



## **COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION (CAEP)**

### **SEVENTH MEETING**

**Montréal, 5 to 16 February 2007**

**Agenda Item 1: Review of proposals relating to aircraft engine emissions, including the amendment of Annex 16, Volume II**

**Agenda Item 2: Review of market-based options to limit or reduce emissions**

**Agenda Item 3: Review of proposals relating to aircraft noise, including the amendment of Annex 16, Volume I**

**Agenda Item 4: Future work**

### **DEMONSTRATION AND ASSESSMENT OF THE US/CANADA ENVIRONMENTAL ANALYSIS TOOL SUITE**

(Presented by the Member from USA)

#### **SUMMARY**

Past modeling tools that supported the CAEP work program separately computed either noise or emissions estimates. These estimates were then separately considered as part of an economic evaluation process. To inform stringency considerations, the economic impact assessment process also only considered a single environmental indicator (e.g., NO<sub>x</sub> emitted or noise generated). However, as the CAEP terms of reference recognize, aviation policies, technologies, and operations that affect noise and emissions are interrelated. Therefore, a need exists for a new set of tools to inform policy decisions. These new tools must be capable of considering the interdependencies among aviation policies, technologies, operations, industry costs, consumer costs, and the human health and welfare impacts of noise, local air quality, and climate change. The US Federal Aviation Administration's Office of Environment and Energy (FAA/AEE), in collaboration with Transport Canada, is working with an international team of researchers to develop a comprehensive suite of software tools that will allow for better assessment of the environmental effects of aviation. The main goal of the effort is to develop a capability to assess the interdependencies among aviation-related noise and emissions effects, and to provide comprehensive cost-benefit analyses of aviation environmental impacts. To further the development of the tool suite, the development team is conducting a set of sample problems (SP) and capability demonstration (CD) analyses and

assessments to advance the breadth and robustness of the tool suite, and to determine the ability of the tools to capture air transportation system response to various policy scenarios. This paper presents a summary of the SP and CD analyses and assessments undertaken to date, as well as those that are ongoing as part of the continued development of the tool suite. The results of these activities demonstrate the ability to conduct the broad range of analyses that are expected to be necessary to support future CAEP work programs. The results also provide valuable input to the model evaluation process.

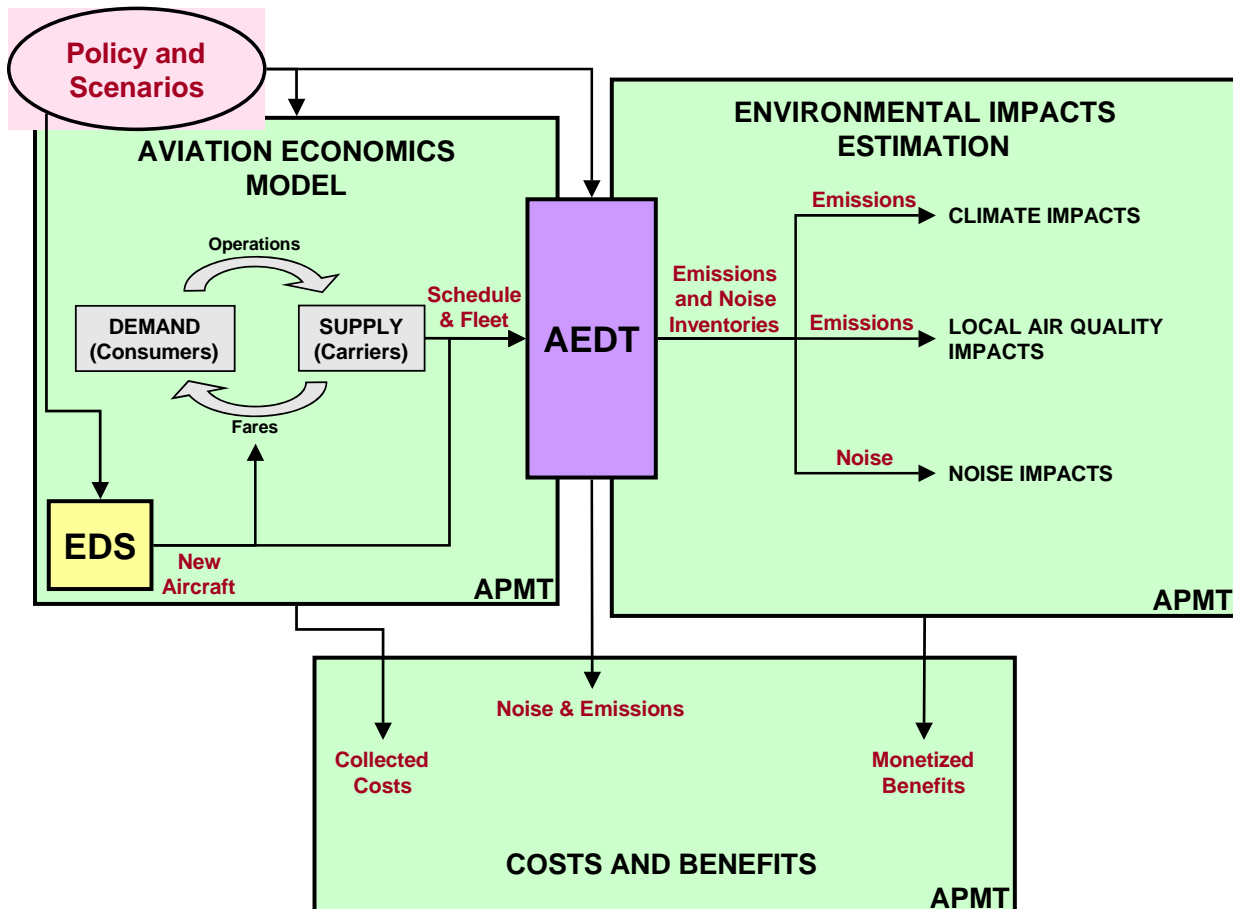
Action by the CAEP is in paragraph 4.

## 1. INTRODUCTION

1.1 Past modeling tools that supported the CAEP work program to assess potential stringencies to mitigate emissions or noise separately computed either noise or emissions estimates based on various potential policy scenarios. These estimates were then separately considered as part of an economic evaluation process of the various scenarios. The economic impact process also only considered a single environmental indicator (e.g., NO<sub>x</sub> emitted or noise generated), rather than the interrelationship among variables, and the cost-benefit of policy considerations. This approach has led to significant improvements in aviation's environmental performance. However, as the CAEP terms of reference recognize, the various aviation-related noise and emissions indicators are interrelated. To help meet this requirement, there is a need for a new, more robust set of tools that is capable of considering the interdependencies among aviation policies, technology, operations, industry costs, consumer costs, and the human health and welfare impacts of noise, local air quality, and climate change. Further, environmental impact analyses to support both cost-effectiveness and cost-benefit considerations are required to fully consider interdependencies. The US Federal Aviation Administration's Office of Environment and Energy (FAA/AEE), in collaboration with Transport Canada, is working with an international team of researchers to develop a comprehensive suite of software tools that will allow for a better assessment of the environmental effects of aviation. The main goal of the effort is to develop a new capability to assess the interdependencies among aviation-related noise and emissions effects, and to provide more comprehensive cost analyses of aviation environmental impacts.

1.2 Figure 1 shows a simplified schematic of the new tool suite. The three main functional components of the tool suite are: the Environmental Design Space (EDS), which is used to estimate aircraft performance trade-offs for different technology assumptions and policy scenarios; the Aviation Environmental Design Tool (AEDT), which takes as input detailed fleet descriptions and flight schedules, and produces estimates of noise and emissions inventories at global, regional, and local levels; and the Aviation Environmental Portfolio Management Tool (APMT). APMT serves as the framework within which policy analyses are conducted and provides additional functional capabilities. APMT functional capabilities include an economic model of the aviation industry that takes as inputs different policy and market scenarios, and existing and potential new aircraft types (the latter from EDS). It then simulates the behaviors of airlines, manufacturers and consumers, producing a detailed fleet and schedule of flights for each scenario year for input to AEDT. APMT also takes the outputs from AEDT and performs comprehensive environmental impact analyses for global climate change, local air quality and community noise. These environmental impacts are quantified using a broad range of metrics (including, but not limited to, monetized estimates of human health and welfare and impacts, thereby enabling both cost-

effectiveness and cost-benefit analyses). Additional descriptions of the tool suite are presented in CAEP/7-IP/23, CAEP/7 IP-24, and CAEP/7 IP-25.



**Figure 1. Schematic of the Components of the New Aviation Environmental Tool Suite**

1.3 Sample problem (SP) and Capability demonstration (CD) analyses are important elements of the tool suite development process. The terminology “sample problem” is used when the aspects of the tool that are being tested are relatively well-developed and should be capable of addressing the problem with limited modification. “Capability demonstration problem” is used for situations where the components of the tool that are being tested are still undergoing significant development. Therefore, one test case may be an SP for one tool suite component and a CD for another. Likewise, one component of the tool suite may be applied to an SP to evaluate its performance for one type of problem, yet applied to a CD to evaluate its performance for another type of problem for which it is still undergoing significant development.

1.4 The goal of the SPs and CDs is to advance tool development by practicing on a set of problems that are similar to those that might be put forth as part of the CAEP/8 Work Program. The practice analyses are accompanied by rigorous assessment processes, so that the strengths and deficiencies in the tool suite can be identified, and appropriate refinements and improvements

implemented. This ensures that the tool suite will be sufficiently robust to support a broad range of potential CAEP/8 analyses. The purpose of the SP and CD analyses and assessments discussed here is to assess system-level responsiveness and sensitivity to policy scenarios, rather than to quantify costs and benefits for specific policies. Thus, emphasis is placed on determining the tool suite's ability to estimate policy effects and to correctly capture trends, as opposed to producing final results for a policy question.

1.5 This paper presents a summary of the sample problems, and of the capability demonstrator analyses and assessments undertaken to date, as well as those ongoing as part of the development of the tool suite. The goal of these activities is to demonstrate the ability to conduct the broad range of analyses that are expected to be necessary to support future CAEP work programs. The process used to identify the SPs and CDs is described, and selected example results, which show the interdependencies among various environmental indicators, are provided in an appendix.

1.6 Performing the development and analyses required for these SPs and CDs proved to be valuable for identifying tool revisions and areas for improvement. We recommend that CAEP adopt a similar process to identify CAEP-wide sample problems that will be used as general test problems for all tools being considered for use to support CAEP/8 analysis needs. We also recommend that modelers interested in participating in the CAEP/8 work program engage in a similar set of sample problems to help evaluate their tool's ability to assess interdependencies, as required under the CAEP/8 work program. The results of the sample problems will provide valuable input to the model evaluation process currently being conducted by WG2/TG2 and FESG (CAEP/7-WP/19).

## 2. INITIAL SAMPLE PROBLEMS

2.1 It is anticipated that NO<sub>x</sub>, and possibly noise stringency assessments, will be considered as part of the CAEP/8 work program. In 2005, the tool suite development team began a sample problem as part of the development of the new tool suite. The sample problem showed that a NO<sub>x</sub> assessment generally based on the CAEP/6-IP/13 aircraft NO<sub>x</sub> stringency analysis framework could be conducted with the Aviation Environmental Design Tool (AEDT) component of the tool suite using common databases and methodologies necessary to conduct both noise and emissions analyses. A secondary objective of the sample problem was to identify potential improvements in the tools and related processes that would more readily facilitate interdependency assessment in preparation for the CAEP/8 work program. In addition to the development of common databases and refined methodologies, this sample problem provided an evaluation of the effects of NO<sub>x</sub> stringencies on all categories of aircraft flying gate-to-gate. The original CAEP/6-IP/13 report only considered the LTO cycle below 3000 feet for commercial jet aircraft. The sample problem process was also refined by allowing emissions values to be computed using performance-based modeling. Although only emissions were computed for this sample problem, the migration to performance-based modeling in the AEE tool suite allows for the simultaneous modeling of noise through common aircraft performance parameters (i.e., thrust, speed, etc.). An airport queuing model was also included, so that the effects of the flight schedule on taxi times and any related terminal-area delay could be captured. Finally, the sample problem results up to 10,000 feet were combined with enroute emissions to determine full flight NO<sub>x</sub> emissions into the atmosphere. The NO<sub>x</sub> sample problem is documented in CAEP/7-WG2-TG2-6-WP/10 and CAEP/7-WG2-TG2-7-IP/01. Further extensions of the NO<sub>x</sub> sample problem are discussed below in Section 3.

2.2 In addition to stringency assessments, it is anticipated that the CAEP/8 Work Program may include assessing the costs and benefits of various operational measures to mitigate aviation environmental impacts, including the assessment of the combined impacts of these measures on noise,

local air quality and climate change. In anticipation of the potential need to assess operational measures in support of the CAEP/8 work program, a sample problem was undertaken to assess the noise, emissions and fuel burn benefits of Continuous Descent Arrival (CDA) procedures. The results of this sample problem are presented in CAEP/7-WG2-TG2-6-WP/06 and CAEP/7-WG2-TG3-7-WP/08.

2.3 As part of a larger effort to engage all interested CAEP modelers, the US took part in the reduced thrust sample problem using the Aviation Environmental Design Tool (AEDT) tool (CAEP/7-SG/20063-WP/30). The goal of this sample problem was to identify deficiencies in the trade-off assessment capabilities of the participating models, which would help prioritize model improvements and provide valuable input to the model evaluation process currently being conducted by WG2/TG2 and FESG (CAEP/7-WP/19). As with the NO<sub>x</sub> sample problem, the reduced thrust sample problem is being taken forward by the US with additional work elements, as discussed below in Section 3.

### 3. ONGOING CAPABILITY DEMONSTRATION PROBLEMS

3.1 The sample problems discussed in Section 2 were limited to the AEDT module of the US/Canada tool suite. The four capability demonstration (CD) analyses discussed herein were selected to capture the effects of different potential policies on the aviation industry and the environment, and to exercise all three modules of the US/Canada tool suite, namely AEDT, Environmental Design Space (EDS), and Aviation Environmental Portfolio Management Tool (APMT). A more detailed discussion of preliminary results of these four CDs is included in Appendix A.

3.2 The four CDs were chosen to span a wide range of responses and exercise many aspects of the tool suite. While any one problem may have limited scope, the four CDs, taken together, provide a broad test of the tool suite's capabilities. Table B-1 of Appendix B provides an overview of the policy responses considered in selecting the four CDs. For each potential policy response, it is noted whether or not the tool suite has the functionality to capture the response (marked as a "yes" or "no"). Then for each CD, the expected responses are indicated by an "X." An expected response that is not yet considered by the tool suite is indicated by an "(X)."

3.3 The four CDs are:

1. Fuel price changes: As a simplified surrogate for estimating some of the industry and environmental responses to fuel levies and open emissions trading, we are studying the impacts of changes in fuel prices. All aspects of the tool suite are being tested, including the economic and environmental impact modeling components. This includes cases with and without aircraft/engine technology trade-off modeling capabilities, and cases with different time periods between the policy announcement and enforcement year. For the technology trades, we are focusing only on the B777 seat class of aircraft, and only on technology trade-offs that are expected to be possible with current levels of technology in the existing fleet.
2. CAEP/6 NO<sub>x</sub> emissions stringency: Similar to the discussion in Section 2.1, the goal of this CD is to assess NO<sub>x</sub> emissions stringencies such as was done in CAEP/6 with the enhancements discussed in Section 2.1. The new elements in the CD beyond those discussed in Section 2.1 for the NO<sub>x</sub> sample problem are incorporation of economic modeling to assess changes in industry and consumer costs, inclusion of

cases with and without aircraft /engine technology trade-off modeling capabilities, and environmental impact analysis to assess the human health and welfare impacts of changes in community noise, local air quality and climate. For the aircraft/engine technology trade-off work we are focusing only on the B777 seat class of aircraft and only on technology trade-offs that are expected to be possible with current levels of technology in the existing fleet.

3. Noise phaseout: A global phaseout of ICAO Chapter 3 minus 9 dB (cumulative) aircraft is being evaluated as part of this CD. The 9 dB (cumulative) criterion was selected as it is generally consistent with the difference in maximum noise level associated with the migration from the Chapter 2 to Chapter 3 noise limits studied in CAEP/5. Although we are considering cases where non-compliant aircraft may be recertified, as well as different time periods between announcement and enforcement year, the analysis framework being developed to support this CD is applicable to any potential phase-out scenario. These policy scenarios are being used to test all components of the tool suite, from economics to evaluating environmental impacts for noise, local air quality, and climate change.
4. Reduced thrust: The reduced thrust CD is based on the assumptions outlined in CAEP/7-SG/20063-WP/30 for the CAEP reduced thrust SP, but augmented to include an initial assessment of the local air quality, community noise and climate change impacts of reduced thrust. For both the SP and the CD, one day of flights (October 18, 2005) is used as a basis for comparing a scenario with full thrust take-offs for all aircraft to a scenario with a 10% reduction in thrust below 10,000 feet (again, for all aircraft). For the CD, the scope of the WP/30 reduced thrust sample problem was expanded to include initial, more direct assessments of the environmental impacts (including many metrics and indicators, from physical metrics to monetary metrics ) so that the interdependencies among the various environmental indicators can be more readily evaluated.

3.4 The CDs were carefully selected by the tools development team, in consultation with the FAA, the Working Group 2, Task Group 2, and the Forecasting and Economic Support Group (FESG) Ad Hoc Group, to represent the types of analyses that are anticipated as part of the CAEP/8 work program; for example, stringency assessments and emissions trading. Although it is anticipated that some additional model development will be necessary once the specific CAEP/8 analyses are agreed upon, we believe the CDs are a necessary precursor to the analyses to be undertaken as part of the CAEP/8 work program, and will ensure the various tools are in a better position to support CAEP/8. Our experience has shown that CDs are essential for identifying strengths and limitations in the tools, databases, and associated modeling assumptions, and only by exercising the tools can these strengths and limitations be properly identified, refined, or corrected. The value of the CDs is specifically exemplified in a WG2/TG2 paper to CAEP/7 (CAEP/7-WP/20), which highlights tool and database limitations identified in conducting the reduced thrust sample problem in support of WG2/TG2.

3.5 While results of these exercises are preliminary, and should not be cited or otherwise relied upon, important findings have emerged. First, for many of the policy questions CAEP may consider in the future, interdependencies will be important. Addressing these interdependencies requires a broader, deeper range of modeling tools, tools that go well beyond estimating traditional cost-

effectiveness measures (e.g., changes in industry costs per change in emissions inventory levels). The results show that changes in industry costs do not capture all of the important costs of a policy (e.g., the impacts on consumers) and that changes in local air quality and climate change impacts for even a simple operational scenario cannot be derived directly by considering changes in inventory levels. Second, with the increased complexity of the problems comes a requirement to consider more metrics, more scenarios and more alternatives for valuing the different effects of aviation. Because of the increased number of metrics, scenarios and assumptions, the decision-making process will involve additional information, will be more complex, and careful consideration will be required to determine how best to employ this added information and the additional metrics. It is also likely that the decision-making body may require some expertise and advice from broader domains of knowledge (e.g., to include local air quality analysis, health impacts assessment, and climate impacts assessment, among others) than has been used in the past.

#### 4. **ACTIONS BY THE CAEP**

4.1 The CAEP is requested to:

- a) take note of the capability demonstration problems being pursued by the US, which are an integral component of the ongoing development of the US/Canada environmental tool suite;
- b) ensure that sample problems and capability demonstrations exercise the full range of analyses anticipated to be undertaken as part of the CAEP/8 Work Program; and
- c) agree with the need to continue development of these capabilities and endorse the development of, and participation in, additional broadly-based sample problems and capability demonstrations for all models to be used in carrying out the CAEP/8 Work Program and agree that these results should be considered as part of the model evaluation process.

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## APPENDIX A

### A.1 Overview

This appendix provides a sample of the results obtained from the ongoing capability demonstrations conducted by an international team of AEDT (Aviation Environmental Design Tool), EDS (Environmental Design Space) and APMT (Aviation Environmental Portfolio Management Tool) tool suite developers on behalf of the U.S. Federal Aviation Administration and Transport Canada. We focus on two of the CDs: reduced thrust and fuel price increases (where the latter is used as a simplified surrogate to model fuel levies or open emissions trading). The results we show are intended to illustrate some of the important interdependencies among aircraft technology, operations, market conditions, environmental policies, consumer costs, industry costs, and the human health and welfare impacts of noise, local air quality, and climate change.

We also highlight many of the new metrics that may be necessary to enable CAEP to fully address interdependencies among environmental impacts. Notably, because of the increased number of metrics, scenarios, and assumptions necessary to address interdependencies, the decision-making process will involve additional information and be more complex. Careful consideration will be required to determine how best to employ this added information and additional metrics. It is also likely that the decision-making body may require some expertise and advice from broader domains of knowledge (e.g., to include local air quality analysis, health impacts assessment, and climate impacts assessment, among others) than has been used in the past.

We caution that the results we present are not the final results, and are only presented to highlight modeling capabilities. In particular, in many cases we are making comparisons across different geographical scales and time periods (e.g., comparing global climate impacts to local air quality impacts for the continental US to noise impacts for 89 US airports). All results are for notional policy cases (e.g., comparing 10% reduced thrust below 10,000 feet for all aircraft to full thrust for all aircraft). The results reflect a particular set of assumptions and scenarios (e.g., demand forecasts, population growth, discount rate<sup>1</sup>, health impact valuation functions, background CO<sub>2</sub> levels, and many more). Finally, there may be errors and important omissions in our modeling—indeed, the purpose of the capability demonstrations is to uncover errors and omissions so that we may improve our modeling capabilities.

### A.2 Reduced thrust

The reduced thrust CD is based on the assumptions outlined in CAEP/7-SG/20063-WP/30, but augmented to include an assessment of the local air quality, community noise and climate change impacts of reduced thrust. A case where all aircraft take off at full thrust is compared to a case where all aircraft take off with a 10% reduction in thrust while below 10,000 ft. The analysis was completed for one day of operations (October 18, 2005). To obtain yearly impacts, the inventories were multiplied by 365. Typical flight profiles for full thrust and reduced thrust are shown in Figure A.1.

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<sup>1</sup> The discount rate is used to calculate the equivalent present value of costs and benefits that occur sometime in the future. The equivalent present value is calculated based on one or both of the following concepts: overall growth of wealth in the world (such that a unit of cost is a smaller fraction of total wealth in the future)-this is termed growth discounting-or because a unit cost or benefit in the future is regarded as being less valuable than that same unit today-this is termed a pure rate of time preference. A pure rate of time preference may arise because of an ability to invest the money today and make a return on the investment over time, or because costs and benefits to future generations, for example, are regarded as being less important than costs and benefits today.



The reduced thrust CD provides an excellent test case for the evaluation of interdependencies among environmental impacts. Indeed, this CD focused only on assessing environmental impacts (we did not consider the industry and consumer economic impacts of reduced thrust, preferring to exercise those aspects of our modeling in the other CDs). For the reduced thrust CD, a single change in aircraft operations (reducing the throttle setting during take-off and climbout) leads to a multitude of changes: CO<sub>2</sub> increases, NO<sub>x</sub> decreases, SO<sub>x</sub> increases, PM decreases and noise decreases. The estimated changes in inventories are shown in Table A.1.

Our assessments of these emissions and noise results suggest there are several important methodological improvements required. The results from the improved methods are expected to be significantly different from the results presented in Table A.1. For example, volatile and non-volatile primary PM emissions were estimated using the First Order Analysis Method, FOAv2.0. FOAv2.0 was recently replaced in AEDT by FOAv3.0, and the trends in PM with reduced thrust differ significantly. Second, the methods used to specify the fuel flow and emissions indices for this CD led to significant under-prediction of the change in NO<sub>x</sub> at the highest throttle settings (0 to 1500 feet above ground level). Third, the procedures used for the test case are not necessarily representative of procedures flown by airlines. For procedures with thrust cut-backs, noise has been found to increase with reduced thrust, not decrease as shown in Table A.1. These are just a few of many examples where careful assessment and identification of deficiencies in the SPs and CDs is directly leading to substantive improvements in modeling capability.

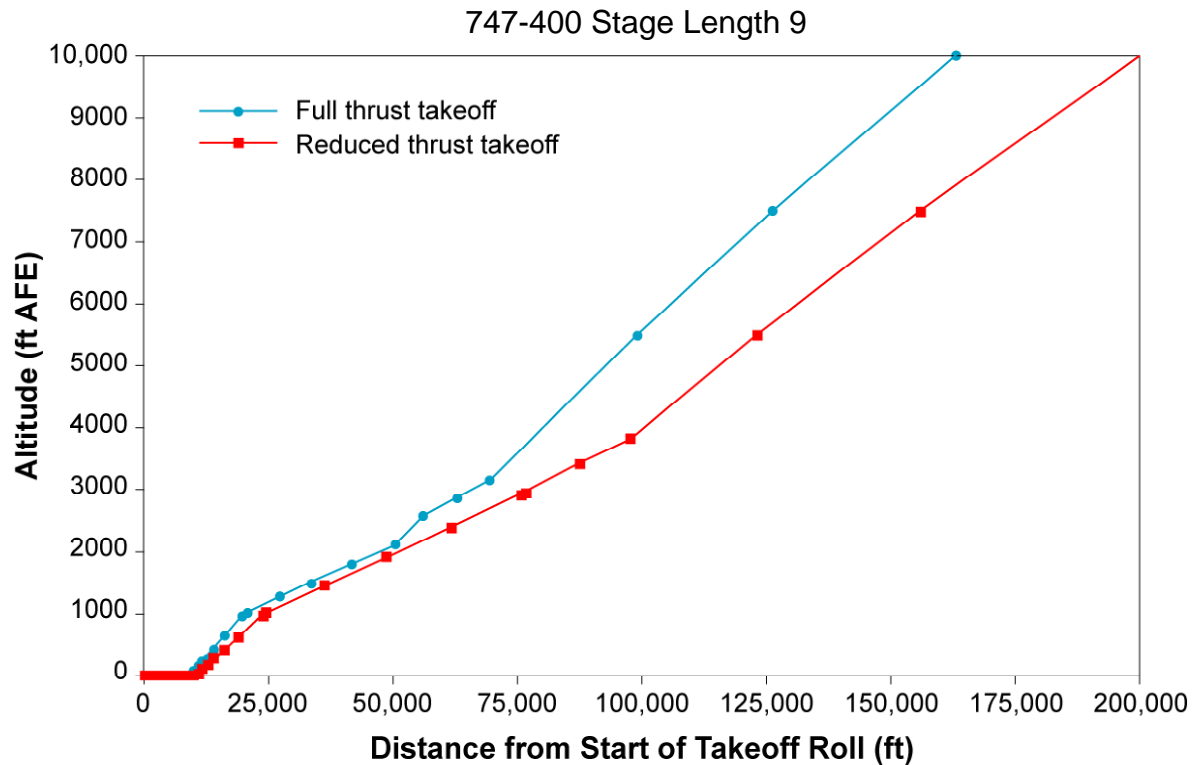


Figure A.1 An example of the differences in flight profiles for the cases of full thrust and 10% reduced thrust.

**Table A.1 Changes in inventory levels for Reduced Thrust compared to Full Thrust. Please refer to the text for a discussion of the some of the important modeling deficiencies and how they may influence these results.**

Table results are preliminary. Do not cite or quote.

Inventory quantity	Percent change for reduced thrust test scenario compared to full thrust
Global CO <sub>2</sub>	+0.31%
Global NO <sub>x</sub>	-0.15%
NO <sub>x</sub> below 3000' (U.S. only)	-0.33%
SO <sub>x</sub> below 3000' (U.S. only)	+3.8%
Primary PM below 3000' (U.S. only)	-9.5%
Number of people in 55 dB DNL contour (global)	-14%

Although the results shown in Table A.1 are expected to change as the modeling methods are improved, they still provide an excellent illustration of the need for more advanced environmental impact analyses than have been used to support CAEP decision-making in the past. In particular, it is not possible to evaluate the net effect of this single change in operations (reduced thrust) by considering changes in inventories—or even to determine the sign of the effect (positive or negative) since some quantities increase and others decrease. To understand the effect of this change in operations, it is necessary to more fully estimate the health and welfare impacts. For local air quality alone, the situation is complex requiring evaluation of the impact pathway from changes in emissions inventories to changes in ambient pollutant concentrations to changes in adverse health incidences to changes in health costs:

$$\Delta \text{healthcosts} = \Delta \text{emissions} \times \frac{\Delta \text{ambient concentration}}{\Delta \text{emission}} \times \frac{\text{healthincidence}}{\Delta \text{ambient concentration}} \times \frac{\text{cost}}{\text{healthincidence}}$$

Standard practices exist for evaluating such health and welfare impacts. These have been applied widely in the US, Canada and EU for regulatory and other analyses [See for example, European Commission, ExternE - Externalities of Energy: Methodology 2005 Update, EUR 21951 EN, 2005, and EPA, Benefits of the Proposed Inter-State Air Quality Rule, EPA 452/-03-001 January 2004, ]. We have adopted methods that are consistent with these standard practices as described in CAEP/7-IP/25. Further, Professor Jonathon Levy of the Harvard School of Public Health has reviewed these methods and concurred with their appropriateness. As Figure A.2 shows, such an analysis is complicated by the fact that changes in NO<sub>x</sub> produce changes in both ambient ozone and secondary particulate matter (PM) concentrations. And these changes in NO<sub>x</sub>-related secondary PM are different from the changes in SO<sub>x</sub>-related secondary PM, and different from the changes in primary PM. Moreover, the relationship to health consequences depends on whether the ambient PM originate from primary PM emissions, or secondary PM formation due to NO<sub>x</sub> or SO<sub>x</sub>. Finally, the costs per incidence depend on whether the source of the adverse health effects is ozone or PM.

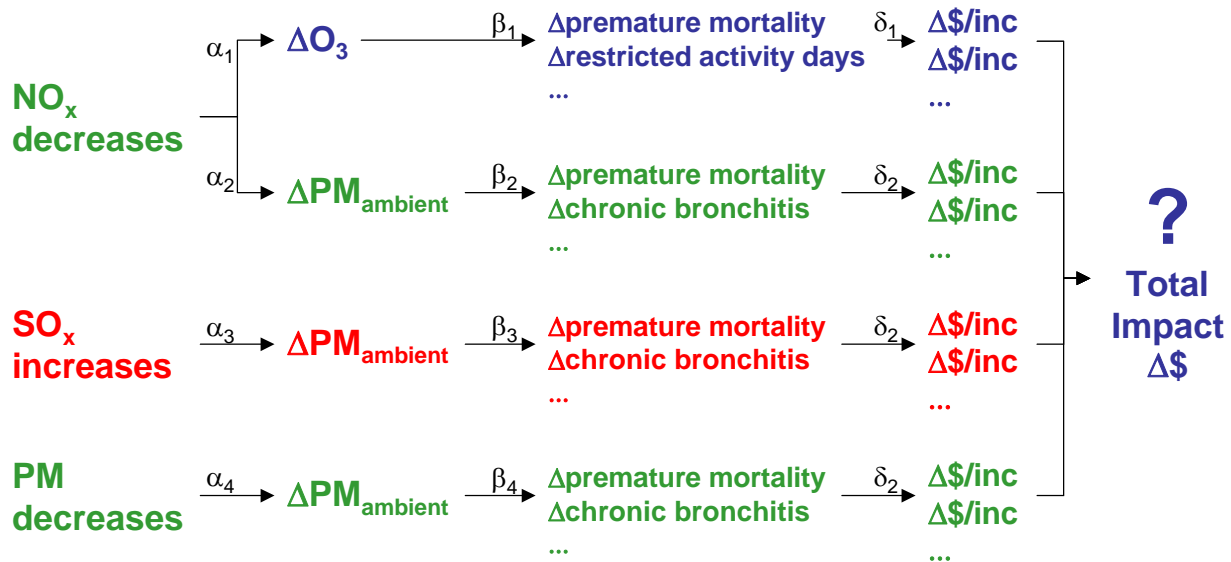


Figure A.2 Illustration of the complex local air quality health impacts pathways.

After completing a detailed air quality and health impacts analysis using methods recommended by the US EPA and the EU ExternE Program, we derived the following aggregate metrics that show a preliminary estimate of the balance among these different effects for the local air quality effects of aviation in the continental US<sup>2</sup>. Note, there are many non-linear interactions, so these aggregate metrics are not general, meaning they cannot necessarily be applied to other policy cases. Further, as noted earlier, these are preliminary estimates and may contain errors and omissions. We show them here to illustrate the complexity of the interdependencies among aviation operations, emissions and health impacts and to demonstrate our ability to assess these complex interdependencies in a manner that is consistent with best practice. We estimate that on a per kilogram basis, primary PM (soot and volatile particles formed in the near-field aircraft plume) is more damaging than secondary PM from SO<sub>x</sub> (condensed far downstream from SO<sub>2</sub> emissions), which, in turn, is more damaging than secondary PM from NO<sub>x</sub> (condensed far downstream from NO<sub>x</sub> emissions), which, in turn is more damaging than ozone from NO<sub>x</sub>. However, in general, quantities of aviation local air quality emissions follow the opposite trend (NO<sub>x</sub> emissions are greater than SO<sub>x</sub> emissions, which are greater, than primary PM emissions). Therefore, the total health costs estimates for NO<sub>x</sub>-related PM are greater than those for SO<sub>2</sub>, which, in turn are greater than those for primary PM. Further, for the reduced thrust problem, two of these quantities decrease (NO<sub>x</sub> and primary PM), while the third increases (SO<sub>x</sub>). Therefore, because of these complex interdependencies, arriving at aggregate estimates of the consequences of a change in aviation operations requires capabilities that go well beyond methods to estimate changes in emissions inventories as is the current practice within CAEP.

<sup>2</sup> For this we used an intake fraction method recommended by the Harvard School of Public Health and reported in Greco SL, Wilson AM, Spengler JD, Levy JI. "Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States," *Atmos Environ*, in press. The concentration-response and health cost valuation relationships were taken from the US EPA Benefits Mapping Program (BenMAP) and are further described in Abt. Associates, Environmental Benefits Mapping and Analysis Program: Technical Appendices, prepared for US EPA-OAQPS, May 2005.

**Table A.2 Aggregate estimates of the yearly health impacts of aviation local air quality emissions in the US and relation to inventory levels. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)**

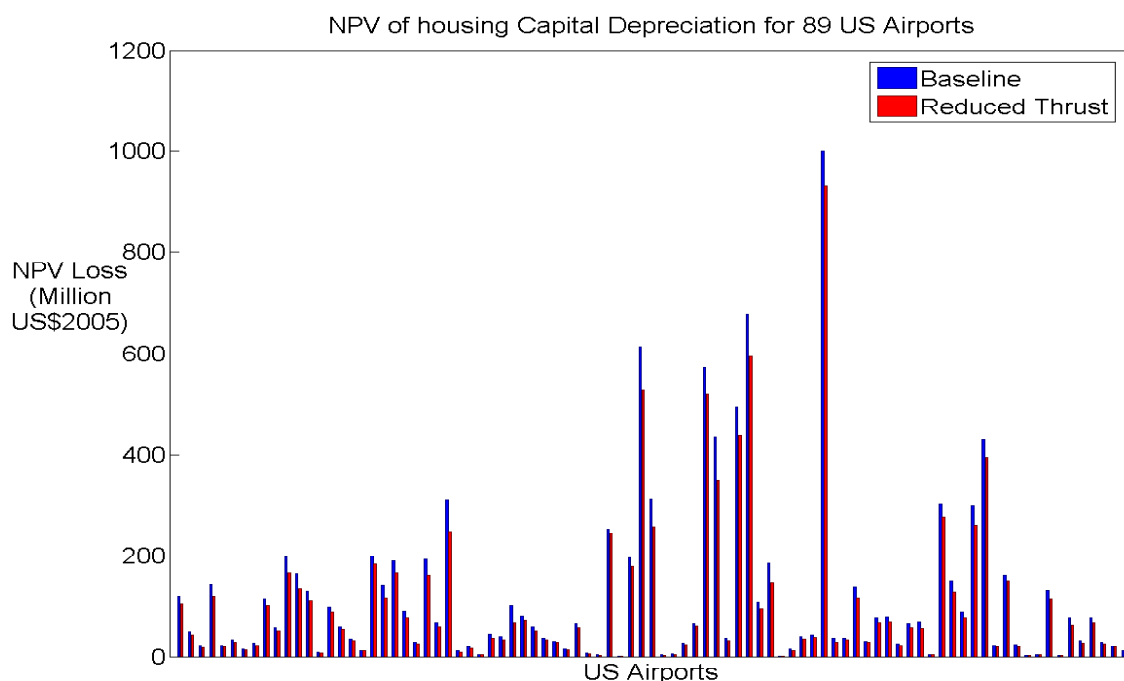
Table results are preliminary. Do not cite or quote.

Metric	Primary PM	SO <sub>x</sub> via PM	NO <sub>x</sub> via PM	NO <sub>x</sub> via Ozone <sup>3</sup>
Total health impact of pollutant (\$ per kg emitted)	530	112	14.0	2.0
Amount emitted (10 <sup>6</sup> kg per year)	0.27	1.58	43.3	43.3
Cost (\$M per year)	144	177	605	84

The noise impacts are evaluated by considering both changes in the number of people within different Day-Night-Average Sound Level (DNL) dB contour levels and also changes in housing capital depreciation under different assumptions for noise depreciation indices (% change in property value per dB). The latter are used as surrogates for the more complex relationship among aviation noise and health and welfare and were specified to capture the range of estimates available in the literature. Estimates for a selected set of US airports are shown in Figure A.3.

<sup>3</sup> Total ozone health impact divided by total NO<sub>x</sub> emissions

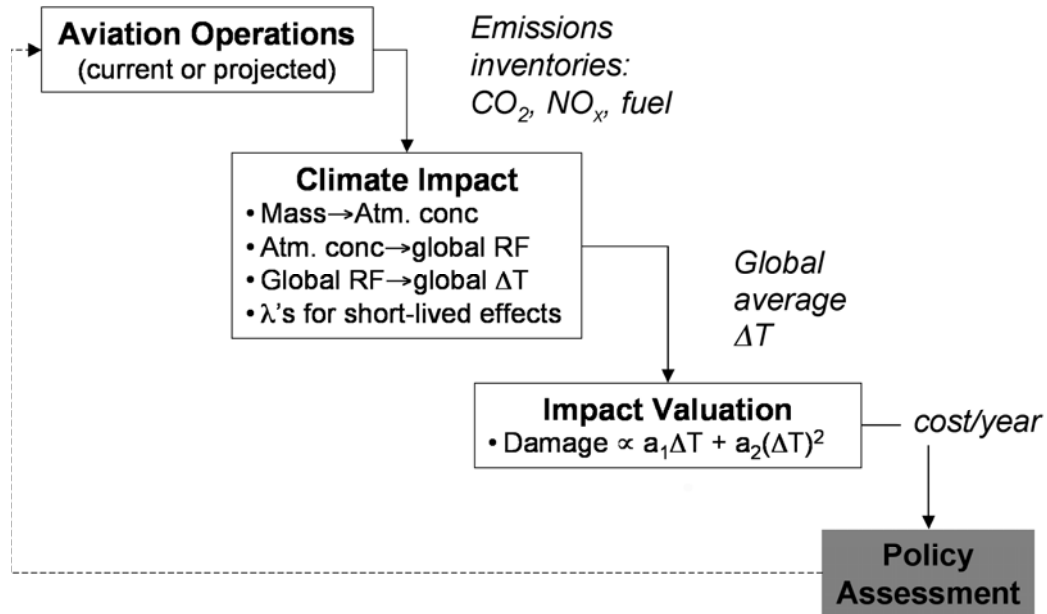
Figure results are preliminary. Do not cite or quote.



**Figure A.3 Estimates of the change in housing capital associated with changes in aviation noise. Note that in contrast to the local air quality results, which are yearly, these are a one-time change in value of capital. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)**

Much like the local air quality analyses, the impacts on climate of a single change in aircraft operations (the throttle setting at takeoff and climb-out) are not directly observable by considering changes in inventories:  $\text{NO}_x$  emissions decrease and  $\text{CO}_2$  emissions increase, and both of these have different impacts on climate. Moreover, these changes occur below 10,000 feet, and will have little effect on the potential for formation of contrails or aviation-induced cirrus cloudiness. To evaluate these effects, we use simplified impulse response functions for the climate and independently attribute changes in globally-averaged surface temperature change over time (among many other metrics we consider) to different aviation physical and chemical sources (e.g.,  $\text{CO}_2$ , impacts of  $\text{NO}_x$  on methane, impacts of  $\text{NO}_x$  on ozone, contrails and aviation-induced cirrus cloudiness<sup>4</sup>, soot, sulfate, and water). Our methods are outlined in Figure A.4 and described in more detail in CAEP/7-IP/25. These methods are based on those presented in the scientific literature by Hasselmann et al. (1997), Sausen and Schumann (2000), Fuglestedt et al. (2003), Shine et al. (2005) and Nordhaus and Boyer (2000). The APMT methods were also formally assessed by three climate-modeling experts: Professor Keith Shine (University of Reading, United Kingdom), Professor Donald Wuebbles (University of Illinois, United States), and Professor Robert Sausen (DLR, Germany). These experts provided assistance in the refinement and assessment of the model and have completed a report on our modeling methods (available as an appendix to CAEP/7-IP/25).

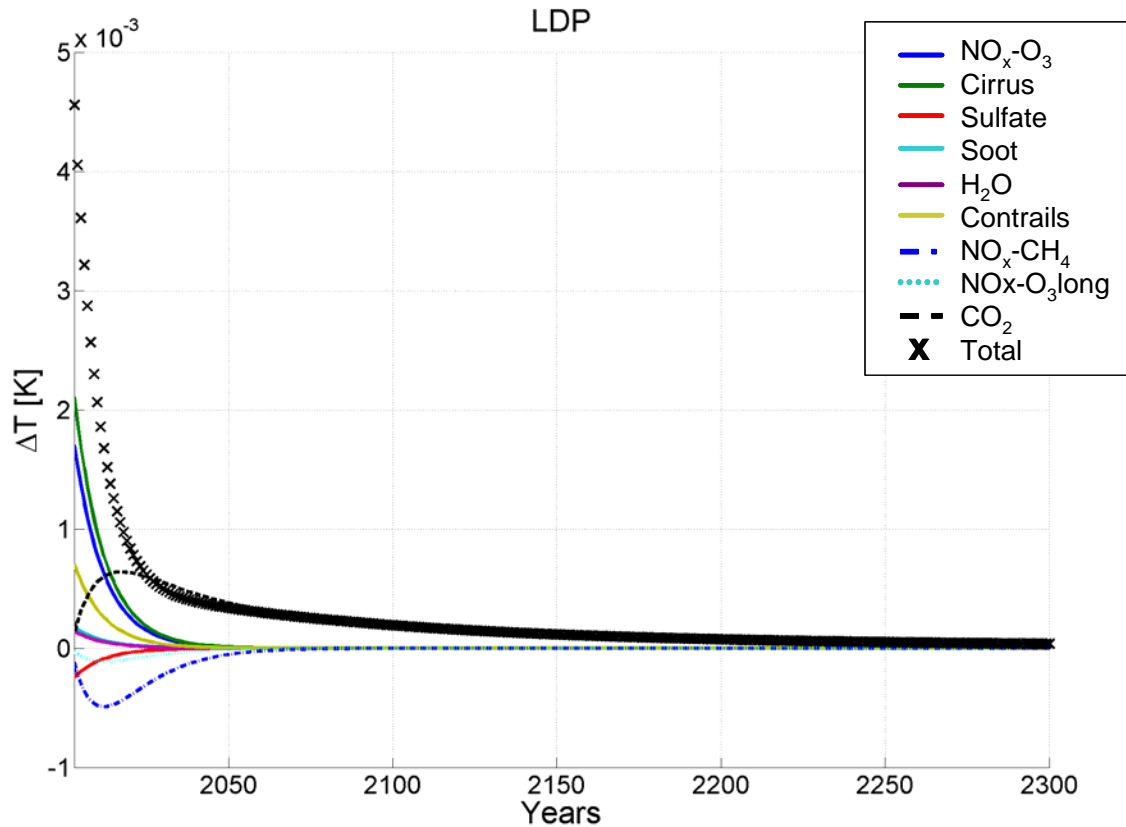
<sup>4</sup> Although the changes in operations in our test case occur below 10,000 feet, and therefore are not expected to impact contrails and aviation-induced cirrus, these are important effects for estimating the impacts of aviation on climate (some of which we show in this appendix). Thus, although these effects do not change between the full thrust and the reduced thrust cases, we calculate them for all of the scenarios.



**Figure A.4 Outline of methods for assessing climate impacts of aviation**

An example result for a single year of aviation emissions is shown in Figure A.5. Initially, the most significant impact on surface temperature results from contrails and aviation-induced cirrus formation, although it must be noted that the level of confidence in estimating the radiative forcing due to aviation-induced cirrus is quite low. The second most significant impact on surface temperature is that due to ozone changes from  $\text{NO}_x$ . On the time-scale of 10-30 years, the reduced methane due to  $\text{NO}_x$  leads to an impact of the opposite sign. Then on a time-scale of decades to centuries, the small warming due to the carbon dioxide added remains as the sole impact.

Figure results are preliminary. Do not cite or quote.



**Figure A.5** Example result showing the impact of one year of aviation emission on globally-averaged surface temperature changes. This includes the effects of  $\text{NO}_x$  through the immediate production of ozone ( $\text{NO}_x\text{-O}_3$ ), the reduction of methane over a period of 10-30 years, and the associated longer term reduction in ozone ( $\text{NO}_x\text{-O}_3$  long); the production of contrails and aviation-induced cirrus, the effects of sulfate aerosols and soot, and the effects of water ( $\text{H}_2\text{O}$ ) and carbon dioxide ( $\text{CO}_2$ ). (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)

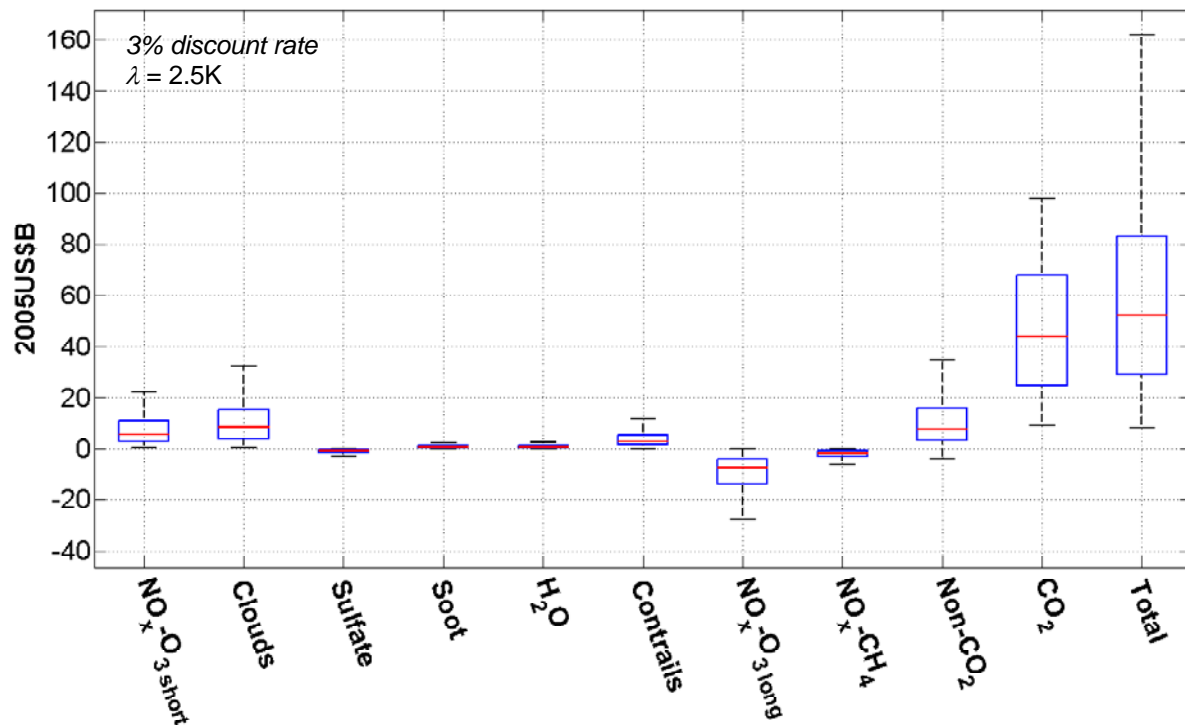
There are a great number of uncertainties in evaluating the climate impacts of aircraft. We explicitly account for many of these uncertainties in our analysis by representing some parameters as probabilistic distributions and then performing Monte Carlo analyses. In other cases we address the uncertainties by performing different scenario and sensitivity analyses.

There are different methods for estimating the monetary damages of climate change and we have several options for doing so within APMT, depending on choice of damage function and methods for discounting. An example estimate of climate monetary damages is shown in Figure A.6 where the net present value<sup>5</sup> of the global climate damages due to one year of aviation emissions is shown for a particular set of assumptions regarding climate sensitivity, background atmospheric change, GDP growth

<sup>5</sup> The net present value is the monetary value summed over time and put in terms of present day monetary value; prior to summing the values, future year monetary values are discounted to account for their different value relative to the present day.

and discounting (among other assumptions). Notably, we have the ability to independently attribute changes in climate impacts (whether physical metrics like globally-averaged surface temperature, or economic metrics like changes in %GDP) to different aviation effects. This capability is required to assess interdependencies among aviation technology, operations, policies and market conditions since changes in some of these drivers produce different (and sometimes conflicting) effects on some of the component impacts of climate change (e.g., increasing  $\text{NO}_x$  while decreasing  $\text{CO}_2$  or decreasing contrails while increasing  $\text{CO}_2$ ).

**Figure results are preliminary. Do not cite or quote.**



**Figure A.6** Estimates of the net present value of global climate impacts for a particular set of assumptions regarding climate sensitivity, background atmospheric change, GDP growth and discounting (among other assumptions). This includes the effects of  $\text{NO}_x$  through the immediate production of ozone ( $\text{NO}_x\text{-O}_3$ ), the reduction of methane over a period of 10-30 years, and the associated longer term reduction in ozone ( $\text{NO}_x\text{-O}_3$  long); the production of contrails and aviation-induced cirrus, the effects of sulfate aerosols and soot, and the effects of water ( $\text{H}_2\text{O}$ ) and carbon dioxide ( $\text{CO}_2$ ). *(These results are preliminary and may contain errors or important omissions. Do not cite or quote.)*

We wish to provide information that allows decision-makers to best balance policies across environmental impacts and to balance impacts across various policies. Ultimately, this requires consideration of many alternative metrics and testing of different scenarios and assumptions. It also requires, where possible, explicit accounting of the uncertainties underlying the various estimates. The tools we are developing are designed to address these needs. In Figure A.7 we present a summary comparison of the relative costs of aviation environmental impacts. Note again, that these comparisons are done for different geographical regions and time periods – yearly global climate costs are compared to yearly local air quality costs for the continental US, and to a “one-time” total depreciation in housing



capital in proximity to 89 US airports. Expansion of data sources and analyses beyond these regions is one of the current focus areas for APMT development. More importantly, these comparisons are for only one set of assumptions, scenarios, and methodological choices, and would be insufficient by themselves for informing policy. Finally, as noted earlier, the results are preliminary and may contain errors. Nonetheless, they illustrate the ability to consider jointly, the relative effects of aviation operations on local air quality, community noise and climate change. The change in each of these impacts due to reduced thrust is presented in Figure A.8. All the same caveats apply to these results.

Figure results are preliminary. Do not cite or quote

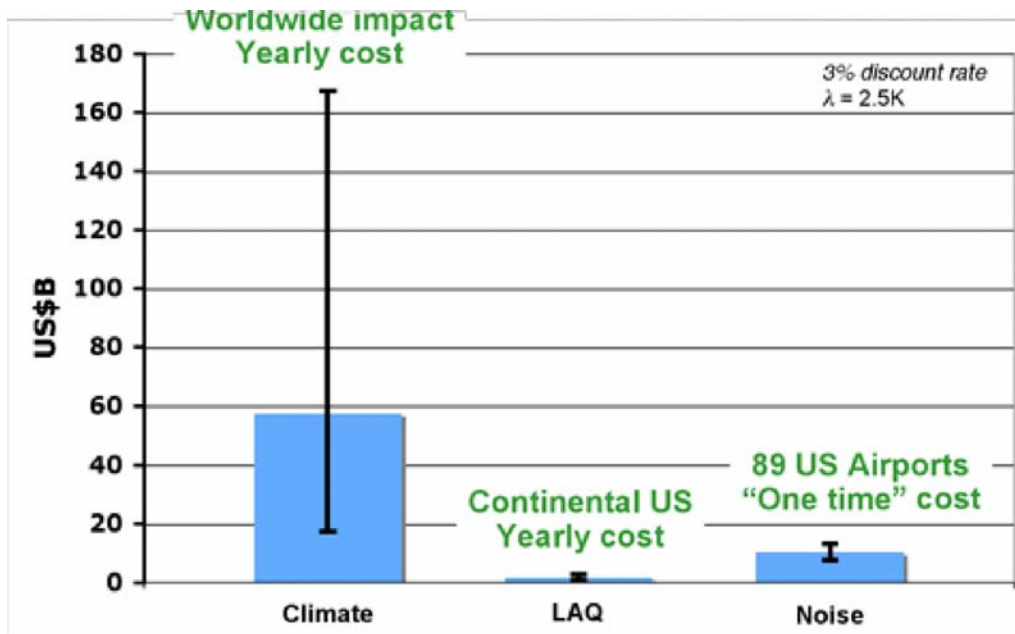
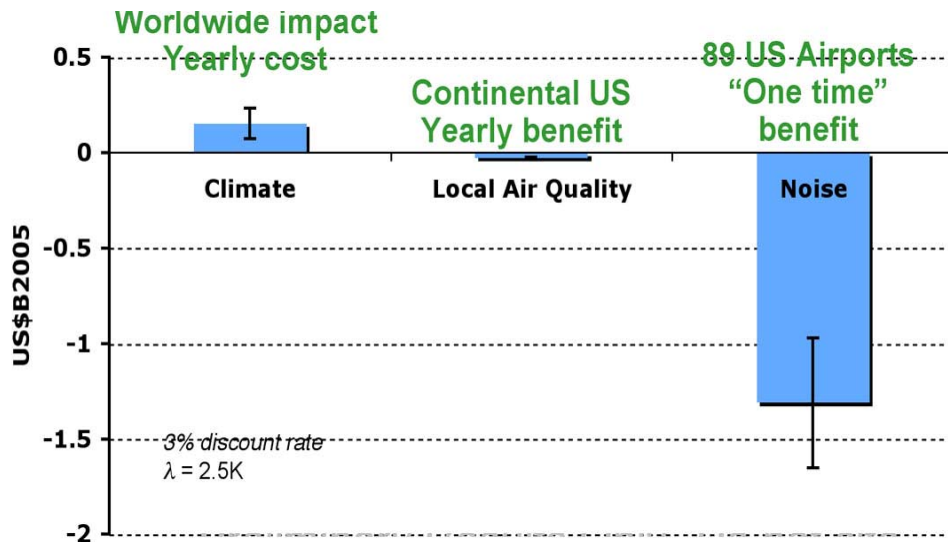


Figure A.7 An example comparison of the net present value of aviation impacts for a particular set of assumptions regarding climate sensitivity, background atmospheric change, population growth, health impact assessment, noise depreciation index, GDP growth and discounting (among many other assumptions). Note that this comparison is across different geographical regions and time periods—yearly global climate costs are compared to yearly local air quality costs for the continental US, and to a “one-time” total depreciation in housing capital in proximity to 89 US airports. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)

Figure results are preliminary. Do not cite or quote



**Figure A.8** An example comparison of the change in net present value of aviation impacts between full thrust and reduced thrust for a particular set of assumptions regarding climate sensitivity, background atmospheric change, population growth, health impact assessment, noise depreciation index, GDP growth and discounting (among many other assumptions). Note that this comparison is across different geographical regions and time periods —yearly global climate costs are compared to yearly local air quality costs for the continental US, and to a “one-time” total depreciation in housing capital in proximity to 89 US airports. *(These results are preliminary and may contain errors or important omissions. Do not cite or quote.)*

### A.3 Fuel Price Capability Demonstrator

Changes in fuel price are being used as a simplified surrogate for estimating some of the industry and environmental responses to fuel levies and open emissions trading. For this capability demonstration we exercise all of the same environmental impact modeling capabilities described in Section A.2 for the reduced thrust CD, except that these are simulated over a 20-year period of time.

However, in this document we will focus only on an important economic interdependency: the relationship between industry costs and consumer costs. Although the short-term economic behavior of the aviation industry may differ, it is generally understood that increases in industry costs will be passed on to consumers (or some fraction of the costs will be passed on to consumers), and that these increased costs will result in changes in demand. There are many studies of the elasticity of demand for aviation services where this relationship is statistically derived from observing industry and consumer behavior.

One important aspect of the aviation industry economic modeling within APMT is that we take a baseline demand projection as an input (e.g., from the CAEP FESG forecast), but, if industry costs change, some fraction of these may be passed on to consumers as changes in fares, and then the demand is adjusted in response to these changes in fares until an equilibrium is reached among supply, demand, and price. A schematic of our modeling methods is shown in Figure A.9.

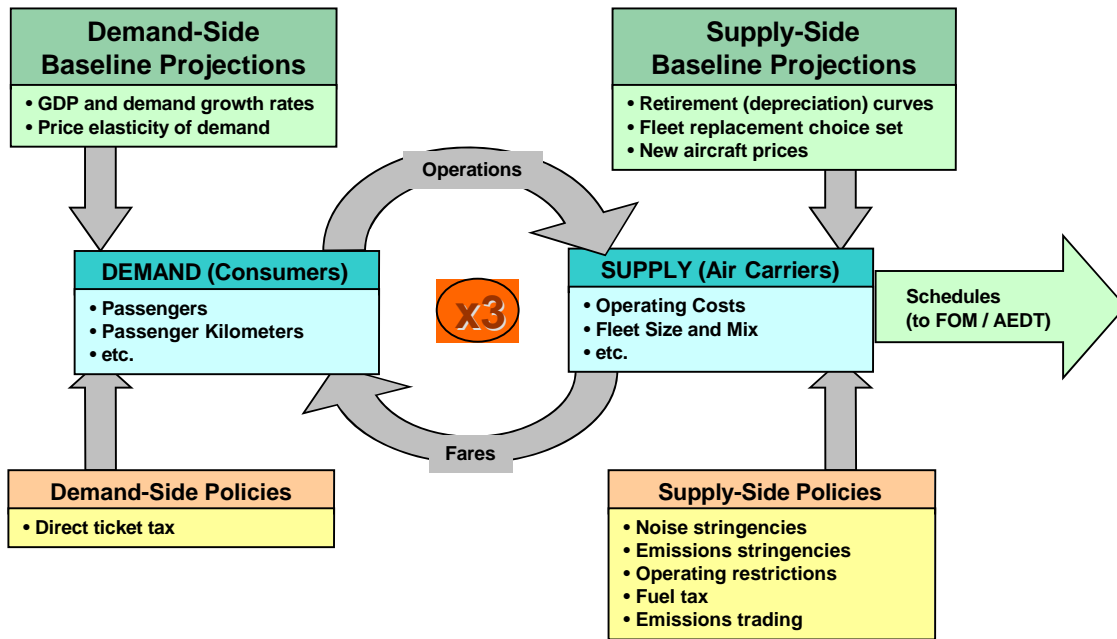


Figure A.9 Schematic of the aviation industry economic modeling within APMT.

Modeling the effects of increased industry costs on consumers is important for understanding the *economic interdependencies* associated with a policy scenario. Example results are shown in Figures A.10 and A.11. Figure A.10 shows the changes in number of aircraft, total fuel consumed and total operating costs for a 100% increase in fuel price. These metrics are typical of those presented in prior ICAO/CAEP cost analyses.

Figure results are preliminary. Do not cite or quote

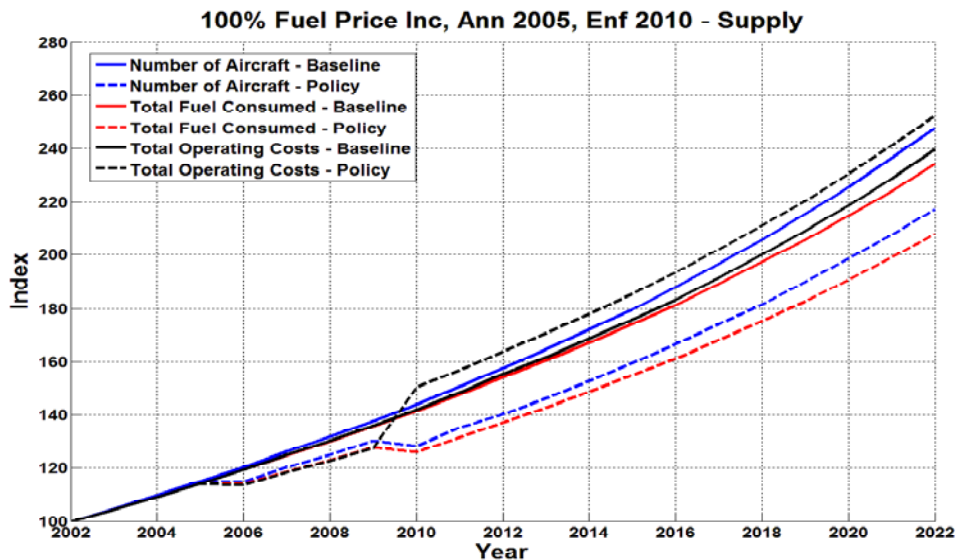
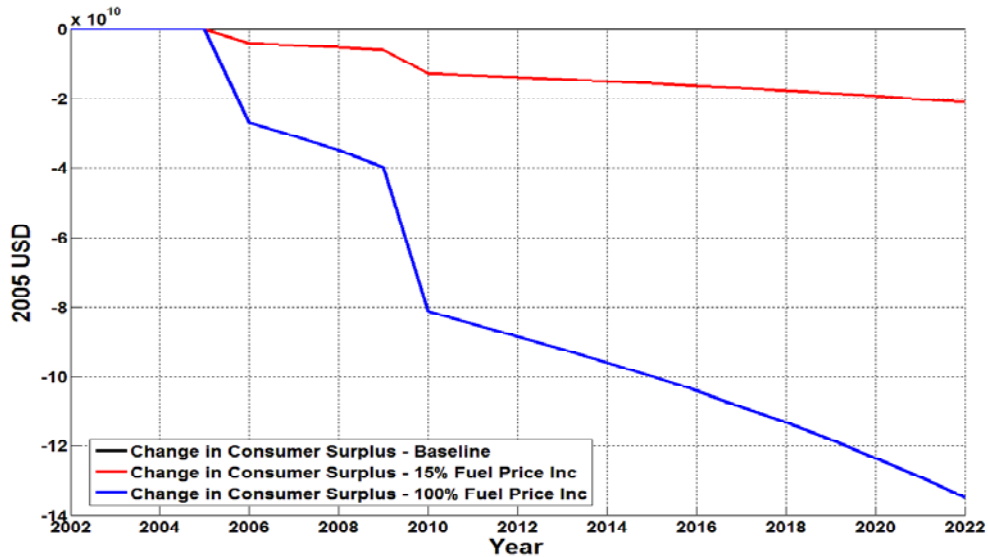


Figure A.10 Changes in number of aircraft, total fuel consumed and total operating costs for a 100% increase in fuel price. These results are for a particular set of assumptions and scenarios. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)

Figure results are preliminary. Do not cite or quote



**Figure A.11 Changes in consumer surplus for 15% and 100% increase in fuel price. These results are for a particular set of assumptions and scenarios. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)**

Figure A.11, shows the changes in consumer surplus (an integral measure of the impact on consumers of changes in prices) that result from these changes in industry costs. Notably, while the results are for a particular set of assumptions and scenarios, the changes in consumer surplus are larger than the changes in industry costs, as shown in Table A.3.

**Table A.3: Changes in industry and consumer costs for fuel price capability demonstration. (These results are preliminary and may contain errors or important omissions. Do not cite or quote.)**

Table results are preliminary. Do not cite or quote

[US\$2005]	Costs to Airlines-- $\Delta$ Total Operating Costs		Costs to Aviation Consumers-- $\Delta$ Consumer surplus	
Fuel Tax (15%, 100%)	\$B30.3	\$B197.1	\$B158	\$B1010

#### A.4 Summary and conclusions

In this appendix we have illustrated a few of the emerging capabilities of the combined AEDT//EDS/APMT tool suite. Our focus is on quantifying the interdependencies among noise, local air quality, climate change, industry and consumer costs, market conditions, and policy scenarios. All of the results we presented are preliminary. They may contain errors or important omissions, and they are likely to change as we continue to develop and improve our modeling capabilities.

Nonetheless, several important conclusions may be drawn. First, for many of the policy questions CAEP may consider in the future, interdependencies will be important. Addressing these interdependencies requires a broader, deeper range of modeling tools, tools that go well beyond estimating traditional cost-

effectiveness measures (e.g., changes in industry costs per change in emissions inventory levels). We have shown that changes in industry costs do not capture all of the important costs of a policy (e.g. the impacts on consumers); we have shown that changes in local air quality and climate change impacts for even a simple operational scenario cannot be derived directly by considering changes in inventory levels. Second, with the increased complexity of the problems comes a requirement to consider more metrics, more scenarios and more alternatives for valuing the different effects of aviation. Because of the increased number of metrics, scenarios and assumptions, the decision-making process will involve additional information, be more complex and careful consideration will be required to determine how best to employ this added information and the additional metrics. It is also likely that the decision-making body may require some expertise and advice from broader domains of knowledge (e.g., to include local air quality analysis, health impacts assessment, and climate impacts assessment, among others) than has been used in the past.

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**APPENDIX B**

The four current capability demonstrations were chosen to span a wide range of responses and exercise many aspects of the tool suite. While any one problem may have limited scope, the four CDs taken together provide a broad test of the capabilities of the tool suite. Table B-1 provides an overview of the responses considered in selecting the four capability demonstrations. A potential response is indicated by an “X.” A potential response not yet considered by the tool suite is indicated by an “(X).”

**Table B-1 Modeling of policy responses to be considered in relation to Capability Demonstrations**

Response types	Response in Tool Suite	Capability Demonstrations			
		Fuel price	NO <sub>x</sub> Certification standards	Noise Phaseout	Reduced thrust
<b>Block 1: APMT Partial Equilibrium Block</b>					
Supply side response					
Accelerated fleet renewal (forced)	Yes			X	
Accelerated fleet renewal (financial)	Yes	X			
Redistribution of aircraft operation	No			(X) <sup>1)</sup>	
Recertification of existing aircraft	Yes <sup>3)</sup>			X	
Improvement of existing aircraft	Yes <sup>3)</sup>	X			
New aircraft technology shift	Yes	X	X		
Best available technology shift	Yes <sup>4)</sup>	X <sup>2)</sup>	X		
New aircraft capacity shift	No	(X)	(X)	(X)	
Demand side responses					
Demand response to direct cost change	Yes	X			
Demand response to indirect cost change	Yes	X	X	X	(X)
Operational responses					
Changes in flight path	No	(X)			X
Changes in flight speed	No	(X)			X
Weight reduction (e.g. reduction of on board service levels)	No	(X)			
Load factors	Yes <sup>6)</sup>	(X)			
Utilization rates	No	(X)			
Evasive responses					
Destination switching	No	(X) <sup>1)</sup>			
Fuel tinkering	No	(X) <sup>1) 5)</sup>			
<b>Block 2: AEDT</b>					
Noise	Yes	X	X	X	X
Emissions	Yes	X	X	X	X
<b>Block 3: APMT Benefits Valuation Block</b>					
Benefits of reduction climate impacts	Yes	X	X	X	X
Benefits of reduction noise impacts	Yes	X	X	X	X
Benefits of reduction local air quality impacts	Yes	X	X	X	X

<sup>1)</sup> Response is only there in the case of a regional application of the policy.

<sup>2)</sup> Response is only there if a policy is applied to a significant part of global air traffic.

- 3) Only if data for the possibilities for recertification / modification are made available.
- 4) Possibilities for modeling of this response is depending on availability of inputs from the EDS.
- 5) Only in the case of a fuel taxation.
- 6) Only 'what if' changes to load factors can be tested.

— END —