

Estimating the Environmental Benefits of Aviation Fuel and Emissions Reductions

by

Christopher S. Dorbian

B.S., Johns Hopkins University, 2008

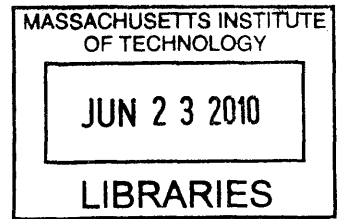
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Abstract

With commercial aviation continuing to grow and environmental policymaking activity intensifying, it is becoming increasingly necessary to assess the environmental impact of measures that result in changes in aviation fuel burn levels. For estimating air quality and climate impacts, it is important to employ a multi-gas approach that accounts for the effects of all emitted species, not just carbon dioxide (CO₂). The main objective of this thesis is to develop a simplified framework for monetizing the CO₂ and non-CO₂ co-benefits of aviation fuel and emissions reductions. The approach is based on two main pieces, both of which are derived using the Aviation environmental Portfolio Management Tool (APMT). First, the air quality marginal damage cost of a unit of fuel is estimated using an air quality response surface model. Second, a simplified probabilistic impulse response function model for climate is employed to derive a non-CO₂/CO₂ impact ratio that can be multiplied by a social cost of carbon to estimate the additional benefits of fuel burn reductions from aviation beyond those associated with CO₂ alone. The sensitivity of the non-CO₂/CO₂ climate ratio to metric choice, scientific assumptions, background scenarios, and other policymaker choices is explored. Notably, it is found that given the large uncertainties in short-lived effects, the choice of metric is not particularly influential on the overall ratio value (that is, similar results—within the range of uncertainty—are found for the different metrics considered).

This thesis also validates the use of the climate ratios and air quality marginal damages through two sample applications. The first study explores the impact of various aviation growth scenarios and demonstrates the applicability of this framework to a multi-year analysis. The second study concerns the introduction of an advanced aircraft concept into the present-day aviation fleet and demonstrates the ability of the climate ratios to capture scientific and valuation-based uncertainties. In both cases, the derived ratios and air quality damage costs are found to be a good surrogate for a full impact analysis in APMT, relative to the overall uncertainty in estimating impacts.

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1 Introduction

1.1 Background

The U.S. Environmental Protection Agency (EPA) has determined that carbon dioxide (CO₂) and other greenhouse gases (GHGs) endanger public health and welfare 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) (1). 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,” (2).

The proposed endangerment finding 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,” (3). The Obama Administration has expressed a preference for Congress to limit GHG emissions through a clean energy and climate bill over having the executive branch take action by way of EPA regulation (4). Regulation of GHGs by either branch of government could have far reaching implications for transportation, manufacturing, and power generation, as these sectors are responsible for emitting significant quantities of these pollutants. Commercial air transportation—an industry that has grown rapidly over the past 50 years and is expected to continue growing at a rate of 5% per year over the next 20-25 years—is particularly challenged by environmental concerns as strong growth in demand has been accompanied by increasing emissions of some pollutants from aviation against a background of emissions reductions from many other sources (5). While there is currently no government-wide precedent for employing the marginal damages of greenhouse gases in order to regulate emissions that have a direct or indirect radiative or warming, a recent U.S. interagency

working group report suggests a move in this direction. The interagency report develops social cost of carbon estimates meant to allow U.S. government agencies to incorporate the social benefits of reducing CO₂ emissions into cost-benefit analyses of regulatory actions (6).

1.2 Motivation

When conducting policy analysis, it is becoming increasingly important to assess the environmental impact of measures that result in changes to aviation fuel burn levels. For climate change impacts, it is necessary to account for the effects of all emitted species, not just carbon dioxide (CO₂). Greenhouse gases such as methane, nitrous oxide, and a number of other short-lived gases and their precursors are all important contributors to climate change. Although the Kyoto Protocol targets a number of relatively long-lived GHGs beyond CO₂, most climate change discussions and abatement cost assessments have focused almost entirely on CO₂. While CO₂ is the largest single contributor to climate change, there are strong physical and economic arguments for the inclusion of non-CO₂ gases in policies to address climate change. Short-lived effects—such as ozone precursors, aerosols, contrails and contrail-induced cirrus—are believed to contribute significantly to human-induced climate change (7). This is true in general, but particularly for aviation where non-CO₂ impacts on changes in surface temperature may be of the same magnitude as impacts due to CO₂. In addition, reducing aviation's adverse effects on climate beyond CO₂ may have significant co-benefits in terms of air quality. Primary and secondary particulate matter from aircraft engine exhaust cause serious health problems (including premature mortality) when inhaled over long periods of time by humans.

Because of these short-lived impacts, Reilly et al. (8) assert that a cost-effective abatement strategy would focus heavily on non-CO₂ gases in the early years. The relative value of reducing non-CO₂ emissions, discerned from global warming potentials, is one reason that including non-CO₂ emissions can help lower implementation costs of a climate policy. Some non-CO₂ gases have high carbon-equivalent values and thus even a small carbon-equivalent price on these gases could motivate emissions reductions. Tol (9) compared the cost of two emissions reduction scenarios aimed at meeting some level of anthropogenic

radiative forcing. In one scenario, CO₂ emissions reduction was the only possibility to meet the target. In another scenario, abatement of methane and nitrous oxide was added. Tol found a cost savings of nearly 27 percent in the second scenario compared to the CO₂-only scenario.

The challenge in including non-CO₂ emissions in cost benefit analyses results from the fact that these emissions can have effects on the environment and human health and welfare that differ by the type, magnitude, timing, and geographic location of the impact. Further, there are different levels of scientific uncertainty for the different impacts and disagreement on an appropriate metric for quantifying the effects. For this reason, Forster et al. (10) as well as Shine et al. (11) maintain that it is premature to include non-CO₂ effects from aviation in trading schemes until a robust emissions based index is available in addition to a consensus across climate models on metric values.

Given the need for a multi-gas approach to climate impact analysis, it would be valuable to many policy-makers to have a simple method for monetizing CO₂ and non-CO₂ impacts. Within the Federal Aviation Administration (FAA), for example, many projects deal with changes in fuel burn at the fleet level. If provided with a simplified framework for doing environmental monetization, more of these activities will be inclined to include CO₂ and non-CO₂ impacts in their cost-benefit analyses. Accounting for these effects can further motivate various fuel burn reduction schemes and other policy implementations.

This thesis has two primary objectives. The first is to develop a simplified means for estimating the non-CO₂ co-benefits of aviation fuel burn reductions. The second is to apply this framework to two aviation scenarios: one in which changes in operations growth and procedures are studied and one in which an advanced vehicle concept is introduced into the fleet.

1.3 Approach

This thesis develops aviation-specific ratios representing the impacts of non-CO₂ species relative to the impact of CO₂; these ratios may be applied to user-specified social cost of carbon (SCC) values to estimate the monetized benefits of reducing CO₂ and non-CO₂ emissions from aircraft. For air quality

health impacts, estimates of the marginal damage costs of different emissions are provided directly in terms of dollars per tonne of fuel burn or emission change. The method of applying an aviation-specific ratio and an air quality marginal damage cost in order to calculate the total benefit of a reduction in fuel burn is presented here in words:

$$\textit{Benefit} = (\textit{full-flight fuel burn reduction} * 0.86 \textit{ units of carbon per unit of fuel} * \textit{social cost of carbon} * \textit{aviation-specific ratio of CO}_2 \textit{ and non-CO}_2 \textit{ climate impacts}) + (\textit{below 3,000 feet fuel burn reduction} * \textit{air quality marginal damage})$$

The SCC is the marginal damage cost of an additional unit of carbon emissions, and hence the aviation-specific ratios provided are intended to scale the social cost of carbon to account for the non-CO₂ effects associated with aircraft emissions relative to those of CO₂. The SCC can be used to place a value on aviation CO₂; there are approximately 27 tonnes of carbon in 100 tonnes of CO₂. There are recent precedents from the U.S. Environmental Protection Agency (EPA) and Department of Energy (DOE) using the SCC to help quantify the monetary benefits of reducing greenhouse gas (GHG) emissions (12) (13). It is expected that the SCC will become an increasingly common regulatory specification associated with cost-benefit analysis guidance for the assessment of federal actions, such as infrastructure improvements to the air transport system. SCC estimates vary widely in literature and are highly sensitive to the particular modeling choices and assumptions used. The ratio of CO₂ effects to non-CO₂ effects for aviation is less sensitive—though not insensitive—to these scenarios and assumptions. This is the rationale in this thesis for deriving aviation-specific ratios using a range of assumptions and then allowing the user of the ratios to specify the SCC exogenously according to their own needs.

The climate ratios and air quality damage costs were estimated using the Aviation environmental Portfolio Management Tool (APMT), which is being developed as a component of the environmental tools suite by the Federal Aviation Administration Office of Environment and Energy (FAA-AEE) (14). APMT uses a flexible, probabilistic framework for estimating the physical and socio-economic

environmental impacts of aviation. This tool allows for the inclusion of much of the uncertainty present in understanding the different effects, and thus the tables in this thesis provide ranges on non-CO₂/CO₂ ratio and SCC estimates using different combinations of assumptions. Since CO₂ and other GHGs persist and mix in the atmosphere for long periods of time, thus affecting climate on the global scale, non-CO₂/CO₂ ratios presented in this thesis represent the global impacts of U.S. aviation as opposed to the effects only within the U.S. The analysis also adopts the context of considering only globally-averaged impacts; the impacts on any region of the world will necessarily be different from this average.¹ Additionally, the non-CO₂/CO₂ ratios and damage costs are designed to be applied to U.S. fleet-wide analyses and are not, in general, applicable to individual aircraft or airport analyses.

One important goal of this work was to understand the influence of metric choice, current scientific uncertainties, and value-based judgments (e.g. discount rate or time period used for a physical metric) on the ratio. Non-CO₂/CO₂ ratios were calculated using three different aviation metrics and the estimates are compared across these metrics. The sensitivity of the derived ratios to metric choice and to the various categories of uncertainty was tested.

1.4 Thesis Organization

This section briefly describes the organization and structure of this thesis. The thesis consists of six chapters, the contents of which are summarized below.

Chapter 2 provides an overview of aviation's impacts on the environment as well as a discussion of current decision-making practices concerning aviation and the environment. The chapter begins with a discussion of the health impacts attributable to pollution from aircraft. Next, the chapter reviews the climate impacts of aircraft emissions. Finally, the chapter introduces recommended best practices for economic analysis of environmental regulations and describes the current practices and organization of environmental decision-making.

¹ Accounting for U.S. aviation's impacts within the U.S. only would require the use of an SCC that values the impact of carbon on the U.S. only. The multiplier values would not change.

Chapter 3 presents approaches for modeling the environmental impacts of aviation. In particular, the chapter discusses the methods employed within the APMT-Impacts air quality and climate modules, with a focus on non-CO₂ impact modeling.

Chapter 4 presents an alternate means of capturing air quality health costs through the derivation of a marginal damage cost on fuel burn. Next, the concept of using a ratio of non-CO₂/CO₂ impacts for climate impact valuation is introduced, along with a discussion of possible metrics for such a ratio followed by the presentation of APMT-derived values for these ratios. Lastly, the chapter outlines the appropriate usage of this framework for policy analysis.

Chapter 5 applies the concepts covered in Chapter 4 to two sample scenarios. The first application examined is a study in which the impact of many different combinations of operations growth trajectories and NextGen-enabled operational procedures is explored. The second application explores the introduction of a NASA N+3 generation advanced aircraft concept into the fleet in the 2035 EIS timeframe. In each case, the monetized environmental impact is determined using both APMT-Impacts and the climate ratios and air quality marginal damage costs. The results are then compared across the two methods.

Chapter 6 concludes this thesis, highlighting key findings from the work as well as possible areas of further research.

1.5 Key Contributions

Listed below are the key contributions of this thesis in the area of aviation environmental impact modeling and policy assessment.

- Development of a simplified framework for assessing the environmental co-benefits of aviation fuel burn and emissions reductions, specifically through the use of the social cost of

carbon, APMT-derived non-CO₂/CO₂ climate ratios, and APMT-derived air quality marginal damage costs.

- An assessment of the sensitivity of the derived non-CO₂/CO₂ ratios to metric choice and to the various categories of uncertainty, showing that the ratio is insensitive to metric choice *relative to the overall uncertainty in estimating non-CO₂ impacts*.
- Validation of APMT results through social cost of carbon comparison studies with other well-recognized integrated assessment models and U.S. Government estimates.
- An assessment of the environmental impacts of two NASA studies, one exploring the effects of various growth scenarios and another exploring the impact of an advanced aircraft configuration. These sample cases also validate the use of the derived non-CO₂/CO₂ ratios and air quality marginal damages as a surrogate for a full APMT-Impacts analysis.

2 Aviation Environmental Impacts

The structure and content of the following sections closely follows the work of Mahashabde (15), Fan (16), and the CAEP/8 NO_x Stringency Cost-Benefit Analysis Demonstration using APMT-Impacts (17).

2.1 Air Quality Impacts

Aircraft engine exhaust consists primarily of CO₂ and water at shares of 70% and slightly less than 30%, respectively. The remaining emissions from aircraft engines are nitrogen oxides (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), unburned hydrocarbons or volatile organic compounds (VOCs), particulate matter, and other trace species. While these species account for less than 1% of aircraft exhaust emissions, they are the dominant concern in terms of aviation's impact on air quality in the vicinity of airports (18). In fact, most of these species are designated as "criteria pollutants" by the US EPA. Under the Clean Air Act, the US EPA sets National Ambient Air Quality Standards on six pollutants that are linked to adverse health impact: CO, lead (Pb), nitrogen dioxide (NO₂), ozone (O₃), particulate matter, and sulfur dioxide (SO₂). The following sections provide an overview of the three aviation pollutants of greatest concern: NO_x, SO_x, and particulate matter.

Nitrogen oxides (NO_x):

NO_x forms from the oxidation of nitrogen gas. In a jet engine, the formation of NO_x occurs when air passes through high temperature and pressure combustion processes. The recent US EPA integrated science assessment linked NO₂ to respiratory morbidity (19). However, it is unclear whether the impact is solely a product of NO₂ or whether NO₂ is a surrogate for impacts related to a different pollutant. The more significant impact of NO_x is its role as a precursor to both O₃ and secondary particulate matter in the form of. The formation of O₃ is highly dependent on ambient levels of NO_x and VOCs in the atmosphere. NO_x emissions affect levels of particulate matter through the formation of ammonium nitrate (19). In the aviation sector, ozone-related health impacts are insignificant relative to the more significant health risks associated with particulate matter, which are discussed in more detail below (20).

Sulfur oxides (SO_x):

Sulfur oxides are produced when small quantities of sulfur, present in essentially all hydrocarbon fuels, are oxidized during the combustion stage of a jet engine. Gases produced include sulfur dioxide (SO₂), sulfur trioxide (SO₃), and gas-phase sulfuric acid (H₂SO₄). Sulfuric acid forms when sulfur oxides dissolve in water vapor, which can then nucleate with water to create volatile particles (21). Because of the large volumes produced, SO₂ is the dominant concern in terms of health impacts. The recent US EPA integrated science assessment for sulfur oxides concludes that evidence from health studies supports a “causal relationship between respiratory morbidity and short-term exposure to SO_x” (22). Additionally, as for NO_x, sulfur oxides combine with other compounds in the atmosphere to form secondary particulate matter. SO_x can react with ammonia to form ammonium sulfate, which can be harmful to human health.

Particulate Matter (PM):

Unlike the other species discussed above, particulate matter is not a defined chemical species, but rather a general title for particles that form and are small enough to be inhaled by humans. Aviation particulate matter emissions fall into the EPA-defined class known as fine particulate matter (PM_{2.5}), where the aerodynamic diameter of the particles is less than 2.5 micrometers (20). Aircraft PM_{2.5} includes small particles that are directly emitted as non-volatile PM (nvPM)—i.e. soot or black carbon—as a result of incomplete combustion. The larger portion of aircraft-sourced particulate matter comes from secondary PM. Secondary PM forms when other aircraft exhaust components, such as NO_x and SO_x, react with other sources of pollution and natural sources to create ammonium sulfates and ammonium nitrates (henceforth referred to as PM sulfates and PM nitrates, respectively) (20) (23).

When humans breathe in particulate matter, fine particles get lodged within their lungs and can pass into the bloodstream, potentially causing serious health problems. The correlation between chronic PM_{2.5} exposure and various adverse health incidences is well documented. Health endpoints related to PM_{2.5} include asthma, chronic bronchitis, restricted activity days, respiratory hospital admissions,

cardiovascular hospital admissions, and premature mortality in infants and adults (24). These health endpoints can be related to changes in PM_{2.5} concentrations through concentration-response functions based on epidemiological studies. The US EPA uses the Environmental Benefits Mapping Program (BenMAP) for performing health impact analyses. Using this tool, a recent study estimates 64-270 yearly premature mortalities which are attributable to aviation emissions (25). Brunelle-Yeung, meanwhile, estimates the aviation-related risk of premature mortality to be 210 incidences in the year 2005 (with a 90% confidence interval of 130-340 yearly deaths). The impacts from PM nitrates and PM sulfates dominate those from non-volatile PM and secondary PM from hydrocarbons (26).

2.2 Climate Impacts

Aviation's impact on the global climate occurs through effects that have varying time and spatial scales. Some impacts last for only a few hours or days and are primarily felt regionally where aircraft fly while other impacts persist for centuries and are realized on the global scale. Each effect perturbs the planetary radiative balance in some way, resulting in a warming or cooling impact. Radiative forcing 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 (7). The IPCC Fourth Assessment Report estimates the total anthropogenic radiative forcing from subsonic aviation to be about 3% of total anthropogenic radiative forcing, not accounting for the impact of cirrus clouds (7). The discussion in this thesis is focused around commercial subsonic aviation, where aircraft typically fly in the 9-13 km altitude band, or nominally in the upper troposphere and lower stratosphere. The impact pathway for aviation-induced climate change starts with direct emissions of CO₂, NO_x, H₂O, SO_x, HC, and soot. The following discussion summarizes the impact of these emissions and other forcing agents from aircraft on climate.

Carbon dioxide (CO₂):

CO₂ emissions have a net warming impact through a positive radiative forcing. CO₂ emissions persist in the atmosphere on the order of centuries and have impacts that are spatially homogeneous (27).

Water vapor (H₂O):

Water vapor emissions have a direct warming influence that persists on the order of days. H₂O emissions from subsonic aircraft in the troposphere and lower stratosphere do not have a significant impact relative to other effects. However, water vapor emissions at stratospheric altitudes in excess of approximately 10-15 kilometers, e.g. from supersonic aircraft, can have a potentially significant warming influence (27).

Nitrogen oxides (NO_x):

NO_x emissions have both a warming and cooling influence on the global climate. Increased NO_x levels in the upper troposphere lead to increased column ozone, which has a short-lived, local warming influence. NO_x emissions also produce OH radicals which increase the oxidative capacity of the atmosphere. This leads to a decrease in methane (CH₄) concentrations and a long-term decrease in methane-related tropospheric ozone formation, both of which are cooling effects. The climate impacts of NO_x are susceptible to seasonal variation in solar insolation and background concentrations of NO_x and HO_x (27). The effects vary spatially and temporally, with the short lived O₃ warming impact lasting on the order of months while the NO_x-CH₄ interaction and associated primary mode NO_x-O₃ effect lasting on the order of decades (28) (29). When looking at globally-averaged impacts, the shorter term warming effects (largely felt in the northern hemisphere where aircraft fly) balance the longer term cooling effects (felt globally); however, regional impacts can have significant variation (15).

Contrails and aviation-induced cirrus:

Warm, moist exhaust from aircraft can often mix with colder, less humid ambient air at altitude, triggering ice particles to nucleate and form contrails. Under some atmospheric conditions, contrails can persist and lead to larger areas of cirrus than would occur otherwise. The formation of ice particles is highly dependent on water vapor emissions and ambient conditions (i.e. pressure, temperature, and relative humidity). If ice supersaturation is present in the ambient atmosphere along an aircraft flight

track, persistent contrails can spread through wind-shear to form cirrus-like cloud structures which cannot be distinguished from naturally forming cirrus clouds if their history is unknown (30). The correlation of contrail and cirrus cloud formation with aviation is certain, both of which produce a net warming effect that persists from hours to days (27).

Sulfate aerosols and particulate matter:

Sulfate aerosol emissions from aircraft reflect incoming radiation and thus have a cooling impact. Black carbon particles, or nvPM, absorb incoming radiation and thus have a warming impact. The effects of both species last on the order of days to weeks in the atmosphere. An area of ongoing research is the indirect effect that aerosols have on naturally occurring clouds. Aerosol emissions may alter the microphysical properties of clouds, possibly leading to a change in the precipitation rate, cloud lifetime, and cloud radiative properties. Current scientific uncertainty on this interaction is significant (27). Additionally, particulate matter emissions from aircraft may act as cloud condensation nuclei and thus serve as a mechanism for aviation-induced cirrus cloud cover (30).

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

CO and VOC emissions from aircraft are thought to have an insignificant effect on climate relative to the other impacts discussed thus far. CO emissions from aircraft are also significantly smaller compared to CO emissions from other sources (27).

The current level of understanding of the different aviation climate impacts varies by effect. The most recent radiative forcing estimates from the IPCC are shown in Figure 1. In the figure, Lee et al. present the different climate effects along with uncertainty bands and a qualitative rating for level of scientific understanding. CO₂ has a relatively well understood impact. Aviation-induced cirrus has the highest uncertainty, as reflected by the presentation of bounds on the RF of this effect with no mean estimate (30).

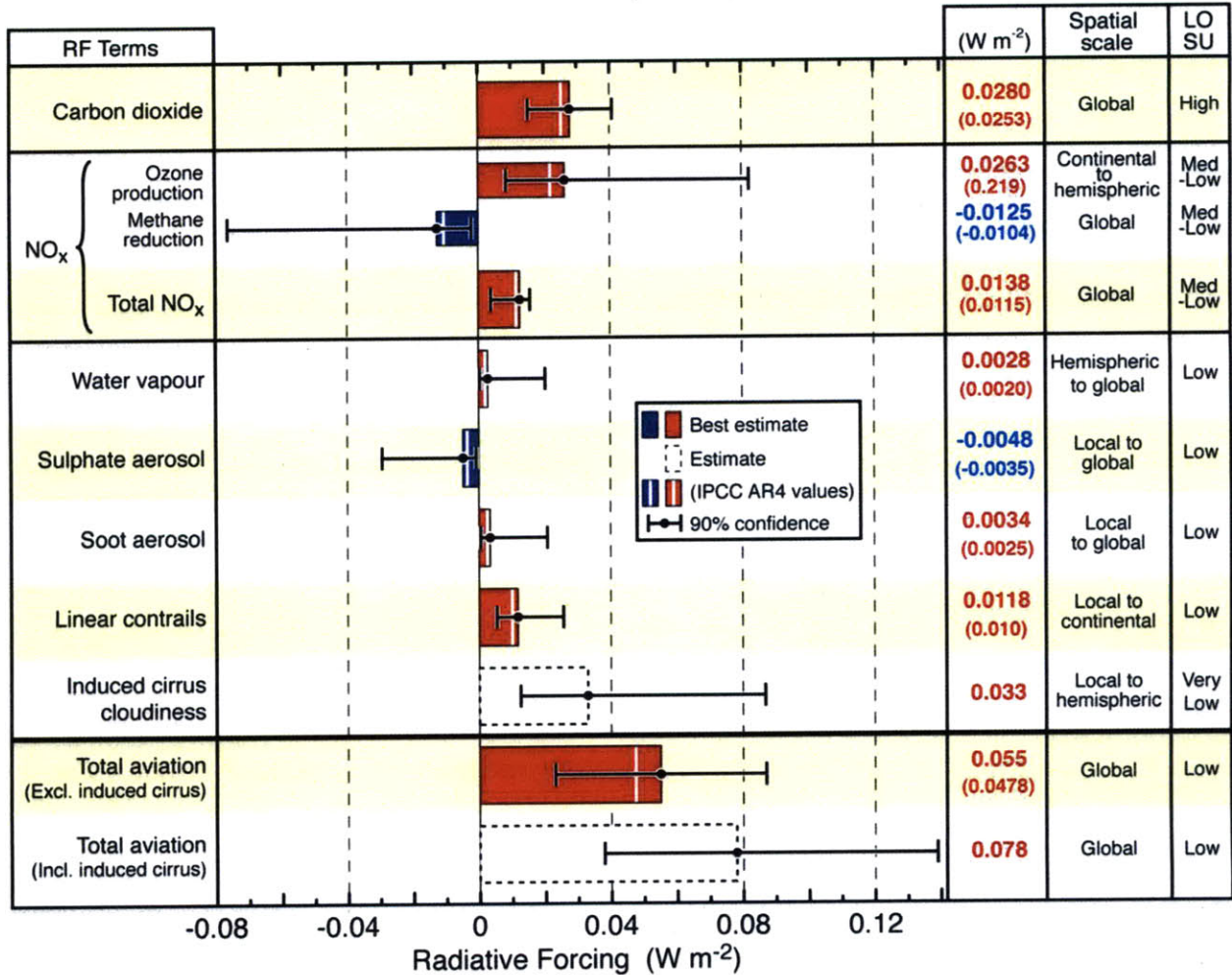


Figure 1 Radiative forcing from aircraft emissions (30)

2.3 Current Aviation Environmental Decision-making

An important component in the decision-making process for regulatory agencies around the world is the evaluation of tradeoffs among the various objectives of a given policy. In the sector of aviation, for example, every airplane design or operational procedure represents a balance of economics, performance, noise, and emissions. Since capital costs are high and time scales are long for new airplane programs, it is important to gather all of the information on the costs and benefits of a program before making a decision. Three common approaches to economic evaluation of a policy are cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), and distributional analysis. Distributional analysis is a detailed type of

CBA that is useful for determining how benefits and costs are distributed among various stakeholders (e.g. economic sectors and/or groups of people and/or geographical regions).

CBA typically consists of monetizing the costs and benefits of a policy so as to allow for a direct comparison of the two. The favorable effects (i.e. positive impacts on social welfare) of policy actions are defined as benefits whereas the opportunities foregone because of a new regulatory policy are defined as economic costs (31). The goal of CBA is to maximize the net benefit of a policy implementation, where the net benefit is the benefit of the regulation minus the costs. The cost of a policy can extend beyond implementation cost of a regulation to the societal cost associated with a negative impact on human health and welfare.

CEA consists of selecting the policy that costs the least for the same expected results. CEA is most useful for evaluating policies with very similar expected benefits. CEA can be misleading, however, if there is a non-linear relationship between the physical metric that is regulated and the ultimate health and welfare impacts. The US EPA guidelines for economic analysis states that “Cost-effectiveness analysis does not necessarily reveal what level of control is reasonable, nor can it be used to directly compare situations with different benefit streams,” (31). For instance, a CEA approach to NO_x regulation would not provide an estimate on the air quality or climate impacts for the given reduction in NO_x emissions which makes it impossible to say if the costs of the regulation are justified.

While all federal agencies within the United States are required by directives and executive orders from the Office of Management and Budget to evaluate costs and benefits of regulatory measures, other economic evaluation approaches are often used in cases where sufficient data is not available to quantify costs and/or benefits (32) (33). Within the International Civil Aviation Organization’s Committee on Aviation Environmental Protection (ICAO-CAEP), for example, some environmental analyses are conducted in a CEA framework with benefits quantified in terms of physical measures such as tons of NO_x reduced or number of people removed from a certain noise level. These measures are then

normalized by economic costs to allow for comparison of different options. For environmental policy analysis, CBA has drawn criticism due to the monetization of health and welfare impacts such as air quality health cost, damage to ecosystems due to climate change, etc. However, though there is uncertainty in monetizing environmental impacts, the value of CBA is that it decreases the uncertainty in a decision-maker's understanding of a policy's impact. This effect is depicted qualitatively in Figure 2. The figure shows that, while scientific uncertainty increases as one moves towards a comparison of environmental costs and benefits, decision-making uncertainty decreases when comparing costs and benefits rather than just physical quantities such as emissions inventories. Mahashabde (15) further elaborates on the value of CBA in environmental policy analysis.

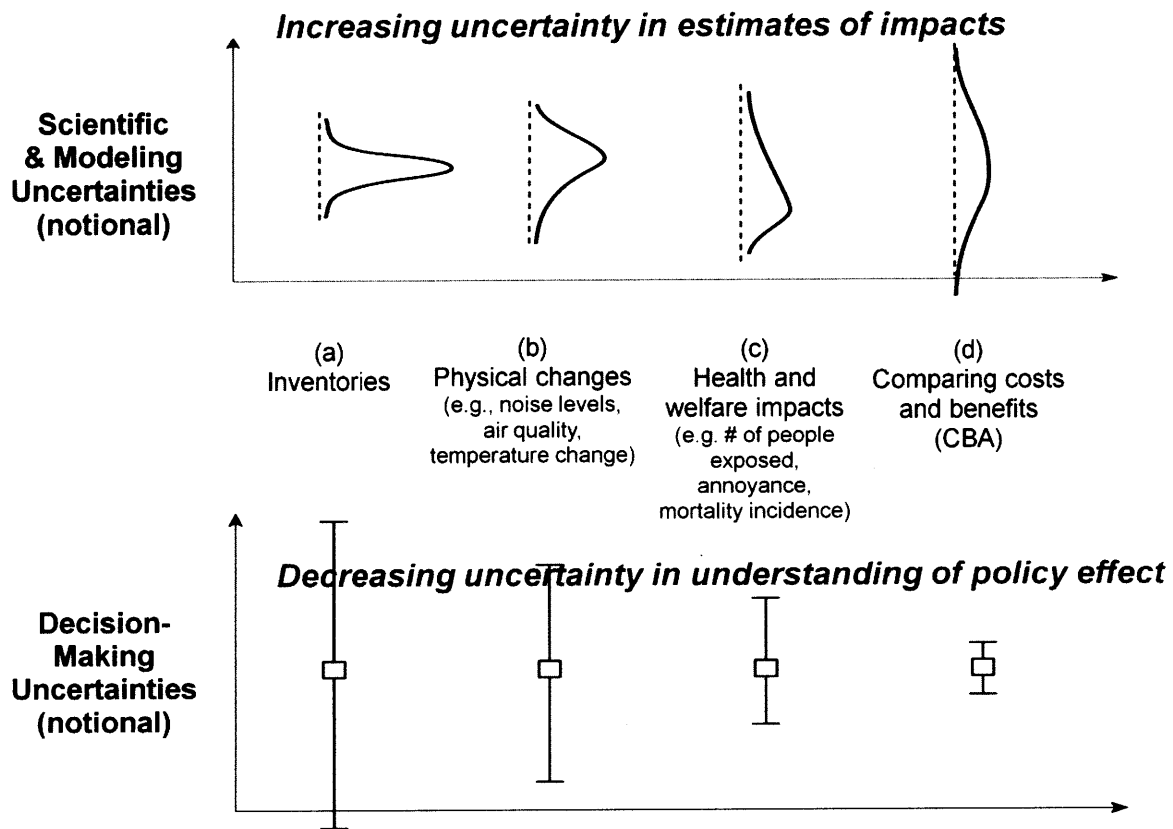


Figure 2 Scientific vs. policy-making perspectives on uncertainty (15)

Specific procedures for conducting CBA and other environmental assessment practices were laid out by the US EPA in 2000 in accordance with executive orders and OMB guidance (31). The EPA is the

primary governmental body conducting environmental analysis for federal regulations within the United States, but there are many other agencies performing environmental impacts assessment as well. The Federal Aviation Administration Office of Environment and Energy has been responsible for the development of several tools to assess the environmental impacts of aviation, such as the Aviation Environmental Design Tool (AEDT), Emissions Dispersion Modeling System (EDMS), Model for Assessing Global Exposure to Noise from Transport Aircraft (MAGENTA), Integrated Noise Model (INM), and System for Assessing Global Emissions (SAGE) (34). While many FAA activities calculate fuel burn levels for various policy or technology scenarios, there is little monetization of environmental impacts for use in CBA. One simple step towards incorporating environmental costs or benefits of fuel burn changes is to use the social cost of carbon (SCC) as a surrogate for climate impacts. The SCC is an estimate of the marginal cost of emitting one unit of carbon emissions into the atmosphere at a particular point in time. SCC estimates can be taken from literature and, when applied to fuel burn changes, can be used to quantify the climate impacts due to the change in CO₂ that results from a change in fuel burn. However, this approach does not account for the non-CO₂ climate and air quality impacts associated with aviation fuel burn changes and thus does not capture the whole CBA picture.

3 Aviation Environmental Impact Modeling

The Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) is a Center of Excellence in the US that focuses on improving understanding of aviation environmental impacts, assessing policy options, and supporting the decision-making process. PARTNER—which is supported by the US FAA, the National Aeronautics and Space Administration (NASA), and Transport Canada—is a collaboration of members from academia, industry, and government. Through the PARTNER Center, FAA-AEE, NASA, and Transport Canada have led an initiative to develop a comprehensive tool suite for assessing the environmental impacts of aviation activity.

The Aviation environmental Portfolio Management Tool (APMT) is a component of the FAA-NASA-Transport Canada tool suite that is focused on the economic analysis and environmental impact assessment aspects of the venture’s broader research objective. The goal of APMT is to allow decision-makers to examine the economic costs and environmental benefits of aviation policies while accounting for associated uncertainties. APMT was developed according to published best practices for policy assessment methods; every requirement was drawn directly from US and European policy guidance after an extensive review of the relevant literature and documentation (15). The findings of this study and detailed requirements were laid out in the Requirements Document for the Aviation environmental Portfolio Management Tool (14), which was reviewed by the Transportation Research Board of the U.S. National Academies (35).

APMT’s place in the FAA-NASA-Transport Canada’s aviation environmental tools suite is depicted schematically in Figure 3. In this framework, APMT interacts with three other tools in order to process policies and scenarios and output costs and benefits: Emissions Prediction and Policy Analysis for Aviation (EPPA), the Environmental Design Space (EDS), and the Aviation Environmental Design Tool (AEDT) (36) (37) (38). EDS conducts detailed aircraft and engine analyses while AEDT estimates aviation noise and emissions for a given fleet and schedule. APMT itself has two components: APMT-

Economics models the economics of the aviation industry and APMT-Impacts models the environmental impacts of aviation. The economic cost outputs and environmental impacts estimates from these models can be used for either cost-benefit or cost-effectiveness analyses. Only APMT-Impacts was used for the work conducted in this thesis.

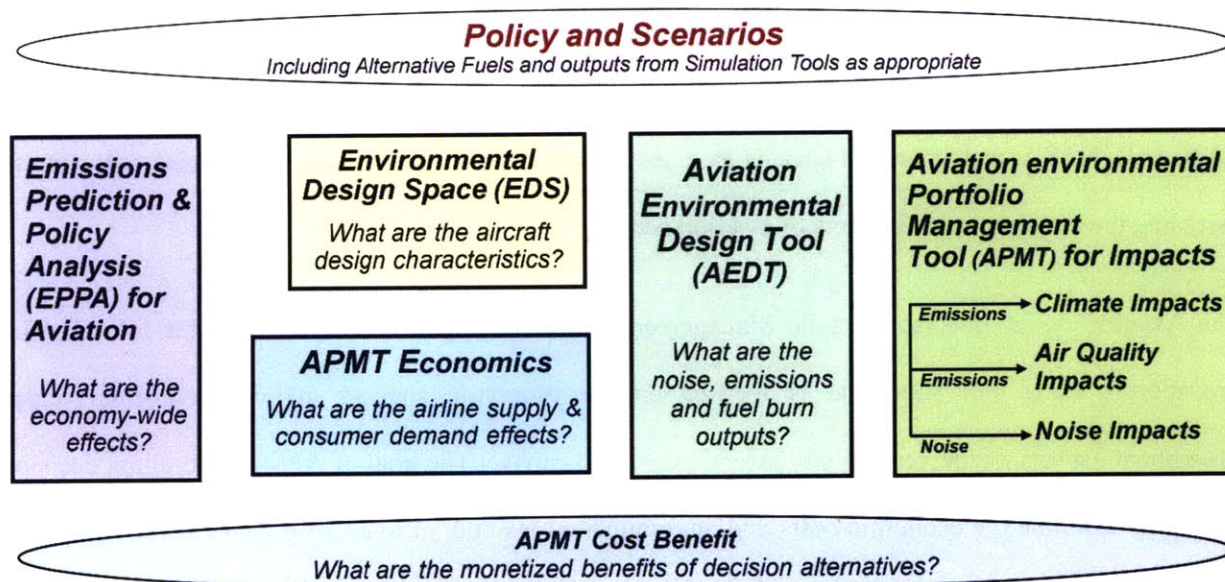


Figure 3 Environmental analysis framework of the FAA-NASA-Transport Canada environmental tool suite

APMT-Impacts takes as inputs emissions inventories and models the physical impacts of a policy or scenario and also monetizes those impacts, allowing for a direct comparison between benefits and costs. The primary metrics that APMT-Impacts captures for air quality and climate effects are presented in Table 1. APMT-Impacts is also capable of modeling noise impacts. This thesis is focused on the environmental impacts of fuel burn and emissions changes; thus noise analysis was not performed for this study and the noise metrics are not presented in the table. The following sections describe the modeling approaches utilized in the Air Quality and Climate modules of APMT-Impacts.

Table 1 APMT-Impacts environmental modeling overview

Impact type	Effects modeled	Primary Metrics	
		Physical	Monetary
Air Quality	Secondary PM by NO _x and SO _x Volatile PM due to sulfur and organics Nonvolatile Primary PM	Incidences of premature mortality	Net present value of health risks
Climate	CO ₂ Non-CO ₂ : NO _x , Cirrus, Sulfates, Soot, H ₂ O, Contrails	Globally-averaged surface temperature change	Net present value of socio-economic damages

3.1 APMT-Impacts Air Quality Module

The APMT-Impacts Air Quality Module evaluates the surface air quality impacts associated with aviation PM_{2.5}. The air quality health impact pathway used in APMT-Impacts is presented at the broad level in Figure 4 (20). An air quality modeling tool is used to calculate changes in ambient PM_{2.5} concentrations due to emissions in a baseline or policy scenario. Dose-response functions are then used to relate changes in health endpoints to changes in pollutant concentrations. The changes in health incidences are given a monetized impact by applying a set of valuations for all endpoints. The total cost of the scenario in terms of air quality health impacts can then be compared to other costs and benefits, such as those related to climate and noise impacts, and can be weighed against the cost of implementing a particular policy.

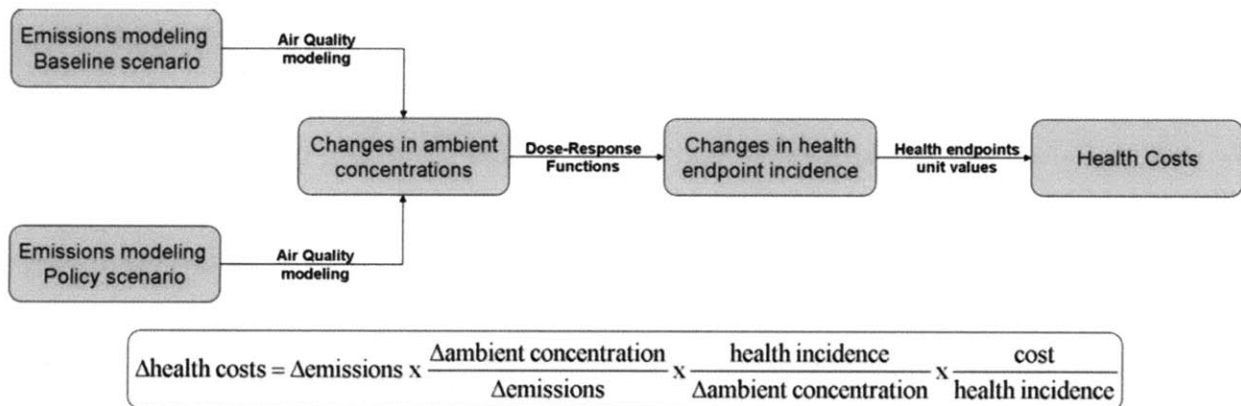


Figure 4 Health impact pathway for air quality assessment (20)

Policy assessment processes typically consist of analyzing multiple policy scenarios over long timeframes. To estimate the impacts of aircraft emissions on air quality, changes in pollutant concentrations at ground level are computed by atmospheric chemistry transport models (CTMs). These complex models simulate the chemical reactions and transport mechanisms of the atmosphere. The results of an example CTM air quality simulation are plotted in Figure 5. This figure shows a map of the national changes in average annual $PM_{2.5}$ due to aviation as modeled in the Community Multiscale Air Quality Modeling System (CMAQ), a 3-dimensional, grid-based air quality model (39). The analysis shows that aircraft emissions lead to an increase in average ambient $PM_{2.5}$ concentration of less than 0.1 percent (25).

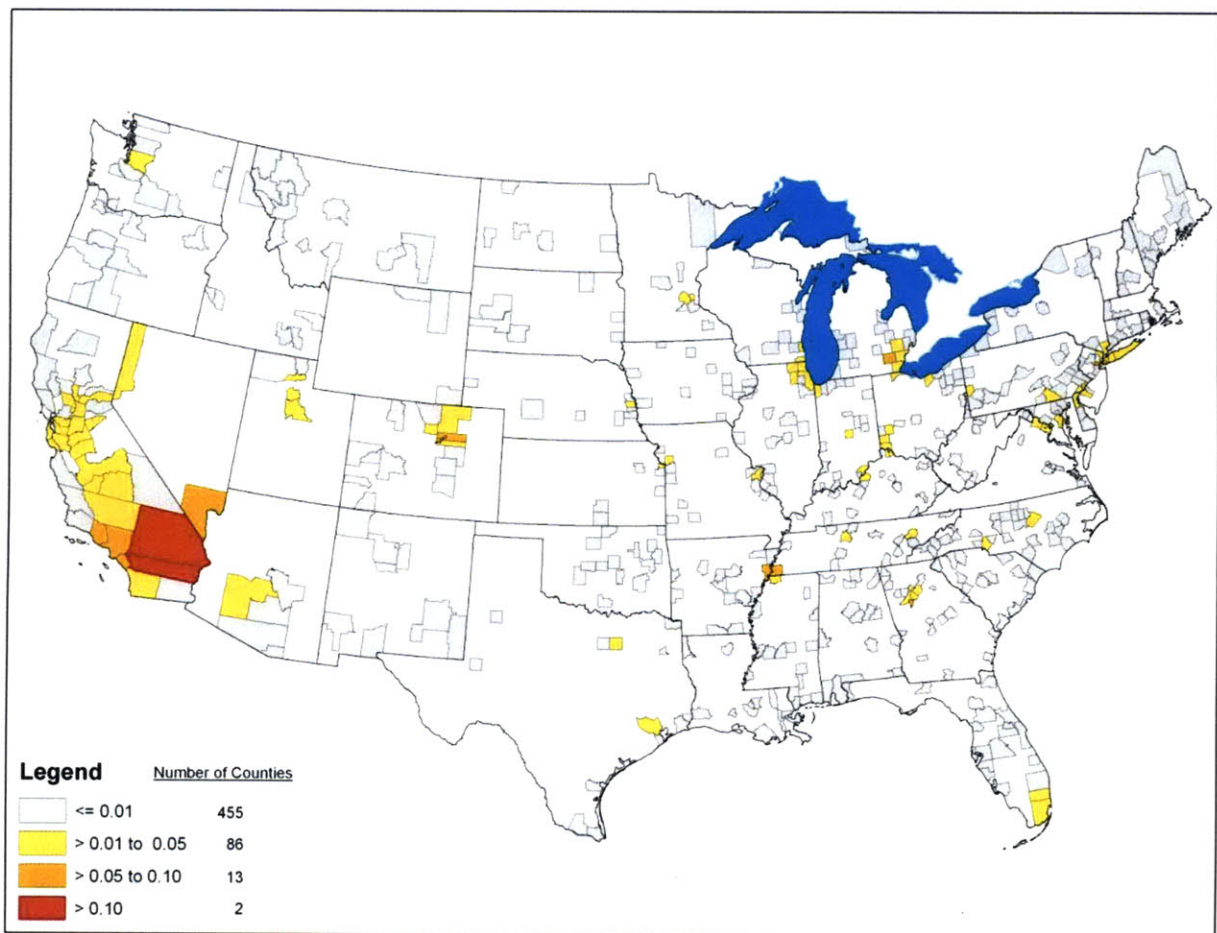


Figure 5 Estimated changes in annual $PM_{2.5}$ concentration ($\mu\text{g}/\text{m}^3$) due to aircraft emissions (25)

CTMs, though capable of high levels of fidelity, are currently computationally intensive and require long runtimes that often make them unsuited for rapid assessment of many policy scenarios. In this context, a reduced order model has the advantage of producing results in a timely fashion, having limited complexity and hence higher transparency. These reduced order models have accuracy levels that are less than CTMs but useful in a policy-making context (26).

The APMT-Impacts Air Quality Module uses a surrogate instead of a more complex CTM to calculate changes in ambient $PM_{2.5}$ concentration, thus accelerating the impact assessment process. APMT-Impacts uses a response surface model (RSM) built from statistical analyses of simulations performed using CMAQ. The RSM computes changes in $PM_{2.5}$ concentration for a given set of aircraft emissions below 3,000 feet as a function of four independent parameters: fuel burn, fuel sulfur content, nvPM, and NO_x . Changes in population exposure are computed directly from the RSM estimated changes in $PM_{2.5}$ concentration multiplied by the affected population. The RSM resolution corresponds to CMAQ's 36 km by 36 km Lambert conformal grid resolution over the US. Population exposure and associated health impacts are calculated on a cell-by-cell basis. Changes to population exposure are related to changes in health endpoints by means of concentration response functions (CRFs), which are derived from epidemiological studies (26). The valuation scheme used in the APMT-Impacts health impacts model is explained in detail in (20). Table 2 reviews the most recent CRFs used for each air quality endpoint and the valuation used.

Table 2 Concentration-response functions and valuations for air quality health impact analysis (26)

PM_{2.5} – related endpoints	Risk increase (% per µg.m⁻³ PM_{2.5})	Value of a Statistical Incidence (US 2000\$)
Premature mortality: Long-term exposure (adults age 30+)	Triangular 1.0 (0.6 – 1.7)	Lognormal distribution with mean \$6.3 M and standard deviation \$2.8 M (5% - 95% CI : \$2.9 - \$12 M)
Long-term exposure (infants age < 1 yr)	Triangular 0.7 (0.4 – 1)	
Chronic bronchitis	Triangular 1.5 (1.3 – 2.0)	Mean \$0.34 M Distribution described in Supporting Information
Hospital admissions - respiratory	Triangular 0.2 (0.14 – 0.29)	Discrete distribution \$15,647 (75%) \$31,294 (25%)
Hospital admissions - cardiovascular	Triangular 0.16 (0.14 – 0.19)	Discrete distribution \$18,387 (75%) \$36,774 (25%)
Emergency room visits for asthma	Triangular 0.8 (0.6 – 1.1)	Discrete distribution \$286 (75%) \$572 (25%)
Minor Restricted Activity Days	Triangular 0.7 (0.6 – 0.9)	Discrete distribution \$25 (25%) \$52 (50%) \$75 (25%)

APMT-Impacts can be used to calculate air quality damage costs broken down by four PM components: nvPM, PM nitrates, PM sulfates, and PM organics. The apportionment of impacts with respect to these PM components can be plotted as shown in Figure 6. The figure depicts the pollutant that contributes the most to changes in PM_{2.5} concentrations for each individual grid cell as given by the RSM. In the figure, PM_{2.5} from secondary nitrates dominates the largest area of the map.

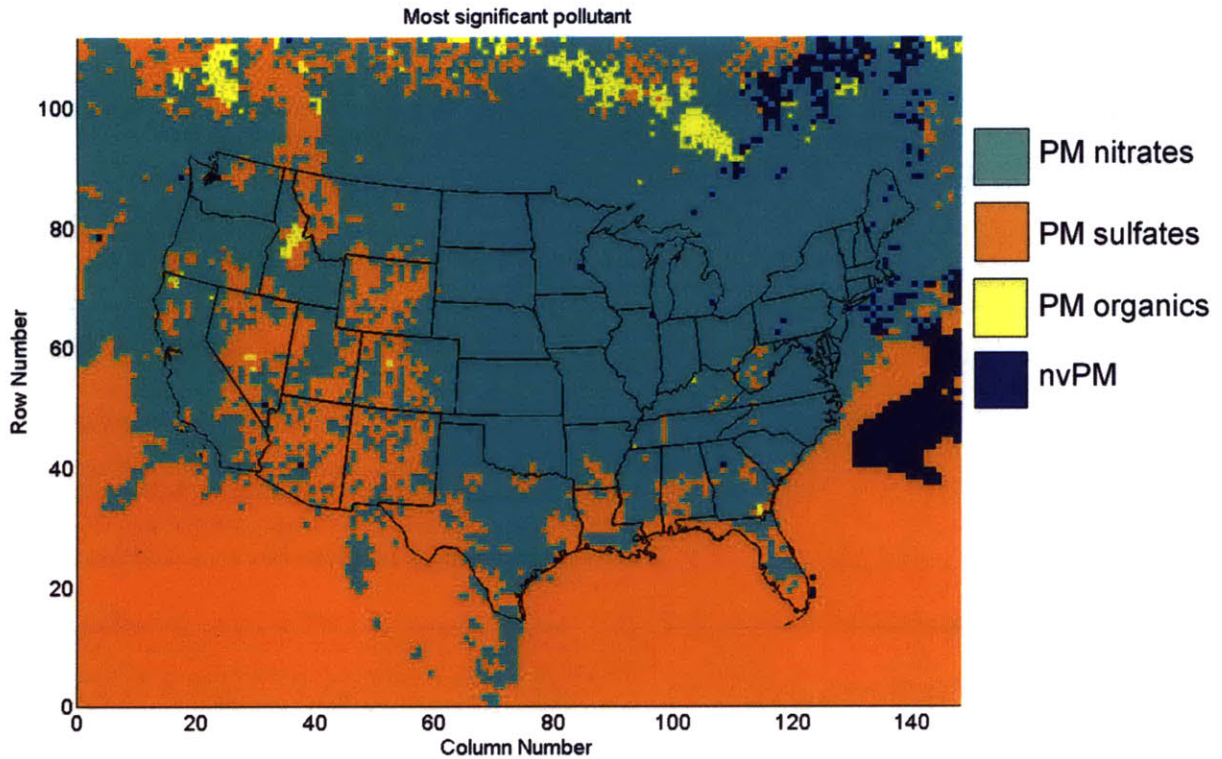


Figure 6 Map of largest contributing pollutant to changes in PM_{2.5} concentration by grid cell (26)

The APMT-Impacts air quality health impact analysis focuses on particulate matter and does not include ozone or hazardous air pollutants (HAPs) impacts. The choice to focus on PM_{2.5} was justified by Rojo and was based on an analysis that found that impacts of ozone due to aviation were about 49 cases of acute mortality (90 % CI: 3 to 95 cases) in 2002 compared to 670 mortalities from PM_{2.5}, thus indicating an ozone contribution equal to 7% of PM_{2.5} mortalities (20). This choice is further justified in a recent study by Ratliff et al. in which it is stated that “the modeled ozone changes (...) are small enough that they challenge the resolution and accuracy of the modeling methods,” (25). The known interactions and dependencies between the four components of PM_{2.5} and the four input parameters of the RSM are presented in Table 3.

Table 3 Known dependencies between PM_{2.5} components and the four independent variables (26)

PM - Component	Known interactions/dependencies with:	Description of interaction/dependency
PM organics	Fuelburn NO _x	Amounts of unburnt and partially-burnt hydrocarbons (HC) (volatile organic compounds, soot) increases with increasing fuelburn. NO _x EI affects secondary organic aerosols (SOA).
Ammonium (NH ₄)	SO _x NO _x	NH ₄ in the atmosphere reacts with SO ₄ and NO ₃ to form ammonium-sulfate and ammonium-nitrate.
PM Nitrates	NO _x SO _x nvPM	The amount of NO ₃ ions in aerosol form (given by ANO3I + ANO3J) in CMAQ corresponds to fully reacted nitrates with NH ₄ . There is a dependency with the amount of NH ₄ left over after it has reacted with sulfates. Also, EC (i.e. nvPM) can have small effects on nitrate formation due to its alteration of aerosol optical depth.
PM Sulfates	SO _x NO _x	The amount of SO ₄ ions in aerosol form (given by ASO4I + ASO4J) in CMAQ corresponds to fully reacted sulfates with NH ₄ . There is a dependency with the amount of NH ₄ available in the environment at a specific geographic location, which depends on NO _x in certain areas. The amount of PM Sulfates depends on the amount of SO _x emissions produced, i.e. fuel sulfur content.
nvPM (elemental carbon)	nvPM	Non-volatile PM consists of EC, dust and metals. It is not chemically reactive and comes directly out of the engine.

As per EPA practice, air quality concentrations are SMATed in the APMT RSM. The Speciated Modeled Attainment Test aims to reconcile empirical monitor data from different networks, using a variety of ground sensors, with that of computational models such as CMAQ (40). In general, SMATing reforms the absolute baseline of a model to reflect measured speciation profiles and concentrations. The SMAT process can alter the speciation split of a set of outputs; in APMT, the result of SMATing is a shift in sulfates upwards and in nitrates downwards.

Health incidences are translated into monetary terms in the RSM using the US Department of Transportation (DOT) recommended Value of a Statistical Life (VSL) as well as willingness-to-pay (WTP) and cost-of-illness (COI) estimates from literature. The Air Quality Module uses a VSL of 6.3

million US \$2000, with a standard deviation of 2.8 million US \$2000 (26) (41). More detailed information regarding the valuation of other health endpoints can be found in Rojo (20).

Current limitations of the RSM include a lack of accounting for the health impacts of cruise emissions from aircraft, the scope of geographic coverage, and the use of a fixed background scenario. These are ongoing research items in the APMT-Impacts Air Quality Module development effort at MIT.

3.2 APMT-Impacts Climate Module

The impact pathway for climate impacts can be described as going from emissions to societal impacts as seen in Figure 7 (42). The impact pathway is not unique to aviation effects, but is described here in the aviation context. Direct emissions of CO₂, NO_x, H₂O, SO_x, HC, and black carbon or soot from aircraft engines are propagated through to changes in atmospheric concentrations, radiative forcing, global surface temperature, socio-economic impacts and subsequent damages to human health and welfare. As one proceeds from estimating emissions to estimating societal impacts, the information collected becomes increasingly relevant to the policymaking community. However, the uncertainties associated with impact estimates also increase as one proceeds further down the impact pathway.

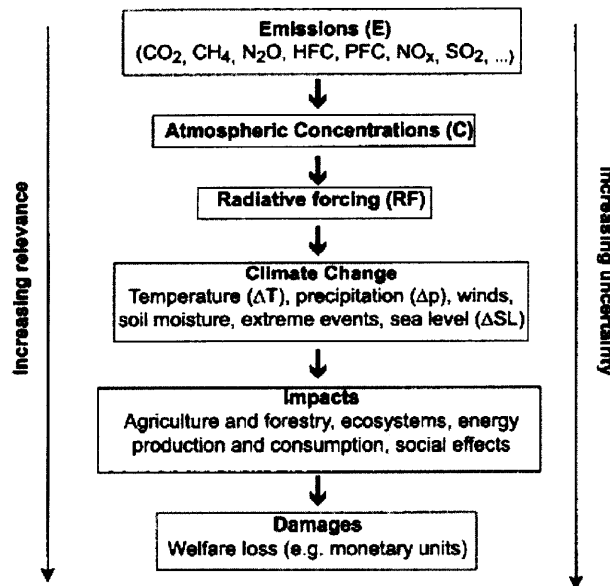


Figure 7 Climate change impact pathway (42)

The relative climate impacts of the non-CO₂ and CO₂ effects of aviation emissions provided in this thesis are derived from the Climate Module within APMT-Impacts. The Climate Module estimates CO₂ and non-CO₂ impacts using both physical metrics such as globally-averaged surface temperature change attributed to aircraft emissions and monetary metrics such as the net present value of the resulting climate damages. The modeling approach used is not new; it is based on the work by Hasselmann et al. (43), Sausen and Schumann (44), Fuglestad et al. (42) and Shine et al. (11). Given the need for a capability to analyze several different policy scenarios, computationally inexpensive reduced-order methods are used for estimating physical metrics of climate change. The effects modeled include long-lived CO₂, and short-lived non-CO₂ effects including the short-lived impact of NO_x on ozone (NO_x-O₃ short), the production of cirrus, sulfates, soot, H₂O, and contrails. Also included are the NO_x-CH₄ interaction and the associated primary mode NO_x-O₃ effect (referred to as NO_x-O₃ long). The estimates are quantified at the globally-averaged spatial scale. A detailed description of the APMT-Impacts Climate Module can be found in Marais et al. (45) and in Jun (46).

Here, a brief description of the modeling methodology adopted within the APMT-Impacts Climate Module is provided. Starting with aviation emissions, one proceeds along the impact pathway to globally-averaged radiative forcing (RF), surface temperature change, and associated socio-economic damage. Figure 8 provides a qualitative description of the computation process in going from aviation CO₂ emissions to changes in climate damages and indicates the temporal response of the impacts at different stages in the pathway.

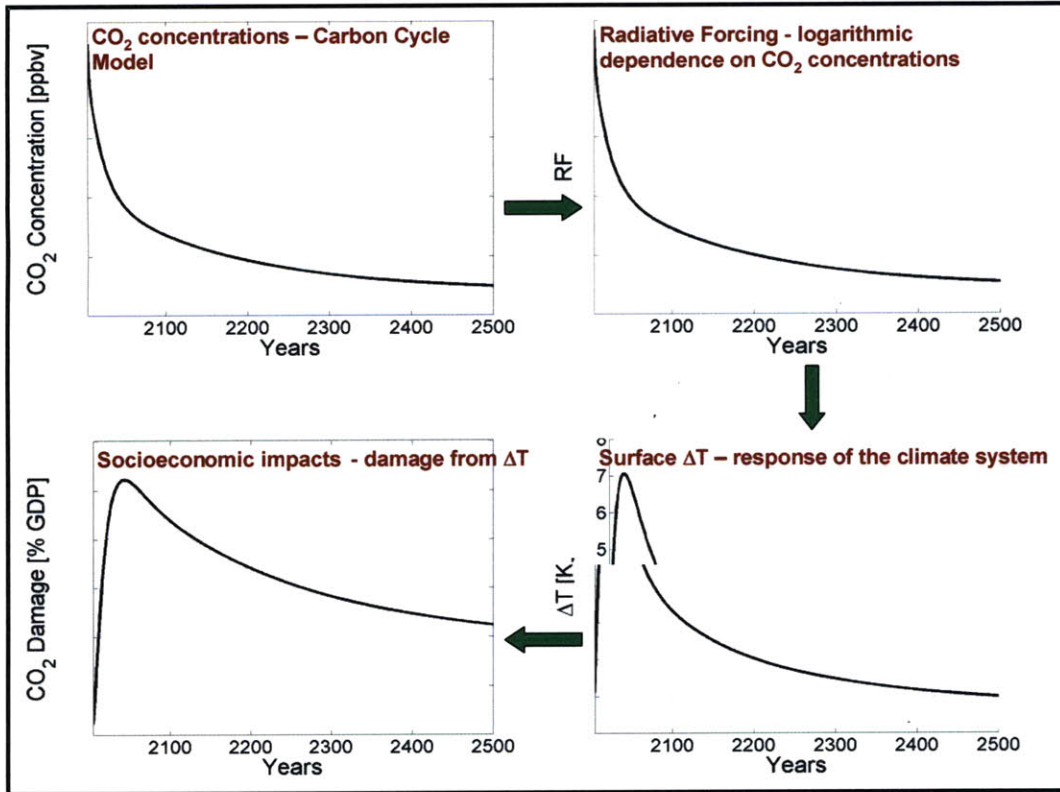


Figure 8 Evolution of a pulse of CO₂

The APMT-Impacts Climate Module takes as inputs CO₂ emissions from aviation and computes the resulting changes in atmospheric concentrations of CO₂ based on impulse response functions derived from complex carbon cycle models. For this step, the model currently uses the Bern Carbon Cycle impulse response coefficients (47). The perturbation in the global radiative balance due to CO₂—i.e. the corresponding radiative forcing—is estimated based on a logarithmic relationship between CO₂ concentration changes and RF. To compute globally-averaged surface temperature change from the estimated radiative forcing, a simplified energy balance model by Shine et al. (11) is used. Although this approach has a lower fidelity as compared to using impulse response functions derived from detailed general circulation models (GCMs), it allows for an explicit representation of the impacts of uncertainty in climate sensitivity on the model results. It is important to note that this approach does not capture feedbacks between the climate system and the carbon-cycle model.

The climate impacts of non-CO₂ effects of aircraft emissions are estimated following the Sausen and Schumann (44) approach and scaled relative to emissions based on most recent radiative forcing estimates from the scientific literature. For the soot, sulfates, water vapor, cirrus, and contrails impacts, radiative forcing estimates with uncertainty bounds from Sausen et al. (48) are used. The NO_x-related impacts on ozone and methane are derived from three different studies: Wild et al. (29), Hoor et al. (49), and Stevenson et al. (28). Different forcing agents lead to varying magnitudes of response in the climate system and this is captured by the efficacy concept. Efficacy is defined as the global temperature response per unit radiative forcing relative to that resulting from a CO₂ forcing. For non-CO₂ impacts, the most recent efficacy values provided by Hansen et al. (50) and the IPCC (47) are employed. With the exception of the longer-lived NO_x-CH₄ and NO_x-O₃-long effects, it is assumed in the model that the RF due to non-CO₂ impacts lasts only during the year of emissions. It is important to note that in making future projections, the influence of non-CO₂ effects is assumed to be independent of the change in the background atmosphere and meteorology. That is, APMT-Impacts plays forward the current balance of effects as reflected in the RF estimates of Sausen et al. (48). The climate radiative forcing and temperature response to a one kilotonne impulse of fuel burn in 2006, as estimated by APMT-Impacts, is presented in Figure 9 and Figure 10, respectively.

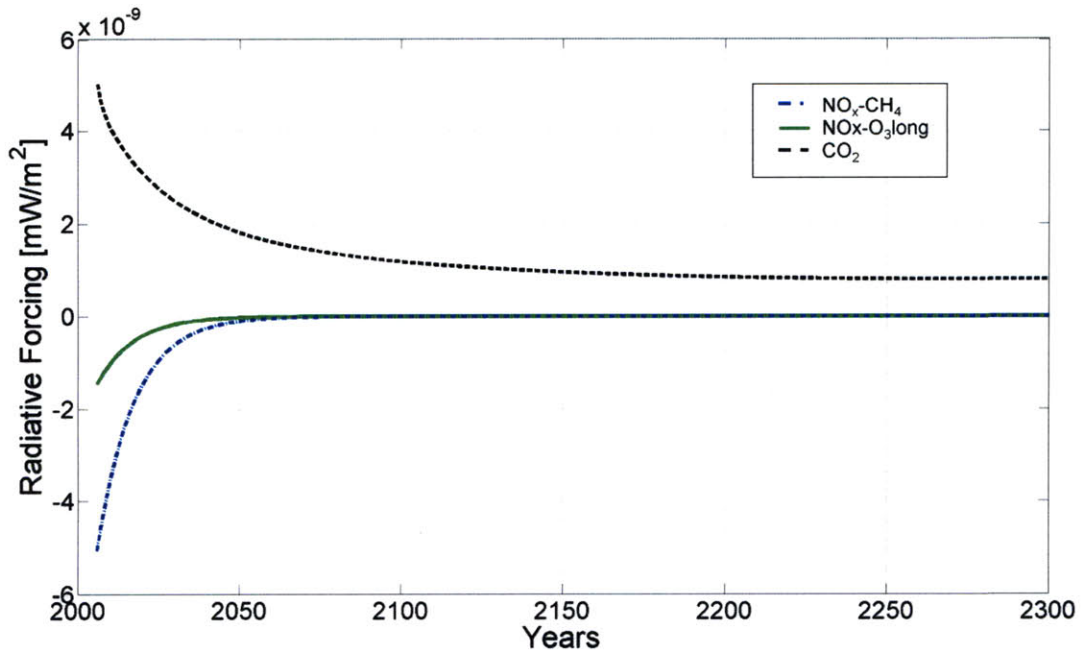


Figure 9 Radiative forcing response for a unit impulse of emissions in 2006; radiative forcing from effects other than those shown are assumed to be active only in the year of the emissions.

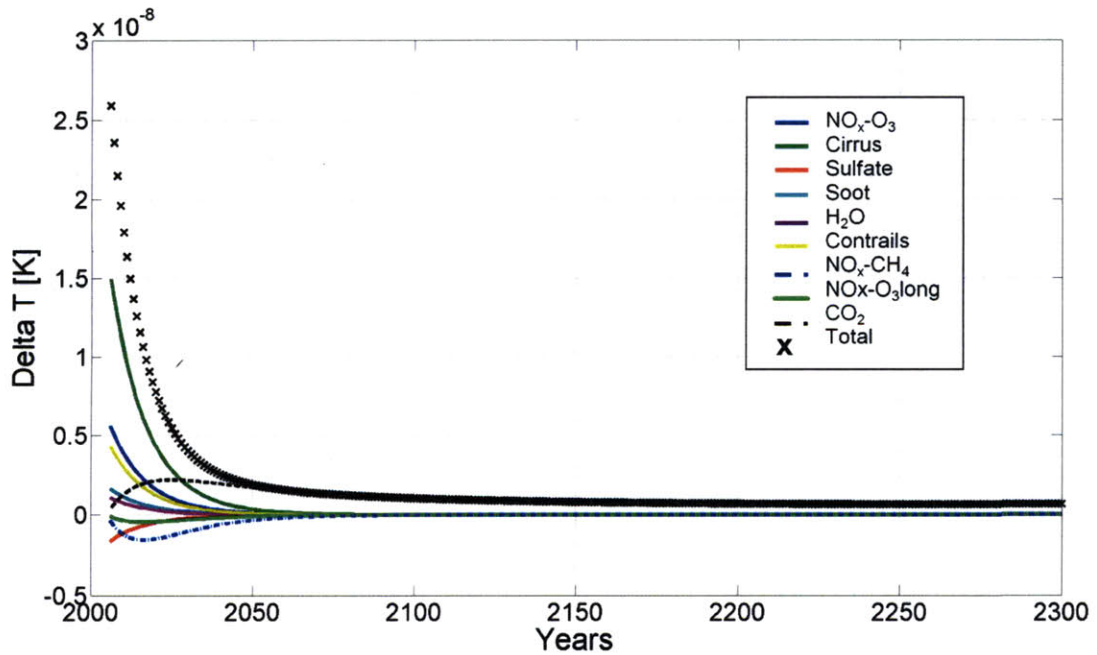


Figure 10 Temperature response to a unit impulse of emissions in 2006

Figure 9 and Figure 10 present all of the aviation climate impacts captured by APMT-Impacts. Radiative forcing is plotted in Figure 9 for CO₂ and the effect of NO_x on methane and ozone; the other radiative forcings occur only in the year the pulse is emitted and were not plotted. The temperature change resulting from the non-CO₂ effects dominates that due to CO₂ during the years immediately following the year of emissions. In the long term, warming due to the carbon dioxide remains the sole impact.

Next, the health, welfare and ecological impacts are modeled using damage functions and discounting methods in terms of the percentage change of global GDP and net present value of damages. The damage function relates changes in globally-averaged surface temperature to resulting health and welfare impacts. The specific function applied is the Nordhaus and Boyer (51) damage function with recently updated coefficients from the DICE model (52). The Nordhaus and Boyer approach has received criticism for its simplifying assumptions, such as excluding non-market impacts (for instance, loss of natural beauty or extinction of species) (53). However, the DICE damage function has a distribution that does a reasonable job of capturing the range of damage estimates from other well-recognized models such as the PAGE (54) and FUND (9) models. Damage functions from these three models are plotted in Figure 11.

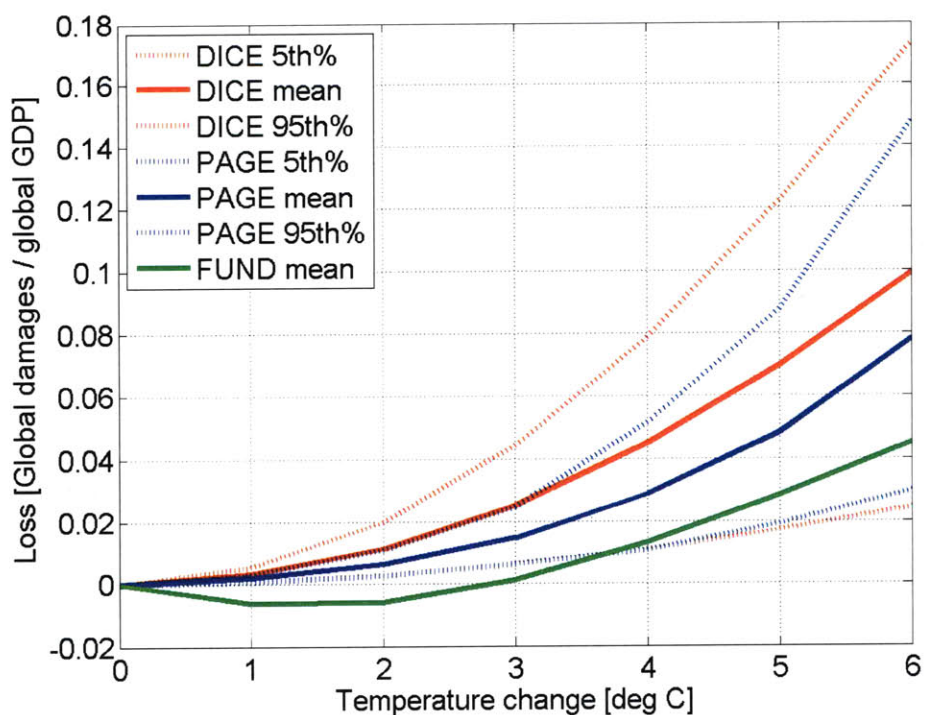


Figure 11 Damages as a fraction of global GDP due to an increase in annual global temperature in the DICE, FUND, and PAGE models²

While the range covered using the DICE model is representative of the range produced in the PAGE model, the approach in APMT-Impacts does not capture the damage region of the FUND model at lower temperature changes. Incorporating this lower bound damage function into the valuation process in APMT-Impacts is an ongoing development item. For discounting climate damages, a range of constant discount rates is used from 2% to 7% following the recommendations of the U.S. Office of Management and Budget (33). The US OMB requires that federal agencies show analyses using discount rates of 3% and 7% for near term impacts experienced by the current generation. For assessing impacts on future generations, the US OMB recommends sensitivity analyses using lower discount rates (33). Figure 12 depicts the evolution of damages for a one kilotonne aviation impulse, discounted at a rate of three percent, as calculated in APMT-Impacts using the DICE 2007 damage function. Again, the damage

² The damage functions represented in Figure 11 are the outcome of default assumptions. For instance, under alternate assumptions, the damages from FUND may cross from negative to positive at less than or greater than 3°C.

resulting from CO₂ dominates over the long term, despite the initially higher impact of the non-CO₂ effects during the years directly following the year of emissions.

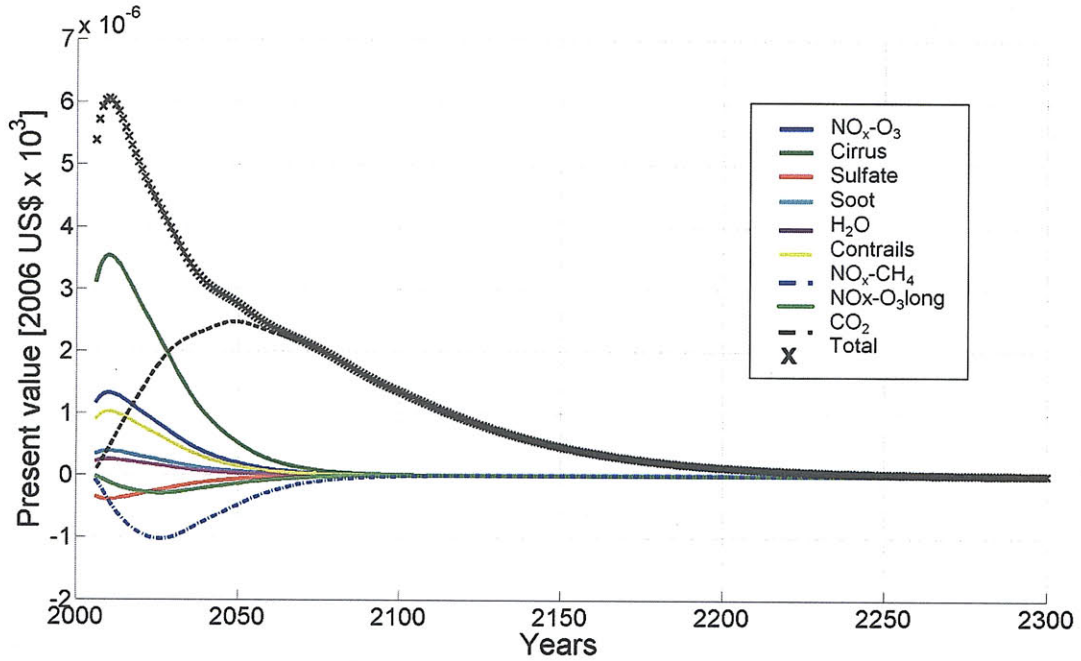


Figure 12 Present value of climate damages for a unit impulse of emissions in 2006 (3% discount rate)

4 Derived Ratios and Air Quality Marginal Damages

While APMT is a valuable tool for detailed analysis of environmental policies, it is also useful to simplify the accounting of aviation's impact on air quality and climate. Firstly, offering a basic approach to accounting for environmental impacts beyond CO₂ could motivate decision-makers to include non-CO₂ effects in policy assessment, thus improving their understanding of a particular policy's impact. Additionally, APMT is a research code and is not widely available (nor particularly amenable to the non-expert user). As such, it would be useful to have a summary of APMT outputs for a range of assumptions and scenarios in a form that would enable others to perform approximate high-level assessments. In this chapter, a simplified framework for accounting for the non-CO₂ impacts of aviation emissions is presented. As previously discussed in Section 1.3, the method utilizes the social cost of carbon, APMT-derived non-CO₂/CO₂ climate impact ratios, and the air quality marginal damage cost of a unit of fuel.

4.1 Air Quality Marginal Damages

The SCC equivalent for air quality is the marginal air quality damage cost of a unit of fuel. This can be estimated by inputting a one kilotonne fuel burn scenario into APMT-Impacts and then calculating the NPV of air quality damages. In particular, the scenario used in this analysis is one kilotonne of fuel distributed across U.S. airports in line with the distribution of emissions in the CAEP/8 NO_x Stringency analysis baseline scenario for the year 2006 (17). In this section, the input assumptions of the analysis are first presented along with the sensitivity of health costs to those assumptions. Then, the air quality marginal damage costs are presented on both a per-unit-emission and per-unit-fuel-burn basis.

APMT-Impacts uses Monte Carlo analysis to randomly sample from probabilistic inputs. Additionally, the model groups assumptions into three "lenses" that are used to represent best case, midrange, and worst case perspectives on potential impacts. These low, mid, and high lens assumptions for air quality analyses are outlined in Table 4. The sensitivity of air quality damages to these parameters is illustrated

in Figure 13. The nominal case is depicted by the middle vertical bar while the horizontal green bars represent the range of estimates obtained when a single parameter is varied from its low to high values. The figure shows that VSL is the largest contributor to output uncertainty, followed closely by emissions inventory bias and then CRF.

Table 4 Lens values and assumptions (note: table is not a complete list of all model inputs)

Air Quality Assumptions	Low Lens (Best case/low impact)	Mid Lens (Nominal)	High Lens (Worst case/conservative)
Population growth	No growth	No growth	No growth
Emissions inventory bias and uncertainty 1. Fuel burn 2. SO _x (FSC) 3. NO _x 4. Non-volatile PM	1. 0.92 2. 0.0066 (5 th percentile) 3. 0.83 4. 0.52	1. Uniform [0.92 1.12] 2. Weibull [mean = 0.0627, std = 1.2683] 3. Uniform [0.83 1.23] 4. Uniform [0.52 2.06]	1. 1.12 2. 0.154 (95 th percentile) 3. 1.23 4. 2.06
Adult premature mortality CRF [% per µg/m ³ PM _{2.5}]	0.6	Triangular distribution [mode = 1, range = 0.6-1.7]	1.7
Value of a statistical life	\$2.9M (US2000) (90% CI lower)	Lognormal distribution [mean = \$6.3M, std = \$2.8M]	\$12M (US2000) (90% CI upper)
Background emissions	NEI 2001	NEI 2001	NEI 2001

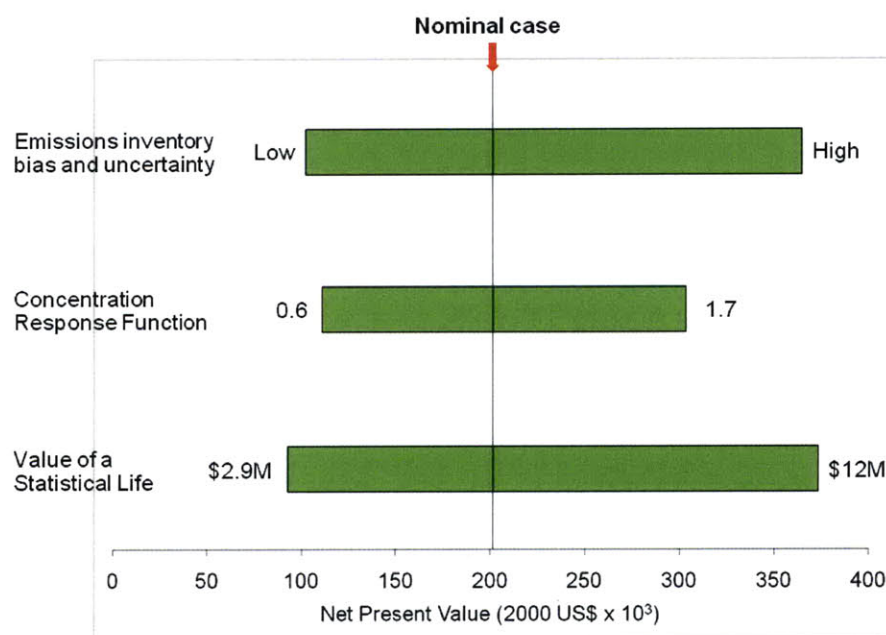


Figure 13 Air quality cost sensitivity to input uncertainties (one kilotonne impulse)

Marginal damages are expressed in Table 5 as the air quality damages due to a one kilotonne pulse of fuel burn broken down into four components of particulate matter and then normalized by the relevant emissions species. The damages in Table 5 are calculated for the U.S. only and only for emissions from aircraft that occur below 3000 feet. They also assume present day background emissions.

Table 5 Air quality marginal damages due to one kilotonne of fuel (2006 US\$ x 10³ per tonne species)

	Low	Mid	High
nvPM (\$/tnvPM)	136	581	1594
PM Nitrates (\$/tNO _x)	2	11	31
PM Sulfates (\$/tSO _x)	0	56	216
PM Organics (\$/tHC)	384	1376	2951

Finding suitable aviation marginal damage values to benchmark these air quality estimates against is difficult. Looking across industries, however, makes it possible to compare to other studies on air quality health costs. Average cost estimates from a handful of these relevant studies are shown in Table 6.

Table 6 Air quality average costs (2006 US\$ x 10³ per tonne species)

	Dings 2002: Literature	Rojo 2008: U.S. ATO	Rojo 2008: EPA/NEI Tier-1 highway	Rabl and Spadaro 2000: Europe autos
\$/tnvPM	226	601	350	261
\$/tNO _x	14	24	16	32
\$/tSO _x	8.8	95	61	19

The above studies include estimates based on aviation (Dings and Rojo, U.S. ATO) as well as estimates based on automobile pollution (Rojo, EPA/NEI and Spadaro and Rabl (55)). While the variation of assumptions is wide across these approaches, the range and overall magnitude of the estimates are similar. In particular, the nominal APMT-Impacts marginal damage estimates are well aligned with the air quality average costs according to this sampling of the literature. It should be noted that cruise emissions are not included in APMT-Impacts estimates. Barrett et al. (56) estimate that including cruise impacts may lead

to an increase in total air quality impacts by a factor of 2-12. The impact of U.S. cruise emissions is realized both within the US and also globally. The extent of transboundary air pollution is significant due to strong zonal westerly winds aloft, thus displacing impacts to the east.

In order to perform a total cost calculation of a given fuel burn reduction, it is necessary to place the APMT-Impacts air quality costs on a per-unit-fuel-burn basis. This is done by taking the outputs from APMT-Impacts directly and not applying any emissions normalization. The ranges of values for this quantity are presented in Table 7 for a one kilotonne pulse of fuel.

Table 7 Air quality marginal damages due to one kilotonne of fuel (2006 US\$ per tonne of fuel)

	Low	Mid	High
nvPM	3	33	145
PM Nitrates	24	130	445
PM Sulfates	0	56	611
PM Organics	3	10	24
Total Fuel	29	230	1226

When analyzing policies that extend into the future, it is recommended that the user apply a discount rate to the air quality damages that aligns with the choice of discount rate for the ratio and SCC value used. For instance, the air quality costs in the i^{th} year of a scenario can be discounted at some rate r by dividing the damages in that year by $(1 + r)^i$. The user should be careful however, in using these results for analyses far into the future since the background concentrations of atmospheric pollutants and population are likely to change over time and this is expected to change the marginal damage costs (taking account of these effects in the APMT-Impacts Air Quality Module is an area of current research).

Deriving air quality marginal damage costs in this section was a fairly straightforward process. Deriving non-CO₂/CO₂ climate ratios in the following section is somewhat more complex because it involves the introduction of another parameter in the equation (SCC) and the question of what is the appropriate metric and assumptions for creating a ratio.

4.2 Derived non-CO₂/CO₂ Ratios

This section of this thesis discusses the derivation of ratios of non-CO₂ to CO₂ impacts using the APMT-Impacts Climate Module. The section begins with a discussion of the social cost of carbon, followed by an assessment of the different metrics available for ratios, a discussion of uncertainty, the presentation of ratio values, and an analysis of ratio sensitivity to input assumptions. The motivation and approach behind this study were previously discussed in Sections 1.2 and 1.3.

4.2.1 Social Cost of Carbon

The SCC is the marginal damage cost of an additional unit of carbon emissions, and hence the aviation-specific ratios provided are intended to scale the social cost of carbon to account for the non-CO₂ effects associated with aircraft emissions relative to those of CO₂. The SCC differs from the “carbon price”, which refers to the market price of carbon. It also differs from the abatement cost, which refers to the cost to reduce a unit of carbon. The SCC indicates the maximum value for carbon price or carbon tax in any reasonable emissions-control program. In other words, the optimal carbon price is that which balances the incremental benefit of reducing climate damages, i.e. the SCC (57).

EPA guidance suggests that the social cost of carbon should be calculated as the net present value of impacts, realized over hundreds of years, associated with one additional metric tonne of GHG emissions emitted at some point in time (12). It is the marginal damage cost of carbon, usually given as dollars per tonne C or CO₂. This marginal value is typically derived from a pulse of emissions in a simplified climate model, as is the case in APMT-Impacts. SCC estimates vary across a wide range in scientific and environmental economics literature due to modeling differences including varying damage functions, background climate and economic scenarios, discounting, and other assumptions to which SCC is sensitive. What follows is a review of these literature estimates and a comparison to APMT-derived values.

Based on a meta-analysis of peer-reviewed studies by Tol (58), the SCC is estimated to be \$57/tC (metric tonne of carbon) with a standard deviation of \$109/tC in 2006 dollars for changes in carbon emissions close to 1995. In 2008, Tol updated this analysis of peer-reviewed studies and found three different SCC values based on the different distributions he fit to the data (59). These values are presented in Table 8.

Table 8 Tol (59) values for social cost of carbon (2006 \$/tC, peer-reviewed studies only)

Distribution	Mean	Std. Dev.
Fisher-Tippett	94	130
Gauss 1	65	130
Gauss 2	72	246

The EPA has also made recent evaluations of the social cost of carbon. The EPA estimates the SCC to have a mean of \$62/tC in 2006 dollars for carbon emissions in 2007 with a 90% confidence interval between -\$22/tC and \$484/tC using a 3% discount rate and derived using the FUND model (12). The meta-analysis conducted by the EPA of SCC estimates in the literature, meanwhile, revealed a mean value of \$147/tC with a 90% confidence interval ranging from -\$15/tC to \$389/tC. Additionally, in a recent rulemaking justification, the Department of Energy, in implementing the Energy Conservation Program for Commercial and Industrial Equipment, set the SCC in accordance with IPCC, which is based on the 2005 estimate from Tol. This value of the SCC estimates the world benefit of CO₂ reductions, but is being used by the DOE to estimate the benefit to the U.S. since there currently is no consensus on regional estimates for the U.S. (13). Lastly, a recent Department of Transportation Federal Register Notice includes SCC guidance, suggesting \$33 per tonne of carbon as a placeholder to measure the global benefits of reducing U.S. CO₂ emissions (60).

The variation and uncertainty in estimates is quite large within the literature. In Tol alone, many different sets of assumptions are used for the different SCC values, including different damage functions, equity weighting, background scenarios, and discounting. In APMT-Impacts, one can match many of the input assumptions used in FUND and other models in order to derive estimates for the SCC. Such comparisons

serve to validate the APMT-Impacts climate model and demonstrate the ability of the model to capture uncertainty across the varying approaches to impact valuation. The assumptions used for this comparison are shown in Table 9. The settings for climate sensitivity, pre-industrial CO₂ concentration, concentration response model, and ocean heat capacity were taken from the technical description of the FUND model by Anthoff and Tol (61).

Table 9 Input assumptions for APMT-Impacts comparison to FUND SCC estimates

Background scenario	SRES A1B, A2, B1, B2 (62)
Climate sensitivity	2.5K
CO₂ in 1750 (ppm)	275
Concentration response model	Hasselmann (43)
Temperature response function	Shine (11)
Ocean heat capacity (J/m²K)	2.33E+09
Damage Function	DICE 2007

By matching assumptions across the models as detailed above, APMT-Impacts produces estimates for SCC that are well-aligned with the range of values from EPA and scientific literature. Low, mid, and high estimates are compared for different discount rates in Table 10 in units of 2006 US\$ per tonne carbon.

Table 10 APMT-Impacts comparison to EPA SCC estimates (2006 \$/tC)

	2% DR			3% DR			7% DR		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
Meta global	-11	249	583	-15	147	389	n/a	n/a	n/a
FUND global	-22	323	2548	-22	62	484	-11	-4	18
APMT	49	211	1389	18	81	436	2	9	29

The APMT-Impacts estimates of SCC are derived in accordance with standard practice for calculating SCC and fall within the range of the EPA’s FUND global and Meta global estimates. They are also in line with Tol’s meta-analysis as shown in Table 8.

More recently, a United States Government Interagency Working Group on Social Cost of Carbon released SCC estimates using three Integrated Assessment Models: the DICE, PAGE, and FUND models (6). For this study, five different background scenarios were used from the Stanford Energy Modeling Forum (EMF-22) (63). The EMF emissions scenarios are depicted against the IPCC SRES scenarios that are typically used for analyses in APMT-Impacts in Figure 14. Note that the IPCC scenarios are extended beyond 2100 so as to mimic the proposed Representative Concentration Pathway (RCP) extensions of the Integrated Assessment Modeling Consortium working group (64).

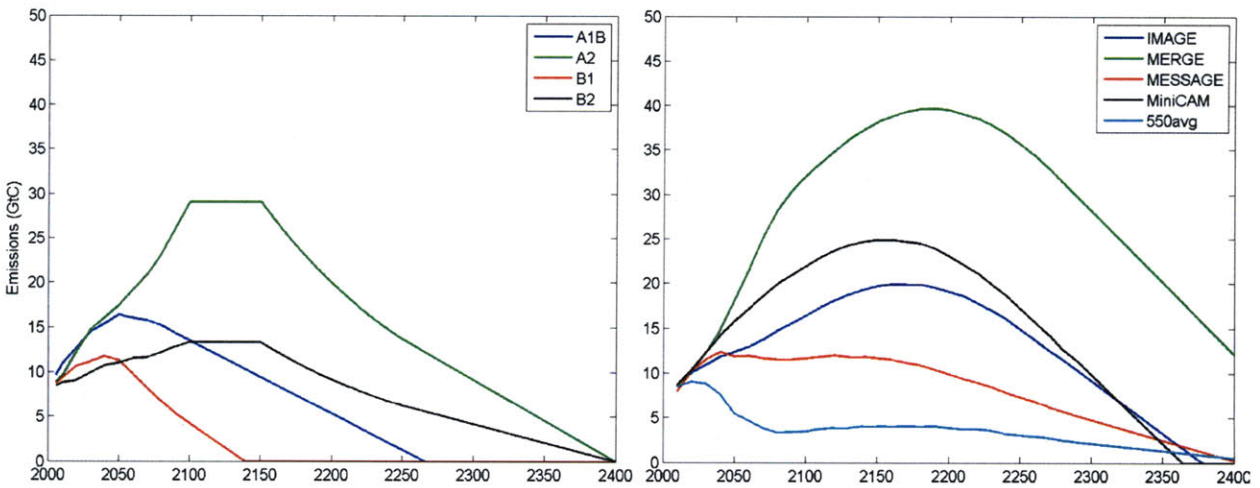


Figure 14 Comparison of IPCC SRES background emissions scenarios (left) against EMF-22 scenarios (right)

A selection of SCC estimates from the report is shown in Table 11. The table presents mid and 95th percentile estimates from the DICE model and mid estimates from the PAGE and FUND models as reported in the document for the SCC in 2010 (in Y2007 US\$ per tonne carbon) for the five EMF scenarios. Table 11 also contains SCC estimates as produced in APMT-Impacts with assumptions closely aligned to the DICE, PAGE, and FUND calculations for the EMF background scenarios. When similar input settings are used, the DICE, PAGE, and FUND values for SCC from the document compare well to values produced in APMT-Impacts.

Table 11 APMT-Impacts comparison to USG Interagency Working Group on SCC estimates (2007 \$/tC)

	DICE		APMT		PAGE	APMT	FUND	APMT
	Mid	95th	Mid	High				
IMAGE	131	260	156	274	145	115	30	38
MERGE	81	154	109	192	82	81	29	24
Message	109	215	131	230	111	94	13	28
MiniCam	106	212	133	234	117	101	37	36
550 Avg	91	186	127	223	93	87	-1	25

This section demonstrated that APMT-derived SCC estimates are consistent with estimates produced by the U.S. Government and by the larger research community with assumptions appropriately aligned. The main message from this SCC overview, however, is that estimates of SCC vary widely and are highly sensitive to the particular modeling choices and assumptions used. In Section 4.2.3, it will be shown that the ratio of non-CO₂ effects to CO₂ effects for aviation is less sensitive—though not insensitive—to these scenarios, model choices, and assumptions. This is the rationale in this thesis for deriving aviation-specific ratios in APMT-Impacts using a range of assumptions and then suggesting that these ratios may be applied to exogenously-specified SCC values (given certain restrictions). It should be noted however that this method has the potential for producing inconsistencies where SCC assumptions do not align with those used for ratio derivation.

4.2.2 Ratio Metrics

The non-CO₂/CO₂ ratio is an effort to simplify the accounting of aviation climate forcing from effects other than CO₂ accumulation. The implementation of multi-gas climate agreements requires a metric that puts emissions on a common scale, and for this task there are several options. Starting with aviation emissions, one can proceed along the impact pathway to globally-averaged radiative forcing (RF), surface temperature change, and associated socio-economic damage. A qualitative description of the computation process in going from aviation CO₂ emissions to changes in climate damages was previously shown in Figure 8.

Radiative forcing is a relatively basic measure for comparing the effects of emissions on climate in the sense that it lies early on in the climate impact cause and effect chain. By itself, RF has strengths and weaknesses, as laid out in IPCC reports (e.g. (65), (66), (7), (47)). Two RF metrics that are useful for evaluating aviation’s climate impact relative to some reference gas—CO₂, in particular—are the Radiative Forcing Index (RFI) and the Global Warming Potential (GWP). RFI is representative of instantaneous radiative forcing, which is the total RF from aviation (or some other sector) at a point in time divided by the total RF from aviation CO₂ at that same time. RFI is dependent only on the history of past emissions. It is thus less useful for considering the future impacts of new emissions, especially because these emissions have different atmospheric lifetimes. More useful is an integration of the radiative forcing over some future time period. The GWP has been defined by the IPCC as the ratio of the time-integrated radiative forcing of a trace species relative to that of a reference gas (typically CO₂) for an emissions pulse or scenario:

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

where *TH* is the time horizon over which the impacts are calculated, *a_x* is the radiative efficiency due to an emission of the species of interest, [*x(t)*] is the time-dependent decay of the species in the atmosphere, and the term in the denominator represents the corresponding quantities for the reference gas (7). GWP can be computed over a range of time horizons, but IPCC practice generally consists of presentation of a GWP₂₀, GWP₁₀₀, and GWP₅₀₀ corresponding to 20-, 100-, and 500-year time periods, respectively (47). It can also be computed for a range of background scenarios, though a constant background is often assumed as the reference. In addition to IPCC regularly publishing updates of GWPs, the Kyoto Protocol adopted GWP for use in a multi-gas approach. The use of GWPs has been strongly debated in the literature (e.g. Rotmans et al. (67); Fuglestvedt et al. (42); O’Neill (68); Skodvin et al. (69); Smith et al. (70)) due largely to the fact GWP is only a direct indicator of climate change under a restrictive set of assumptions. However, the summation of globally-averaged RF from both regional and non-regional

effects tracks globally-averaged surface warming to first-order (Cox et al. (71); Ramaswamy and Chen (72)). Also, the widespread use and acceptance of GWP in policymaking is another rationale to present it as a ratio for climate effects.

A second physical metric that is relevant to policymaking and can be used to create a non-CO₂/CO₂ impact ratio is that of time-integrated temperature change (see e.g. Marais et al. (45)). Temperature change is an attractive metric in that it lies further down the cause and effect chain from emissions to impacts than RF. The ratio of the temperature change due to a non-CO₂ species to that due to CO₂ sets up a physical-metric based ratio in the same vein as GWP:

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

where $\Delta T_x(t)$ and $\Delta T_r(t)$ represent the time-dependent temperature change due to emissions of the species of interest and reference gas, respectively. Here, too, different background emissions scenarios can be adopted for the calculation. Finally, one step beyond temperature change due to aviation emissions is a metric of economic damages due to aviation emissions. Estimates for the marginal damage costs of non-CO₂ species can be used to specify multiplicative factors on the marginal damage cost of CO₂. The ratio of marginal damage costs can be quantified as the net present value (NPV) of climate damages due to a unit emission of a given species relative to the same quantity for a reference gas. Here, assumptions about both future background emissions changes and future economic behavior (e.g. GDP growth) must be made. This sort of cost-based index is particularly applicable to cost-benefit analysis of different climate policies.

The different metrics discussed above have some common features. For example, each metric can be used to describe different emissions scenarios, with pulse, sustained, and specific aviation scenarios being the most common. All of the metrics must employ assumptions about background emissions scenarios (and GDP growth scenarios in the case of economic metrics). Additionally, all of the metrics have

common types of uncertainty underlying them: structural uncertainty, the degree to which the metric represents the real world; scenario uncertainty, the degree to which the metric addresses or is sensitive to different projections of future world behavior; value-based uncertainty, the degree to which short or long-lived effects are weighted; and scientific uncertainty, the degree to which the underlying processes effect the metric.

4.2.3 Uncertainty Characterization

In APMT-Impacts, and in the derived ratios, the impacts of uncertainties and assumptions on the estimated physical and monetary measures of climate change are carefully taken into consideration. Some scientific parameters are specified with probabilistic distributions from which values are randomly sampled in Monte Carlo analyses. These parameters include RF values for non-CO₂ and NO_x-related effects, overall climate sensitivity, and damage coefficient. Other parameters such as discount rate, reference temperature change, and the overall aviation and background emissions scenarios are fixed at deterministic values selected as modeling choices by the user.

For the purposes of this work, uncertainty takes three forms: economic, parametric, and structural. Economic uncertainty is concerned with the choice of discount rate. Ratios are calculated at discount rates of 2%, 3%, and 7% to be consistent with EPA practice and OMB guidance (12) (33). For each discount rate, parametric uncertainty captures the distribution of ratio estimates across Monte Carlo runs in the APMT-Impacts analysis. The output distribution is a function of random sampling from probabilistically distributed input parameters. The mid ratio is taken as the mean of this output distribution. For structural uncertainty, rather than treating certain input parameters as random variables, the range of results is established by setting the following inputs at their lower and upper bounds: RF values for non-CO₂ and NO_x-related effects, climate sensitivity, and damage coefficient. These deterministic settings on the inputs to the APMT-Impacts Climate Module are referred to as the low and high “lenses”. The low lens has the effect of reducing aviation’s impacts on climate whereas the high lens results in a larger estimate of potential damages. Table 12 summarizes the makeup of each lens,

including which inputs are varied and what values these inputs take. More detail on the rationale for these assumptions can be found by referring to Mahashabde (15).

Table 12 Climate lens values and assumptions for ratio derivation (15). Note: table is not a complete list of all model inputs

Climate Assumptions	Low Lens (Best case/low impact)	Mid Lens (Nominal)	High Lens (Worst case/conservative)
Climate sensitivity	2K	Beta distribution (alpha = 2.17, beta = 2.41) to generate [mean = 3.0, range 2.0-4.5] K	4.5K
NO _x -related effects	Stevenson et al. RF values (2004)	Discrete uniform distribution: Wild, Stevenson, Hoor et al (2009) values	Wild et al. RF values (2001)
Short-lived effects radiative forcing [Cirrus, Sulfates, Soot, H ₂ O, contrails]	[0, 0, 0, 0, 0] mW/m ²	Beta distribution [alpha, beta, (range)] [2.14, 2.49 (0 – 80)], [2.58, 2.17 (-10 – 0)], [1.87, 2.56 (0 – 10)], [2.10, 2.58 (0 – 6)], [2.05, 2.57 (0 – 30)] mW/m ²	[80, -10, 10, 6, 30] mW/m ²
Background scenario	IPCC SRES B2	IPCC SRES A1B	IPCC SRES A2
Damage coefficient	5 th percentile of DICE (deterministic)	DICE 2007 (normal distribution)	95 th percentile of DICE (deterministic)

Figure 15 captures the sensitivity of climate costs to the parameters presented in Table 12. The chart shows the range of estimates obtained for net present value of climate damages due to a one kilotonne pulse of fuel burn given some of the uncertainties in modeling parameters. The spread of NPV estimates around the nominal, or baseline case, (indicated by the vertical black line), is shown for five different input parameters; the width of the horizontal bars indicates the contribution of the given input parameter or assumption to output uncertainty. For instance, the NPV can vary from approximately 50 to 350 thousand 2006 U.S. dollars as a function of damage coefficient alone with all other inputs fixed. Damage coefficient is the biggest contributor to uncertainty in NPV estimates followed by climate sensitivity, discount rate, short-lived RF, background scenario, and NO_x effect.

The sensitivity bars are further divided to indicate how the relative contributions of CO₂ and non-CO₂ effects change with respect to the input parameter choice. It is clear that longer lived CO₂ effects become

increasingly important with decreasing discount rate. This is consistent with the fact that low discount rates result in low present values for short term, non-CO₂ effects and increase the contribution of CO₂ to the total NPV. Setting the RF values for short-lived effects to the lower bounds also dramatically increases the contribution of CO₂ to total NPV. The relative contribution of CO₂ and non-CO₂ effects is unaffected when the remaining input parameters are varied.

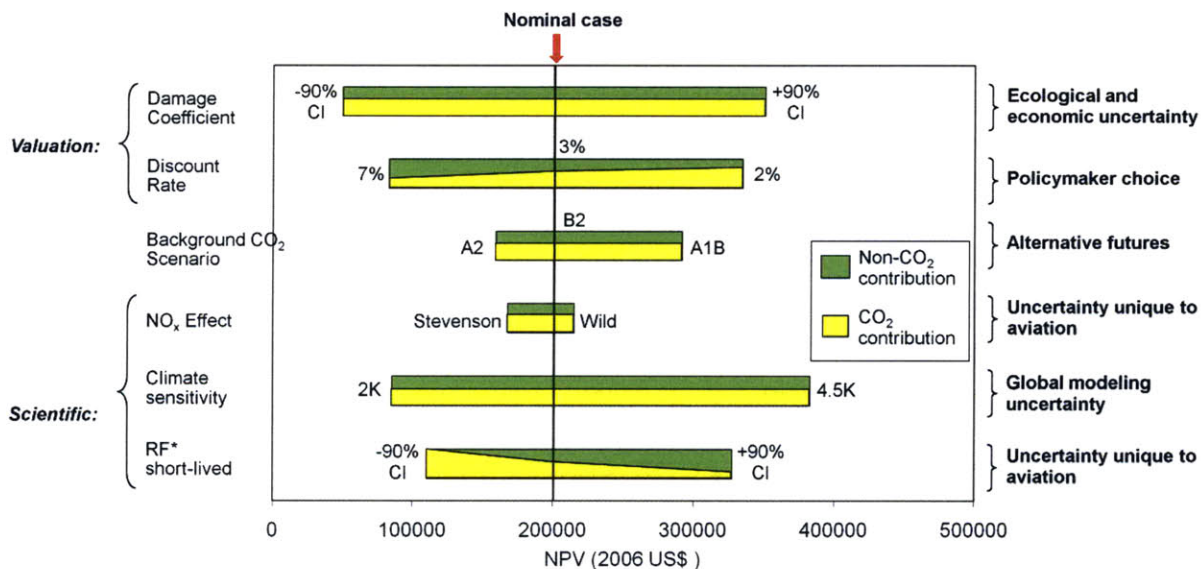


Figure 15 Climate cost sensitivity to uncertainties, background scenarios, and policy-maker preferences for a one kilotonne pulse of fuel burn

The total impacts are sensitive to many factors (much like the SCC) and this can lead to large ranges for estimates of impacts. However, the ratio of non-CO₂/CO₂ effects is only sensitive to two parameters: discount rate and the RF for short-lived effects. Therefore, separating the SCC from the non-CO₂/CO₂ climate ratio is quite useful. Furthermore, when deriving ratios, explicitly varying discount rate and RF for short-lived effects (and combinations thereof) is appropriate for capturing the range of ratio estimates.

4.2.4 Ratio Derivation and Values

A range of different metrics on which to base the ratios are considered, including one based on integrating the radiative forcing over different time horizons (i.e. GWP-based), one based on integrating the change

in globally-averaged surface temperature over different time horizons, and one based on the net present value of climate damage costs at different discount rates. For each metric, a scenario is assessed in which the impacts due to a one-year pulse of emissions are estimated over a period of hundreds of years. As previously discussed, the metrics have some common sources for variation, with time window or discount rate (which are equivalent concepts for physical metrics and socio-economic metrics, respectively) being one of the more dominant sources. Therefore, in deriving climate ratios, the aim was to separate this dependence from the dependence of the ratios on background scenarios and on scientific uncertainty. Different background scenarios are represented through the low, mid, and high lenses as previously shown in Table 12, while the remaining scientific parameters are represented probabilistically.

The EPA suggests that “the marginal value of GHG emissions is equal to the net present value of climate change impacts over hundreds of years of one additional net global metric tonne of GHGs emitted to the atmosphere at a particular point in time” (12). The approach for calculating ratios used in this thesis is consistent with this guidance. APMT-Impacts was used to calculate damages over 800 years in the future for a one-kilotonne impulse of fuel burn in the year 2006. The calculated damage costs are discounted to determine the net present value (NPV) of the climate impact due to CO₂, NO_x, contrails, cirrus, sulfates, soot, and water vapor. These NPVs are representative of the marginal damage costs of aviation per tonne of fuel. An appropriate SCC ratio is calculated by summing the present values of non-CO₂ species and dividing by the NPV of CO₂. The results of this analysis are shown here in Table 13.

Table 13 Marginal damage ratios on the social cost of carbon to account for the climate impacts of aircraft engine exhaust emissions (one kilotonne pulse of fuel burn in 2006)

	2% Discount Rate			3% Discount Rate			7% Discount Rate		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
CO ₂	1	1	1	1	1	1	1	1	1
NO _x -total	-0.07	-0.09	-0.04	-0.09	-0.12	-0.03	-0.02	-0.03	0.18
Contrails	0.00	0.06	0.22	0.00	0.12	0.39	0.00	0.44	1.22
Cirrus	0.00	0.21	0.74	0.00	0.41	1.32	0.00	1.53	4.10
Sulfates	0.00	-0.02	-0.08	0.00	-0.05	-0.15	0.00	-0.17	-0.45
Soot	0.00	0.02	0.09	0.00	0.05	0.16	0.00	0.17	0.49
H ₂ O	0.00	0.02	0.06	0.00	0.03	0.10	0.00	0.11	0.31
Total Multiplier	0.93	1.20	1.99	0.91	1.45	2.79	0.98	3.05	6.85

The total ratio at a discount rate of 3% has a mean of 1.45 and a range of 0.91 to 2.79, while the mean values at 2% and 7% discounting are 1.20 and 3.05, respectively. A positive number in the table represents a cost due to a warming effect, while a negative number represents a benefit due to a cooling effect. The most influential parameters are the impacts of contrails and aviation-induced cirrus, and the discount rate. The choice of discount rate is a value-based judgment that is unrelated to the scientific and scenario uncertainty.

For the scenarios considered, additional units of CO₂ in future years cause progressively less radiative forcing due to the increased background concentration of CO₂. This effect leads to a higher overall ratio for a one kilotonne pulse in later years because the denominator in the ratio (the CO₂ impact per unit of fuel burn) decreases in magnitude. For this reason, it is appropriate to apply yearly growth rates on the NPV ratio used for analyses that extend into the future. The appropriate yearly growth rate for each ratio value is presented in Table 14.

Table 14 Marginal damage total ratio growth rates

2% Discount Rate			3% Discount Rate			7% Discount Rate		
Low	Mid	High	Low	Mid	High	Low	Mid	High
0.2%	0.8%	1.0%	0.2%	1.1%	0.9%	0.2%	1.0%	0.6%

The nominal NO_x ratio (3% discount rate, mid) is worth discussing further. As can be seen in Figure 10, NO_x has a warming impact on climate through its short-lived effect on O_3 and a cooling impact through the NO_x - CH_4 interaction and the associated primary mode NO_x - O_3 effect (referred to as NO_x - O_3 long). In the first ten or so years of impacts, the total temperature change due to NO_x is positive, but the temperature change curve has a long negative tail once the short-lived O_3 impact has run its course and the long-term effects take over. The Nordhaus damage function adds a non-linear effect that places a lot of weight on this tail when calculating the total damage due to NO_x . The result is a negative mid-range ratio for the lower two discount rates. Despite this caveat, in all cases the total NO_x ratio is close to zero and thus the sign on the value is of little consequence to the total ratio calculation. However, it is important to recognize that this does not imply there are no effects from NO_x , only that the shorter-term warming effects (largely felt in the northern hemisphere where aircraft fly) balance the longer term cooling effects (felt globally) when a single globally-averaged change in temperature is calculated. Similar caveats exist when considering the impacts of contrails and aviation-induced cirrus cloudiness; there are strong regional differences in impacts (with the dominant effect occurring where aircraft fly), and these differences are not represented when considering a single global average. While the aviation-induced cirrus effect is the most dominant non- CO_2 contributor in the ratio, it is also the impact that has the highest uncertainty. The implication is that this is the key scientific uncertainty to resolve in terms of aviation's impact on climate.

In order to explore the role that metric choice plays in evaluating the ratio of non- CO_2 to CO_2 effects, several alternatives for ratios based on physical metrics are presented here. The approach of marginal damage-based ratios is well-suited in the context of cost-benefit analysis, when the policy targets are monetary. In the framework of a cost-effectiveness analysis and other policy considerations, however, it may be more appropriate to implement ratios derived from physical metrics. For instance, if a policy goal is to limit temperature change relative to pre-industrial times, it would be useful to have a temperature-

based ratio on hand for the analysis. The ratio application depends on the policy goal as well as the regulated metric.

The APMT-Impacts GWP-based ratio values are presented in Table 15 for a one kilotonne pulse of fuel burn.

Table 15 GWP-based ratios on the social cost of carbon to account for the climate impacts of aircraft CO₂ and non-CO₂ engine exhaust emissions (one kilotonne pulse of fuel burn in 2006)

Integrated RF Ratio	500 Years			100 Years			20 Years		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
CO ₂	1	1	1	1	1	1	1	1	1
NO _x -total	-0.02	0.01	0.03	-0.04	0.02	0.07	0.04	0.23	0.37
Contrails	0.00	0.12	0.35	0.00	0.31	0.70	0.00	0.85	1.89
Cirrus	0.00	0.41	1.17	0.00	1.07	2.36	0.00	2.93	6.33
Sulfates	0.00	-0.04	-0.13	0.00	-0.12	-0.26	0.00	-0.32	-0.70
Soot	0.00	0.04	0.14	0.00	0.12	0.28	0.00	0.32	0.76
H ₂ O	0.00	0.03	0.09	0.00	0.08	0.18	0.00	0.21	0.47
Total Ratio	0.98	1.56	2.65	0.96	2.47	4.33	1.04	5.22	10.12

Applying a time window on the physical ratios has a similar effect to applying three different discount rates to the cost ratios. The short time horizon is comparable to a high discount rate in that the short-lived effects have a greater impact relative to CO₂, whose impacts are fully realized over a longer time horizon. The 500-year window, meanwhile, captures the extent of lasting CO₂ effects and is thus comparable to a low discount rate in which the relative weight of short-lived effects diminishes. The low, mid, and high values correspond to the different assumptions for uncertain parameters.

The temperature-based impact ratios are presented in Table 16 for a one kilotonne pulse of fuel burn. Again, in place of discounting, time horizons of 20, 100, and 500 years are used to present the impacts in different windows.

Table 16 Temperature-based ratios on the social cost of carbon to account for the climate impacts of aircraft CO₂ and non-CO₂ engine exhaust emissions (one kilotonne pulse of fuel burn in 2006)

Integrated deltaT Ratio	500 Years			100 Years			20 Years		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
CO ₂	1	1	1	1	1	1	1	1	1
NOx-total	-0.02	0.01	0.03	-0.04	0.02	0.08	0.20	0.56	0.87
Contrails	0.00	0.12	0.35	0.00	0.33	0.77	0.00	1.19	2.80
Cirrus	0.00	0.41	1.19	0.00	1.14	2.59	0.00	4.10	9.38
Sulfates	0.00	-0.05	-0.13	0.00	-0.13	-0.29	0.00	-0.45	-1.04
Soot	0.00	0.05	0.14	0.00	0.13	0.31	0.00	0.45	1.12
H ₂ O	0.00	0.03	0.09	0.00	0.08	0.19	0.00	0.30	0.70
Total Ratio	0.98	1.57	2.68	0.96	2.58	4.66	1.20	7.15	14.84

For the above physical effect-based ratios, a growth rate of 0.3% per year is recommended when applying the 100-year mid ratio to analyses that run out into the future. Growth rates for the remaining physical effect-based ratio values are shown in Table 17.

Table 17 Physical effect-based total ratio growth rates

500 Years			100 Years			20 Years		
Low	Mid	High	Low	Mid	High	Low	Mid	High
0%	0.1%	0.3%	0%	0.3%	0.5%	0.1%	0.5%	0.6%

The metrics presented above have many common sources of uncertainty. Table 18 communicates which uncertainties apply to which metrics. The scientific uncertainties that APMT-Impacts captures and the specific values and ranges used for these parameters were previously shown in Table 12.

Table 18 Sources of uncertainty for different non-CO₂/CO₂ ratio metrics

	GWP-based ratio	Temperature-based ratio	Marginal damage ratio
Background scenario	X	X	X
Radiative forcing for short-lived effects	X	X	X
Climate sensitivity		X	X
Damage coefficient			X

Figure 16 depicts the effects of these categories of uncertainty on the total ratio values as reported in Table 13, Table 15, and Table 16. The low, mid, and high estimates refer to the low, mid, and high lenses as described in Table 12, while the error bands on the red bars (mid values) depict the influence of varying time window for the physical metrics and discount rate for the NPV ratio. Presenting the ratios in this manner allows for the separation of science- and scenario-based uncertainty (e.g. background scenario, NO_x-related effects, etc) from valuation-based uncertainty (e.g. time horizon or discount rate).

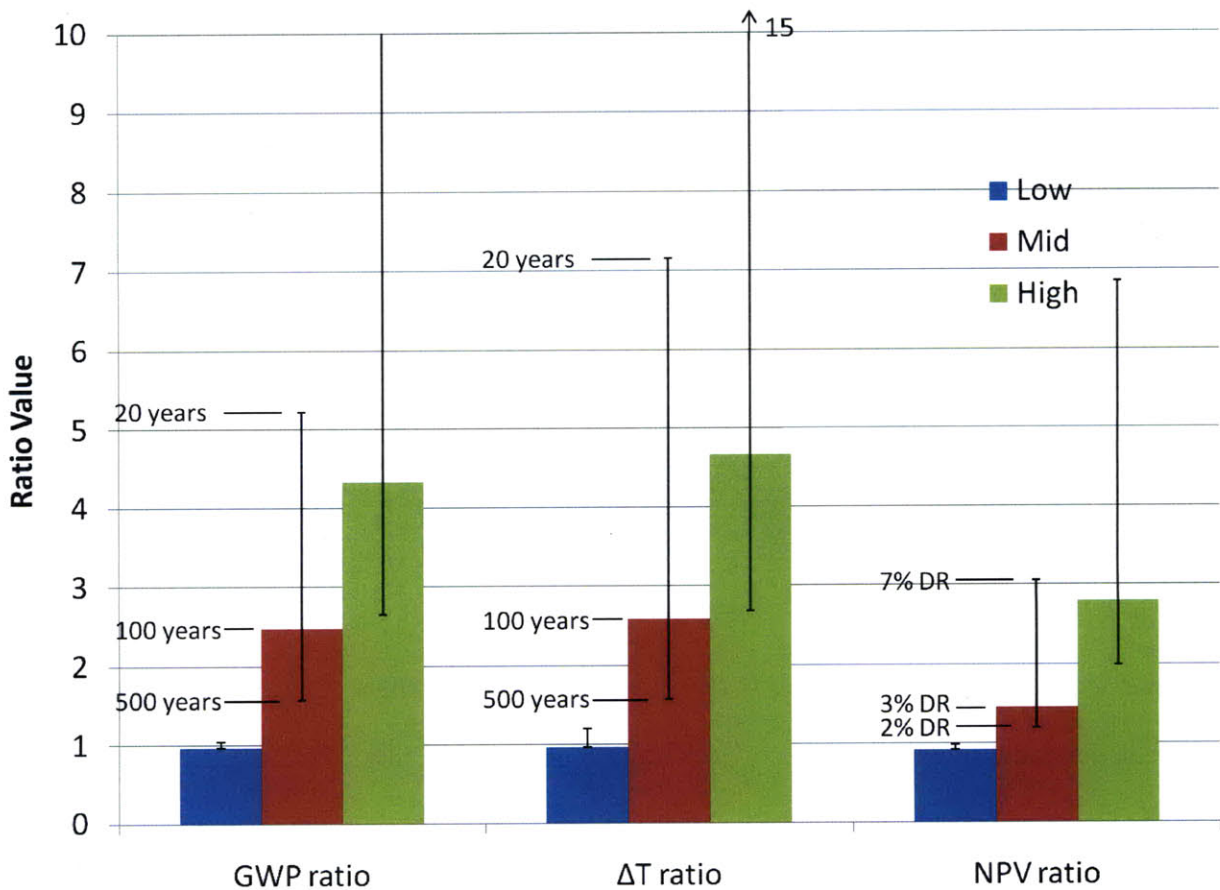


Figure 16 Non-CO₂/CO₂ ratio sensitivity to metric choice and uncertainty for a one kilotonne pulse of fuel burn in 2006

Considering how the non-CO₂/CO₂ ratios are calculated, any trend that drives the ratio closer to one is synonymous with reducing the relative contribution of non-CO₂ effects to total damages. In Figure 16, the ratio is driven closer to one as time window increases or, equivalently, discount rate decreases, as

would be expected given the direct relationship between CO₂ contribution to physical impacts and time window and the inverse relationship between CO₂ contribution to total damages and discount rate. Though not shown in Figure 16, it should be noted that the scientific uncertainty ranges would become wider for shorter time windows or higher discount rates. For a short time window or high discount rate, short-lived effects have greater importance and, consequently, so do the uncertainties on these effects. The increased importance of the uncertainty on the input parameters of RF for non-CO₂ and NO_x-related effects increases the uncertainty in the output.

When considering all of the uncertainties and assumptions in the calculations of the physical effect ratios, it is encouraging to see that the different metrics produce similar ranges for ratio values (to first order). The implication is that the ratio values are largely insensitive to the choice of metric *relative to the overall uncertainty in estimating the impacts*. For instance, for the midrange estimates in Figure 16, the ratio value varies from 1.45 to 2.58 when only the choice of ratio metric is varied. However, the range of ratio estimates produced when reflecting the scientific and scenario uncertainties for a single metric are much wider. Furthermore, the dominant difference between the magnitude of the economic ratios and physical effect ratios is likely the effective discounting applied through the time windows (i.e. a 100-year time window is not necessarily the exact equivalent of a 3% discount rate). The RF and temperature effect ratios, therefore, can be used with confidence for cases in which the policy goal and regulated metric are physical (e.g. regulation on emissions, concentrations, temperature change, etc). The economic ratio is used for the applications in this thesis because it is the most appropriate metric for the goal of impact monetization.

4.3 Application and Guidance for Use

The method of applying an aviation-specific ratio and an air quality marginal damage cost in order to calculate the total benefit of a reduction in fuel burn is again presented here in words:

$$\textit{Benefit} = (\textit{full-flight fuel burn reduction} * 0.86 \textit{ units of carbon per unit of fuel} * \textit{social cost of carbon} * \textit{aviation-specific ratio of CO}_2 \textit{ and non-CO}_2 \textit{ climate impacts}) + (\textit{below 3,000 feet fuel burn reduction} * \textit{air quality marginal damage})$$

As an example, a proposed policy measure has the potential of reducing full-flight fuel consumption by 100,000 tonnes and LTO fuel consumption by 10,000 tonnes in the year 2006. The monetized climate and air quality benefit of this reduction using the midrange climate ratio and air quality damage costs can be estimated by:

$$\begin{aligned} \textit{Benefit} &= M_{\textit{Total}} * \textit{SCC} * (100,000 \textit{ tonnes fuel}) * (0.86 \textit{ tonnes carbon per tonne fuel}) \\ &\quad + MD_{\textit{AQ}} * (10,000 \textit{ tonnes fuel}) \\ &= 1.45 * \textit{SCC} * (86,000 \textit{ tonnes carbon}) + (\$230 \textit{ per tonne fuel}) * (10,000 \textit{ tonnes fuel}) \\ &= \$\textit{xyz} \end{aligned}$$

where $M_{\textit{Total}}$ is the total climate ratio, the SCC is the social cost of carbon taken from the literature or provided by the user, and $MD_{\textit{AQ}}$ is the total air quality marginal damage. The full-flight fuel burn reduction is converted to carbon units in order to align with the SCC's units of dollars per tonne carbon.

The specific values that one uses for the parameters of this equation should to be tailored to the application. For an analysis that extends into the future, increasing the SCC and ratio values for future years is recommended. The SCC is grown because future emissions are expected to produce larger incremental damages as climate change increases and physical and economic systems become more stressed. The IPCC, for example, suggests an increase of 2% to 4% per year on the SCC, while the U.S. Government Interagency Working Group on SCC recommends a growth rate that declines over time in the 1% to 4% range depending on discount rate (47) (6). Likewise, the simulations in this study suggest that the ratio value used should be increased for future year analyses (this is due to the reduced impact of additional units of CO₂ over time as background levels increase, not due to increased impacts of the non-CO₂ effects). To account for the increased relative contribution of non-CO₂ effects, the ratio values from

Table 13 ought to be increased according to the growth rates shown in Table 14. The total climate benefit is then calculated by multiplying the fuel burn reduction in each year by the appropriate SCC and ratio values, discounting the yearly monetized impact to the base year of the scenario being analyzed, and then summing over all years to determine net present value. The user may adjust the final dollar benefit for inflation to different years as desired using U.S. consumer price indexes. The combination of ratios used should also align with the specific application. For example, analysis of scenarios that affect ground-based or LTO operations only should remove the contrails and cirrus components from the total climate ratio. Lastly, one must align the assumptions across SCC value and ratio value (e.g. discount rate) as closely as possible for consistency.

The above considerations can be demonstrated for a simple example case by extending the single year analysis into a five year scenario that has a fuel burn savings of 100,000 tonnes per year full-flight and 10,000 tonnes per year LTO starting in 2010. The setup and results of this sample problem are shown in Table 19 using each of the ratio metrics. The order of information in the table is consistent with the order of steps in applying the derived ratios and air quality marginal damage costs. Estimates for SCC from the recently released U.S. Government Interagency Working Group on the Social Cost of Carbon report will be used. This report presents SCC values that grow over time from 2010 through 2050. Midrange results only are presented and a discount rate of 3%—consistent with the 3% assumption of the NPV ratio—is applied to the yearly climate and air quality benefits stream in order to allow for the calculation of net present value. Note that the ratios presented in Section 4.2.4 were calculated for the year 2006 and thus had to be grown to 2010 values for this example according to their respective growth rates. Also note that the climate ratios are multiplied by tonnes of carbon (calculated from fuel by multiplying by 0.86) in order to be consistent with the units of the SCC while the air quality marginal damage costs need only be multiplied by LTO tonnes of fuel.

Table 19 Multi-year scenario sample problem

Parameters					
Year	2010	2011	2012	2013	2014
SCC (2007\$/tC)	78	80	82	84	85
ΔFuel (full-flight tonnes)	100000	100000	100000	100000	100000
ΔCarbon (full-flight tonnes)	86000	86000	86000	86000	86000
ΔFuel (LTO tonnes)	10000	10000	10000	10000	10000
NPV mid ratio (3% DR)	1.47	1.48	1.48	1.49	1.49
GWP₁₀₀ mid ratio	2.48	2.48	2.48	2.48	2.48
ΔT₁₀₀ mid ratio	2.59	2.59	2.59	2.59	2.59
Air Quality Damage (2007\$/tFuel)	237	237	237	237	237
Discounted Benefit (2007 US\$M; 3% DR)					
NPV ratio	9.9	7.5	7.7	7.8	8.0
GWP ratio	16.7	10.4	10.6	10.6	10.7
ΔT ratio	17.5	16.7	17.1	17.5	17.9
Air Quality	2.4	2.3	2.2	2.2	2.1

Using the climate ratios and air quality marginal damage value, the total expected environmental benefit of the fuel burn reduction scenario in the sample problem ranges from \$52 million to \$98 million in Y2007 US\$, depending on the choice of ratio metric. While only midrange values are presented in this example, it is generally recommended to also show an upper and lower bound estimate to account for sensitivity of assumptions and modeling uncertainty. The benefit estimated using the economic ratio translates to a savings of approximately 25 cents per gallon of jet fuel in terms of climate impact while the air quality benefit comes to approximately 67 cents per gallon of LTO jet fuel. Prorated on a full-flight fuel burn basis, the air quality benefit is likely about one tenth of the benefit in terms of LTO jet fuel. From this prorated perspective, the climate benefit is then approximately four times greater than the air quality benefit per gallon of full-flight fuel burn. As a frame of reference, the U.S. Department of Energy's Information Administration reported the price of kerosene jet fuel on May 18, 2010 to be approximately \$2.03 per gallon in the New York Harbor area.

It is important to understand the limitations and caveats of using the framework for environmental impact assessment described in this chapter. Firstly, the estimates presented in this thesis for quantifying impacts of fuel burn changes are applicable to conventional jet fuel only. While the framework can be extended to alternative fuels, the particular values for ratios and marginal damage costs would change according to the emissions characteristics of the fuel in question. The air quality valuations introduced in Section 4.1 are based on U.S. LTO impacts only with no accounting for the impact of cruise emissions. The air quality framework is also based on a nationwide analysis and is thus not applicable to airport or regional level assessment. The same is true for the ratios introduced in Section 4.2.4, which are derived from globally-averaged climate impacts and should only be used for evaluating fleet-level fuel burn changes. Lastly, the resolution of the models used to estimate air quality damage costs and non-CO₂/CO₂ climate impact ratios is such that results using this framework should not be presented to any greater number of significant digits than what is shown in this thesis.

5 Sample Applications

In this chapter, the results from two different studies are presented, one of which is system growth-focused while the other is vehicle-focused. The goal of this chapter is to provide an environmental assessment of these two projects and also to demonstrate the applicability of the non-CO₂/CO₂ climate ratios and air quality marginal damage costs introduced in Chapter 4 as a surrogate for a full APMT-Impacts analysis.

The first study is a NASA-supported project entitled “Modeling of Vehicle Environmental Characteristics Including New Technologies/Concepts for the Next Generation Air Transportation System.” This study deals primarily with assessing the environmental impact at the system-wide level of commercial aviation in the face of strong growth and also to assess the impact of disparate future concepts operating out of a wide variety of airports. In particular, this project explores different combinations of growth projections and operational procedures for a variety of cases over the 2006-2050 timeframe.

The second study is also a NASA project and is entitled “Aircraft and Technology Concepts for an N+3 Subsonic Transport.” This project aims to define the key technologies needed to meet or surpass aggressive noise, LTO NO_x, and fuel burn goals set by NASA for the 2030-2035 EIS timeframe. The goal is to develop advanced vehicle concepts that can deliver large leaps in subsonic transport aircraft performance and not just evolutionary improvements (73).

In the following sections, the environmental impacts results are presented using both APMT-Impacts and the non-CO₂/CO₂ ratios and air quality marginal damages. These examples demonstrate the application of this framework to a multi-year scenario and also show how the results compare to a more detailed APMT-Impacts analysis.

5.1 System Growth Scenario

5.1.1 Background

The main collaborators in this study were the Aerospace Systems Design Lab (ASDL) at the Georgia Institute of Technology, the Sensis Corporation, and the PARTNER Lab at the Massachusetts Institute of Technology. Each participant contributed to the process of creating aviation scenarios and assessing the environmental impact thereof. The environmental analysis framework and primary tools utilized for this study are depicted in Figure 17.

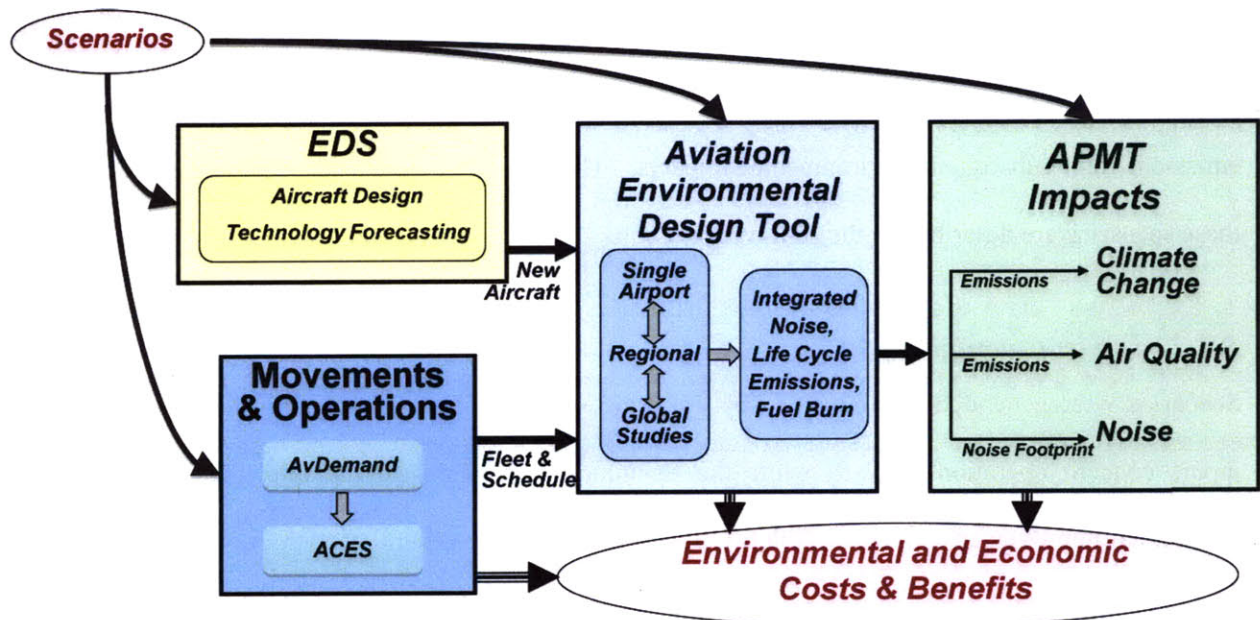


Figure 17 Environmental analysis framework

The Environmental Design Space (EDS) is a tool run by Georgia Tech that estimates source noise, emissions, performance, and vehicle cost characteristics for existing and future aircraft. AvDemand is a demand generation tool run by Sensis that models future air traffic demand according to a wide variety of parameters and can also be used when evaluating futuristic and advanced concepts. AvDemand has been designed to directly feed demand input data into other fast-time NAS simulation models such as the Airspace Concept Evaluation System (ACES). ACES, also run by Sensis, produces flight schedules and four-dimensional aircraft trajectories. The fleet and schedule created by AvDemand and ACES is then fed into AEDT along with vehicle characteristics from EDS. AEDT uses these inputs to produce fleet-

level fuel burn and emissions levels, which is what APMT-Impacts requires to calculate environmental impacts. Noise impacts were not considered for this analysis.

Using this framework, the study aimed to capture the predicted future fleet growth as well as the environmental characteristics necessary to allow for assessment of the impact of a wide array of aviation scenarios. Sensis provided expertise in flight demand prediction, demand scenario generation, and in assessing the impact of operational improvements, while Georgia Tech and MIT provided reduced-order modeling capability for performance and environmental impact. This framework was utilized to study the impact of different growth projections and operational improvements on fleet-wide changes in fuel use, emissions, and subsequent environmental impacts. The particular parameters that were used to create these scenarios are described in the following section.

5.1.2 Environmental Cases

Scenarios were generated for this study by adjusting seven different input parameters. Three of these inputs concern operations growth while the remaining four represent the implementation of certain operational improvements. The variables X , Γ , and LF affect the general growth in operations, the shape of that growth, and the growth in load factor, respectively. The four operational improvements explored in this study were: Depeak, representing a rescheduling of flights to off-peak times; UpGauge, representing flight consolidation or a shift to larger aircraft; De-connect, representing the use of increased point-to-point flying; and Metroplex, representing the diversion of flights to secondary airports in congested areas.

The specific cases assessed for this study and their corresponding input assumptions are listed in Table 20. The growth variables were applied as multipliers on the CAEP/8 forecast, which is what was used to generate the baseline case. For each of these variables, setting the value to one corresponds to setting the multiplier to the maximum value (implying aggressive growth) and setting the value to negative one corresponds to setting the multiplier to the minimum value (implying slow or negative growth). For cases

where the CAEP/8 growth assumptions were used, these parameters were set to zero. The operational improvements, meanwhile, were set to either on or off across the scenarios. For this study, environmental impacts were assessed for 32 different scenarios plus a baseline case. Since the aim of the study was to learn the impact of each of the scenarios relative to a baseline case, the focus in this thesis is on presenting the change in impacts from the baseline to the policy scenarios. The emissions inventories were generated by Georgia Tech using AEDT for five years—2006, 2020, 2030, 2040, and 2050. APMT interpolates between these years and calculates results over a time spanning the entire scenario.

Table 20 Input assumptions for aviation scenarios

CASE	X	Gamma	LF	DePeak	Up Gauge	De-Connect	Metroplex
Baseline	CAEP/8	CAEP/8	CAEP/8	Off	Off	Off	Off
Case02	-1	1	-1	Off	Off	On	On
Case03	1	1	1	On	Off	On	Off
Case04	1	-1	-1	On	Off	On	On
Case05	1	-1	1	On	Off	Off	On
Case06	1	1	-1	On	Off	Off	Off
Case07	1	-1	1	Off	On	On	Off
Case08	-1	1	-1	On	On	Off	Off
Case09	-1	-1	-1	Off	Off	Off	Off
Case12	-1	-1	-1	On	On	On	On
Case13	1	-1	-1	Off	On	Off	On
Case15	1	1	1	Off	On	Off	On
Case16	1	1	-1	Off	On	On	Off
Case17	1	1	1	On	On	Off	Off
Case19	-1	1	-1	Off	On	Off	On
Case20	-1	1	-1	On	Off	On	Off
Case21	1	1	-1	Off	Off	Off	On
Case22	1	1	-1	On	On	On	Off
Case24	-1	-1	-1	On	Off	Off	On
Case25	1	-1	1	On	On	On	On
Case28	1	1	1	Off	Off	On	Off
Case29	1	1	-1	Off	On	Off	Off
Case30	1	1	-1	Off	On	On	On
Case31	-1	-1	-1	Off	On	On	Off
Case32	1	-1	-1	Off	Off	On	Off
Case33	1	-1	1	Off	Off	Off	Off
Case34	1	-1	-1	On	On	Off	Off
Case37	1	1	-1	On	On	Off	On
Case39	1	0	0	On	Off	On	On
Case40	0	1	1	On	Off	Off	On
Case41	0	-1	1	On	On	Off	On
Case42	0	-1	0	On	Off	Off	Off
Case43	0	0	-1	Off	Off	Off	On

The percent change in total fuel burn for each of the cases relative to the baseline scenario is plotted in Figure 18. The changes in LTO fuel burn and full-flight fuel burn are what drive air quality and climate

impacts, respectively, in the environmental analysis that follows. In the figure, the cases are grouped by operations growth factor, X , and then sorted in order of increasing positive full-flight fuel burn change to illustrate how air quality and climate impacts closely track with fuel burn.

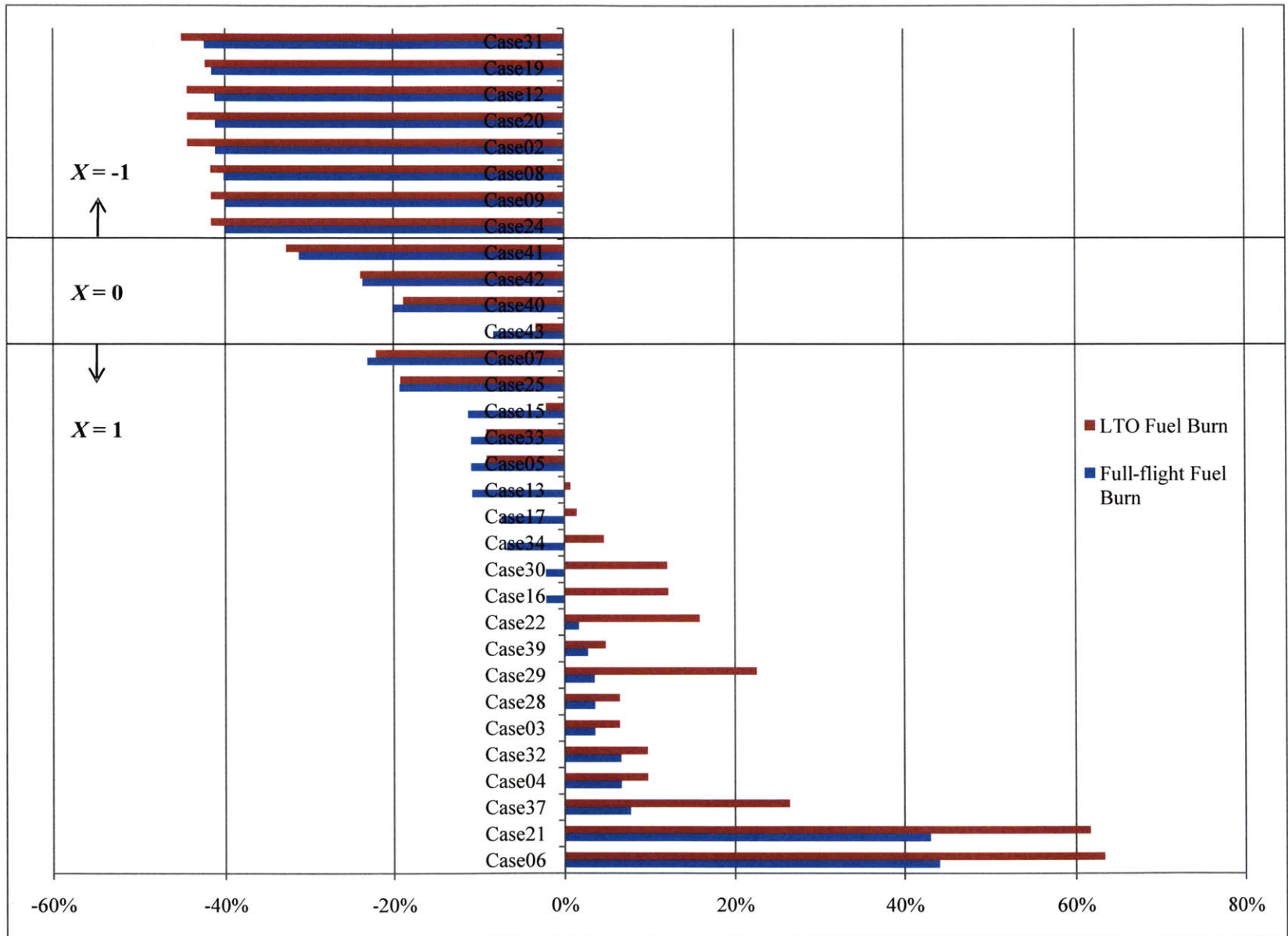


Figure 18 Percent change in total fuel burn relative to baseline scenario

5.1.3 APMT Results

5.1.3.1 Air Quality

For air quality, APMT-Impacts calculates the incidences of premature mortality as well as the net present value of the health risks associated with the increase in ambient particulate matter. Uncertainty is captured by representing a few key input parameters as probabilistic distributions and then running the analyses in Monte Carlo mode. The primary input assumptions to the air quality module were previously shown in Table 4. Due to the large number of scenarios in this analysis, only the mid lens assumptions were used. Physical air quality impacts, which in this analysis are limited to premature mortalities, are presented for each of the thirty-two policy cases with respect to the baseline scenario in Figure 19. Monetized impacts, or the change in net present value of the premature mortalities, are also shown in Figure 20. The values in the figures represent the difference in overall impacts—aggregated across 325 airports in the continental United States and summed over all years of the scenario (2006 through 2050)—between the policy cases and the baseline. The mid estimate, indicated by the vertical red line, represents the mean of the output distribution while the error bars on the values represent the 90 percent confidence interval of the distribution (i.e. the 5th percentile to the 95th percentile). The figures are binned into cases that have the same operations growth factor, X , and then sorted in order of increasing positive change to illustrate the strong influence of that parameter and to help discern the impact of some of the other parameters.

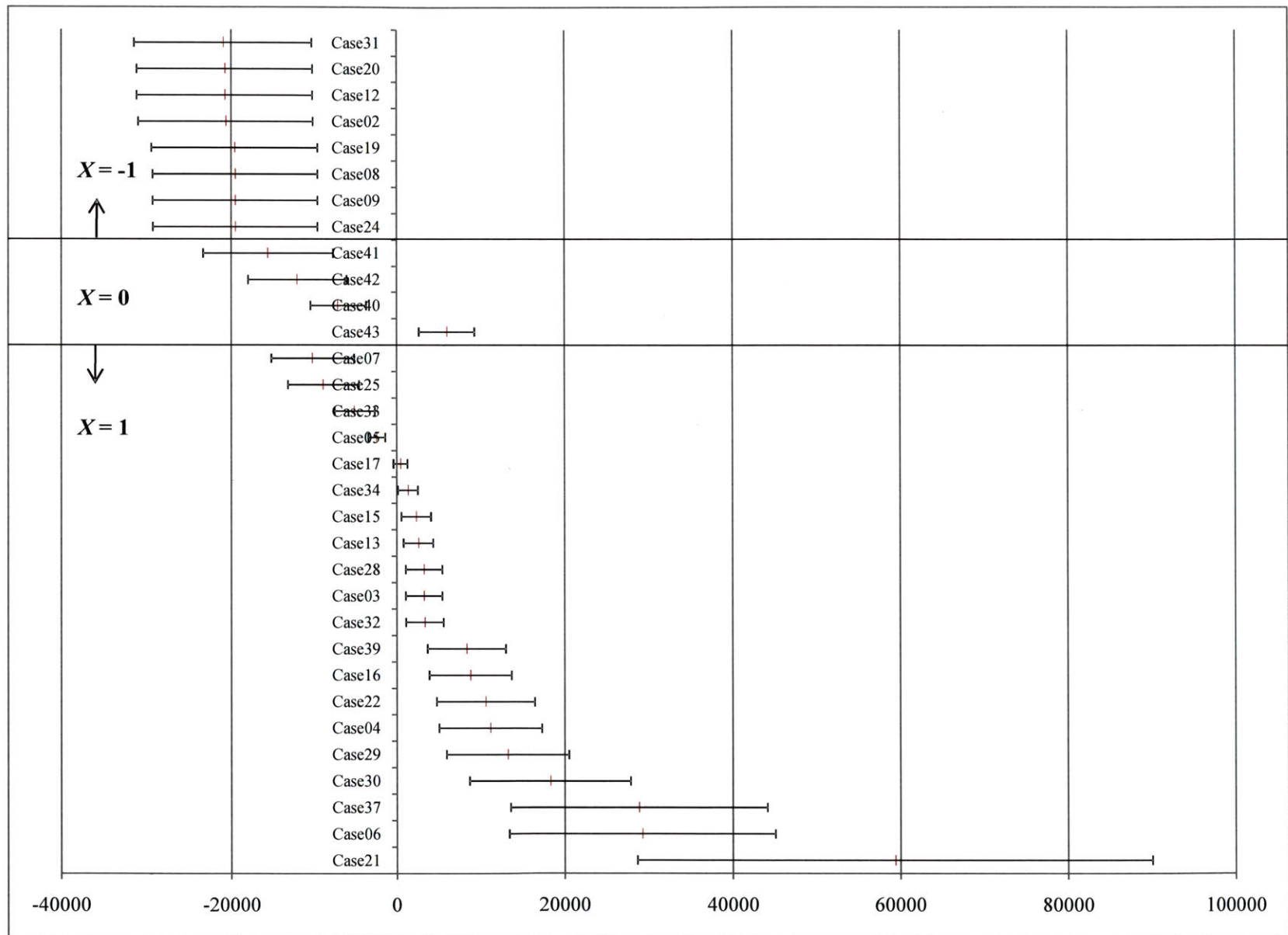


Figure 19 Change in premature mortalities (Policy - Baseline; Impacts summed over 325 airports from 2006-2050)

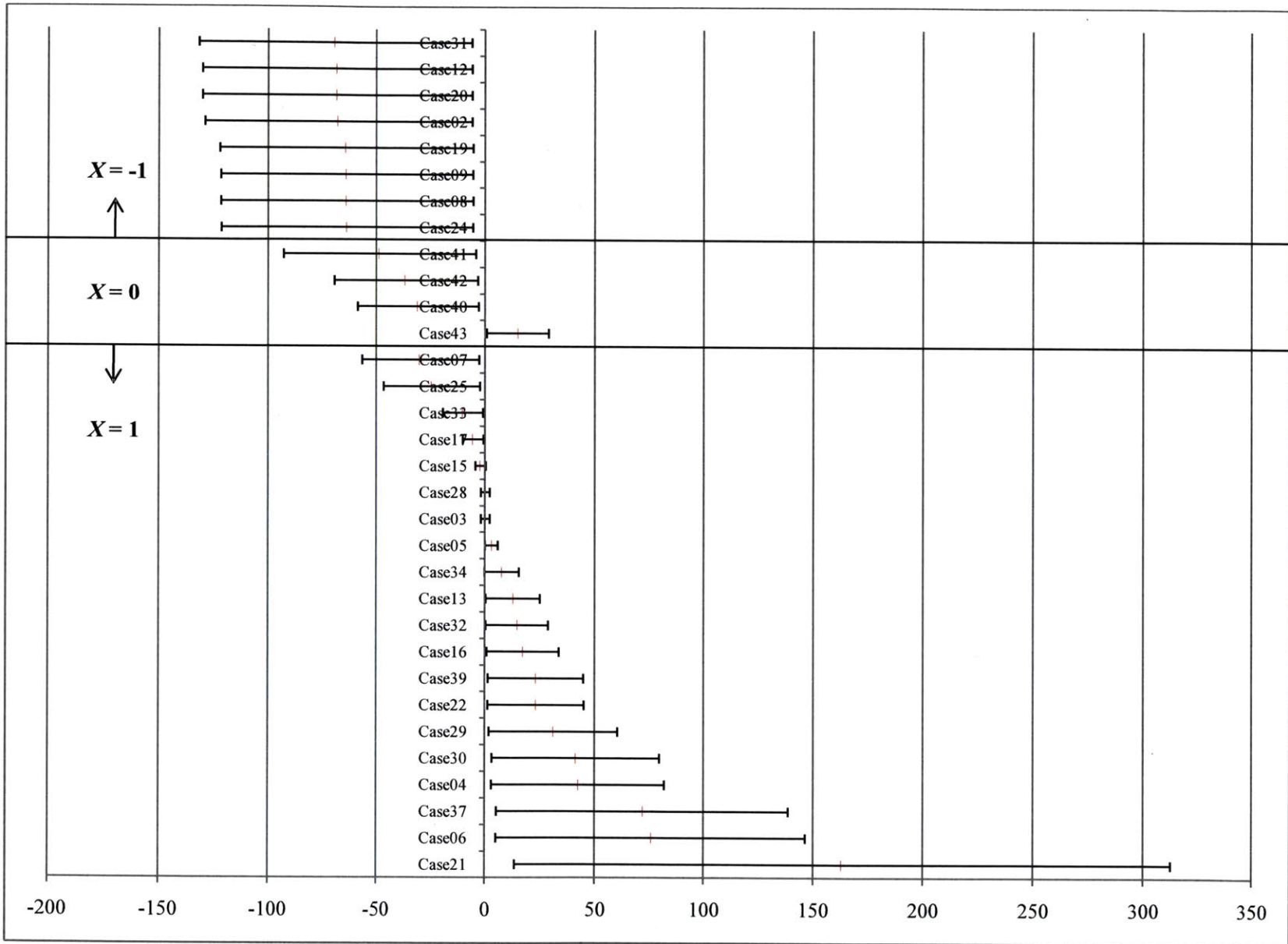


Figure 20 Change in NPV of health costs (Policy - Baseline; 2006 US\$; 3% DR; Impacts summed over 325 airports from 2006-2050)

Figure 19 and Figure 20 provide some insight into which scenario assumptions are the primary drivers in terms of air quality impacts. Each of the parameters that were used to build the scenarios has a different effect on the total system-wide emissions profile. Knowing that differences in environmental impacts are driven primarily by differences in absolute quantities of emissions, it is not surprising that the parameters that shape the growth in operations (X , Γ , and LF) for each scenario have a large influence on the sign and magnitude of the change in impacts from the baseline to policy cases. For example, cases 2, 8, 9, 12, 19, 20, 24, 31—all of which have the operations growth factor, X , set to the minimum value—lead to decreased health costs, which is an air quality benefit, relative to the baseline case. The fact that these scenarios fall in a relatively small impact range indicates that the operational improvements (DePeak, UpGauge, De-Connect, and Metroplex) are less significant than the growth assumptions in determining changes in the impacts associated with air quality. Cases 5, 25, and 33 also lead to low or decreased health costs relative to the baseline due to a low value for Γ , despite having high growth factors. Case 31 has the greatest decrease in health costs, which is primarily a result of low operations growth (attributed to reduced values for X and Γ) and perhaps also a result of operational improvements that lead to fewer operations for a given level of demand (attributed to the implementation of both UpGauge and De-connect).

Most of the remaining cases are set to the maximum values for X and Γ and thus lead to increased growth and health costs relative to the baseline. Cases 4, 13, 32, and 34 also lead to increased health costs despite having gamma factors set to the minimum value. Case 21 results in the largest increase in health costs due to its high operations growth parameters and also due to the implementation of the Metroplex operational improvement. Cases 39 through 43, which have certain parameters set to intermediate values, are driven by the operations growth factor. Case 39 has this value set to the maximum value and thus leads to an increased health cost, while cases 40 through 42 have this parameter set to a middle value and thus lead to decreased health costs (a benefit). Case 43 has similar settings to 40 through 42, but leads to

an increased health cost due to its low load factor and implementation of the Metroplex operational improvement.

Cases 5, 15, and 17 demonstrate the effect that discounting can have on valuing short- versus long-term impacts. For each of these cases, moving from physical to monetized impacts results in a reversal of sign (e.g. positive to negative). This occurs because discounting of the monetized impact places less weight on impacts that occur in the future, relative to those that happen today. For example, while Case 5 results in fewer total premature mortalities than the baseline case, the fact that most of the reduction in premature mortalities occurs in the second half of the scenario results in a net health cost in moving from the baseline case to Case 5.

5.1.3.2 Climate

For global climate change, APMT-Impacts provides both the globally-averaged surface temperature change and the net present value of the socio-economic damages that result. Uncertainty for a given change in fuel burn and emissions is captured by using a range of input assumptions in the form of probability distributions. The analysis is conducted using Monte Carlo methods and the outputs are generated for several thousand runs. Table 12 lists the primary assumptions used in the climate analysis for this study. Again, due to the large number of scenarios in this analysis, only the mid lens assumptions were used for a single discount rate (set at 3% in line with EPA practice). Physical climate impacts—i.e. temperature change—are presented for each of the thirty-two policy cases with respect to the baseline scenario in Figure 21. Monetized impacts, or the change in net present value of climate damages, are also shown in Figure 22. Note that the scale on the chart is an order of magnitude larger than the scale on the air quality impacts in Figure 20. The mid estimate, indicated by the vertical red line, represents the mean of the output distribution while the error bars on the values represent the 90 percent confidence interval of the distribution (i.e. the 5th percentile to the 95th percentile). The figures are again binned into cases that have the same operations growth factor, X , and sorted in order of increasing positive change.

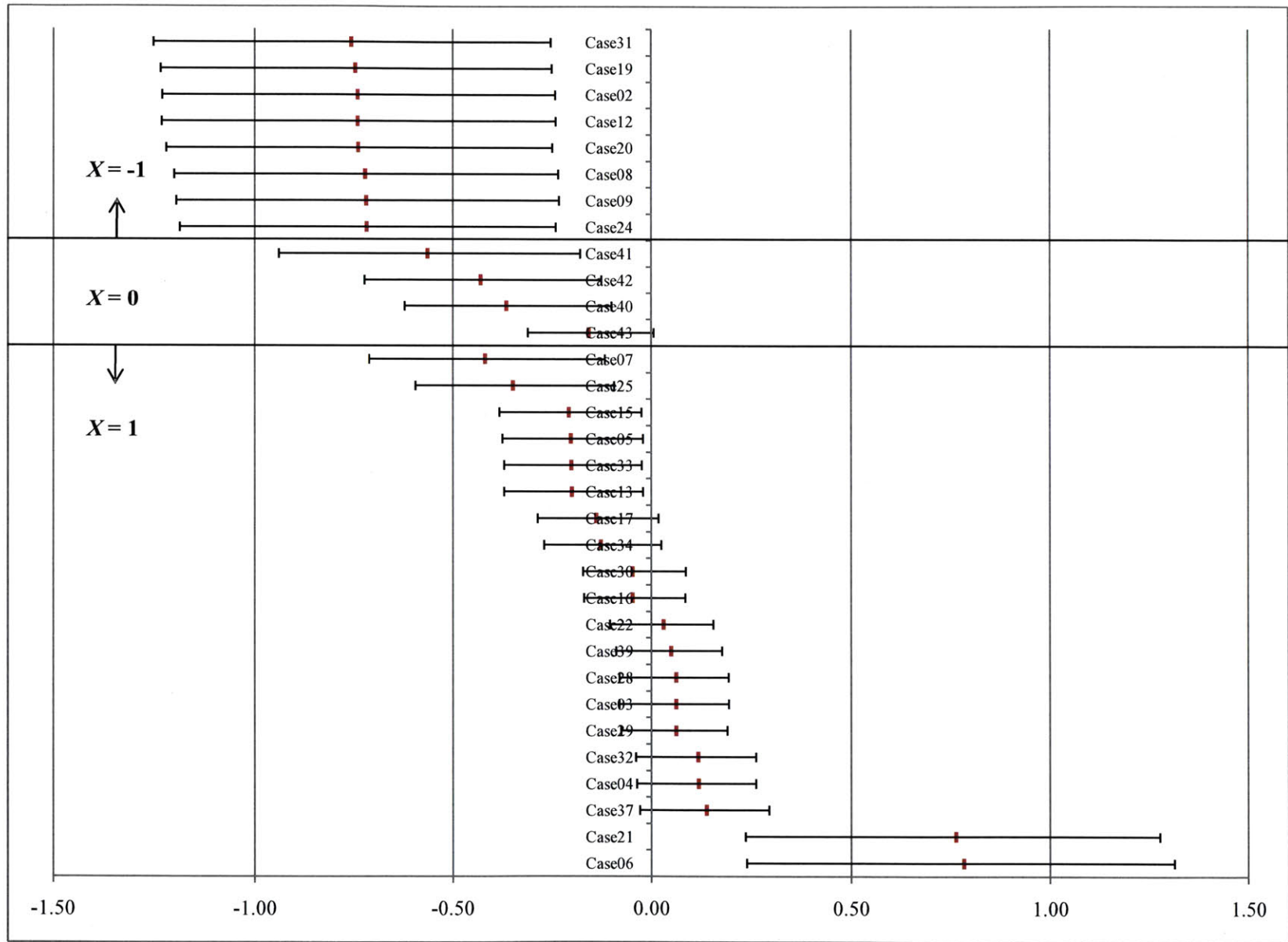


Figure 21 Change in deltaT-yr (Policy - Baseline; Kelvin)

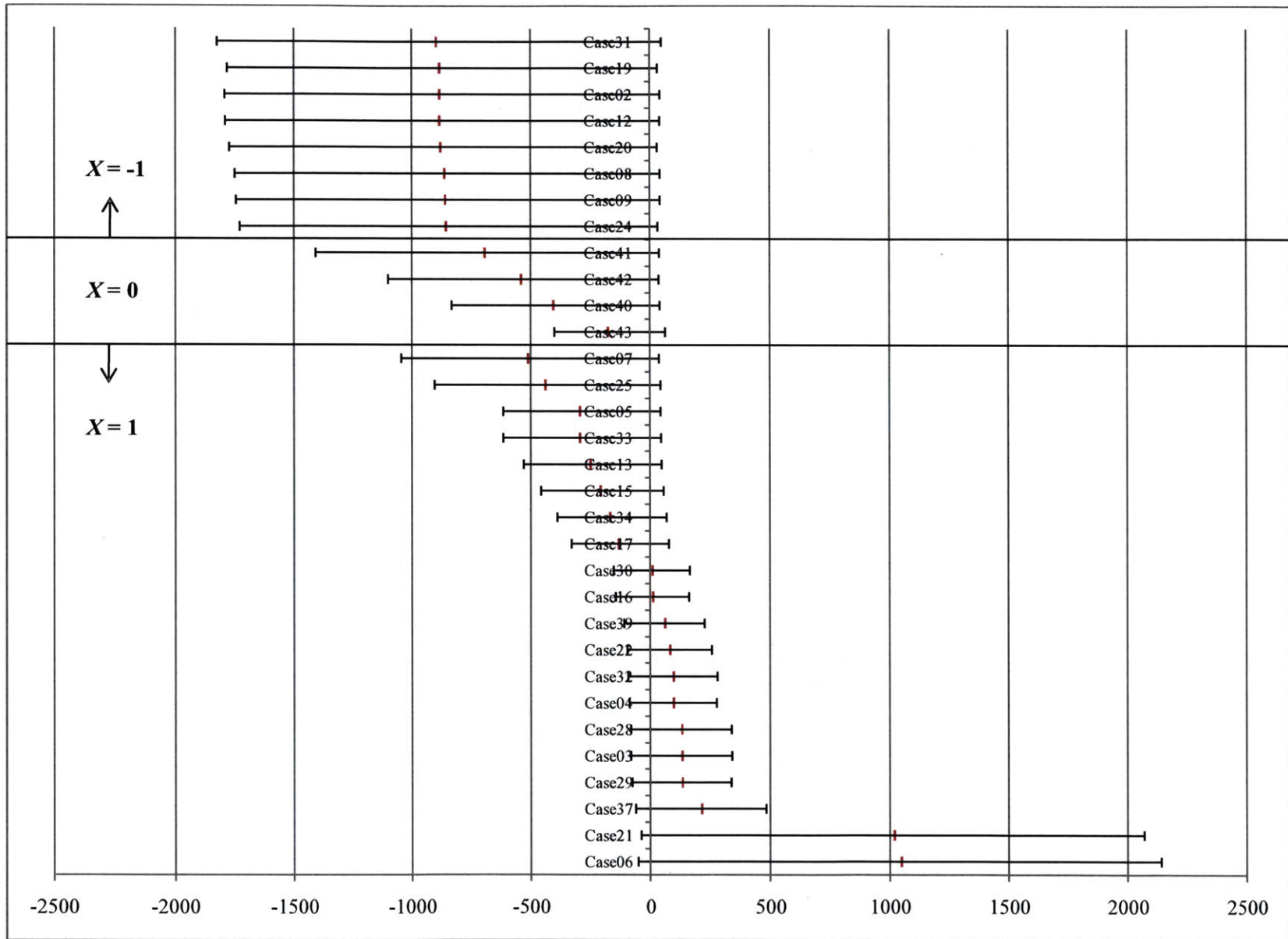


Figure 22 Change in NPV of damages (Policy - Baseline; 2006 US\$; 3% DR)

As was the case with air quality, climate impacts are driven by the behavior of the fuel burn and emissions inventories for the different scenarios. Thus, understanding the assumptions out of which the scenarios were created is essential to understanding the differences in climate impacts across the scenarios. In general, the monetized climate impacts are larger than the monetized air quality impacts. The scenario parameters that were found to be most influential on air quality are also the primary drivers on climate change. Again, the operations growth parameters that shape a scenario (X , T , and LF) tend to dictate the climate impact of that scenario relative to the baseline. For instance, all of the scenarios that have the operations growth factor, X , set to the minimum value, (i.e., cases 2, 8, 9, 12, 19, 20, 24, and 31), have similarly large climate benefits (reduced costs due to the environmental impact of climate change). For the other cases, however, the operational improvements (DePeak, UpGauge, De-Connect, and Metroplex) also influence the results. This differs from the air quality results and is a consequence of the climate analysis including emissions that extend beyond the vicinity of airports. Unlike the air quality analysis, the climate analysis includes emissions both above and below 3,000 feet. In other words, the impact of these parameters (i.e. DePeak, UpGauge, De-Connect, and Metroplex) is more noticeable at the system-wide scale, but this is only true for scenarios where the operations growth factor, X , is set to the maximum value.

With the cases divided into groups in which each case has the same operations growth parameters, the effect of the operational improvements becomes more noticeable. Cases 3, 15, 17, and 28 can be used to demonstrate the costs and benefits of UpGauge, or increased use of larger aircraft, and De-connect, or increased point-to-point flights. Cases 3 and 28, which include De-connect but not UpGauge, have increased climate costs relative to the baseline, while cases 15 and 17, which have the opposite settings for these two parameters, result in climate benefits relative to the baseline (decreased monetized costs). These trends are also demonstrated via a comparison of cases 4, 13, 32, and 34. Meanwhile, UpGauge is not present in cases 6 and 21, which have the largest climate costs. This suggests that for a given demand level reduced climate impact can be achieved by using larger aircraft.

With this knowledge of the influence of the operational parameters De-connect and UpGauge, more can be said about the cases that do not have the operations growth factor set to the minimum value. With the exception of cases 15, 16, 17, and 30, having the Γ factor set to the minimum value is the primary factor associated with the climate benefit. The four aforementioned exceptions have a climate benefit in terms of total temperature change that is primarily due to the implementation of UpGauge. The other cases have a climate cost relative to the baseline that results from settings that lead to high operations growth. Case 4 results in a climate cost despite having the minimum Γ value; this is due to the inclusion of De-Connect and Metroplex, which both lead to higher fuel burn. As a reminder, the two scenarios that lead to the largest climate damages, cases 6 and 21, do so because of high operations growth settings and a lack of the UpGauge operational improvement.

Cases 39 through 43 can be observed somewhat independently from the rest of the scenarios as these cases have certain operations growth parameters set to intermediate values. Case 39 is a high operations growth factor case and thus leads to climate costs, but the other cases have this parameter set to a middle value that drives them to be beneficial in terms of climate. The greatest climate benefit arises out of case 41 due to its low Γ factor, which slows operations growth, and the implementation of UpGauge. In general, of the operational improvements, the inclusion of UpGauge (i.e. flight consolidation through the use of larger aircraft) appears to have the largest benefit in terms of reduced climate impacts while the inclusion of De-connect (i.e. increased point-to-point flying) appears to be the most detrimental in terms of increased climate impacts.

5.1.4 Ratios and Air Quality Marginal Damages Validation

The monetized results presented in Figure 20 and Figure 22 can also be calculated using the climate ratios and air quality marginal damages as outlined in Section 4.3. The APMT-derived ratios can be applied to SCC values to calculate the monetized climate impact of the fuel burn changes for each of the 32 scenarios relative to the baseline case of this study. The air quality marginal damage values can also be used to monetize air quality costs or benefits for the different cases. For consistency, APMT-Impacts

was used to derive SCC estimates and growth rates on SCC using the assumptions laid out in Table 12. Since this is a multi-year analysis, growth rates from Table 14 were applied to the ratios. The results of this framework are depicted against the APMT-Impacts results in Figure 23 for air quality impacts and Figure 24 for climate impacts. The estimates are provided for the mid lens at a 3% discount rate only, as this example mainly aims to illustrate the applicability of the climate ratios and air quality marginal damage costs to analyses that extend many years into the future and not the ability of the ratios and air quality marginal damages to capture uncertainty. The cases are sorted in order of increasing percent difference between the APMT-Impacts results and the simplified approach results, as indicated by the data labels for each of the scenarios.

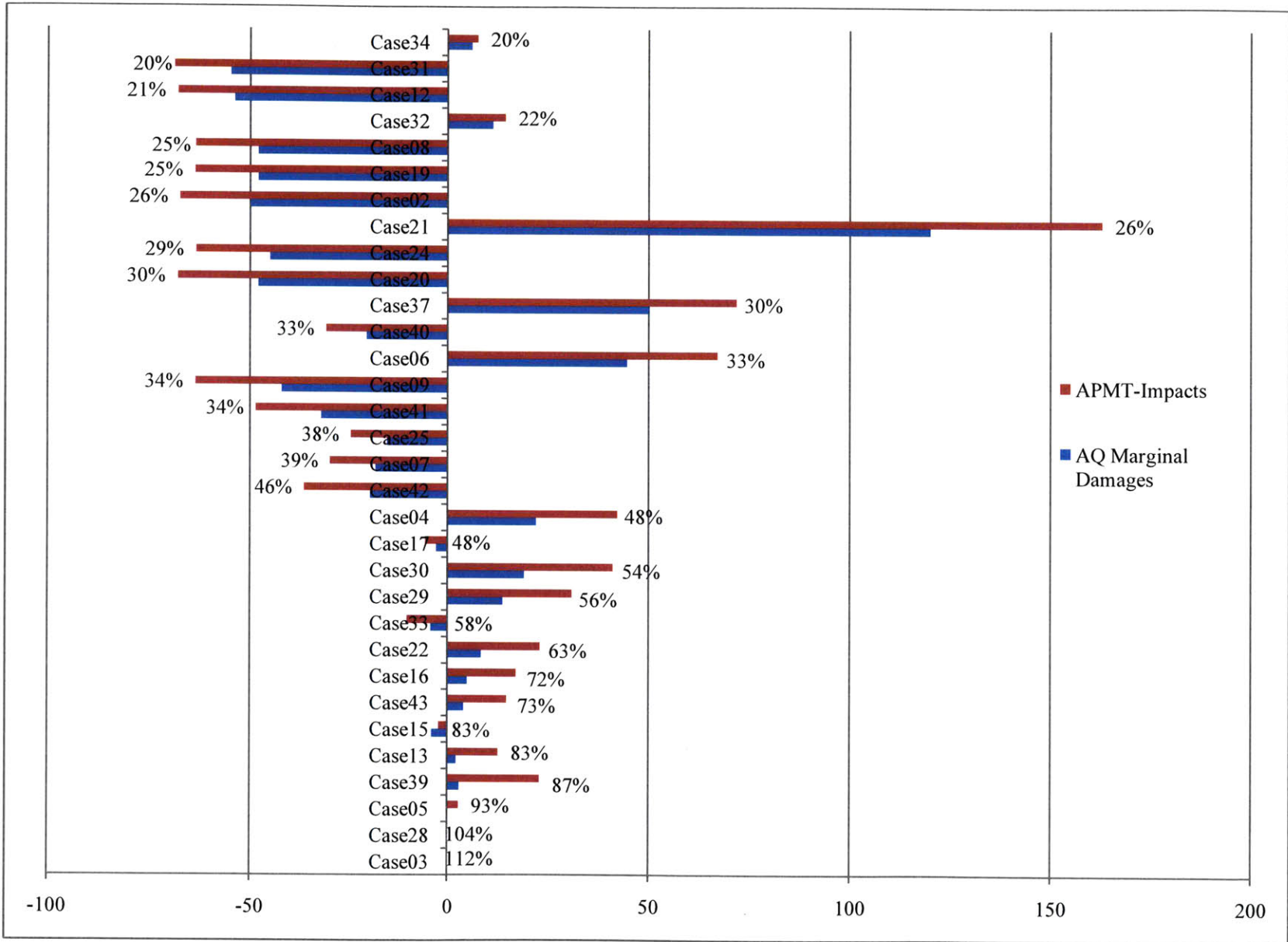


Figure 23 Change in NPV of health costs (Policy - Baseline; 2006 US\$; 3% DR; calculated using air quality marginal damage cost)

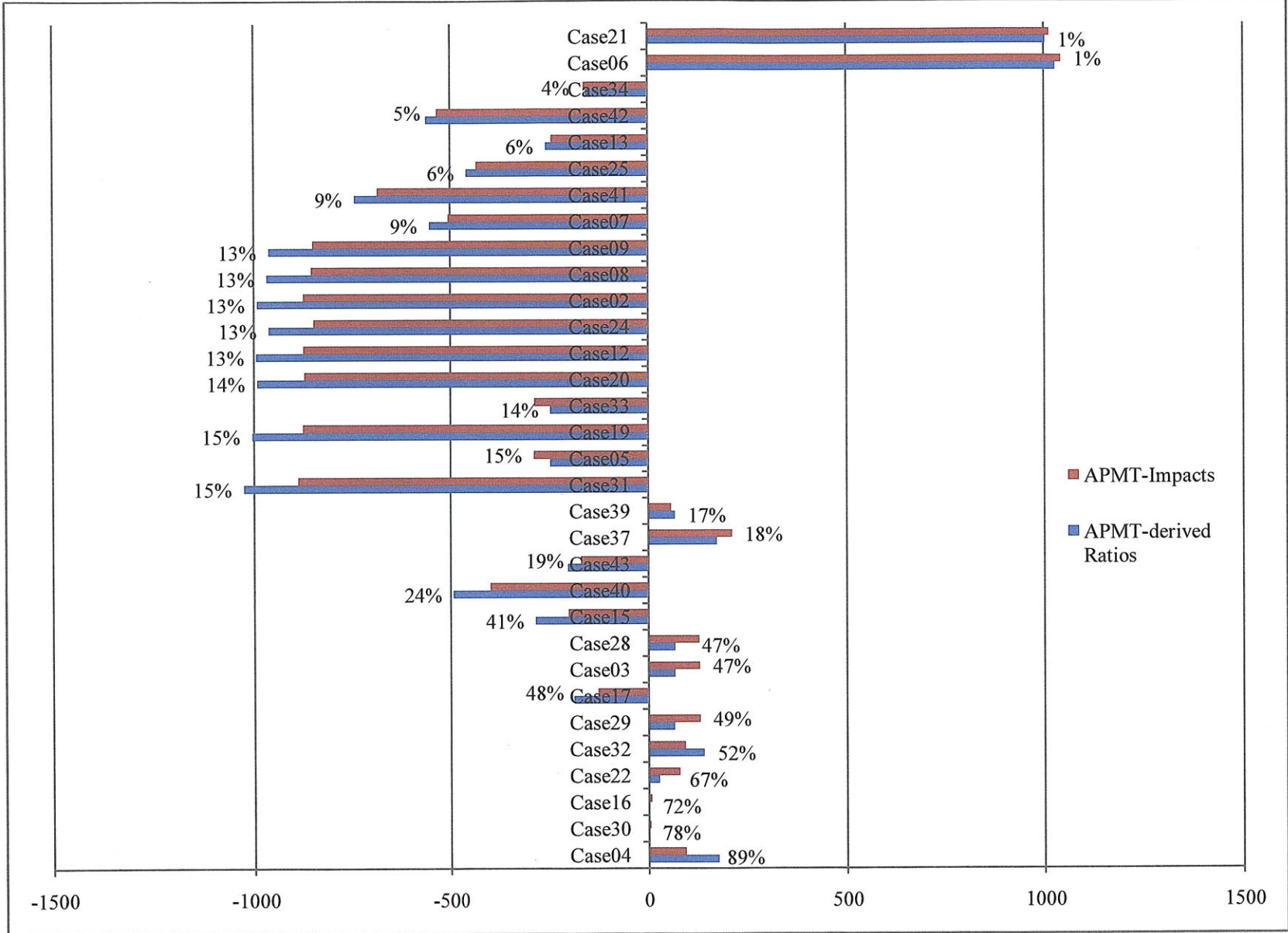


Figure 24 Change in NPV of damages (Policy - Baseline; 2006 US\$B; 3% DR; calculated using APMT-derived ratios)

Using the climate ratios and air quality marginal damages, 17 of the 32 scenarios assessed deviated from the APMT air quality results by less than 40% and 21 of the 32 scenarios assessed deviated from the APMT climate results by less than 20%. It should also be noted that the use of the climate ratios and air quality marginal damage costs would enable the exploration of sensitivity to different assumptions (e.g. the low and high lenses and different discount rates) with little additional effort. The comparison above shows that, with assumptions aligned appropriately, the derived ratios and air quality marginal damages are a reasonable substitute for a full APMT-Impacts climate and air quality. The differences are small relative to the range of results one would get when incorporating scientific and valuation-based uncertainties, which is the recommended practice for a typical analysis. This study demonstrates that the ratios and air quality marginal damages are an appropriate and computationally efficient tool for analyzing a multi-year scenario. The application in Section 5.2 will show how the ratios can be used to capture uncertainty in estimating non-CO₂ impacts, though only a single year scenario will be assessed.

5.2 New Vehicle Scenario

5.2.1 Background

The aim of this project was to identify the critical enabling technologies needed for an aircraft to meet ambitious environmental goals and to demonstrate the impact of these technologies on aircraft performance through conceptual design. The NASA targets for noise, NO_x emissions, and fuel burn are listed in Table 21. The N+3 goals—referring to a timeframe of 2030-2035 EIS—are shown in the last column of the table. The main collaborators in this study were the Department of Aeronautics and Astronautics at MIT, Aurora Flight Sciences, Aerodyne Research Inc., and Pratt & Whitney.

Table 21 NASA figures of merit for N+1, N+2, and N+3 Generation aircraft

CORNERS OF THE TRADE SPACE	N+1 (2015) ^{***} Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020) ^{***} Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2025) ^{***} Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	-71 dB (cum below Stage 4)
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

The MIT-led team took a system-level approach to developing integrated solutions that provide the best balance in performance enhancements in the areas of aerodynamics, propulsion, operations, and structures. From the analysis, two aircraft were identified and carried through conceptual design, one of which is analyzed in this thesis. The requirements for these concepts were driven by the expected scenario, which reveals a market segment that represents a substantial portion of the commercial fleet. The primary design addresses the role currently filled by the B737/Airbus A320 class vehicle, i.e. a 180 seat aircraft with transcontinental range. This double-tube and wing design is referred to as the D8 Series. The capability of the D8 design is given in Table 22, which shows the NASA metrics, the baseline aircraft, the N+3 goals, and the vehicle performance. The italicized items in the fourth column represent goals that were met by the proposed design (73).

Table 22 Performance of D8 Series aircraft and B737-800 baseline

NASA Metric	Baseline (B737-800)	N+3 Goals	Double-bubble (D8.5)
Fuel Burn (Represented by Payload Fuel Energy Intensity, PFEI, in [KJ/kg-km])	7.43	2.23 (70% reduction)	2.17 (70.87% reduction)
Noise [EPNdB] (EPNdB below Stage 4)	277	202 (-71 EPNdB)	213 (-60 EPNdB)
LTO NOx [g/KN] (% below CAEP 6)	43.28 (31% below CAEP 6)	>75% reduction	10.5 (87.3% reduction)
Field Length [ft]	7680 ft for 300 nm mission	Metroplex	5000

5.2.2 Environmental Cases

In addition to the progressive warming of the planet, the anticipated increased stringency of environmental policymaking and regulation motivates the expectation that it will become increasingly important to design aircraft for a climate-constrained world. For this reason, climate impact was included as part of the suite of parameters for evaluating aircraft concepts in this project. In particular, it would be valuable to estimate the climate impact of a scenario in which the D8 Series is integrated into the commercial aviation fleet. APMT-Impacts can be used to estimate the magnitude of the benefit of these vehicles at the fleet-level given the large performance gains that these aircraft achieve in terms of fuel burn and emissions.

The approach used to create a fleet-level integration scenario was to replace existing flights in the 120-180 seat class with the D8 aircraft. This seat class covers vehicles such as the Airbus A320 and Boeing 737 families and generally corresponds to the target market of the D8 design. The dataset that was used is an existing 2006 emissions inventory created by the Volpe Transportation Center with AEDT. Only U.S. operations were considered for this analysis, that is flights originating in or departing from the U.S. in the database. Calculating fuel burn for a D8 flight consisted of multiplying the productivity (payload times distance) of the flight being replaced by the Payload Fuel Energy Intensity (PFEI) value for the D8 aircraft. From Table 22, this PFEI value is 2.17 kJ/kg-km for the D8.5 design. This approach captures the D8 aircraft's ability to perform the same mission as many existing aircraft at a considerably reduced fuel energy usage. It should be noted, however, that the D8.5 achieve this fuel efficiency at a range of 3,000 nautical miles. At shorter ranges, the performance is worse, and thus 2.17 kJ/kg-km is a slightly optimistic evaluation of the PFEI and subsequent environmental benefit. Having created a baseline and policy scenario, the impact of the D8 integration was estimated through both APMT-Impacts and the derived ratios. Air quality analysis was not performed for this study.

5.2.3 APMT Results

The metrics of interest in assessing climate impacts are globally averaged surface temperature change and net present value of damages. Since baseline and policy scenarios were created, the focus is on the change in these metrics across the two cases. The scenarios were assessed in APMT-Impacts using the same set of input assumptions that were used to calculate the APMT-derived ratios; these settings were presented in Table 12. The results of the APMT-Impacts climate analysis of the D8 integration case are shown in Table 23. Note that the temperature results do not vary with discount rate.

Table 23 APMT-Impacts results for N+3 analysis

	2% Discount Rate			3% Discount Rate			7% Discount Rate		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
Change in ΔT (K)	"	"	"	-0.005	-0.011	-0.018	"	"	"
% Change in ΔT	"	"	"	-32%	-32%	-32%	"	"	"
Change in NPV (2006 US\$B)	-0.31	-8.4	-18.7	-0.15	-4.2	-11.5	-0.04	-1.3	-4.5

The scenario in which the D8 concept is introduced into the fleet as a replacement for the 120-180 seat aircraft class results in a 32 percent improvement in terms of physical climate impact. The monetized benefit of the D8 scenario ranges from \$40 million to \$19 billion, with a nominal value of approximately \$4 billion for a discount rate of 3 percent. This analysis does not account for the potential air quality benefit associated with inserting the D8 concept into the U.S. fleet. It should also be noted that this analysis is notional in that it only looks at the impact of the D8 against the background of a single year of current-day aviation activity and not in any projected 2030-2035 context when the fleet mix, airspace, and operational landscape will necessarily be different.

5.2.4 Ratios Validation

This analysis can be used to demonstrate the ability of the ratios to capture both scientific and valuation-based uncertainties associated with estimating non-CO₂ impacts. Here, the APMT-derived ratios are used to calculate the net present value of climate benefits resulting from the D8 scenario relative to the baseline

case. The SCC values used for the calculation were also derived in APMT-Impacts in line with the assumptions detailed in Table 12. The results of this analysis are presented alongside the full APMT-Impacts results for comparison in Table 24 and graphically in Figure 25.

Table 24 Change in NPV of benefits due to integration of D8 concept into fleet (Policy – Baseline; 2006 US\$)

	2% Discount Rate			3% Discount Rate			7% Discount Rate		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
APMT-Impacts	-0.31	-8.4	-18.7	-0.15	-4.2	-11.5	-0.04	-1.3	-4.5
APMT-derived Ratios	-0.61	-8.3	-19.4	-0.29	-4.2	-12.0	-0.08	-1.4	-4.8
% Difference	106%	0.6%	3.5%	109%	0.3%	4.3%	109%	7.0%	7.4%

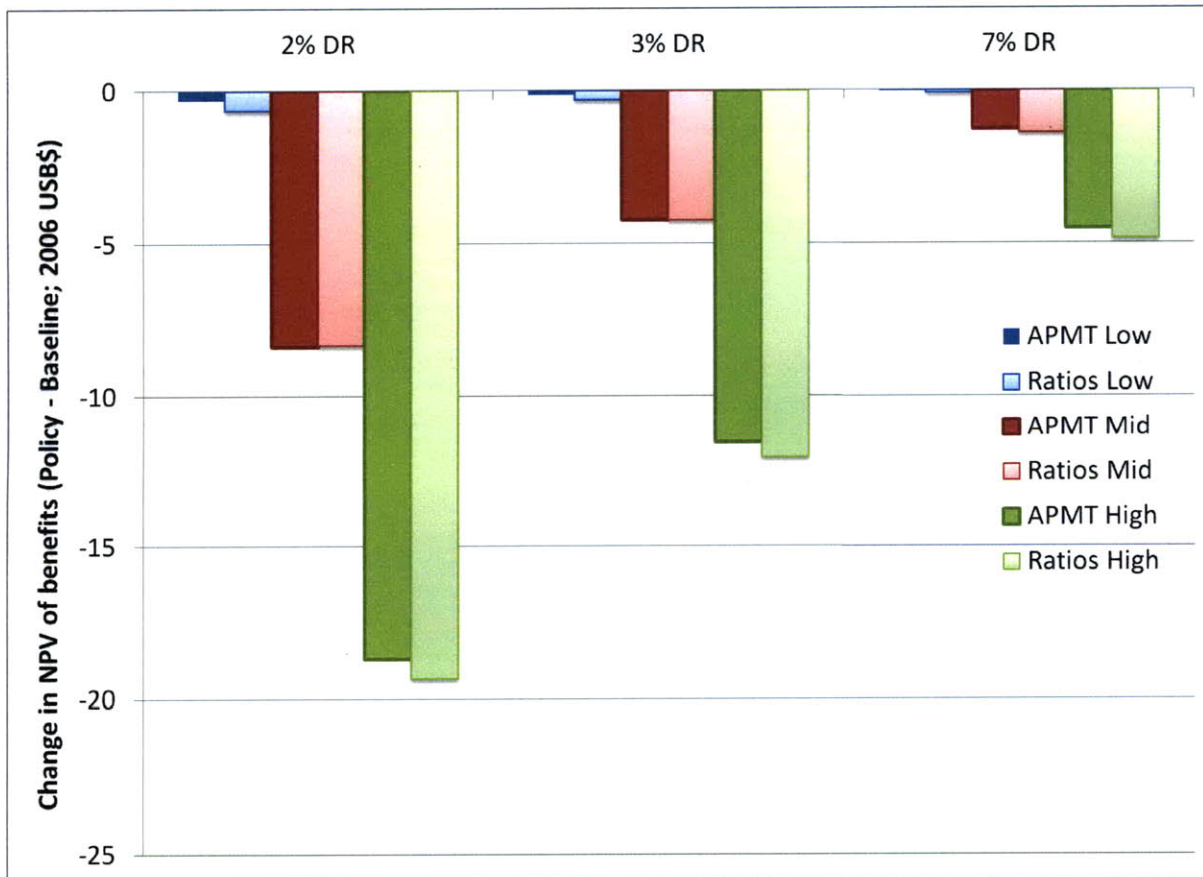


Figure 25 Comparison of APMT-Impacts and non-CO₂/CO₂ climate ratio results for N+3 study

As can be seen from the table and figure, the impact calculation using the APMT-derived ratios compares favorably with the APMT-Impacts calculation. The APMT-derived ratio NPV estimates mostly fall within 10 percent of the APMT-Impacts estimates. The lower bound comparison does not compare as favorably due to the inability of the ratios to resolve small changes in impacts with high accuracy. Again, having consistent assumptions across SCC and ratio values allows for the climate ratios and air quality marginal damage results to align closely with the APMT-Impacts results. This analysis demonstrates the ability of the ratios to provide a range of impact estimates that captures the underlying scientific and decision-maker uncertainties associated with monetizing climate impacts.

6 Conclusions

6.1 Summary and Conclusions

This thesis has presented a simplified method for assessing the non-CO₂ co-benefits of aviation fuel burn reductions. The extent to which the ratio of non-CO₂ effects to CO₂ effects for aviation is sensitive to metric choice was also examined. The method utilizes non-CO₂/CO₂ climate ratios in conjunction with the social cost of carbon to value climate impacts and estimates for the air quality marginal damage cost of a tonne of fuel. These quantities were both derived in APMT-Impacts through a probabilistic analysis that accounts for many important sources for uncertainty and presents ranges on the outputs. The APMT-Impacts Climate Module was benchmarked against other climate models through SCC comparison studies where it was shown that SCC estimates produced in APMT-Impacts are well-aligned with estimates from U.S. government studies and other literature. The wide range of SCC estimates found in literature provided the rationale for deriving aviation-specific non-CO₂/CO₂ ratios in APMT-Impacts using a range of assumptions and then applying these ratios to exogenously-specified SCC values.

A range of different metrics on which to base the non-CO₂/CO₂ climate ratios were considered including one based on integrating the radiative forcing over different time horizons (i.e. GWP-based), one based on integrating the change in globally-averaged surface temperature over different time horizons, and one based on the net present value of climate damage costs at different discount rates. For each metric, a scenario was considered in which the impacts due to a one-year pulse of emissions were estimated over a period of centuries. At a discount rate of three percent, the mid-range marginal damage ratio value was found to be approximately 1.5 with a low to high range of 0.9 to 2.8. These ratio values indicate that policy analyses that account for the environmental impact of CO₂ only are neglecting a non-zero and potentially significant component due to the non-CO₂ environmental impacts. Considering the ratio values for the other metrics, one finds that the ratio ranges are largely insensitive to the choice of metric relative to the overall uncertainty in assessing aviation non-CO₂ impacts. This observation has important

implications in the scientific community where there has been much contention over what is the best metric for quantifying the climate impact of non-CO₂ species. The work in this thesis suggests that metric choice is a relatively less important consideration in quantifying non-CO₂ impacts with quantified uncertainty than is work to reduce uncertainty in some of the non-CO₂ impacts (most particularly the contrails and induced cirrus cloudiness). Notably, the most significant factor influencing the magnitude of the non-CO₂/CO₂ ratio is not a scientific uncertainty, but is a value-based judgment related to the relative importance of impacts far in the future compared to those nearer in time (as reflected through the discount rate or time period used for a physical metric). The magnitude of the non-CO₂ impact can be estimated from a sample social cost of carbon. The nominal SCC from the U.S. Government Interagency Working Group report for a 3% discount rate is \$78/tC (6). This value implies that the CO₂ damage cost of a gallon of jet fuel is approximately 20 cents. The nominal climate ratio and air quality marginal damage cost subsequently indicate the non-CO₂ climate damage to be approximately 10 cents per gallon of jet fuel and the non-CO₂ air quality damage to be approximately 69 cents per gallon of LTO jet fuel. Prorated on a full-flight fuel burn basis, the air quality benefit is likely about one tenth of the benefit in terms of LTO jet fuel. This prorated perspective results in a climate benefit that is approximately four times greater than the air quality benefit per gallon of full-flight fuel burn.

Environmental analyses were performed for two NASA-sponsored projects to examine the utility of the derived ratios and air quality marginal damages. The first project dealt with operational procedures and growth projections over the 2006-2050 timeframe. The impacts for the system-wide climate analysis were generally greater in magnitude than the air quality impacts. In each area, whether a given case resulted in an environmental cost or benefit, relative to the baseline scenario, was highly dependent on the operations growth assumptions embedded in the scenario. The scenarios in which the operations growth factor was set to a minimum typically resulted in an air quality benefit with respect to the baseline case, while the scenarios in which this parameter was set to the maximum value typically resulted in an air quality cost. The operational improvements were found to have a small effect on the overall air quality

impact for the different scenarios. The operational improvement that was found to have the largest climate benefit was the consolidation of flights through the use of larger aircraft while the procedure that was found to be the most detrimental to global climate change was the use of increased point-to-point flying. This analysis was also used to demonstrate how the APMT-derived climate ratios and air quality marginal damages could be applied to a multi-year scenario. Using this approach, 17 of the 32 scenarios assessed deviated from the APMT air quality results by less than 40% and 21 of the 32 scenarios assessed deviated from the APMT climate results by less than 20%. Cases with deviations greater than this typically consisted of relatively small changes in fuel burn.

The second NASA project addressed in this thesis dealt with the design and integration of an advanced vehicle concept for the 2030-2035 EIS timeframe. An MIT-led team conceived and designed two vehicle types, each targeting a specific market, with the aim of meeting aggressive noise, LTO NO_x, and fuel burn reduction goals. For this thesis, a one-year scenario was created in which one of the MIT team's concepts was integrated into the fleet as a replacement for the B737/Airbus A320 class aircraft. This scenario resulted in a mean climate benefit of \$4 billion with a range of \$15 million to \$11.5 billion for a discount rate of 3%. This study also showed how the APMT-derived climate ratios can be used to capture scientific and valuation-based uncertainties in estimating non-CO₂ impacts.

6.2 Future Work

One topic introduced in this thesis that merits further consideration is the relationship between time windowing and discounting future climate impacts. This valuation-based uncertainty is highly influential in deriving ratios and also in comparing ratios across different metrics. Another item to address in future work is to align the ratio derivation process in this thesis with the assumptions that are laid out in the U.S. Government Interagency Working Group on SCC report as this document will likely serve as guidance for many future policymaking activities. This includes implementing an approach to account for uncertainty in damage function that samples across the three models cited in the report—DICE, PAGE, and FUND—and then exploring the impact thereof on the climate ratios. There is also ongoing work in

PARTNER to extend the ratios concept to alternative fuels, the results of which are included in Stratton (74). Lastly, the results presented in this thesis are an accurate representation of what is known given the current state of environmental science and impact modeling. Development of APMT-Impacts is an ongoing task that goes hand-in-hand with progress in the scientific community's understanding of environmental impacts and modeling, and the answers presented in this thesis may change as general knowledge improves in these areas and the models and methods used in APMT are updated.

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