AEDT GLOBAL NO_X DEMONSTRATION

Ted Thrasher, Alex Nguyen, Clifford Hall, CSSI, Inc., Washington D.C.
Gregg Fleming, Chris Roof, Sathya Balasubramanian, DOT Volpe Center, Cambridge, MA
Fabio Grandi, Scott Usdrowski, Wyle Laboratories, Inc., Arlington, VA
Eric Dinges, ATAC Corporation, Sunnyvale, CA
Carl Burleson, Lourdes Maurice, Ralph Iovinelli, FAA, Washington, D.C.

Abstract

The Global NOx (Oxides of Nitrogen) demonstration is the first Capability Demonstrator (CD) sample problem of the Aviation Environmental Design Tool (AEDT). AEDT is intended to facilitate the analysis of tradeoffs between noise and emissions and make the evaluation of air quality and noise impact seamless between the local and global domains. This CD marks an initial step toward creating a harmonized air quality module suitable for local and global analyses by leveraging the work already invested in developing the Emissions and Dispersion Modeling System (EDMS), the System for assessing Aviation's Global Emissions (SAGE), the Integrated Noise Model (INM), and the Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA). This initial CD focused on building a tool that assesses the impacts of different NOx stringencies to support the development of NOx emissions standards and highlights improvements over the previous modeling capabilities in many ways. AEDT implements Boeing Fuel Flow Method 2 (BFFM2) which allows for the use of thrust-specific emission indices corrected for atmospheric conditions, instead of relying on the sea level static certification data collected in the ICAO Aircraft Engine Exhaust Emissions Databank. BFFM2 is implemented in conjunction with a new, gate-to-gate, dynamic aircraft performance module based on the Society of Automotive Engineers' Aerospace Information Report 1845 (SAE-AIR-1845) and EUROCONTROL's Base of Aircraft Data (BADA). AEDT also implements input data processing enhancements to enable a more detailed fleet mix to be modeled. AEDT combines the International Official Airline Guide (IOAG) and FAA's Enhanced Traffic Management System (ETMS) data with the CAEP-developed fleet forecast from their Forecasting and Economics Support Group (FESG) to produce a comprehensive global operations forecast. The resultant aircraft-type-specific route information, allows the results to be aggregated in multiple ways, as opposed to being limited to only assessing global performance. The methodologies used in this demonstration of AEDT capabilities are described in the paper.

Introduction to AEDT

The Aviation Environmental Design Tool (AEDT) is under development to facilitate the analysis of tradeoffs between noise and emissions and to make the evaluation of air quality and noise seamless between the local and global domains. A phased development approach is being used to build AEDT, by progressively upgrading and integrating the current state-of-the-art emissions and noise models, including the associated databases. AEDT leverages the work already invested in developing the Emissions and Dispersion Modeling System (EDMS), the System for assessing Aviation's Global Emissions (SAGE), the Integrated Noise Model (INM), and the Model for Assessing Global Exposure from Noise of Transport Airplanes (MAGENTA). To facilitate the architecture design process for AEDT, a series of capability demonstrator (CD) sample problems are being performed to demonstrate new capabilities that will result from enhancements to and the integration of the existing models, and to identify potential areas of improvement for AEDT.

Overview of the NOx Demonstration Analysis

The NOx (Oxides of Nitrogen) demonstration is the first modeling demonstration of AEDT. and marks an initial step toward creating a harmonized air quality module suitable for local and global analyses by leveraging the work already invested in developing EDMS and SAGE. It also demonstrates early efforts toward harmonizing components of the noise modules (INM and MAGENTA) into the AEDT framework.

The ultimate objective of the NOx CD is to make evident new advanced modeling capabilities that utilize databases and methodologies common to both noise and emission evaluations. Achievement of this objective proves a positive step towards evaluating interdependencies between aviation noise and emissions. Conceiving the basis of this demonstration required a benchmark to which these new modeling capabilities can be compared and better understood. As a result, the Federal Aviation Administration (FAA) decided to replicate the 2004 NOx stringencies analysis used by the International Civil Aviation Organization's (ICAO) Committee for Aviation Environmental Protection (CAEP). The 2004 NOx stringencies analysis was the product of CAEP's Forecasting and Economic Support Group (FESG), tasked to quantify the cost and benefit analysis of NOx stringency options and is described in CAEP's Information Paper 13 (IP/13), entitled "Economic Analysis of NOx Emissions Stringency Options." The NOx Demonstration described in this document only focuses on replicating the benefits side of the NOx stringency analysis (i.e., potential NOx reductions). FAA's Aviation Portfolio Management Tool (APMT) will replicate the cost side of the NOx stringency analysis and is documented in another paper.

The intent of the CD is to demonstrate the AEDT modeling capabilities, including modeling an aircraft fleet that is beyond the scope of the 2004 analysis. This CD does not suggest changes to policies that were based on the 2004 analysis and the reader is cautioned that the assumptions made for the 2004 analysis do not completely coincide with those used in this CD. To demonstrate AEDT, the following steps were required: development of baseline and future fleet and operations, modeling the emissions, and evaluating the results. Each of these steps are described in detail in the following paragraphs.

Software to Utilize the FESG Forecast

The CAEP FESG forecast provides projections of aircraft operations by route group, seat class, and stage length through the year 2020. The AEDT Fleet Operations Module (FOM) was developed by leveraging the work already accomplished during MAGENTA development for applying the FESG forecast for global noise modeling purposes.

The FOM requires several datasets which are generated by preprocessing information from various sources to capture both the operational and fleet aspects associated with worldwide aircraft operations. The databases necessary to generate a basic forecast are the:

- Baseline operations database;
- Growth factors database;
- Retirement factors database; and
- Replacement aircraft fleet databases.

The software and methodologies needed to generate the required information were implemented during the initial stages of MAGENTA development. Since, MAGENTA was originally developed to perform noise analyses, for the NOx demonstration these processes were updated to support the additional data requirements associated with emissions modeling.

Baseline Operations

The baseline operations database is developed using ETMS data for North and Central America, along with the U.K., and the IOAG elsewhere. However, neither of these operations data sources provide sufficient information for accurately modeling aircraft emissions, since they do not include specific airframe and engine combination information. Instead, the IOAG uses the International Air Transport Association (IATA) three-letter aircraft codes (e.g. 737), and ETMS uses the International Civil Aviation Organization (ICAO) four-letter aircraft codes (e.g. B737). To overcome this limitation, the AEDT operations database is augmented by a retrieval of detailed information from an aircraft registration database. Several aircraft registration databases are commercially available that provide the necessary information, but because the NOx CD sample problem is being conducted as part of the CAEP/7 assessment, the Campbell-Hill registration database was selected, given that it had been used in the two previous CAEP cycles.

Detailed Aircraft Mapping

The ETMS data used in the development of the AEDT baseline data were augmented by adding to each record, wherever possible, the tail number of the aircraft performing the operation. This information was retrieved from the Airline Service Quality Performance (ASQP) database and included to provide a direct mapping to the registration database information for the actual aircraft.

When it is not possible to definitively determine the exact aircraft/engine combination using the method described above, the linking of the generic aircraft IDs to the specific airframe and engine information contained in the registration database is performed through a multi-step process. Each generic code is first associated with all the aircraft types that it can possibly represent. The information is then joined to engine distribution data by airline and aircraft type information derived from the source aircraft registration database. Operations records for which matches are found are assigned the indicated aircraft and engine types in the associated proportions. The remaining records are separated, and the process is repeated, using a table that holds regional engine and distribution data derived from the source database. For the NOx CD, two regions are defined: (1) all countries that implemented the Noise Chapter 2 phase-out; and (2) all the remaining ones. This distinction captures the significant change in engine technology associated with the migration from low to high bypass ratio engines. Aircraft records within the source database are assigned to each region based on the country of registration of the airline. For this step, matching to the detailed aircraft information is based on departure airport region and the aircraft type. Once the matched records have been updated as in the previous step, the remaining records are updated by direct assignment to specific engine types from a separate look-up table. By design, this last step covers all remaining records, since its information is dynamically developed during the execution of the mapping software. The application is designed to query the operations and registration data during the initial stages of its execution in order to identify any missing information and to prompt the user for the required data.

As noted in the description of the FESG mapping process, the aircraft mapping application is also responsible for completing the FESG mapping by determining the Seat Class for each operation. In general, the Seat Class is determined using the available seat information retrieved from IOAG and stored in the Operations Key table. Unscheduled operations found in ETMS, however, do not have corresponding entries in the IOAG scheduled database and, therefore, lack seating information. For these records, such information is retrieved from the registration data, if a match is achieved, or from a generic seating capacity table, if the aircraft types are directly mapped to specific engine types. Currently, this process assumes the seating information retrieved from IOAG is correct. However, the modeling effort has revealed that this assumption is not always correct and results in minor errors in aircraft replacement selection during the forecasting process.

FESG Operations Normalization

Future operational levels are provided by the FESG group in the form of projected operations by Route ID, Seat Class, and Stage Length. In order to generate meaningful comparisons between modeled conditions, the baseline year operational levels must be consistent with the baseline data used to generate the forecast information. Since the AEDT operations database and the FESG baseline data are generated through different processes, the number of operations do not necessarily agree. The last step in the preprocessing sequence is designed to eliminate any discrepancy between the two.

In order to achieve the most accurate reconciliation, the operations normalization process takes place at the finest level of detail permitted by the FESG data: adjustments are performed on the basis of each possible Route ID, Seat Class, and Stage Length combination. First, the baseline Operations database is queried to obtain the total number of operations for each combination of FESG fields. This information is then joined with the FESG data for the corresponding year, and adjustment factors are calculated that quantify the differences as ratios. Finally, these adjustment factors are applied to the operations data and the new number of operations calculated. The resulting database derives its fleet composition from the more accurate data used for its initial development but retains the operational levels indicated by the FESG data.

Modeling the Future Fleet

In addition to assigning the correct number of operations to the future scenarios, it is equally important to capture the effects of fleet changes with time. The retirement percentage calculation is based on the age information contained in the Campbell-Hill fleet registration database and on the aircraft survival relationships provided by FESG. In the case of passenger aircraft, there are four equations defined to model the retirement of different aircraft types, as shown in Table 1 and Figure 1. For freight aircraft, a single step function is used which applies to all aircraft, as shown in Table 2.

Computing the retirement percentages for passenger aircraft using the FESG-provided curves is a multi-step process: First, the fleet database is queried to obtain the number of units in service for each aircraft type by age. Next, the original number of aircraft in the fleet, according to the retirement curve, is computed by projecting the current number of aircraft in the fleet back to year zero of the retirement curves. Then, the number of aircraft remaining in the fleet for the future year of interest is calculated by applying the retirement curve to the number of aircraft computed in the previous step. Finally, the retirement percentage value needed to reduce the number of aircraft in the baseline year to the number for the projected year is calculated.

Once generated, the retirement data for each year are assigned a unique key value, and the records are combined into a single aircraft replacements database according to the new forecasting engine data requirements.

Table 1. Passenger Aircraft Retirement Curves as a Function of Aircraft Age

	Curve 1	Curve 2	Curve 3	Curve 4
	7 to 47 years	7 to 36 years	12 to 36 years	5 to 14 years
Constant	0.7912	0.875867	0.277046	0.782491
A	0.0975	0.039574	0.136525	0.080313
B	-0.016835	-0.00352285	-0.0076598	-0.00931738
C	0.0013517	0.0000478103	0.000103682	
D	-0.000053636			
E	0.00000097731			
F	-6.581E-09			

Curve 1: All aircraft except for those corresponding to curves 2-4
Curve 2: 1^{st} generation wide body aircraft (A300B4, L1011, DC10, 747-100/200/300)
Curve 3: B727s and B707s
Curve 4: MD-11
S = constant + $ax + bx^2 + cx^3 + dx^4 + ex^5 + fx^6$ = survival factor (fraction of aircraft that survived)
x = age of aircraft

Figure 2 presents a graphical representation of the Table 1 data.

Figure 1. Passenger Aircraft Retirement Curves as a Function of Aircraft Age

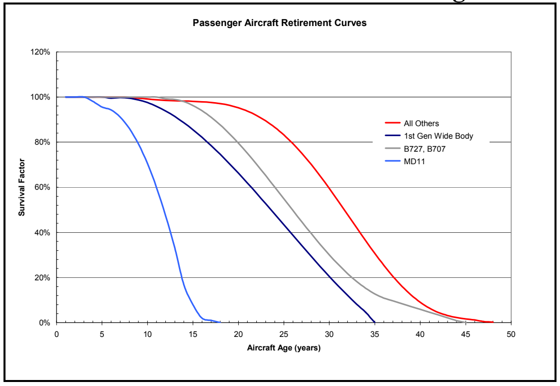


Table 2. Freight Aircraft Retirement Curve as a Function of Aircraft Age

	0 to 35 years	35 to 45 years	> 45 years
Retirement %	0	45	100

Fleet Replacements

After retiring aircraft, appropriate replacements are assigned. The replacement aircraft fleet databases were derived from the No-Action Jet 9 aircraft best practices database developed by ICAO/CAEP Working Group 1 and used with MAGENTA under CAEP/5. Using this database as the basis, the appropriate future Technology Level (TL) designations were assigned to reflect the various stringency levels. As a result, different sets of replacement aircraft and engines were developed for each stringency scenario. The TL designations were assigned only to those engines in the No-Action database that matched one of the production engines in the TL designation spreadsheet provided by FESG as part of the data used for the NOx stringency work under CAEP/6. No TL designations were applied to the older, non-production engines. This reflects the reasonable assumption that it is technically and/or economically unfeasible for an engine manufacturer to retrofit new engine combustors into older engine models currently in service. As specified in the TL designation spreadsheet, an appropriate TL was assigned to an engine if the characteristic NOx value was greater than the calculated allowable NOx value. The assigned TL was specific to the stringency level such that more advanced TLs were assigned to the higher stringency levels. Therefore, of the six replacement databases created for this work (each corresponding to a stringency level), the replacement database with the highest stringency level (30%) contained the most TL assignments, as well as the more advanced TLs.

The replacement databases list the replacement aircraft available for each Seat Class and Stage Length. Along with the TL designations, an operations percentage is applied to each combination of aircraft and engine within the Seat Class and Stage Length categories. The percentages for the aircraft and engine combinations within each Seat Class and Stage Length category add up to 100%. These distributions were developed such that each aircraft and engine manufacturer is treated equally. That is, the distribution within each Seat Class and Stage Length combination is first evenly split between each aircraft manufacturer, then by the aircraft type, followed by the engine manufacturer, and, finally, the engine model. This approach is consistent to that agreed to under the CAEP/5 IP-13 assessment.

Aircraft Performance Modeling

The result of the previously described process is a complete database of operations for the baseline and future scenarios with aircraft type, engine model, and stage length defined. Next, the AEDT Aircraft Performance Module (APM) was developed to generate both terminal-area (below 10,000 ft Above Field Elevation (AFE)) and en-route (above 10,000 ft AFE) fuel burn values. This module calculates the terminal-area aircraft performance primarily using the SAE-AIR-1845 [Flathers 1982] methods and data as they are implemented in the INM [Bishop 1992, Olmstead 2002]. It calculates fuel burn values in the terminal area using these aircraft performance results and BADA [Eurocontrol 2004] methods and data. For en-route portions of the modeled flight paths, the module calculates both aircraft performance and fuel burn using BADA. A more detailed description of these methods follows.

Terminal Area Calculations

For this demonstration, two-dimensional flight paths (vertical flight profiles without ground tracks) were calculated for each flight operation using standard INM flight profiles. The standard INM profiles were developed by aircraft manufacturers to represent the way a particular aircraft would normally be operated at a typical commercial airport. The profiles describe the flap and speed schedules, as well as the climb/decent rates to be used for each flight operation. For departures, they also define the thrust settings and the location of the thrust cutback. An example of a typical, standard INM procedural departure profile definition is presented in Table 3.

Table 3. Typical INM Procedural Profile

Segment Type	Thrust Type	Flap Configuration	Endpoint Altitude (ft AFE)	Rate of Climb (ft/min)	Endpoint Speed (KCAS*)
Takeoff	Max Takeoff	5	--	--	--
Climb	Max Takeoff	5	1000	--	--
Accelerate	Max Climb	5	--	1192.6	192.8
Accelerate	Max Climb	1	--	1343.1	211.9
Climb	Max Climb	ZERO	3000	--	--
Accelerate	Max Climb	ZERO	--	1470.2	250
Climb	Max Climb	ZERO	5500	--	--
Climb	Max Climb	ZERO	7500	--	--
Climb	Max Climb	ZERO	10000	--	--

*Calibrated airspeed, in knots

The AEDT APM uses this information, along with aircraft weight, atmospheric, and airport/runway data, to calculate the resultant flight paths and thrust values for each flight operation. Since aircraft weight is not directly provided by any of the input data sources, it was assumed that aircraft takeoff weight relative to minimum and maximum operating weights was proportional to the stage length or trip distance of the flight. In addition, an airports database was compiled using multiple sources. For the NOx demonstration, annual average surface temperature and pressure were provided to the APM, which applied a standard lapse rate to determine the meteorological data at above-airport altitudes within a given terminal area. The calculated thrust values and speeds for each flight path segment are used in conjunction with BADA's thrust-specific fuel consumption calculation methods to determine fuel flow and fuel burn values for each flight path segment. The aircraft's weight is reduced per flight segment based on the amount of fuel burned on the previous segment, so calculated climb rates, accelerations, thrust levels, and fuel burn values account for the aircraft's changing weight throughout the flight path.

Due to the dynamic nature of the calculated profiles, events of interest for emissions calculations, such as thrust cutbacks, will not occur at consistent altitudes, distances from start of takeoff, or times from start of takeoff between different aircraft types or even between different weights for the same aircraft type. Therefore, for emissions calculation purposes, the APM labels each calculated flight path segment with an emissions mode. The emissions modes used for this analysis are limited to those listed in Table 4.

Table 4. AEDT Aircraft Performance Module Emission Modes

Emissions Mode	Description
Takeoff ground roll	Ground roll segments of departure profiles
Takeoff airborne	Airborne segments of departure profiles using maximum takeoff power
Terminal climb	Airborne segments of departure profiles using maximum climb power
Enroute climb	Airborne segments of departure profiles between 10000 ft AFE and Cruise Altitude
Cruise	Airborne segments at Cruise Altitude
Enroute descent	Airborne segments of approach profiles between Cruise Altitude and 10000 ft AFE
Approach	Airborne segments of approach profiles
Landing ground roll	Ground roll segments of approach profiles not using reverse thrust
Landing ground roll w/ reverse thrust	Ground roll segments of approach profiles using reverse thrust.

En-Route Calculations

Above 10,000 ft AFE, aircraft performance is modeled using the BADA methods and data. Aircraft follow the speed schedules dictated by a unique BADA Airline Procedure for each aircraft type. An example of typical BADA Airline Procedures for a specific aircraft type are presented in Table 5. BADA-defined reduced-climb thrust, maximum cruise thrust, and descent thrust are used throughout the flight path as appropriate. With the BADA specified speeds and thrusts, the resulting Rate of Climb or Descent (ROCD) is calculating using the BADA Total Energy Model (TEM) along with the appropriate aircraft weight and atmospheric data. More details on methods used by the APM for calculating en-route flight profiles and merging them with terminal-area flight profiles can be found in the APM's Algorithm Description Document (ADD) [Dinges 2006].

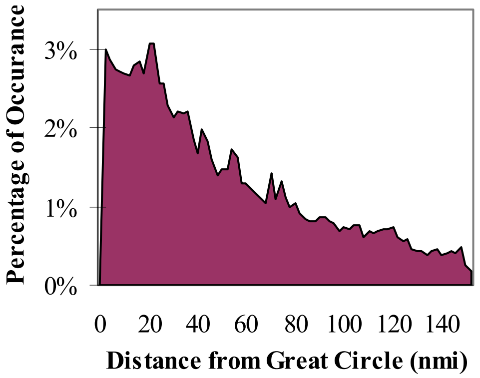
Table 5. Typical BADA Airlines Procedure

Mass Range	Climb CAS 1	Climb CAS 2	Climb Mach
LO	250	310	0.78
AV	250	310	0.78
HI	250	310	0.78
Mass Range	**Cruise CAS 1**	**Cruise CAS 2**	**Cruise Mach**
LO	250	310	0.78
AV	250	310	0.78
HI	250	310	0.78
Mass Range	**Descend Mach**	**Descend CAS 2**	**Descend CAS 1**
LO	0.78	310	250
AV	0.78	310	250
HI	0.78	310	250

Although ETMS data provide position information for Instrument Flight Rule (IFR) traffic, these data were not available for the entire world. Therefore, to be consistent across all flights, position data were not used for this demonstration; instead, a constant altitude and horizontal track dispersed around a Great Circle (GC) route was used to model cruise. Both the altitude and horizontal track are assigned to a flight based on distributions. That is, a single altitude and a single horizontal track are selected pseudo-randomly from distributions developed by analyzing a large sample of ETMS radar data. As a result, these distributions statistically mimic radar trajectories to provide more accuracy than a single GC route provides. Both the altitude and track distributions are functions of the Origin-Destination (OD) pair trip distance and are also categorized into jet and turboprop categories.

Horizontal track distributions were developed using offsets from the GC route. When a dispersed track is picked from the distribution, it is defined by a set of perpendicular offsets from the GC, spaced equally along the Great Circle starting at 20% from the beginning and finishing 80% of the way along the flight path. The GC route was further segmented between these two points at 10% increments (i.e., at 30%, 40%, 50%, 60% and 70% of the GC route). Figure 2 presents the horizontal dispersion distributions for flights that range from 1,500 to 2,000 nautical miles, 50% of the distance along the route.

Figure 2. Horizontal dispersion distribution.



By default, for en-route calculations the module uses ISA conditions for a sea-level airport as the basis for lapsing to above-airport altitudes. Winds are not modeled within the module, but provisions exist within to take into account head or tail winds in a future version of the module (when global, grid-based wind data are integrated into AEDT/SAGE). Other than the simple head or tail wind modeling currently undertaken, fully accounting for winds will require wind direction and aircraft bearing (from aircraft trajectories) as a function of time.

Emissions Modeling

AEDT is capable of modeling the following emissions: NOx, Carbon Monoxide (CO), Total Hydrocarbons (THC), Carbon Dioxide (CO_2), Water (H_2O), Sulfur Oxides (SOx), non-Methane Hydrocarbons (NMHC), Volatile Organic Compounds (VOC), Particulate Matter (PM) with an aerodynamic diameter of less than or equal to 10 μm (PM_{10}), and PM with an aerodynamic diameter of less than or equal to 2.5 μm ($PM_{2.5}$). All aircraft PM emissions are assumed to be less than 2.5 μm in diameter, therefore PM_{10} and $PM_{2.5}$ are equivalent for this demonstration. Different methods are used to model emissions based on the pollutant.

NOx, THC, and CO are modeled through the use of the Boeing Fuel Flow Method 2 (BFFM2). As described in [Baughcum 1996] and [ICAO[b] 2005], the method uses fuel flow generated from an external source, such as the APM, to determine an emissions index, while accounting for engine installation effects and atmospheric conditions. At the heart of this method is the development of a log-log relationship between emissions indices (EI) and fuel flow data from the ICAO emissions databank [ICAO[a] 2005]. In contrast, CO_2, H_2O, and SOx emissions are modeled based on fuel composition under a complete fuel combustion assumption. The resulting emissions indices were derived by Boeing [Baughcum 1996] and are presented in Table 6.

Table 6. Emissions Indices and Conversion Factors for Aircraft.

Pollutant	Emissions Index / Conversion Factor
CO_2	3,155 g/kg
H_2O	1,237 g/kg
SO_x (modeled as SO_2)	0.8 g/kg
NMHC	Set equal to THC
VOC conversion factor based on type of flight	
• Default	VOC = THC * 1.0
• Commercial	VOC = THC * 1.0947
• Military	VOC = THC * 1.1046
• General Aviation & Air Taxi, Piston	VOC = THC * 0.9649
• General Aviation & Air Taxi, Turbine	VOC = THC * 1.06631
$PM_{10}/PM_{2.5}$	FAA first order approximation version 2.0 (FOA) [Wayson 2003]

A simplified version of BFFM2 was used due to a current lack of standardized guidance regarding PM modeling. Fuel flow is adjusted for engine bleed and atmospheric effects as prescribed in BFFM2. However, the PM smoke number (SN) or derivative EI values from the FOA are not corrected, due to the aforementioned lack of standardized guidance. This was deemed acceptable, due to the overall uncertainties associated with using the SNs from the ICAO emissions databank. That is, the errors associated with correcting for atmospheric effects are likely to be much smaller than the errors associated with using SNs. The FOA is used to convert the SNs to EI values which are then used to plot EI versus fuel flow relationships (i.e., rather than smoke number versus fuel flow). This method is consistent with the EI versus fuel flow plots used for the other pollutants (CO, HC, and NO_x). For this analysis, however, only the following emissions were reported: NOx, CO_2, and H_2O.

Idle Fuel Flow Module

Because power is assumed to remain at a constant 7% thrust during taxi (idling) operations, standard fuel flow from the ICAO emissions databank for that power level were used, instead of a BADA fuel flow equation.

These ICAO fuel flow data are adjusted for temperature, pressure, and Mach number exactly as prescribed in BFFM2.

Results

The emphasis of this paper is on the demonstration of new capabilities and not on the results themselves. That said, it is impossible to demonstrate new modeling capabilities without presenting results to illustrate said capabilities. Table 7 not only provides the NOx emissions below 3,000 as is typically shown, but also includes emissions within the terminal area, defined as below 10,000 feet, as well as the total NOx from the entire flight, including cruise. The NOx emissions above 10,000 feet were calculated using BFFM2. Table 7 includes the emissions from the entire global fleet, including turboprop and piston aircraft. This table illustrates possible trends that were not previously available. Some observations are:

- NOx emissions from aircraft below 3,000 feet account for less than 10 percent of the total NOx from the entire flight, of which half of the NOx emissions below 3,000 feet are from 100-210 seat aircraft.

- There are fewer aircraft in the 211-650 seat category than the 100-210 seat category, yet the larger aircraft spend more time en-route and consume more fuel, thereby producing more NOx emissions for an entire flight.

Table 7. Baseline NOx emissions according to altitude and entire flight, reported as metric tons for the *entire world fleet*

Seat Class	2002	2006	2008	2012	2016	2020
	Metric Tons	Metric Tons	Metric Tons	Metric Tons	Metric Tons	Metric Tons
	Below 3,000 feet (914.4m) AFE					
20 – 99	14,526	17,779	21,359	28,750	36,760	46,075
100 – 210	87,415	95,254	103,169	119,683	135,531	147,128
211 – 650	55,810	63,168	70,311	86,262	107,074	135,730
Total	**157,750**	**176,201**	**194,839**	**234,695**	**279,364**	**328,933**
	Terminal Area: Below 10,000 feet (3048m) AFE					
20 – 99	27,009	32,971	39,519	53,044	67,683	84,659
100 – 210	151,244	164,814	178,691	207,721	235,619	256,061
211 – 650	95,275	108,094	120,573	148,478	184,845	234,966
Total	**273,528**	**305,879**	**338,783**	**409,243**	**488,148**	**575,687**
	Entire Flight					
20 – 99	80,252	92,459	106,248	134,715	165,407	200,957
100 – 210	775,516	833,527	899,067	1,035,410	1,167,627	1,272,087
211 – 650	1,029,453	1,156,272	1,288,886	1,571,232	1,875,945	2,176,668
Total	**1,885,221**	**2,082,258**	**2,294,201**	**2,741,357**	**3,208,978**	**3,649,713**

The stringency analysis consisted of six NOx certification stringencies ranging from 5% to 30%. Each stringency was evaluated for implementation years of 2008 and 2012. Table 8 and Figure 3 illustrate the impact of imposing various NOx stringencies in these future years. As expected, the sooner that a NOx stringency is imposed (in this case 2008 instead of 2012), the greater the cumulative benefit. The NOx stringency was only applied to ICAO-certified engines.

Table 8. Effects of stringency implementation ranked by amount of total NOx reduction

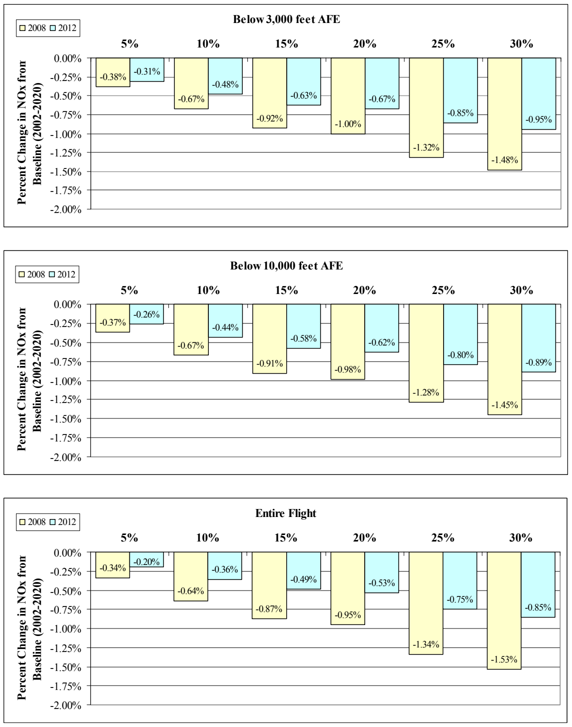
	Below 3,000 Feet AFE	Below 10,000 Feet AFE	Entire Flight
Rank	Stringency	Stringency	Stringency
Highest	-30% in 2008	-30% in 2008	-30% in 2008
2nd	-25% in 2008	-25% in 2008	-25% in 2008
3rd	-20% in 2008	-20% in 2008	-20% in 2008
4th	-30% in 2012	-15% in 2008	-15% in 2008
5th	-15% in 2008	-30% in 2012	-30% in 2012
6th	-25% in 2012	-25% in 2012	-25% in 2012
7th	-20% in 2012	-10% in 2008	-10% in 2008
8th	-10% in 2008	-20% in 2012	-20% in 2012
9th	-15% in 2012	-15% in 2012	-15% in 2012
10th	-10% in 2012	-10% in 2012	-10% in 2012
11th	-5% in 2008	-5% in 2008	-5% in 2008
Lowest	-5% in 2012	-5% in 2012	-5% in 2012

A sensitivity check of the results presented in Table 8 was conducted to see if the inclusion of non-certified engines (therefore comprising the complete global fleet) would make any difference in the rankings of NOx reductions below 3000 ft. Table 9 confirms that the inclusion of non-certified engines does not alter the rankings. This is intuitive since these engines are not affected by the stringencies and hence, they would not provide any reductions in NOx.

Table 9. Sensitivity-check of NOx reduction rankings below 3000 ft AGL by including non-certified engines

Rank	Complete Global Fleet (includes Non-Certified Engines)	Aircraft with ICAO-Certified Engines Only
	Stringency	Stringency
Highest	-30% in 2008	-30% in 2008
2nd	-25% in 2008	-25% in 2008
3rd	-20% in 2008	-20% in 2008
4th	-30% in 2012	-30% in 2012
5th	-15% in 2008	-15% in 2008
6th	-25% in 2012	-25% in 2012
7th	-20% in 2012	-20% in 2012
8th	-10% in 2008	-10% in 2008
9th	-15% in 2012	-15% in 2012
10th	-10% in 2012	-10% in 2012
11th	-5% in 2008	-5% in 2008
Lowest	-5% in 2012	-5% in 2012

Figure 3. NOx percent change in cumulative emissions from baseline between 2002-2020 according to altitude



Conclusions

In order to assist ICAO in attaining the goal to "limit or reduce the impact of aviation emissions on local air quality," the FAA's Aviation Environmental Design Tool (AEDT) has been developed and demonstrated for evaluating aircraft NOx emissions. The NOx CD successfully confirmed that harmonized databases and methodologies can be used to assess noise and emissions simultaneously. Improvements include both technical and administrative enhancements to the methodologies used previously and results from a demonstration of AEDT have been presented. The assessment highlights the need for an updated aircraft replacement database that is representative of both noise and emissions.

AEDT successfully implemented the following technical enhancements that improve the overall emissions estimate and demonstrate that it is possible to compute a refined global emissions estimate using this methodology:

- Incorporation of dynamic gate-to-gate aircraft performance data, methodologies, and a global airport, operations and fleet database that are necessary to assess interdependencies;
- Implementation of a CAEP-approved flexible forecasting system rather than a set of static lookup tables;
- Use of meteorological data;
- Use of BFFM2;
- A broader range of aircraft types and traffic types – no longer restricting the analysis to commercial jets;
- Use of schedule data and delay modeling; and
- Addition of unscheduled flights, through the addition of radar data, resulting in a more precise representation of actual global flights.

This capability demonstrator sample problem has been thoroughly documented to ensure that the study is repeatable and that any follow-on studies can benefit from the work conducted in this area to date. Using AEDT also provided the ability to view global emissions beyond the LTO cycle, which highlighted that the LTO cycle is a small component (less than 10%) of the total NOx emitted by aircraft in flight and therefore provides a new capability for supporting policy decision making in the future.

Keywords
AEDT, EDMS, SAGE, INM, MAGENTA, emissions, NOx.

References

Bishop, D.E. and Miller, J.F. "Update of Aircraft Profile Data for the Integrated Noise Model Computer Program." U.S. Department of Transportation. DOT-VNTSC-FAA-91-4, Vol. 1. 1992.

Dinges, Eric "AEDT Algorithm Description Document, Aircraft Performance Module",

Document #AEDT-ADD-01, FAA Office of Environment and Energy, Washington, D.C., June 2006.

Federal Aviation Administration (FAA^{a}). "System for assessing Aviation's Global Emissions (SAGE), Version 1.5, Technical Manual." FAA, Office of Environment and Energy. FAA-AEE-2005-01. September 2005

Federal Aviation Administration (FAA^{b}). "System for assessing Aviation's Global Emissions (SAGE), Version 1.5, Validation Assessment, Model Assumptions, and

Uncertainties." FAA, Office of Environment and Energy. FAA-AEE-2005-03. September 2005.

Eurocontrol. "User Manual for the Base of Aircraft Data (BADA)." Revision 3.6. EEC Note No. 10/04. Project ACE-C-E2. September 2004.

Flathers, G. W., II. "A Comparison of FAA Integrated Noise Flight Profiles with Profiles Observed at Seattle-Tacoma Airport." FAA-EE-82-10. December 1982.

Gunston B., Jane's Aero-Engines, Jane's Information Group, Alexandria, Virginia, 1998.

International Civil Aviation Organization (ICAO[a]). "ICAO Engine Exhaust Emissions Databank, Issue 14. http://www.caa.co.uk/default.aspx?categoryid=702&pagetype=90. June 2005.

International Civil Aviation Organization (ICAO[b]). "Issues with Implementing Boeing Fuel Flow Method 2 (BM2) for Computing Emissions using the ICAO Databank." ICAO Committee on Aviation Environmental Protection (CAEP) Working Group 3 (WG3), Alternative Emissions Task Group (AEMTG). IP-4/3. Stockholm, Sweden. June 20-25, 2005.

Kim, Brian, et al. "AEDT Fuel Burn and Emissions (FBE) Module Design Document." Volpe National Transportation Systems Center, Cambridge, MA. June 2005.

Lee, Joosung. "Modeling Aviation's Global Emissions, Uncertainty Analysis, and Applications to Policy." Ph.D Thesis in the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (MIT). February 2005.

Long, D., Lee, D., Johnson, J., Gaier, E., and Kostiuk, P. "Modeling Air Traffic Management Technologies With a Queuing Network Model of the National Airspace System", NASA/CR-1999-208988, Logistics Management Institute, McLean, Virginia, 1999.

Olmstead, J.R., et. al. "Integrated Noise Model (INM) Version 6.0 Technical Manual", Report No. FAA-AEE-02-01, Washington, D.C., Federal Aviation Administration, 2002.

Stouffer, V., WWLMINET User Guide, Logistics Management Institute, McLean, Virginia, 2002.

Wayson, Roger L., Fleming, Gregg G., Kim, Brian. "A Review of Literature on Particulate Matter Emissions From Aircraft." DTS-34-FA22A-LR1, Federal Aviation Administration, Office of Environment and Energy, Washington, D.C. 20591, December, 2003.

Biographies

Mr. Theodore G. Thrasher is the Executive Director for Investment Strategy and Analysis at CSSI, Inc. where he is responsible for projects related to Air Traffic Management Transformation, Business Case and Performance Management, and Enterprise Architecture. He has been a member of the EDMS development team since 1996 and is CSSI's lead on the AEDT development team. He received a B.S. in Aviation from The Ohio State University College of Engineering in 1996.

As Chief of the Environmental Measurement and Modeling Division at the John A. Volpe National Transportation Systems Center, **Mr. Gregg G. Fleming** has over nineteen years of experience in environmental measurement, modeling and analysis. He is co-manager of the FAA's Aviation Environmental Design Tool (AEDT) and is Focal Point for Task Group 2 of Working Group 2 within ICAO's Committee on Aviation and Environmental Protection, which is responsible for all environmentally-related modeling activity within CAEP. He is also chair of the tools panel within the Environmental Integrated Product Team of the Joint Programs Development Office. Mr. Fleming received a B.S. in electrical engineering from the University of Lowell in 1987.

Mr. Fabio Grandi is a Senior Acoustics Engineer in the Research and Consulting Division of Wyle Laboratories where he is the technical lead responsible for the global noise exposure (MAGENTA) and operations forecasting modules of the FAA's Aviation Environmental Design Tool (AEDT). He joined Wyle in 1996 after receiving a BS degree in Audio Technology from American University, and has been responsible for the development of the MAGENTA system since 1997. Mr. Grandi is also responsible for development of Wyle's environmental decision support tool (Dicerno).