Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009)

Assessment of the Aviation Environmental Design Tool

George Noel
Volpe National Transportation Systems Center
Cambridge, MA, USA

Doug Allaire, Stuart Jacobson, Karen Willcox
Department of Aeronautics & Astronautics, MIT,
Cambridge, MA, USA

Rebecca Cointin
Office of Environment and Energy, FAA
Washington, DC, USA

Abstract— **A comprehensive Tools Suite to allow for thorough evaluation of the environmental effects and impacts of aviation is currently being developed by the U.S. This suite consists of the Environmental Design Space (EDS), the Aviation Environmental Design Tool (AEDT), and the Aviation environmental Portfolio Management Tool (APMT). A key priority is that environmental analyses are informed with the associated uncertainty from the tools, inputs and assumptions used in the analysis process. As part of the development of the Tools Suite, an assessment of each tool and a system-wide analysis of the entire suite are being undertaken. This assessment includes sensitivity to inputs and fidelity analyses that will provide an indication of uncertainty in analyses performed using the Tools Suite. Completion of the assessment and evaluation effort described herein is a key element of the development process. This paper presents a summary of the Tools Suite assessment and evaluation effort as it pertains to the AEDT component. AEDT takes detailed fleet descriptions and flight schedules and produces estimates of noise, fuel burn and emissions at global, regional and local levels. The AEDT component of the suite will be a publicly available regulatory tool within the U.S. This paper conveys the work completed so far and provides some insight into some of the findings.**

Keywords- component; environmental, modeling, assessment, uncertainty

I. INTRODUCTION

The U.S. Federal Aviation Administration (FAA) Office of Environment and Energy, in collaboration with Transport Canada and NASA, is developing a comprehensive suite of software tools that will allow for thorough assessment of the environmental effects and impacts of aviation. The main goal of the effort is to develop a new critically needed capability to characterize and quantify the interdependencies among aviation-related noise and emissions, impacts on health and welfare, and industry and consumer costs, under different policy, technology, operational, and market scenarios.

Figure 1 shows a simplified schematic of the Tools Suite. The three main functional components of the Tools Suite are: the Environmental Design Space (EDS), which estimates source noise, exhaust emissions, performance and economic parameters for future aircraft designs under different technological, operational, policy and market scenarios; the Aviation Environmental Design Tool (AEDT), which takes as input detailed fleet descriptions and flight schedules, and produces estimates of noise, fuel burn and emissions at global, regional and local levels; and the Aviation environmental Portfolio Management Tool (APMT), which provides an economic model of the aviation industry and performs comprehensive environmental impact analyses following inputs from AEDT and EDS.

A key element of the FAA Environmental Tools Suite development program is the quantitative assessment and evaluation of the performance of the integrated Tools Suite relative to fidelity requirements and sensitivities to inputs and assumptions. Assessment of the Tools Suite will:

- Provide sensitivity analyses of output response to uncertainties in inputs and assumptions, establishing procedures for future assessment efforts,
- Identify gaps in functionality that significantly impact the

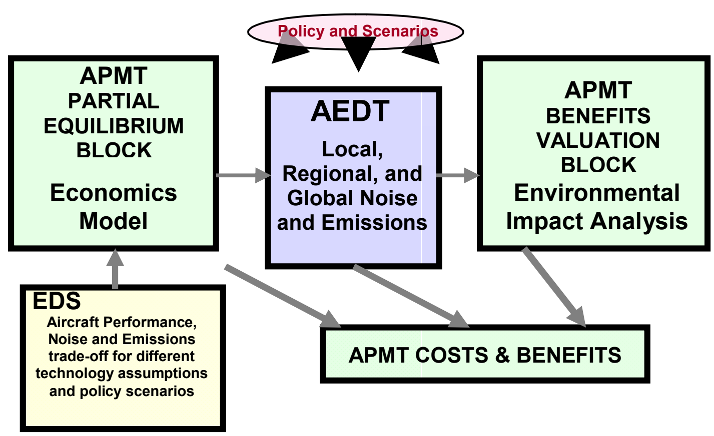

Figure 1. Schematic of the Components of the FAA Environmental Tools Suite

achievement of the Tools Suite requirements, leading to the identification of high-priority areas for further development,

- Provide preliminary quantitative evaluation of the performance of the integrated Tools Suite relative to fidelity requirements for various analysis scenarios such as nitrogen oxide (NOx) stringency and future aircraft technologies, and
- Continue to contribute to the development of external understanding of the FAA Tools Suite capabilities.

To meet these objectives, there are four elements to the Tools Suite assessment program: (a) parametric sensitivity and uncertainty analyses, (b) comparisons to gold standard data (a benchmark that is regarded as the most reliable, representative and/or complete information available), (c) expert reviews, and (d) capability demonstrations/sample problems. This paper contains a summary of the assessment program and preliminary results of the uncertainty analyses for AEDT.

AEDT consists of an integrated set of common modules and databases used for conducting noise, emissions, and fuel burn analyses on a local (down to flight level), national, regional, and global scale. AEDT is a completely redesigned, integrated tool, which builds upon the requirements of the Integrated Noise Model (INM – local noise analysis), the Emissions and Dispersion Modeling System (EDMS – local and regional emissions analysis), Noise Integrated Routing System (NIRS – regional noise analysis), the Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA – global noise analysis) and the System for assessing Aviation's Global Emissions (SAGE – regional and global emissions analysis). Consistent with the historic public release versions of the local noise and emissions tools, FAA plans to release a single, integrated version of the local analysis capabilities in 2011.

Three main modules within AEDT have been assessed. These modules are the Aircraft Performance Module (APM), Aircraft Emissions Module (AEM), and the Aircraft Acoustic Module (AAM).

II. ASSESSMENT PROGRAM OVERVIEW

In this section we present a set of Assessment Questions (AQs), which provide a structured framework in which the assessment is carried out. We then describe the various elements of the assessment, which range from formal uncertainty analyses to sample problems, expert review, and comparisons with gold standard data.

A. Assessment Questions

Through the assessment process, six questions were identified. A complete assessment of the tool requires each of these questions to be addressed. The questions are outlined below.

AQ1. (a) What are the key assumptions employed within the module? (b) How do these assumptions translate into quantifiable uncertainty in module outputs?

AQ2. (a) What are the key assumptions employed within the module databases? (b) How do these assumptions translate into quantifiable uncertainty in module outputs?

AQ3. (a) How do assumptions/limitations in modeling and databases impact the applicability of the module for certain classes of problems (technology infusion, stringency problems)? (b) What are the implications for future development efforts?

AQ4. (a) How do uncertainties in module inputs propagate to uncertainties in module outputs? (b) Further, what are the key inputs that contribute to variability in module outputs?

AQ5. For assumptions, limitations, and inputs where effects cannot be quantified, what are the expected influences (qualitatively) on module outputs?

AQ6. How do assessment results translate into guidelines for use?

These questions cover all aspects of the assessment assumptions and limitations in each module. AQ1 and AQ5 reference sensitivity analyses. In addition, AQ4 addresses the issue of propagation of input uncertainty to model output. To answer AQ2, AQ3, and AQ4, quantitative studies will be defined to determine how data assumptions translate into uncertainty in the module outputs and how those data assumptions limit the applicability of the module for certain classes of problems. When the other AQs have been answered, AQ6 can be addressed.

B. Capability Demonstrations and Sample Problems

In designing and developing a model, including the associated databases, it is difficult to anticipate all of the applications that might be required of the model. In fact, it is always expected that additional development will be necessary to be able to address new analysis areas that a model will be asked to address. One way AEDT has introduced its capabilities to stakeholders is through sample problem and capability demonstration analyses. For AEDT, these efforts began with several iterations of a NOx sample problem [1] and continued with sample problems and capability demonstrations analyses conducted by AEDT and with EDS and APMT.

C. Comparison to "Gold Standard" Data

AEDT is also being assessed by comparing the data computed to "gold standard" data. A "gold standard" is defined as a benchmark that is regarded as definitive. The most reliable and/or complete information at a given time is the gold standard. For example, in the case of greenhouse gas models, airline reported fuel burn has been the gold standard for assessing the performance of the APM within AEDT. Unfortunately, gold standard data in the aviation industry are often proprietary, non-existent, difficult and cost prohibitive to obtain, and/or too cumbersome to effectively incorporate into analytical models.

The AEDT global tools, SAGE and MAGENTA, were created through the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) process with validation as part of that process. For

SAGE, a comparison was performed using a combination of computer flight data recorder information and airline-reported fuel burn data [2,3]. Similar validation activities occurred for MAGENTA. The AEDT local tools have also been compared to data to determine validity. Most of these comparisons were accomplished under the auspices of the Society of Automotive Engineers (SAE) A-21 Committee though efforts of validating the computational components of the INM and EDMS models. These results of these activities are documented in numerous international standards, including SAE-AIR-1845 [4], SAE-AIR-5662 [5], and SAE-AIR-5715 [6], which is currently under development.

D. Expert Review Process

Another form of assessment for AEDT is through expert review. AEDT is being reviewed by multiple groups of experts. The development of AEDT was initiated by a series of stakeholder reviews conducted by the National Academy of Science's Transportation Research Board. The Academy's review resulted in a clearly defined set of requirements upon which the fundamental design of AEDT has been based [7]. A follow-on stakeholder review meeting was conducted by the Academy in December 2006, which resulted in further refinements to AEDT development. In addition, the AEDT development team continues to engage its stakeholders through periodic meetings of its Design Review Group (DRG), made up of members of government, industry, and academia from all around the world. The DRG continues to provide input on AEDT requirements, and helps to refine the design of the integrated system.

AEDT is also reviewed through ICAO's CAEP. AEDT review under the auspices of CAEP involves a three step process, which includes: (1) thorough review and documentation of model capabilities, including an initial assessment of model readiness relative to anticipated CAEP analyses; (2) comparison of model performance with "gold standard" data; and (3) conductance of CAEP-centric sample problems. Part of the review and documentation of modeling capabilities in CAEP requires that the noise and performance computations of all models be compliant with the European Commission's Standard DOC29[8]. To ensure DOC29 compliance, a rigorous, flight-segment-by-flight-segment comparison of AEDT and other candidate models were compared with the standard to ensure compliance.

E. AEDT Formal Parametric Sensitivity and Uncertainty Analyses

The AEDT formal parametric sensitivity and uncertainty analyses consist of a process of quantifying uncertainty and rank ordering the most important assumptions and limitations. This process culminates in an assessment report that serves as a roadmap upon which future AEDT model research and development is based. This process naturally facilitates a measurable approach on which to base future model investment.

The first step of the AEDT parametric assessment process is the documentation of the assumptions and limitations (DAL). The DAL lists in specific detail the assumptions and limitations, how these assumptions and limitations affect the module, where they occur within the module, as well as a literature review of any validation and verification activities that have been accomplished in other related studies. The literature review also helps to define appropriate distributions for module input parameters.

The next step of the AEDT assessment process involves defining a comprehensive set of sensitivity studies and Monte Carlo simulations that are performed to address each of the AQs. These sensitivity studies and Monte Carlo simulations are documented in an individual module assessment plan that guides the assessment team in conducting the parametric sensitivity and uncertainty assessments. The sensitivity studies and Monte Carlo simulations require the development of a surrogate model, which provides an approximation of the input/output behavior of the module it represents, but is less run-time-intensive. The use of surrogate models thus allows for tractable computation time for Monte Carlo simulations, which require hundreds to thousands of model evaluations. The surrogate models are vigorously assessed to ensure they correctly capture the AEDT model. The Monte Carlo simulations were used to complete three different analyses: a global sensitivity analysis (GSA), a local sensitivity analysis (LSA), and a distributional sensitivity analysis (DSA) as defined below.

A Monte Carlo simulation is initiated by defining a probability distribution for each factor, which can either be a parameter describing an assumption or a module input. A random sample for each factor is drawn and run through the module, resulting in a set of outputs for that random sample. The cycle is performed hundreds to thousands of times, resulting in an ensemble set for each output that may be used to estimate means, standard deviations, confidence intervals, and other probabilistic information of interest.

A DSA uses Monte Carlo simulations to determine the sensitivity of the output response to the model factors on a one-at-a-time basis. For each factor, the distribution is altered, either by shifting the mean, increasing the standard deviation, or using an alternate probability distribution. The distributions of other input factors, besides the factor being investigated, are held constant. A DSA is a critical component of module assessment in situations where certain factors do not have well-defined probability distributions.

To determine how model factors contribute to model output uncertainty, a GSA is conducted. For a GSA, all factors are varied during the Monte Carlo simulation. This allows for the calculation of an averaged global contribution to output variance from each factor, which includes all interaction effects among the different factors. That is, it includes any effects that occur by two or more factors directly affecting each other. For this assessment, the Sobol' method [9] was used to compute the average global contribution by computing a total sensitivity index (TSI). The TSI quantifies the impact an input and the distribution assigned to that input have on the variance of a specific output, and is given as the ratio of the output variance caused by a given factor and its interactions and the total output variance. Therefore, the larger a factor's TSI, the larger impact it has on the variance of the output.

An LSA provides sensitivity of output response to inputs and assumptions to support decision making. The goal of an LSA is to understand the behavior of module outputs in the local region of some point of interest [10]. This point of interest could be a specific set of inputs and assumptions given for the analysis of a particular policy, for which the implications of slight changes in some of the assumptions and inputs need to be understood to fully understand the impact the policy could have. Local sensitivity studies have not yet been done for AEDT, but are planned for future assessment work.

The final step of the AEDT assessment is a report covering the entire module assessment. The report contains the information on the module's DAL, assessment plan, and surrogate models, methodologies used and results from the analyses conducted.

The remainder of this paper describes the progress on the parametric sensitivity and uncertainty analyses for APM, AEM, and AAM modules in AEDT.

III. Results of AEDT's formal parametric sensitivity and uncertainty Analyses

Parametric sensitivity and uncertainty analyses for three modules of AEDT are presented below. These results are the first step in an assessment program that will include not only individual module assessment, but also an assessment of the whole tool. The results shown are a small picture of the total assessment that is being performed on AEDT.

A. AEDT APM's Formal Parametric Sensitivity and Uncertainty Analyses

The APM can estimate the flight performance of aircraft using either Enhanced Traffic Management System (ETMS) data or Official Airline Guide flight profiles. The APM sensitivity and uncertainty analyses have thus far concentrated on ETMS defined flights. Inputs to the APM include atmospheric conditions, SAE-AIR-1845 coefficients, and BADA coefficients [11]. There are a total of 51 inputs to the module, however, to make the assessment of the APM more tractable, expert opinion and engineering judgment were used to reduce the number of inputs to be studied to 20, by determining which of the inputs may have a substantial effect on the APM outputs. For each of these 20 inputs, a probability distribution was defined through expert opinion and engineering judgment. The inputs and their associated distributions are given in **Table 1**, where the distribution parameters are given as (minimum, peak, maximum) values of the triangular distributions, and values drawn from each distribution are used as multipliers to default values

The formal parametric sensitivity and uncertainty analyses conducted on the APM focused on estimated thrust, fuel burn, fuel flow, and weight outputs, and consisted of propagating input uncertainty through the module via Monte Carlo simulation, and a GSA. The APM outputs feed directly into the AAM and AEM and thus, the results from the APM analyses can be used first, to check assumptions made regarding the uncertainty associated with these outputs in the AAM and AEM assessment activities, and second, to rank the APM inputs in terms of their impacts on downstream modules in the system.

Due to computational constraints, a surrogate model was used to perform the APM sensitivity and uncertainty analyses. The surrogate consisted of 16 individual aircraft types, chosen through expert opinion and engineering judgment to best represent the range of possible aircraft. For each of those aircraft, a single flight from each stage length flown by the particular aircraft, resulting in 54 total flights, was analyzed.

The results from the uncertainty propagation and GSA for two particular flights for the fuel burn output are given in Table 2 and Figures 2 and 3 respectively. The results are given in terms of nine different flight modes defined in the APM, which are takeoff ground roll (TGR), take off (TA), climb out (TC), En-route climb (EC), cruise (C), en-route descent (ED), approach (A), landing ground roll (LGR), and reverse thrust (RT). Though the analyses were conducted on all of the APM outputs considered, for brevity, the focus here is on the fuel burn output only.

Table 1: Inputs and distributions used in APM Assessment

Input	Distribution Type	Distribution Parameters
Thrust Transition Altitude	Triangular	(0.90, 1.00, 1.10)
Atmospheric Temperature	Triangular	(0.90, 1.00, 1.10)
Atmospheric Pressure	Triangular	(0.70, 1.00, 1.30)
CoeffR (drag-over-lift ratio)	Triangular	(0.86, 1.00, 1.14)
CoeffCD (takeoff and landing speed calibrated airspeed coefficient)	Triangular	(0.86, 1.00, 1.14)
CoeffB (takeoff distance coefficient)	Triangular	(0.86, 1.00, 1.14)
CoeffE (correlated net thrust per engine coefficient)	Triangular	(0.85, 1.00, 1.15)
CoeffF (speed adjustment coefficient)	Triangular	(0.95, 1.00, 1.05)
CoeffGa (altitude adjustment coefficient)	Triangular	(0.975, 1.000, 1.025)
CoeffGb (altitude-squared adjustment coefficient)	Triangular	(0.975, 1.000, 1.025)
CoeffH (temperature adjustment coefficient)	Triangular	(0.98, 1.00, 1.02)
Efficiency	Triangular	(0.90, 1.00, 1.10)
Power	Triangular	(0.90, 1.00, 1.10)
Coeff1 (first thrust specific fuel consumption coefficient)	Triangular	(0.90, 1.00, 1.10)
CoeffCr (cruise fuel flow correction coefficient)	Triangular	(0.90, 1.00, 1.10)
MassMin (flight envelope related)	Triangular	(0.90, 1.00, 1.10)
MassMax (flight envelope related)	Triangular	(0.90, 1.00, 1.10)
MaxOpAlt (flight envelope related)	Triangular	(0.90, 1.00, 1.10)
CoeffCD0 (parasitic drag coefficient)	Triangular	(0.86, 1.00, 1.14)
CoeffCD2 (induced drag coefficient)	Triangular	(0.86, 1.00, 1.14)

Table 2: Fuel burn mean and variance estimates from APM uncertainty propagation

	A320		B777-200	
	Fuel burn mean	Fuel burn variance	Fuel burn mean	Fuel burn variance
TGR	110.94	105.36	320.09	3798.07
TA	42.51	90.25	130.60	530.08
TC	62.74	155.42	120.34	1014.02
EC	36.30	5.26	139.24	68.91
C	294.01	407.81	105.56	49.09
ED	38.73	6.29	165.67	118.81
A	1.24	0.00	2.94	0.02
LGR	1.47	0.00	1.11	0.00
RT	19.36	0.67	21.17	0.83

The uncertainty propagation results for the fuel burn output, shown in Table 2, are given for each flight mode for both an Airbus A320 flight and a Boeing 777-200 flight. Flight modes within the APM are broken up into several segments and the results shown here are for a single representative segment within each flight mode. The uncertainty propagation results show that certain flight modes, such as approach and landing ground roll have little variability associated with the fuel burn output, while other modes, such as climb out and takeoff ground roll have substantial variability associated with the fuel burn output. Further, there are clear differences across the two flights shown here, which reveals the need to assess the APM by looking at several different aircraft types rather than a single representative.

The TSIs given in Figures 2 and 3, show that in general, only a few inputs contribute to variability in the fuel burn output. For example, for climb out (TC) for both aircraft types, CoeffCD and CoeffE contribute the most to fuel burn variability, and for approach (A), Coeff1 contributes nearly all of the fuel burn variability for each aircraft. These sensitivity results may be used within the APM as part of a module verification process and also combined with the uncertainty propagation results to inform future APM development by considering the impact of APM inputs on the APM outputs that are used by downstream modules such as the AAM and

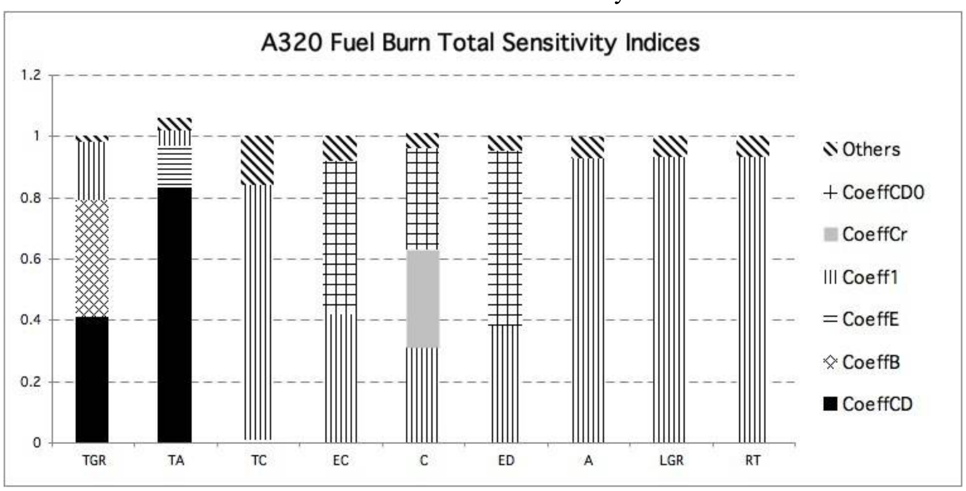

Figure 2: Total sensitivity indices for the fuel burn output of the APM for an A320 aircraft**.**

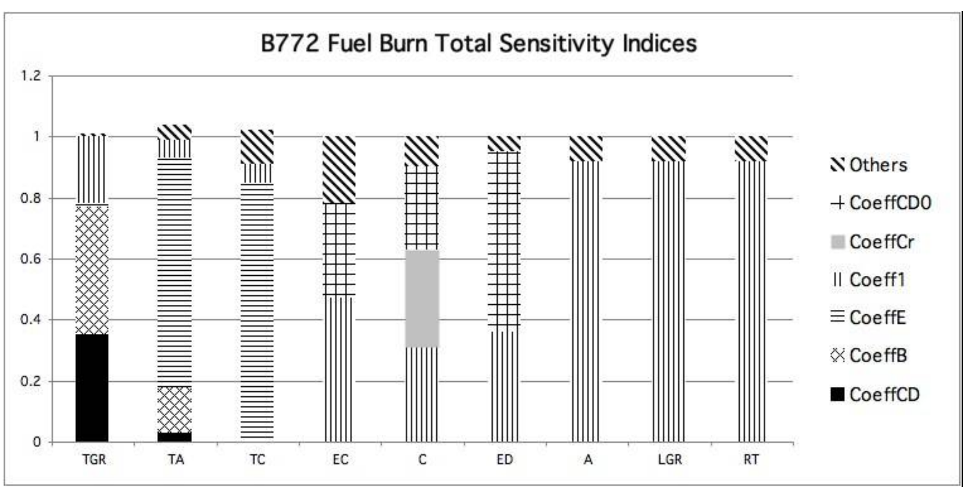

Figure 3: Total sensitivity indices for the fuel burn output of the APM for a B777-200 aircraft.

AEM. This use of the results will be discussed further for the fuel burn output of the APM and its impact on AEM results in Section IIIC.

B. AEDT AAM's Formal Parametric Sensitivity and Uncertainty Analyses

The AAM computes certain noise metrics at grid point locations relative to a flight trajectory for a single flight. The inputs to the AAM are atmospheric conditions, flight trajectories, performance metrics such as speed and thrust from the APM, and noise-power-distance (NPD) curves. The inputs, along with probability distributions associated with them, which were determined through historical databases, expert opinion, and engineering judgment, are given in **Table 3**. Samples drawn from these distributions are applied as multipliers to default values. The triangular distribution parameters are given as (minimum, peak, maximum) and the uniform distribution parameters are given as (minimum, maximum).

The sensitivity and uncertainty analyses conducted on the AAM focused on aggregated sound exposure levels (SEL) from AAM estimates of SEL for individual flights at a specific set of grid points. Rather than assess the AAM at every airport, a set of representative airports was selected for the analyses through expert opinion and engineering judgment. For these representative airports, uncertainty propagation from inputs to outputs via Monte Carlo simulation and a GSA were performed.

The AAM GSA revealed that the NPD curves and atmospheric temperature inputs contributed the most to aggregated SEL variation. The analysis also revealed that pressure and humidity had minor contributions to aggregated SEL variation, and speed, thrust, duration, and bank angle all had effectively zero contribution. This implies that while several APM outputs, such as speed, thrust, duration, and bank angle, are inputs to the AAM, they are responsible for little of the AAM output of aggregated SEL variability, and thus APM inputs that affect these AAM inputs would not need to be considered in AAM development efforts aimed at reducing the variation in aggregated SEL estimates.

Table 3: Inputs and distributions used in AAM assessment

Input	Distribution Type	Distribution parameters
Atmospheric Temperature	Triangular	(0.89, 1.00, 1.11)
Atmospheric Pressure	Triangular	(0.97, 1.00, 1.03)
Atmospheric Humidity	Triangular	(0.828, 1.000, 1.172)
Flight Path Trajectory	Uniform	(-50 ft, 50 ft)
Aircraft Speed	Triangular	(0.95, 1.00, 1.05)
Engine Thrust	Triangular	(0.90, 1,00, 1.10)
Flight Segment Duration	Triangular	(0.95, 1.00, 1.05)
Aircraft Bank Angle	Triangular	(0.90, 1.00, 1.10)
NPD Curve (less than 6000 ft.)	Triangular	(0.985, 1.000, 1.015)
NPD Curve (greater than 6000 ft.)	Triangular	(0.95, 1.00, 1.05)

Figure 4 presents the results of the GSA for aggregated SEL from several arrivals of DC-10 and two departures of an MD-80 aircraft at a particular airport for the NPD curves and temperature inputs. SEL is aggregated at each grid point, thus, for each grid point, the inputs to the AAM have a TSI. The figure shows the contours of different TSI levels for both the NPD curves and the atmospheric temperature. For each of the plots, the origin represents an airport reference point, which typically represents the tower location, and is where the aircraft take-off and arrive. As can be seen from the figure, the uncertainty associated with NPD curves has a substantial impact on aggregated SEL variation for grid points in close proximity to the flight path trajectory, and the temperature has a substantial impact on aggregated SEL variation for grid points far away from the flight path trajectory.

C. AEDT AEM's Formal Parametric Sensitivity and Uncertainty Analyses

The AEM is used to calculate emissions inventories of such pollutants as CO2, CO, NOx, SOx, and many others. Inputs to the module include outputs from the APM, such as fuel burn and fuel flow, reference emissions indices, and atmospheric conditions. The inputs considered in the parametric sensitivity and uncertainty analyses conducted on the AEM are given in **Table 4**. The table also includes probability distributions for each input, which were determined from historical data, expert opinion, and engineering judgment. Like the distributions for the APM and AAM inputs, samples from each of the AEM input distributions are applied as multipliers to default values. The triangular distribution parameters are given as (minimum, peak, maximum) and the uniform distribution parameters are given as (minimum, maximum).

The analyses conducted in this portion of the AEM assessment consisted of uncertainty propagation from inputs to

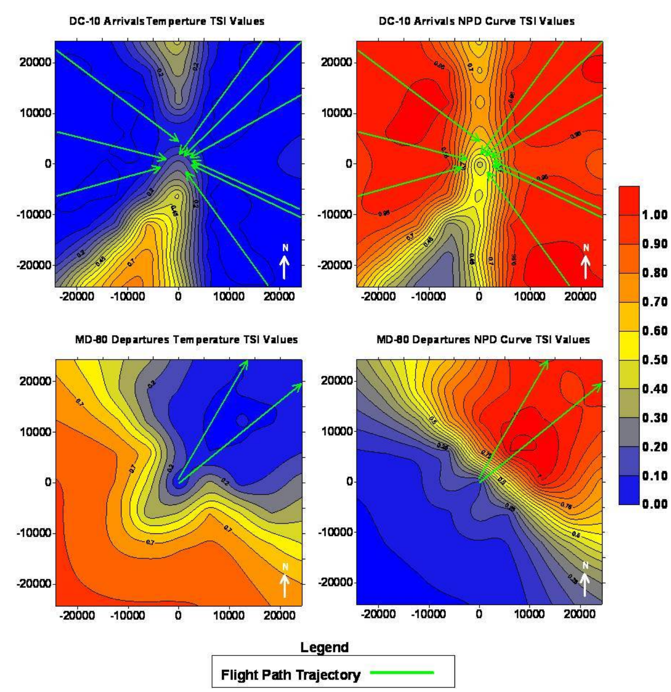

Figure 4: AAM GSA results for the temperature and NPD curve inputs for DC-10 arrivals and MD-80 departures

Table 4: Inputs and distributions used in AEM assessment

Input	Distribution Type	Distribution Parameters
Reference NOx Emissions Index	Triangular	(0.76, 1.00, 1.24)
Reference THC Emissions Index	Triangular	(0.45, 1.00, 1.55)
Reference CO Emissions Index	Triangular	(0.74, 1.00, 1.26)
Atmospheric Temperature	Triangular	(0.89, 1.00, 1.11)
Atmospheric Pressure	Triangular	(0.97, 1.00, 1.03)
Relative Humidity	Triangular	(0.828, 1.000, 1.172)
Fuel Flow	Uniform	(0.95, 1.05)
Fuel Burn	Uniform	(0.95, 1.05)
SO_X Factor	Triangular	(0.875, 1.000, 1.870)
CO_2 Factor	Triangular	(0.997, 1.000, 1.003)
H_2O Factor	Triangular	(0.983, 1.000, 1.017)

outputs via Monte Carlo simulation, as well as a GSA and DSA. The outputs considered in the analyses included global and below 3,000 feet emissions inventories of CO2, NOx, CO, SOx, H2O, and unburned hydrocarbons, however, only the uncertainty propagation and GSA results for global emissions inventories of CO2 and NOx are presented here for brevity. The analyses were performed on a surrogate model of the AEM, which consisted of a randomly selected subset of flights from a representative day of operations [12]. The number of flights required in the subset was determined by a minimax procedure that minimized the maximum difference between the variance of each output calculated by the subset of flights (scaled to the representative day) and the variances of each output as calculated by the representative day of operations. Additional flights were added to the subset until the maximum difference between the subset output variances and the representative day output variances was less than 5%. The process was repeated 30 times and the largest subset of flights that met the minimax criterion in those 30 trials was selected as the surrogate model. The model consisted of 5,266 flights, which is considerably less than the 68,343 flights in the chosen representative day.

The results from the uncertainty propagation and GSA for global emissions inventories of NOx and CO2 are given in Table 5 and Figure 5 respectively. The results apply to the surrogate model of 5,266 flights, and may be scaled to any number of flights using the method described [12].

The total sensitivity indices given in Figure 5 show that different outputs have different key inputs contributing most of the output variation. In the case of NOx and CO2 global emissions, the reference emission index of NOx is responsible for most of the variation in NOx emissions, while fuel burn is responsible for nearly all of the output variation in CO2 emissions. The information gained from these analyses can be put to use in different ways depending on how the module will be used. For example, if NOx emissions are being considered in an environmental impacts analysis and the variability in the estimated NOx emissions from the AEM is too great to be useful in policy-making, these sensitivity and uncertainty analyses show that the variability in NOx emissions is caused primarily by the reference emissions index of NOx, which could then be explored in more detail to determine if uncertainty associated with that input could be reduced. However, if CO2 emissions were being studied and the uncertainty associated with estimated CO2 emissions from the AEM is too great for practical use, the results of these assessment activities show that CO2 emissions variability arises almost entirely from the fuel burn input, which is an output of the APM. This would point to the need to study in more detail the APM inputs that drive the fuel burn output, which, as shown in Figures 2 and 3, are a set of 6 performance coefficients.

IV. Conclusion

Assessment is a critical step within the development process of a simulation tool. A well-assessed tool adds to the confidence and understanding of those using the tool. It allows for a better understanding of the underlying assumptions of the tool and how those assumptions should be considered while making decisions based on analysis made by the tool. In addition, it allows for the identification of functionality gaps, which aides in developing an effective and efficient future development program.

The assessment of AEDT is an on-going effort. As the tool continues to be developed and improvements are made to the modules, individual module assessment will continue. In addition, assessments that take into consideration interactions between modules, building towards an integrated AEDT assessment will also be undertaken. The assessment so far has allowed for the creation of an efficient, repeatable process and has began to provide insight to the developers on where methodology improvements may be necessary.

Table 5: AEM uncertainty propagation results for global NOx and CO2 emissions

NOx		CO2	
Mean	Var (kg2)	Mean (kg)	Var (kg2)
455,080	1,007,249	106,690,490	383,373,572

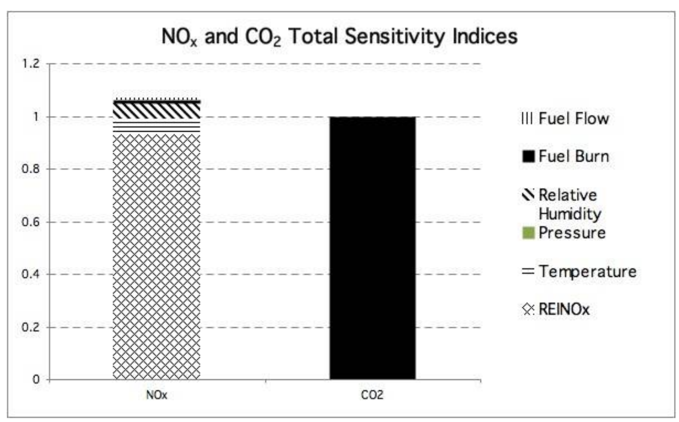

Figure 5: Total sensitivity indices for AEM outputs of global emissions inventories of NOx and CO2.

REFERENCES

[1] Federal Aviation Administration, "NOx Demonstration Analysis Round 3 Nov. 6, 2006, hppt://www.faa.gov/about/office_org/headquarters_offices/aep/models/history/media/NOx_Demonstartoin_Third_Analysis.pdf

[2] Federal Aviation Administration, "SAGE: Valdation Assessment, Model Assumptions and Uncertainties", FAA-EE-2005-03, http://www.faa.gov/about/office_org/headqurters_offices/aep/models/sage/

[3] Lee, J.J. "Modeling Aviations's Global Emissions, Uncertainty Analysis, and Applications to Policy". Mass Massachusetts Institute of Technology. February 2005

[4] Society of Automotive Engineers, Committee A-21, Procedure for the Calculation of Airplane Noise in the Vicinity of Airports, Aerospace Information Report, No. 1845, Warrendale, PA: Society of Automotive Engineers A-21 Committee, 1986

[5] Society of Automotive Engineers, Committee A-21, Method for Predicting Lateral Attenuation of Airplane Noise, Aerospace Information Report No. 5662, Warrendale PA: Society of Automotive Engineers, Inc., April 2006.

[6] Society of Automotive Engineers, Committee A-21, Procedure for the Calcuations of Aircraft Emissions, Aerospace Information Report No. 5715, Warrendale PA: Society of Automotive Engineers, Inc., Up for vote

[7] The National Academies. http://www8.nationalacademies.org/cp/projectview.aspx?key=TAXX-P-03-05-A

[8] European Civil Aviation Conference (ECAC) Report on Standard Method of Computing Noise Contours around Civil Airpots, Doc 20 (3rd Edition), July 2005

[9] Saltelli, Andrea, Chan, Karen, Scott, E. Marian. "Mathematical and statistical methods: Sensitivity Analysis" ISBN: 0-471-99892-3, June 2000.

[10] D.G. Cacuci, Sensitivity and Uncertainty Analysis: Theory (Volume 1), Chapman & Hall, 2003.

[11] Eurocontrol Experimental Center (EEC). "User Manual for the Base of Aircraft Data (BADA), Revision 3 3.6" EEC note no. 10/04. Project ACE-C-E2. September 2004

[12] D. Allaire and K. Willcox, "Surrogate for Modeling for Uncertainty Assessment with Application to Aviation Environmental System Models," AIAA 2008-5890.

AUTHOR BIOGRAPHY

George J Noel is employed at the U.S. Department of Transportation's Volpe National Transportation Systems Center in Cambridge, Massachusetts where he works in the Environmental Measurement and Modeling Division. He has participated in various measurement programs including acoustic measurements for the national park system in support of the Air Tour Management Plan (ATMP). His focus has been mostly concentrated in the area of air quality and measurement and analysis. For measurement programs relating to air quality, he has been part of the Aircraft Particle Emissions Experiment (APEX) which focused on particulate matter emissions from aircraft engines. He has also conducted several air quality model evaluations which include a validation and verification analysis for the Federal Aviation Administration's (FAA) Emissions and Dispersion Modeling System (EDMS) in which the validity of carbon monoxide emissions was analyzed. He has also supported the United States Air Force's Air Research Laboratory and the Navy's Office of Naval Research Program joint High frequency Active Auroral Research Program in obtaining Title I and Title V permits as required by the Clean Air Act for their facility located in Gakona, Alaska. He is currently involved in conducting an assessment of the FAA's Aviation's Environmental Design Tool (AEDT) which will support the development effort of the model. He is an alumnus of Embry-Riddle Aeronautical University in Daytona Beach, Florida and graduated with a B.S. in civil engineering in 2003.

Doug L. Allaire is a Ph.D. candidate at the Massachusetts Institute of Technology. His research focuses on the representation and analysis of uncertainty in large-scale complex system models. He received his S.B. in 2004 and his S.M. in 2006, both in aerospace engineering from the Massachusetts Institute of Technology.

Stuart A. Jacobson is currently the Lead Mechanical Engineer at Joule Biotechnologies developing a next generation of biofuels. Prior to this, he was a Principal Research Engineer in the Department of Aeronautics and Astronautics at MIT. In 2007-2008 he served as the Associate Director of the Partnership for Air Transportation Noise and Emissions Reduction, an FAA/NASA/Transport Canada sponsored Center of Excellence, working on issues associated with the environmental impacts of aviation. He was previously the Deputy Director of the MIT Microengine Project, where he developed microfabricated rocket engines and gas turbine generators. From 2000-2002, he served as the Director of Mechanical Engineering for Confluent Photonics in Andover, MA, a telecom startup developing microfabricated optical components. Dr. Jacobson received a B.S.E. degree from Princeton University and M.S and Ph.D. (1995) degrees from Stanford University, all in Mechanical Engineering.

Karen Willcox is Associate Professor of Aeronautics & Astronautics in the Aerospace Computational Design Laboratory at the Massachusetts Institute of Technology. She holds a Bachelor of Engineering Degree from the University of Auckland, New Zealand, and masters and PhD degrees from MIT. Before joining the faculty at MIT, she worked at Boeing Phantom Works with the Blended-Wing-Body group. Willcox's research and teaching interests lie in computational simulation and optimization of engineering systems with two major research focuses. The first is model reduction for large-scale systems with applications in unsteady aerodynamics, flow control, probabilistic analysis, inverse problems, and variable-fidelity design methods. The second is aircraft system design and optimization with particular emphasis on economic and environmental factors in conceptual design.

Rebecca Cointin is an Operations Research Analyst at the U.S. Federal Aviation Administration (FAA). She holds a B.S. degree from Marquette University, Milwaukee, WI and M.S degree in Applied Mathematics from the University of Nebraska in Lincoln, NE. Before joining the FAA, she was an aviation consultant in both the environmental and air traffic management areas.