forcing, normalized by the RF for a doubling of CO₂.

\[ G_\tau(t) = \sum_{j=1}^{n_j} \alpha_j e^{-t/\tau_j} \]  
(B.9)

\(^4\)Note that in current documentation and papers that are based on the FUND model, the e-folding time is denoted as the “half-time.” Tol has confirmed that this quantity should be termed “e-folding time” instead.

\(^5\)In FUND 3.5, which has not yet been released, the climate sensitivity for a doubling of CO₂ equivalents will be set to 3K, based on correspondence with Anthoff.

\(^6\)Note that in current documentation and papers based on the FUND model, the RF for a doubling of CO₂ is set to 6.3ln(2). This is found to be inconsistent with equation B.4, and has been corrected to 5.35ln(2), as shown in equation B.8. This correction has also been corroborated by Tol and Anthoff.
\[
\Delta T_{CO_2}(t') = \int_{t_0}^{t'} RF_{CO_2}^*(t') \cdot G_T(t - t') dt' \\
\approx \sum_{n=0}^{N-1} RF_{CO_2}^*(t_0 + n\Delta t) \cdot G_T(t - t_0 - n\Delta t) \cdot \Delta t \\
N = \frac{t - t_0}{\Delta t}
\]

In APMT, since \( \Delta F = RF_{2\times CO_2}RF_{CO_2}^* \), \( \alpha \) is equivalent to \( RF_{2\times CO_2}/C \) (see equation B.6), where \( RF_{2\times CO_2} \) is the RF for a doubling of CO\(_2\), and C is specified in APMT as \( 4.2 \times 10^8 \) J/m\(^2\)K at a 100m depth [2]. However, in FUND, since its \( \Delta F \) is defined differently than that of APMT (see equation B.4), the \( \alpha \) parameter is simply the coefficient of \( \Delta F \) from equation B.7, which is \( 1/C \). For comparison purposes, since the radiative forcing due to CO\(_2\) is the same for both APMT and FUND, \( \alpha \) is set to \( RF_{2\times CO_2}/C \), and uses the expression \( C = \tau/\lambda^* \). Note that the coefficient of \( RF_{2\times CO_2} \) in equation B.10 is the same as the coefficient of \( RF \) in equation B.8.

\[
\alpha = \frac{RF_{2\times CO_2}}{C} = \frac{\lambda^*RF_{2\times CO_2}}{\tau} = \frac{\lambda}{RF_{2\times CO_2}\tau} \cdot RF_{2\times CO_2} = \frac{\lambda}{\tau}
\]

The temperature response function in APMT defines the \( \tau \) coefficient, the time constant of the climate system, as \( \lambda^*/C \). Table B.2 shows the values of \( \alpha \) and \( \tau \) used in the temperature response functions of FUND and APMT.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \alpha ) [1/yr] and ( \tau ) [years]</th>
<th>climate sensitivity [k]</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUND</td>
<td>( \alpha ) 0.05 ( \tau ) 50.0</td>
<td>2.5K</td>
<td>Calibrated to the IS92a scenario of Kat-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>tenberg et al. (1996)</td>
</tr>
<tr>
<td>APMT-Shine et al. (2005)</td>
<td>( \alpha ) 0.278 ( \tau ) 8.9</td>
<td>2.5K</td>
<td></td>
</tr>
</tbody>
</table>

Table B.2: Temperature response functions
B.4 Discussion

The analysis above indicates that the differences between the temperature profiles of FUND and APMT can largely be attributed to the different parameters used in the RF functions and the temperature response functions. Although APMT and FUND use the same expression to calculate the radiative forcing due to CO₂, the RF from FUND also includes other non-zero parameters that are not included in the RF calculation in APMT. In comparing the temperature response functions of both models, the APMT α coefficient from Table B.2 is about 5.6 times greater than that of FUND, with the e-folding time of FUND being 5.6 times larger than that of APMT. The primary parameter that leads to these differences is the ocean heat capacity, C. If we calculate the C that is implied in the FUND model using \( \tau = \lambda C \), we find that \( C = 2.33 \times 10^9 \text{ J/m}^2\text{K} \). The ratio of this to the ocean heat capacity used in APMT is about 5.6. A large range of uncertainty surrounds this parameter, making it difficult to determine which model, APMT or FUND, represents the latest science. However, the value of C used in APMT is taken from Shine et al. 2005, and is similar to the value calculated by Schwartz. Using compilations of heat content of the world ocean from Levitus et al. 2005 at depths of 300m, 700m, and 3000m, Schwartz estimates C as being equivalent to \( 14 \pm 6 \text{ W yr m}^{-2}\text{K}^{-1} \), or \( (4.42 \pm 1.9) \times 10^8 \text{ J/m}^2\text{K} \) at a depth of 106 m of ocean water, which is similar to the value used in APMT \( (4.2 \times 10^8 \text{ J/m}^2\text{K}) \) at a 100 m depth [72]. Other estimates of the effective ocean heat capacity are based on the observed change in global mean ocean heat content also from Levitus et al. 2005 at an ocean depth of 3,000 m, and can be found in Andreae et al. 2005 and Frame et al. 2005. Andreae et al. 2005 estimates C to be \( 35 \pm 16 \text{ W yr m}^{-2}\text{K}^{-1} \), or \( (1.1 \pm 0.5) \times 10^9 \text{ J/m}^2\text{K} \) which is much greater than that used by Schwartz, but similar to the implied heat capacity used in FUND [73]. Frame et al. 2005, on the other hand finds C to range from 3.2 to 65 W yr m⁻² K⁻¹, or from \( 1.0 \times 10^8 \text{ J/m}^2\text{K} \) to \( 2.0 \times 10^9 \text{ J/m}^2\text{K} \) (5-95% confidence) [74]. The ocean heat capacities of both APMT and FUND fall within this range. In comparing these models, it is also necessary to consider other factors that may
contribute to the differences in the temperature profiles. Although both models were run with the SRES A1b background scenario, since the CO$_2$ emissions cannot be viewed explicitly, it is possible that the actual CO$_2$ emissions used by both models may be different. Another contribution may be the differences in how APMT and FUND account for the temperature changes from preindustrial times. APMT uses reference temperature change of 0.6K, which is taken from the Nordhaus-Boyer damage function [2]. From the current documentation of the FUND model, it is unclear how the model accounts for temperature changes from pre-industrial times. The model uses the period from 1950 to 1990 to calibrate the model based on the IMAGE database. Both physical and monetized climate impacts in this time period are considered to be "misrepresented" [75].

B.5 Climate Damages

As another metric to compare the APMT and FUND model, monetary damages due to these temperature changes are calculated using the DICE-2007 damage function with a 3% discount rate, as shown in Figure B-3. The damages plotted in Figure B-3 behave similarly to the temperature profiles in B-1. However, when considering the relative magnitude of the total damages, Figure B-3 shows that FUND damages are almost half those of APMT. Since the damages for both models were calculated using the same damage function, the significant difference between the two curves is due to differences in the temperature profiles of both models.
B.6 FUND Model Damage Calculation Assumptions for EPA SCCs

To properly compare the FUND model to APMT, it is also necessary to calculate the damages using the damage function within the FUND model with the temperature profile from APMT. However, since FUND calculates damages across 16 regions and various sectors before aggregating these damages, inputting APMT global temperature profiles into FUND is challenging, and is an ongoing part of research [70]. This section will discuss the assumptions behind the EPA “FUND global” SCCs shown in the EPA’s June 12, 2008 technical support document, that have been made clearer through correspondence with the EPA and the developers of the FUND model, and through closer examination of the model itself. The FUND model begins its model runs in 1950 to initialize the climate change impact model, and continues to 2200 with time steps of years. The EPA SCCs were calculated by running the model deterministically using the SRES A1b, A2, and B2 and the FUND Baseline scenarios using the parameters shown in Table 3 [76]. The climate
sensitivities were also varied with values of 1.5K, 2.0K, 3.0K, 4.5K, and 6.0K [77]. It
should be noted that this range of climate sensitivities is wider than is typically used
in APMT, and is a greater range than that reported by the IPCC. The IPCC’s fourth
assessment report finds 2.5K to 4.5K, to be the “likely” range of climate sensitivities
[78]. For the mid-range case in FUND, a weighted average is applied to the SCCs
calculated from the range of background scenarios and climate sensitivities [78].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea level sensitivity</td>
<td>0.31</td>
</tr>
<tr>
<td>Response time temperature (years)</td>
<td>75</td>
</tr>
<tr>
<td>Response time sea level (years)</td>
<td>50</td>
</tr>
<tr>
<td>Life time methane (years)</td>
<td>8.6</td>
</tr>
<tr>
<td>Life time nitrous oxide (years)</td>
<td>120</td>
</tr>
<tr>
<td>Life time sulphur hexafluoride (years)</td>
<td>3200</td>
</tr>
<tr>
<td>Life time CO₂ (years)</td>
<td>0</td>
</tr>
<tr>
<td>Life time CO₂ (years)</td>
<td>363</td>
</tr>
<tr>
<td>Life time CO₂ (years)</td>
<td>74</td>
</tr>
<tr>
<td>Life time CO₂ (years)</td>
<td>17</td>
</tr>
<tr>
<td>Life time CO₂ (years)</td>
<td>2</td>
</tr>
<tr>
<td>Income elasticity forestry</td>
<td>-0.31</td>
</tr>
<tr>
<td>Income elasticity of vector-borne diseases</td>
<td>-2.65</td>
</tr>
<tr>
<td>Non-linearity forestry</td>
<td>1</td>
</tr>
<tr>
<td>Non-linearity malaria</td>
<td>1</td>
</tr>
<tr>
<td>Non-linearity dengue fever</td>
<td>1</td>
</tr>
<tr>
<td>Non-linearity schistosomiasis</td>
<td>1</td>
</tr>
<tr>
<td>Percent population above 65</td>
<td>0.25</td>
</tr>
<tr>
<td>Value of statistical life</td>
<td>200</td>
</tr>
<tr>
<td>Value of a year diseased</td>
<td>0.8</td>
</tr>
<tr>
<td>Emigration cost</td>
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</tr>
<tr>
<td>Immigration cost</td>
<td>0.4</td>
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<tr>
<td>Change in baseline cardiovascular disease</td>
<td>0.026</td>
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<tr>
<td>Change in baseline respiratory disease</td>
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</tr>
<tr>
<td>Maximum increase cardiovascular and respiratory disease</td>
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</tr>
<tr>
<td>Agriculture adaptation time (years)</td>
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</tr>
<tr>
<td>Dryland adaptation time (years)</td>
<td>0</td>
</tr>
<tr>
<td>Immigration adaptation time (years)</td>
<td>3</td>
</tr>
<tr>
<td>Emission period</td>
<td>2000</td>
</tr>
<tr>
<td>Preindustrial CO₂ (ppm)</td>
<td>275</td>
</tr>
</tbody>
</table>

Table B.3: Parameters used in the FUND 3.3 model
The FUND model produces outputs in both monetary and physical metrics, such as dollars and the number of people affected by climate change. The monetization of damages is derived from the impacts of climate change on number of deaths from vector-borne diseases, cardiovascular and respiratory diseases, and extreme weather events, as well as from migration [70]. It also is based on the change in sea level, temperature, forestry consumer and producer surplus, ecosystem loss, water resources, energy consumption, agriculture production, etc., which are directly computed as monetary impacts, without the intermediate step of determining the physical metric [75]. Damages are then calculated using a second-order polynomial, and are distinguished between “tangible” (market) and “non-tangible” (non-market) impacts. Tangible damages affect investment and consumption; non-tangible damages affect welfare [79]. To determine health impacts of climate change, the FUND model specifies that 25% of the population is over the age of 65; this is done to account for the increased vulnerability of this portion of the population to cardiovascular and respiratory diseases. For a 1% increase in the population over 65, cardiovascular and respiratory disease increase by 2.5% and 0.1% respectively, as denoted by parameters “Change in baseline cardiovascular disease” and “Change in baseline respiratory disease” in Table 3. These values are derived from "the variation of population above 65 and cardiovascular and respiratory mortality over the nine regions in 1990" [70]. The maximum increase of cardiovascular and respiratory disease of 5% is based on expert guess [70]. To monetize these health impacts, the value of statistical life is 200 times the per capita annual income. Also shown in Table B.3, the “emigration cost” or value of emigration is set to three times the per capita income, and the “immigration cost” is 40% of per capita income in the host region [75]. In addition, a risk aversion factor (\( \eta \)), which is also known as the marginal utility of consumption, is included in the monetization process. In the EPA SCC calculations, \( \eta \) is set to one. For \( \eta > 0 \), a greater weight is applied to climate damages in poor countries than to that of rich countries. A higher \( \eta \) implies that one is more concerned about uncertainty, and thus should lead to a higher SCC [80]. In calculating monetary damages, the FUND
model allows for the option of applying an equity weighting to its estimates, which would account for greater loss of utility of a poor person than of a rich person for the same monetary damage [79]. The SCCs calculated for the EPA, however, do not incorporate equity weighting [77].

B.7 Conclusion

To better understand the assumptions behind the SCCs reported by the EPA, a comparison is made between the FUND 3.3 model, which was used in the SCC calculation, and APMT. Climate damages using the DICE-2007 damage function are calculated using mean global temperatures from both models with the SRES A1b background scenario. When considering the SRES A1b scenario, the damages from FUND are found to be almost half that of APMT. Differences in damages can be attributed to both models using differing parameters for RF and the ocean heat capacity parameter in the temperature response functions. Other possible factors contributing to these differences may be the emissions inputs themselves, or the methods in which FUND and APMT account for temperature changes from the preindustrial period. However, in order to fully comprehend the assumptions behind EPA estimates of the SCC, it is also necessary to evaluate the monetization method used in the FUND 3.3 model. From correspondence with David Anthoff, a developer of FUND, we were able to obtain a version of the model that was used in calculating EPA SCCs, as well as better understanding of the parameters within the model. However, due to limited accessibility of Mr. Anthoff, the opaque nature of the model (since it was modified with the assumptions used for the EPA analysis, and given as an executable file), and very few sources available to more thoroughly explain the assumptions of the EPA estimates, questions still remain in understanding and using the model to replicate the EPA SCCs. In the future, more communication and research is necessary to answer these questions, and to find a way to input the temperature profiles of APMT into FUND.
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