NOx Demonstration Analysis

Round 3
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Glossary of Terms

ACCODE	Aircraft Mapping Code
ACI	Airport Council International
ACIM	Air Carrier Investment Model
ACSYNT	AirCraftSYNThesis
ADD	Algorithm Definition Document
AEDT	Aviation Environmental Design Tool
AEE	Office of Environment and Energy
AERMET	AERMOD Meteorological Preprocessor
AERMOD	Steady-state plume dispersion regulatory model
AFE	Above Field Elevation
AGL	Above ground level
AIR	Aerospace Information Report
ANCAT	Abatement of Nuisances Caused by Air Transport
ANP	Aircraft Noise and Performance
ANSI	American National Standards Institute
AOPA	Aircraft Owners and Pilots Association
API	Application Programmer Interface
APU	Auxiliary Power Unit
APMT	Aviation Portfolio Management Tool
ARP	Aerospace Recommended Practice
ARTCC	Air Route Traffic Control Center
ASQP	Airline Service Quality Performance
ASCII	American Standard Code for Information Interchange
ASPM	Aviation System Performance Metrics
ASTM	American Society of Testing and Materials
ATA	Air Traffic and Airspace
ATAA	Air Transport Association of America
ATC	Air Traffic Control
ATM	Air Traffic Management
ATMP	Air Tour Management Plan
ATO	Air Traffic Organization
BACK	BACK Aviation Solutions
BADA	Base of Aircraft Data
BFFM2	Boeing Fuel Flow Method 2
BWI	Baltimore / Washington International Airport
CAEP	Committee on Aviation Environmental Protection
CDA	Continuous Descent Approach
CFDR	Digital Flight Data Recorder data
CFMU	Central Flow Management Unit
CH_4	Methane
CNS	Communication, Navigation, and Surveillance
CO	Carbon Monoxide
CO_2	Carbon Dioxide

COE	Center of Excellence
CREW	Concurrent Read Exclusive Write
CRS	Computer Reservation System
DBF	Flat File Database Format
DCA	Ronald Reagan Washington National Airport
DDD	Database Definition Document
DEM	Digital Elevation Model terrain data
DFAD	Digital Feature Analysis Data
DLG	Digital Line Graph mapping data
DLL	Dynamic Link Library
DLR	Deutsche Zentrum für Luft- und Raumfahrt
DNL	Day Night Average Sound Level
DOT	Department of Transportation
DRG	Design Review Group
DSADS	Detailed System Architecture and Design Specification
DTED	Digital Terrain Elevation Data
EASN	Equivalent Auditory System Noise
ECAC	European Civil Aviation Conference
EDMS	Emissions and Dispersion Modeling System
EI	Emissions indices
EPA	Environmental Protection Agency
EPNL	Effective Perceived Noise Level
ESRI	Environmental Systems Research Institute
ETMS	Enhanced Traffic Management System
Eurocontrol	European Organization for the Safety of Air Navigation
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FBE	Fuel Burn and Emissions
FESG	Forecasting and Economics Support Group
FLOPS	Flight Optimization System
FOA	First-Order Approximation
FOQA	Flight Operational Quality Assurance
FSS	Flight Service Station
GA	General Aviation
GC	Great Circle
GCAM	Generalized Contour Area Model
GCNP	Grand Canyon National Park
GDP	Gross Domestic Product
GIS	Geographic Information System
GMT	Greenwich Mean Time
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center (NASA)
GUI	Graphical User Interface
H_2O	Water

HC	Hydrocarbons
HNM	Heliport Noise Model
IA	Interagency Agreement
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
IDL	Interactive Data Language
IFR	Instrument Flight Rules
IOAG	Interagency Operations Advisory Group
INM	Integrated Noise Model
IP	Information Paper
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
JPDO	Joint Planning and Development Office
KCAS	Calibrated airspeed, in knots
KSN	Knowledge Services Network
LAX	Los Angeles International Airport
LMI	Logistics Management Institute
LMINET	Logistics Management Institute network queuing model of the US
LOS	Line of Sight
LTO	Landings and Takeoffs
MAGENTA	Model for Assessing Global Exposure to the Noise of Transport Aircraft
MIA	Miami International Airport
MIL	Military
MIT	Massachusetts Institute of Technology
MOA	Memorandum of Agreement
MOBILEx	Regulatory Vehicle Emission Modeling System
MOVES	Multi-scale Motor Vehicle and Engine Emissions System
MSL	Mean Sea Level
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASPAC	National Airspace System Performance Analysis Capability
NCDC	National Climatic Data Center
NIRS	Noise Integrated Routing System
NMHC	Non-Methane Hydrocarbons
NOAA	National Oceanographic and Atmospheric Administration
NOx	Oxides of Nitrogen
NPD	Noise Power Distance
NWS	National Weather Service
OAG	Official Airline Guide
OD	Origin-Destination
OEP	Operational Evolution Plan
OMT	Object Modeling Technique
ORD	Chicago O’Hare International Airport
PARTNER	PARTnership in Noise and Emissions Reduction

PDARS	Performance Data Analysis and Reporting System
PM	Particulate Matter
RDBMS	Relation Database Management System
RoW	Rest of World
RPM	Revenue Passenger Mile
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SAGE	System for Assessing Aviation's Global Emissions
SDTS	Spatial Data Transfer System
SEL	Sound Exposure Level
SFC	Specific Fuel Consumption
SIMD	Single Instruction Multiple Data
SN	Smoke number
SOx	Oxides of Sulfur
SQL	Structured Query Language
SRTM	Shuttle Radar Topography Mission
STATFOR	Air Traffic STATistics and FORcast Service
TA	Time Above
TAF	Terminal Area Forecast
TCP/IP	Internet communications Protocol
TEM	Total Energy Method
TERP	Terminal and En Route Procedure
TIM	Time In Mode
TL	Technology Level
TRACON	Terminal Radar Approach Control
TRB	Transportation Research Board
TSFC	Thrust-Specific Fuel Consumption
UID	Unique Identification
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
URL	Uniform Resource Locator
US	United States
USAF	United States Air Force
USDOT	US Department of Transportation
USGS	United States Geological Survey
VFR	Visual Flight Rules
VOC	Volatile Organic Compounds
VQ	Vector Quantization
WAAS	Wide Area Augmentation System for GPS
WG3	Working Group 3
WNC	Weighted NOx Concept
WWLMINET	Worldwide version of the LMINET

1. Introduction

1.1. Overview of the NOx Demonstration Analysis

The NOx (Nitrogen Oxides) Demonstration is the first modeling demonstration of the **Aviation Environmental Design Tool (AEDT)**. AEDT is intended to facilitate the analysis of interdependencies between noise and emissions and make the evaluation of air quality and noise impact seamless between the local and global domains. This demonstration marks an initial step toward creating a harmonized emissions module suitable for local and global analyses by leveraging the work already invested in developing the Emissions and Dispersion Modeling System (EDMS) and the System for assessing Aviation's Global Emissions (SAGE). It also marks initial steps toward harmonizing components of the noise modules [the Integrated Noise Model (INM) and the Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA)] into the AEDT framework.

The ultimate objective of the NOx Demonstration is to make evident new advanced modeling capabilities utilizing 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. The roots of this analysis can be found in CAEP's Information Paper 13 (IP/13), entitled "Economic Analysis of NOx Emissions Stringency Options." This was the NOx analysis performed for the Sixth Meeting of the Committee for Aviation Environmental Protection (CAEP/6) in Montreal, Canada, February 2004. 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.

1.2 Schedule

Development of the NOx Demonstration is being conducted in three Rounds. Round 1 was a proof of concept. The tools were tested during this phase and deficiencies noted prior to the generation of results. Data from the IP/13 analysis were primarily used to populate data tables, and, where data were not available, placeholder values were used so that the tools could be fully exercised. Round 1 development is complete, and a final write-up was submitted to the FAA in October 2005. In addition, ICAO CAEP Working Group 2, Task Group 2 (WG2/TG2) was briefed on the NOx Demonstration proof of concept in Paris, France, September 1, 2005.

Round 2 of the NOx Demonstration development included the use of comprehensive input data so that more meaningful results could be generated. Changes to the software were made to correct deficiencies identified during Round 1. The draft results from

Round 2 were reviewed by the FAA and presented to CAEP WG2/TG2 in Tucson, Arizona, USA on February 8, 2006.

This paper presents the results of Round 3, the final phase of NOx Demonstration development. Round 3 incorporates the Rounds 1 and 2 feedback received from FAA and CAEP. Round 3 constitutes a refinement of the input data from Rounds 1 and 2. These results were published as an information paper for CAEP/7 WG2/TG2 in time for the Rome meeting in May 15-17, 2006.

2. Overview of the Tools

As described in Section 1, the NOx Demonstration is the first step toward development of AEDT. Round 3 of the NOx Demonstration linked the tools described in this section. Figure 1 shows the data flow and processing steps for this Round. In the figure vertical cylinders and rectangular boxes represent databases and processes, respectively. The color code represents organizational responsibility for the respective databases and tasks; ATAC had the responsibility for delivering the Aircraft Performance Module (APM), which was integral to the running of the scenarios.

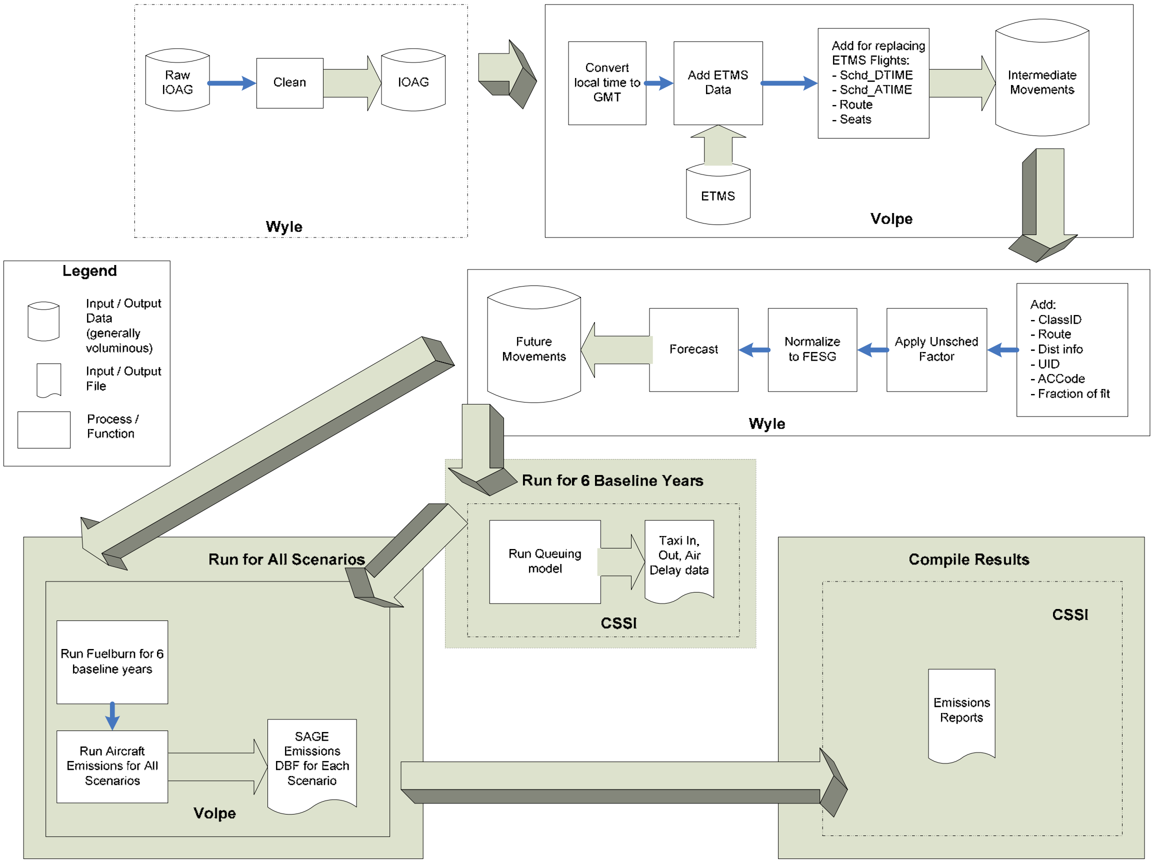

Figure 1. Data flow for NOx Demonstration Round 3

2.1 Software to Utilize the FESG Forecast

The NOx Demonstration leverages the work already accomplished during MAGENTA development for applying the CAEP FESG forecast. In order to use the AEDT/MAGENTA Fleet Operations Module (FOM) to predict current and future aircraft engine fleets, two aspects of the original MAGENTA system had to be reconsidered: (1) the software and processes needed to generate the necessary input data; and (2) the forecasting module itself. In addition to the changes necessary to generate data compatible with AEDT, the FOM was modified to provide support for FAA's APMT. It was adapted to accept multiple aircraft retirement and replacement databases to allow modeling of airline and/or airline group specific fleet replacement strategies.

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;
- The growth factors database;
- The retirement factors database; and
- The replacement aircraft fleet databases.

The software and methodologies needed to generate the required information had been developed during the initial stages of MAGENTA development. MAGENTA was originally developed to perform noise analyses, and these processes were updated to support the additional data requirements associated with emissions modeling for the NOx Demonstration. To support these requirements, a new set of preprocessing software was developed during the first two rounds of the NOx Demonstration. Each individual step was handled by a dedicated application to both facilitate the development of the software and ensure the validity of the inputs and outputs throughout the preprocessing sequence.

During the Round 1 analyses, the original forecasting engine was adapted to handle the demonstration's modeling requirements. Many lessons were learned during Round 1 and, as a result, a new engine was developed for Rounds 2 and 3 that was tailored to forecasting in the context of the AEDT system. As part of this migration process, the forecasting algorithms were first adapted to work with a new input data structure and then reviewed to insure proper functionality.

2.2 The New AEDT Data Structure

For Round 1 of the NOx Demonstration, the original MAGENTA operations data structure was utilized. The structure was functional but not well suited as a source for both noise and emissions modeling. For Rounds 2 and 3, a new AEDT structure was devised to seamlessly accommodate the needs of the various AEDT applications.

The challenge in developing the new structure resides in the need to accommodate both the flight-specific data requirements associated with emissions modeling and the more statistical nature of both the forecasting and noise modeling processes. The solution was to create a database structure that reports the data in both forms and provides the means to link the changing statistical data with the static individual flight information.

The new AEDT data structure is comprised of four databases:

- Movements database - used to create Operations database for the baseline year and stores information for each individual flight;
- Operations database - used for forecasting, emissions modeling, and noise modeling and provides aggregated fleet and operations information;
- Linked Operations Key database - stores information common to the two previous databases and the associated key value that is used to link the three databases; and
- Operations Average Day Time Distribution database - provides the information necessary to distribute the operations to the appropriate time of day, as required in noise modeling.

The Operations database is the core data set, since it is used to store the fleet and operations forecasts. The baseline year table is derived from the Movements table, but during the forecasting process, its fleet information and associated operations are modified to reflect future conditions. Because emissions modeling relies on individual flight data, the operations table provides an operations factor field to quantify the degree of change in operational volume at the individual flight level.

2.3 Development of the Baseline Operations Database

For Rounds 2 and 3 of the NOx Demonstration, the baseline operations data were derived by combining information from both the International Official Airline Guide (IOAG) schedule database and the Enhanced Traffic Management System (ETMS). Generating the final database required multiple steps involving newly developed preprocessing applications and data from multiple source tables. In keeping with the AEDT design goal, these applications retrieved the required aircraft and airport information from the AEDT harmonized fleet and airports databases, thus furthering progress toward the final goal of a single, fully integrated system.

The conversion of the raw ETMS and IOAG data into the final baseline flights database was achieved through the following preprocessing steps:

- Raw IOAG schedule data importation;
- IOAG data extraction and initial screening;
- IOAG and ETMS data joining;
- FESG mapping;
- Operations data generation;
- Detailed aircraft information mapping;
- Airline Service Quality Performance (ASQP)-based aircraft information mapping;
- FESG operations normalization; and
- Correction of data issues.

The resultant database for Round 3 of the NOx Demonstration included information from all 12 months of the 2002 IOAG. In previous CAEP assessments that used the MAGENTA forecasting engine, only the month of September had been used to generate the average day operations, since that was the month used by FESG to generate forecast data. For this analysis, it was deemed more appropriate to utilize a full year of data, since emissions modeling is not based on average information. In addition, this approach allowed for the utilization of all ETMS data available, resulting in a more precise identification of equipment and flight trajectories. However, to maintain consistency with the FESG information to be used for generating forecasted years, the final operational volume was scaled to match the FESG numbers so as to maintain consistency between the baseline and the forecasted operations.

2.3.1 Raw IOAG Schedule Data Importation

The IOAG data files used for the NOx Demonstration are in the form of a formatted text file. The first step in the process involves reading the text files and importing the information into database tables. This step is accomplished using an application capable of parsing the text information into individual fields based on an input file that specifies how many characters are to be imported into each field and the associated data type. This application did not require any modification to be compatible with AEDT data requirements.

2.3.2 IOAG Initial Screening and Extraction

Since the IOAG schedule database's original purpose was to provide the information needed by travel agents, many of the records within the dataset represent duplicate or irrelevant information when the database is used in the context of developing actual aircraft movements. The first step in the processing phase is, therefore, to remove any information not required by or irrelevant to the purpose of the final database.

Given that the IOAG data must be merged with the ETMS data, which are stored in monthly files, the next step in the processing is to split the IOAG information into similar subsets. This process must include all records associated with each scheduled flight because multiple records may be present if the airline has implemented changes in schedule during the year. Each resulting file, therefore, only includes the records pertaining to the specific month and, where necessary, the records used to describe the original schedule, which is valid whenever modifier records are not present.

2.3.3 AEDT MOVEMENTS Database: Joining IOAG and ETMS data

The next processing step consists of combining the ETMS and IOAG data into a single Movements database. The IOAG schedule information is first converted into movements information discarding duplicate records resulting from joint operations, and records that represent virtual direct connections between airports within multiple-leg flights (e.g., a flight with itinerary MIA-DCA-ORD-LAX will have virtual records for connections between MIA-ORD, MIA-LAX, and DCA-LAX). The data are then compared to the information contained in the ETMS database, and data from the latter - along with some itinerary information from the schedule - are used whenever a match is found. This process ensures that no duplication of movements occurs when both databases capture an individual flight and the best available information is ultimately stored in the final AEDT Movements database.

Since the IOAG schedule database covers the scheduled commercial operations worldwide and the ETMS database covers all Instrument Flight Rules (IFR) flights departing or arriving in the US and UK, the final Movements database covers the entire world operations with an increased level of accuracy and detail for the ETMS regions. The AEDT system will eventually also include more detailed information from the European Central Flow Management Unit (CFMU), as well as other data being collected by ICAO CAEP, thus improving its data quality for European and other regional operations.

2.3.4 FESG Mapping

The next step in the development of the Flights database is to develop the information required to perform forecasting based on FESG data. The FESG information is categorized based on three fields: Route ID, Seat Class, and Stage Length. During this processing step, only the two fields pertaining to the flights itinerary are generated (namely the Route ID and the Stage Length), while the Seat Class values are determined once the database is augmented using more detailed aircraft information.

Route ID assignment is based on each record's initial origin and final destination (OD) airports for the flight, which, in the case of multiple leg flights, does not necessarily match the indicated departure and arrival airport. This information is derived from the itinerary data retrieved in the previous step from the IOAG database. Since the FESG forecast data assume that a particular flight's growth factor is controlled by its origin and destination and is not dependent on any stops along the way, this information is vital to perform the appropriate route assignments. By way of contrast, records in ETMS data do not include the necessary route airport information, and the records are assumed to be direct flights.

The Stage Length field is calculated using the Great Circle algorithm distance and the airport coordinates retrieved from the AEDT Airports database. During this step two distances are calculated: The first is based on the route airports and is used to compute the FESG stage length values that correspond to those used by INM; the second is computed based on the record's actual departure and arrival airport coordinates and is used for emissions modeling.

2.3.5 Operations Database Generation

The operations data generation application converts the information contained in the monthly movements files into a single Operations database. This application also creates the Linked Operations Key database and the Operations Average Day Time Distribution database. Records are combined when the airline, aircraft, and itinerary information match, and these fields constitute the basis on which distinct operations' key values are assigned.

This processor first analyzes each monthly file to generate the operations counts and to compute the departure and arrival times based on the airports' time zone data retrieved from the AEDT airports database. This conversion to local time is necessary because the Movements database only stores Greenwich Mean Time (GMT) values, while noise modeling requires local time to compute metrics that include a penalty for operations occurring during specific times of day. Once all files have been processed, the application combines the individual files' counts and collapses the data further to compute the final operations table with the yearly operations.

After the operations data are finalized, the application generates the Linked Operations Key database. A table of distinct combinations of specific airline, aircraft and itinerary information is generated from the operations data, and a unique numeric key is assigned to each record. The key is then appended to both the Movements and Operations databases, and the fields now contained in the Key table are dropped to minimize file size.

Lastly, the processor generates the Operations Average Day Time Distribution database based on the operations local times. During the initial processing of the movements data files, two tables are created to hold each record's departure and arrival hours, along with the same information used to identify distinct operations keys. This information is then combined into a single table that is used to compute counts of the number of operations with the same key information that occurs during the various hours of the day. These counts are then compiled into individual records, and a table of unique time distributions is generated. Finally, the distributions are assigned unique numeric IDs, which are then associated with the operations records that match such distributions. Each operations record is assigned two IDs, one for departure operations and one for arrivals.

2.3.6 Detailed Aircraft Information Mapping

In the source IOAG and ETMS databases, equipment is identified using generic aircraft IDs: IOAG uses the International Air Transport Association (IATA) three-letter aircraft codes, and ETMS uses the ICAO four-letter aircraft codes. However, these generic aircraft codes are not adequate to perform detailed emissions and noise modeling, since they do not identify specific airframe and engine types. 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 Demonstration is being conducted as part of the CAEP/7 assessment, the Campbell-Hill registration database was selected as the source, given that it had been used in the two previous CAEP cycles.

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 it can possibly represent by linking the operations data to a look-up table. 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 Demonstration, 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 will cover 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 the IOAG data 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 the IOAG data to be 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. During the remaining AEDT development effort, the preprocessing application will be improved by adding algorithms that will verify and correct the IOAG derived data.

2.3.7 ASQP 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 ASQP database and included to provide a direct mapping to the registration database information for the actual aircraft. For Round 3 of the NOx Demonstration, this mapping process was accomplished using a set of queries stored in an Access database file. The ASQP mapping capability will be included as a software process in the final and integrated version of the preprocessing application.

The direct aircraft information mapping is accomplished by querying the Movements database to compute the number of matched records for each individual Operation key. The matched number of operations, with the corresponding record information and updated aircraft and engine types, are then appended to the Operations database as additional records. Finally, the operations field of the existing records with the corresponding Operation keys is adjusted so as to account for all the movements that did not have a match to a record in the registration data. This last step is necessary because not all movements within a single Operations key can be mapped to specific aircraft in the registration database and because the statistical aircraft and engine distribution within the dataset must be maintained.

2.3.8 FESG Operations Normalization

The ultimate purpose of the AEDT Movements database is to provide the information necessary to model the projected effects of proposed policy changes. The modeling effort, therefore, must assess both the current and projected conditions and rely on external information to develop the future year conditions. For CAEP-related modeling, the future operational levels are provided by the FESG 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 Movements database and the FESG baseline data are generated through different processes, their operational levels do not coincide and require a reconciliation process. 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 a ratio. 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.

2.3.9 Correction of Data Issues

During the review process of the baseline Movements database, two issues were identified with the baseline operations data: (1) some of the records required updated engine information; and (2) some of the adjustments performed during the FESG normalization resulted in operations factors that were so large that the estimated delays were excessive. The first problem was caused by incorrect values entered in the registration database and was solved by executing queries designed to replace the incorrect engine information. These types of issues are to be expected in a newly developed database, and it is expected that as the AEDT system matures, such errors will be gradually eliminated. The second problem was due to large differences between the operations reported by the FESG data and those found in the Movements database and implied that for those future scenarios additional airport capacity may be required to accommodate the increased demand. The issue was addressed by limiting the operations factors to a maximum value of three (which resulted in a limited loss of operations) and by adjusting the operations data accordingly. This issue might present itself every time a new baseline is generated, since the AEDT and FESG generate their data through different processes.

2.4 Development of the Growth Factors Database

The FESG forecast data are provided in a Microsoft Excel spreadsheet containing number of flights by Route ID, Seat Class, and Stage Length (with Seat Class and Stage Length identifying individual “cells” of each Route ID matrix) for each of the forecasted years.

Generating the growth factors database for use by the MAGENTA forecasting engine entails comparing the baseline year information, or any other year, with that of the target year, and computing the percent growth for each cell. This process is accomplished with the aid of a preformatted spreadsheet that allows for the insertion of each year's information and retrieval of resulting values. In addition to the values, the spreadsheet associates a flag with each Seat Class and Stage Length combination that is used to distinguish growth percentages for existing operations from those associated with the baseline or reference year. When this flag indicates new operations, the forecasting engine creates new records instead of attempting to grow nonexistent cells. Once generated, the growth data for each year are assigned a unique key value, and the records are combined into a single growth database according to the new forecasting engine data requirements.

2.4.1 Development of the Retirement Factors Database

The retirement percentage calculation is based on the age information contained in the Campbell-Hill fleet registration database and on the survival curves provided by FESG. In the case of passenger aircraft, there are four curves defined that are used to model the retirement of different types of aircraft (see Table 1). For freight aircraft, a single step function is used which applies to all aircraft (see Table 2).

Computing the retirement percentages for passenger aircraft using the FESG-provided curves is a multi-step process:

(1) The fleet database is queried to obtain the number of units in service for each aircraft type by age;

(2) 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;

(3) 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; and

(4) 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: 1st 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.

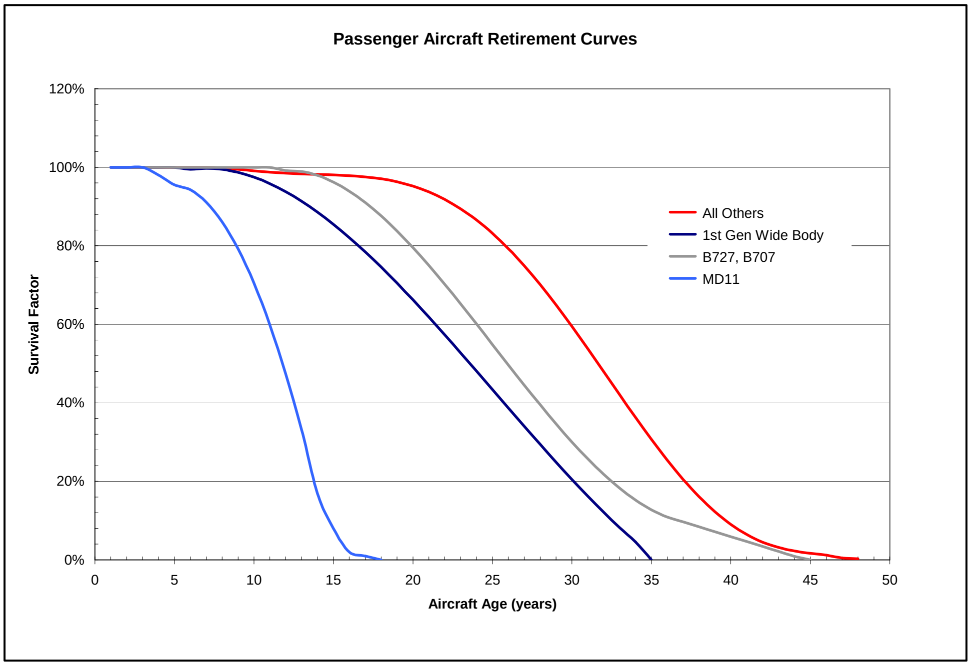

Figure 2. Passenger Aircraft Retirement Curves as a Function of Aircraft Age

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

2.4.2 Development of the Replacement Aircraft Fleet Databases

For the NOx Demonstration analysis, the replacement aircraft fleet databases were derived from the No-Action Jet 9 aircraft best practices database 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 probably 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 process follows the methodology that was approved for CAEP/5 noise modeling. In order to model emissions, each of the engines in these replacement files was assigned an appropriate unique identification (UID) number from the ICAO emissions databank. Using the TL designation spreadsheet from FESG, the process of assigning TLs and the associated distributions has been automated. Once generated, the replacement data for each scenario were assigned a unique key value, and the records were combined into a single aircraft replacements database according to the new forecasting engine data requirements.

2.4.3 Updates to the Forecasting Engine Module

Round 1 of the NOx Demonstration forecasting was performed by adapting the original MAGENTA software to meet the new requirements. Subsequently, a new, dedicated application was developed based on the original algorithms, revised to handle the new Operations database structure. The new engine was also upgraded to use the revised growth, retirement, and replacements database structures that were modified to simplify and streamline the application's input structure.

In addition to the capability of modeling growth, retirement and replacement, the new engine is also capable of generating aircraft replacement records based on user-defined mixes of Best-Practice and existing aircraft types, as required for CAEP modeling of operations in the RoW ("Rest of the World" – non Noise Chapter three phase-out compliant) countries. Given the schedule, however, the development of the new application was targeted to satisfy the NOx Demonstration requirements and, therefore, did not implement all the functionality of the original MAGENTA engine. The capabilities that were omitted were: TAF-based growth values processing, phase-out modeling, user defined targeted replacements, and new FESG cells generation. These capabilities will be added in future development or as dictated by other AEDT-related requirements.

A significant improvement from the original MAGENTA engine is the manner in which aircraft replacements are encoded within the Operations database. In the original MAGENTA system, the replacement aircraft were defined in terms of a relatively limited number of INM aircraft types, and the replacement information was directly appended to the operations data, since it does not add a significant number of records. In AEDT, however, the aircraft replacements are defined in terms of specific aircraft and engine combinations, resulting in a larger number of replacement records and a large number of additional operations records. This causes the system to exceed the maximum size for

DBase database tables, the format utilized to store the Flights database information. The new forecasting software, therefore, does not create a new record for each replacement aircraft, but only one record that stores, in addition to the flight and operations information, a key value that can be used to retrieve the replacement aircraft information appropriate for the scenario being modeled. This approach pushes the burden of generating the replacement aircraft records to the modeling software applications, as they are not processing the entire world operations at once and, consequently, are not likely to exceed the file format limitation. An additional advantage of this approach is that it reduces the number of actual executions necessary to generate multiple scenarios. Whenever multiple scenarios share a common timeline, only one execution of the forecasting engine is required. Once the replacements information for one of the scenarios is generated, all others can be created by making a copy of the database and substituting the replacements key value with the one identifying the different replacement scenario data, thus greatly reducing the system's runtime requirements.

2.5 Aircraft Performance, Fuel Burn and Emissions

The AEDT APM was used to generate both terminal-area (below 10,000 ft Above Field Elevation (AFE)) and en-route (above 10,000 ft Above Field Elevation (AFE)) fuel burn values. This module calculates the terminal-area aircraft performance primarily using the Society of Automotive Engineers (SAE) Aerospace Information Report (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 the Base of Aircraft Data (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.

2.5.1 Terminal Area Calculations

For this analysis, 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 various 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. The module uses the annual average surface temperature, pressure, and humidity from the AEDT Airports weather database as the basis for lapsing to above-airport altitudes within a given terminal area. The 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 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

Emissions Mode	Description
Enroute descent	Airborne segments of approach profiles between Cruise Altitude and above 10000 ft AFE on arrival
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.

2.5.2 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 below. 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	Cruise CAS 1	Cruise CAS 2	Cruise Mach	Descend Mach	Descend CAS 2	Descend CAS 1
LO	250	310	0.78	250	310	0.78	0.78	310	250
AV	250	310	0.78	250	310	0.78	0.78	310	250
HI	250	310	0.78	250	310	0.78	0.78	310	250

Since radar data were not used for this demonstration assessment, a constant altitude and horizontal track dispersed around the Great Circle algorithm 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 radar data. As a result, these distributions allow for statistical mimicking of radar trajectories to provide more accurate results than those based on a great circle route. 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.

The horizontal track distributions were developed using offsets from the Great Circle route. When a dispersed track is picked from the distribution, it is defined by a set of perpendicular offsets from the Great Circle spaced equally along the Great Circle starting at 20% from the beginning and finishing 80% of the way along the flight path. The increments between these two points are in 10% ranges, and these are used to define each segment end point.

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 the code so that head or tail winds could be taken into account 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.

2.5.3 Updates to Performance and Fuel Burn Calculations

The en-route (above 10,000 ft AFE) portions of the gate-to-gate flight trajectories for Round 2 were calculated by SAGE assuming a constant 3-degree (for jets) or 5-degree (for turboprops) glide slope between the cruise altitude and 10,000 ft AFE. The AEDT APM used for Round 3 follows the BADA Airline Procedure speed schedule within this region and the glide slope for each flight path segment is determined using BADA's Total Energy Model. Therefore the calculated glide slopes are a function of the specified speed schedule, the aircraft's performance characteristics, the aircraft's weight, and atmospheric conditions rather than being set to constant values. This change ensures that en-route portions of gate-to-gate flight trajectories more closely follow BADA specifications and therefore potentially improves the accuracy of fuel burn calculations for the descent portions of those trajectories.

For Round 2 of the NOx Demonstration, the flight trajectories were calculated using a previous version of the AEDT performance module using SAE-AIR-1845 methods below 10,000 ft AFE and were calculated using SAGE's implementation of BADA above 10,000 ft AFE. Fuel burn and emissions results from these two methods were subsequently added together without consideration of any potential mismatch between the calculated trajectories at the 10,000 ft transition altitude. For Round 3 the entire gate-to-gate trajectory for each flight was calculated using the AEDT APM, again using 1845 below 10,000 ft and BADA above. The AEDT APM ensures that there are no discontinuities in aircraft speed when the 1845 and BADA trajectories are merged together by adding acceleration or deceleration segments as needed or by changing target speeds. This ensures a continuous, flyable trajectory that is more realistic than two separate trajectories merged at a specific altitude.

The AEDT APM used for the Round 3 analysis sub-segments terminal area trajectories in accordance with SAE-AIR-1845 and ECAC Doc 29, resulting in more points defining flight trajectories in the terminal area than were generated by the previous version of the performance module. It also produces more points defining the en-route (above 10,000 ft AFE) portion of the flight trajectories than SAGE did for Round 2. These additional points provide a higher resolution description of the trajectories and ensure that aircraft weights are decremented more often due to the fuel burned over each flight path segment, resulting in more accurate flight trajectories, thrust levels, and fuel burn values.

In Round 2, the aircraft's weight at 10,000 ft AFE on approach was obtained from SAGE gate-to-gate trajectory results and was given to the AEDT APM to use as a starting weight to calculate the approach trajectory below 10,000 ft AFE. The weight from SAGE included fuel burn numbers using SAGE methods below 10,000 ft AFE on departure that differ somewhat from SAE-AIR-1845 methods. With the Round 3 AEDT APM's strict use of 1845 methods and more realistic descent portions of the trajectories as described above, the weight values used on approach from 10,000 ft AFE to touchdown should be more accurate than the Round 2 values.

2.5.4 Emissions Module

Emissions modeling is conducted through various methods, depending on the specific pollutant. The following emissions were modeled for this demonstration: NOx, Carbon Monoxide (CO), Hydrocarbons (HC), Carbon Dioxide (CO_2), Water (H_2O), Sulfur Oxides (SOx), non-Methane Hydrocarbons (NMHC), Volatile Organic Compounds (VOC), Methane (CH_4), 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 ($PM_{2.5}$).

NOx, HC, and CO are modeled through the use of the Boeing Fuel Flow Method 2 (BFFM2). As described in Baughcum 1996 and ICAO[f] 2005, the method uses fuel flow generated from an external source, such as a performance model, 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[e] 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 as follows:

- CO_2: 3,155 g/kg
- H_2O: 1,237 g/kg
- SO_x: 0.8 g/kg (modeled as SO_2)

The remaining pollutants are modeled as follows:

- NMHC: Set equal to HC
- VOC: EDMS conversion factor based on type of flight
    - All (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)
- CH_4: Not modeled; zero for now
- PM_{10}: FAA first order approximation version 2.0 (FOA) [Wayson 2003]

- $PM_{2.5}$: FAA first order approximation, equivalent to PM_{10}

PM_{10} and $PM_{2.5}$ are modeled identically, since all PM from aircraft have aerodynamic diameters less than 2.5 microns. In modeling these emissions, 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 that are then used to plot EI versus fuel flow plots (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). Due to a lack of SN data for many engines in the ICAO databank, the following scheme was used:

- If only one data point is available, then use that value for all cases.
- If only two or three data points are available, then interpolate/extrapolate as appropriate.
- If no data points are available, then the output is “NULL” indicating that PM cannot be modeled for the engine. For modeling inventories at regional and global levels, the PM emissions are set to zero (0) for the “NULL” cases. In Round 1 of the NOx Demonstration, 13,239 out of a total 2,054,193 operations (<1%) were “NULL”; since aircraft PM was not reported, this has no impact on the NOx Demonstration.

In the future, the ICAO emissions databank will be preprocessed so that all empty entries for SN will be filled using various methods so that the aforementioned interpolation/extrapolation and "NULL" results will not occur. For this analysis, however, only the following emissions were reported: NOx, CO_2, and H_2O.

2.5.4 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.

2.6 Airport (Airside) Delay Modeling

Airport (airside) queuing is modeled using Logistics Management Institute’s (LMI) network queuing model of the US (LMINET) [Long et al. 1999, Stouffer, 2002]. LMINET models airside queuing by using the queuing network shown in Figure 3.

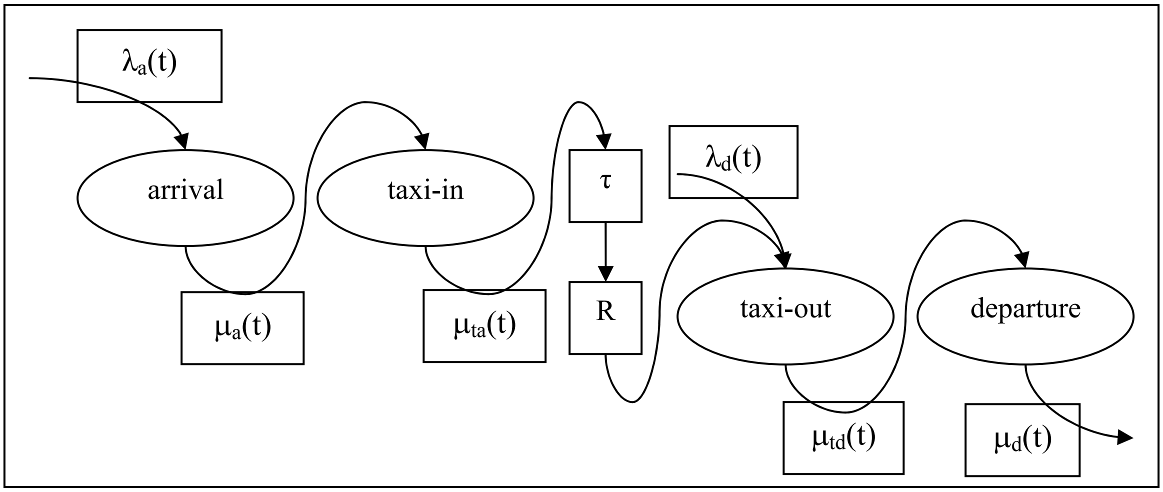

Figure 3. Airside queuing in LMINET

Two queuing processes are depicted in Figure 3, one for arrivals and another for departures. Arrival and departure processes are not independent, and a departure may be released only if there is an available aircraft in the reservoir (R). Arriving aircraft enter the arrival queue as a Poisson process with parameter $\lambda_a(t)$. After being processed by the arrival server, the arriving aircraft enters the taxi-in queue. Upon processing by the taxi-in server, arriving aircraft are delayed for a service time (τ) and released into the reservoir (R).

Departing aircraft are processed by two servers as well. The departure process is driven not only by the Poisson process with parameter $\lambda_d(t)$, but also the state of the reservoir (R). The reservoir balances the total number of arrivals and departures over time. After being processed by the taxi-out server, departure aircraft enter departure queue and, after processing, are released.

Arrival and departure servers may be modeled as M/M/1 or M/Ek/1 queues. Taxi times (both taxi-in and taxi-out) may be modeled as M/M/1 queues only. Arrival $\lambda_a(t)$ and departure $\lambda_d(t)$ demands are determined straight from the schedule. Arrival and departure service rates are determined by taking into account the appropriate airport capacity Pareto frontier based on the weather input (see Figure 4).

LMINET has a limited ability to handle taxi-in and taxi-out queuing. The model allows taxi-in and taxi-out capacities to be considered as constant values over time only.

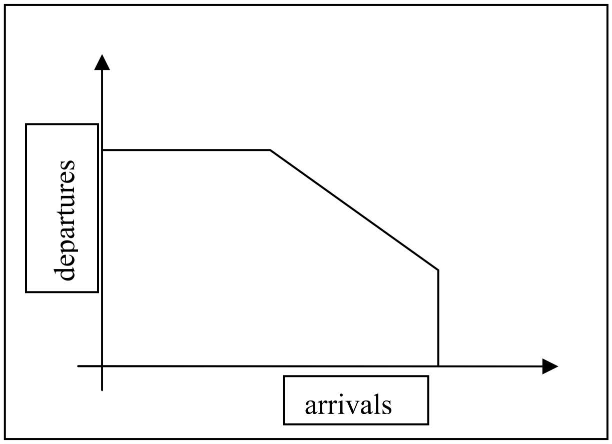

Figure 4. Capacity Pareto frontier

The average airborne and ground delays of arrival and departure aircraft are determined as follows:

$$\overline{t_a(t)} = \overline{t_{u\_in}} + \overline{t_{in}(t)} + \overline{t_{ad}(t)} \tag{1}$$
$$\overline{t_d(t)} = \overline{t_{u\_out}} + \overline{t_{out}(t)} + \overline{t_{dd}(t)} \tag{2}$$

where:

$\overline{t_a(t)}$, $\overline{t_d(t)}$ = average taxi-in and taxi-out times respectively,
$\overline{t_{u\_in}}$, $\overline{t_{u\_out}}$ = average unimpeded taxi-in and taxi out times respectively,
$\overline{t_{in}(t)}$, $\overline{t_{out}(t)}$ = average taxi-in and taxi-out delay times respectively,
$\overline{t_{ad}(t)}$, $\overline{t_{dd}(t)}$ = average airborne delay and runway delay respectively.

3 Documentation of Assumptions

The assumptions made for Round 3 of the NOx Demonstration analysis are given in this section. At the end of the section, a table summarizing these assumptions is provided.

3.1 Forecast Application Assumptions

The AEDT forecast output database was generated based on the following assumptions:

- The modeled stringency would go into effect starting from the baseline year, and
- No records for new Seat Class and Stage Length combinations would be generated in the forecasted year.

3.2 Airside Queuing Assumptions

While airside queuing is modeled, the following assumptions were made due to lack of available data and/or modeling limitations:

- WWLMINET requires a capacity frontier to be supplied for each of the following conditions: VMC, Non-precision, Category I, Category II, and Category III. A predetermined set of capacity Pareto frontiers exist for only 257 worldwide airports, and
- Unimpeded taxi-in and taxi-out times exist for only 75 US airports (ASPM data).

The total number of airports included in the delay modeling for the Round 3 study is 68 (the intersection of the two sets of airports). The list of airports considered in the airside delay modeling is presented in Appendix D.

Due to lack of available data, as well as the WWLMINET's modeling limitations, taxi-in and taxi-out capacities are set to 200 operations/hour (200 came as an initial input setting for all 257 airports modeled by WWLMINET).

Assuming that the input schedule is synchronized, the initial state of the reservoir was set to 500.

WWLMINET selects a capacity frontier based on weather information. To avoid a large data gathering of weather data for various locations, it was assumed for all the airports that operations are done under IMC.

3.3 Emissions Assumptions

For the Round 3 analysis, some assumptions were required due to the lack of available data and to bound the scope of the analysis. The following assumptions were made and apply specifically to the NOx Demonstration Round 3 analysis. The performance and emissions calculations and supporting data implicitly have their own assumptions that are not reiterated in this list.

- Average annual mixing height of 3,000 ft AGL was assumed for each airport;
- An average wind value was available for many airports. For this round, it was assumed that the average wind consisted of a direct headwind and was applied to all aircraft below 3,000 ft. When an average wind value was not available for an airport, 8 kts was assumed;
- All of the runways were assumed to be dry and level;
- With the use of constant altitudes for cruise, step climbs were not modeled;
- Special-use airspace was not modeled;
- Cruise altitude and track distributions were only based on trip distance and jet/turboprop categories;

- Cruise was modeled using a single, constant Mach number based on aircraft type;
- Fuel tanker operations were not modeled;
- No derated takeoffs were modeled;
- For Round 3, airborne and ground delays were modeled for airports where capacity and unimpeded taxi times were available. For these 68 airports, the queuing model was used to calculate taxi-out and taxi-in times for 15-minute time bins, and the average of all these bins for the entire year was used. When the data were not available, 19 minutes of taxi-out and 7 minutes of taxi-in time were assumed;
- For the en-route portion of flight, only one flight track and cruise altitude was used for each origin-destination pair and aircraft type;
- The effects of engine deterioration and time-in-service were not modeled;
- Aircraft weight was assumed to remain constant for each flight segment but gets debited by the amount of fuel burn after each segment (i.e., after each step); and
- A 7% power setting was assumed for taxi operations.

3.4 Aircraft Performance Assumptions

The basis for the AEDT APM is the INM flight performance module. INM standard approach profiles are defined from a starting altitude of 6,000 ft AFE. In order to calculate fuel burn for approach operations starting at 10,000 ft AFE for this analysis, each of the standard INM approach profiles was extended to 10,000 ft by adding an additional segment with a 3-degree glide slope.

Starting weight values for the dynamic procedural profiles were determined through a surrogate method of correlating the OD distance with INM stage weights for departure operations, and through dynamic modeling of both departure and cruise (Section 2.2.2) to debit the weight along the flight path for approaches. The atmospheric data such as temperature and pressure, used in the calculations of the trajectories, were obtained from the annual average surface data from the AEDT airports weather database used as the basis for lapsing to above-airport altitudes. Similarly, airport parameters used in the calculations such as airport elevation and runway gradient were also obtained from the AEDT airports database. Due to the inclusion of fuel burn calculations, the AEDT APM is able to improve on the profile calculation capabilities of the INM by accounting for aircraft weight changes due to fuel burn between each segment of the flight profile.

3.5 Output Assumptions

Since some of the operations were defined from the IOAG, IATA airport codes were used. This resulted in the origin or destination airport being ambiguous in some cases. To resolve this issue, the IATA code and country code were used to uniquely select the appropriate ICAO airport code. The results were aggregated by attributing all of the emissions to the origin airport.

3.6 Assumptions Summary

Table 6. NOx Demonstration Round 3 assumptions summary.

Category	CAEP/6	NOx Demonstration Round 1	NOx Demonstration Round 2	NOx Demonstration Round 3
Process documentation	The process for applying the FESG forecast was not thoroughly documented	Fully documented process from MAGENTA was used, facilitating future re-use of the application	Same as round 1	Same as round 1
Number and scope of the scenarios	Baseline year of 2002 and forecast years of 2006, 2008, 2012, 2016, and 2020 with implementation dates of 2008 and 2012 for stringency levels 5%, 10%, 15%, 20%, 25%, and 30%. For a total of 48 analysis cases.	The FESG forecast was applied to September 2002 data to obtain a September 2020 baseline scenario and a single NOx stringency scenario analysis year of 2020 with an implementation year of 2002.	Same as CAEP/6	Same as CAEP/6 and round 2
Route and Seat Class	Future scenarios used the same seat class of aircraft for existing routes as the baseline scenario and no new route groups were created.	Same as CAEP/6	Same as CAEP/6	Same as CAEP/6 and round 2

Category	**CAEP/6**	**NOx Demonstration Round 1**	**NOx Demonstration Round 2**	**NOx Demonstration Round 3**
Fleet retirement	All retired aircraft were replaced with new deliveries.	Same as CAEP/6	Some retired aircraft will be replaced with used aircraft.	Same as round 2
Mixing height	All airports were assumed to have a mixing height of 3,000 ft AGL.	Same as CAEP/6	Same as CAEP/6	Same as CAEP/6 and round 2
Surface Winds	An 8-knot headwind was assumed for all operations.	Same as CAEP/6	Average annual winds were used and assumed to be a direct headwind	Same as round 2
Runways	All runways were assumed to be dry and level.	Same as CAEP/6	Same as CAEP/6	Same as round 2
Airport elevation	All airports were assumed to be at sea level.	Actual airport elevation was used	Same as round 1	Same as round 2
Surface weather	Standard day conditions (at sea level) were used.	ISA temperatures for the field elevation were used with 60% relative humidity and a specific heat ratio of 1.4	Average annual temperature, humidity, and pressure.	Same as round 2
Altitude / climb profile during cruise	N/A	Constant cruise altitudes and unimpeded climbs	Same as round 1	Same as round 2
Cruise altitude selection	N/A	Based on trip length and jet/turboprop aircraft distinction	Same as round 1	Same as round 2

Category	**CAEP/6**	**NOx Demonstration Round 1**	**NOx Demonstration Round 2**	**NOx Demonstration Round 3**
Special use airspace	N/A	N/A	N/A	N/A
Cruise speed	N/A	Constant mach number was assumed based on aircraft type	Same as round 1 for IOAG flights, otherwise, altitude information from ETMS was used.	Constant mach number was assumed based on aircraft type
Fuel tankering	N/A	Not modeled	Not modeled	Not modeled
Derated takeoff	Not modeled	Not modeled	Not modeled	Not modeled
Ground delays	All aircraft assumed to operate on the ground for 26 minutes (ICAO default value)	Like, CAEP/6, 26 minutes of taxi/idle time was assumed, although this was divided as 19 minutes taxi out and 7 minutes taxi in.	Where airport capacity and unimpeded taxi times are available, a queuing model was used to estimate the average taxi time.	Same as Round 2
Airborne arrival delays	N/A	Not modeled	Not modeled	Not modeled
Effects of engine deterioration	Not modeled	Not modeled	Not modeled	Not modeled
Aircraft weight along its path	N/A (ICAO default times in mode were used).	Weight is debited for each flight segment	Same as round 1	Same as round 2
Taxi thrust	7% for all aircraft	Same as CAEP/6	Same as CAEP/6	Same as CAEP/6 and round 2

4 Output

Standard Output tables are presented below for CO_2, H_2O and NOx. All of the emissions reported are applied back to the departure airport. Tables 7 through 9 show the net change in emissions between the stringency scenario and baseline for each pollutant, stringency scenario, implementation year, and forecast analysis year chosen by the user. The tables show the data separately for each ICAO region chosen by the user, and present the data for the flight regime broken out in three ways, respectively: terminal area, en-route, and entire flight. If additional forecast analysis years or implementation years were added, the data would appear as additional columns. If additional stringency percentages were added, the data would appear as additional rows. The selection of the emissions inventory units is determined by the user.

Table 10 presents for each ICAO region a cumulative ranking of the LTO NOx benefits for each forecast analysis year. All the stringency scenarios selected are ranked in order of increasing net change (greater emission reduction or more negative net change is ranked higher) and shown with the implementation year and stringency percentage.

Figure 5 shows, for a particular stringency, implementation year scenario, the total amount of emissions for the user-specified pollutants, and the number of LTO cycles. The results are broken down into 3 seat classes, and also include the absolute amount and percentage for each seat class. Multiple analysis years are shown according to the years chosen by the user.

Although the tools are capable of reporting the emissions of additional pollutants, including CO, HC, SOx, and PM, since EDS does not yet report the change to those emissions for a given NOx stringency, the results would have little value. Therefore, only NOx, H_2O, and CO_2 are presented in the tables that follow.

The combining of IOAG and ETMS flight schedules and flight plans represent a concerted effort to provide the most comprehensive accounting of all global flights. Due to the inclusion of ETMS flights, most of the unscheduled flights within North America and parts of Western Europe will have been accounted for. Therefore, the inclusion of ETMS data for these regions will likely have resulted in approximately a 10% better estimate of flights for these regions. Since the unscheduled flights (at least for these regions) tend to be made up of smaller aircraft types that burn less fuel, the 10% increase in flights may get propagated through the modeling process and result in less than 10%. Due to other factors, such as emission indices of the engines used on the unscheduled flights, it is currently uncertain how much of the 10% will be reflected in the emissions outputs.

An added result of deriving the aircraft fleet from ETMS data was the inclusion of turboprop and piston aircraft. This accounts for the dramatic increase in the number of flights in the smallest Seat Class (20-99), as shown in Table 7. The results prepared for Round 3 include the emissions from those smaller aircraft. However, in the context of a policy analysis for CAEP, only those engines certified by ICAO would be regulated. The comprehensive fleet (including piston and turboprop aircraft) was included in Rounds 1 and 2 to demonstrate the capability of the system, however for Round 3 only the results from aircraft using “certified” engines are presented.

Table 7 provides a direct comparison with the CAEP/6-IP/13 results. What is most striking about this table is that while for many of the scenarios a greater number of LTOs were modeled, the total NOx in each scenario decreased. The increase in LTOs is likely due to the difference between using the route group-based FESG forecasted operations for this demonstration work and the BACK cycle-based operations in the CAEP/6-IP/13 study. Since the FESG forecasted operations for this demonstration work were based on normalizing OAG and ETMS flights, the inclusion of unscheduled flights from ETMS likely provided a better distribution of OD pairs and by aircraft type as well. These flights were typically made by smaller aircraft, whose total NOx emissions are lower. In addition, as CAEP7_WG2_TG2/4_4_WP10 indicated, the ICAO certification times overestimate the time spent in the LTO cycle.

As previously discussed, the Round 3 results only include aircraft using engines certified by ICAO. This results in a fleet mix that is more similar to the one used for CAEP/6-IP/13.

Table 7. Comparison of NOx Demonstration Round 2-generated results with those from CAEP/6-IP/13 for Baseline scenario (NOx in short tons below 3,000 ft).

	NOx Demonstration Round 2						CAEP/6-IP/13					
Seat Class	**2002**	**2006**	**2008**	**2012**	**2016**	**2020**	**2002**	**2006**	**2008**	**2012**	**2016**	**2020**
20 - 99	21,714	25,623	29,979	38,977	48,747	60,216	12,630	15,507	18,886	26,555	34,255	42,225
100 - 210	108,941	118,327	128,112	148,587	168,354	183,219	148,485	165,375	179,619	210,325	242,176	275,168
211 - 650	66,428	75,587	84,439	104,444	130,688	166,996	108,877	132,888	156,600	216,729	288,356	381,380
Total	**197,082**	**219,537**	**242,531**	**292,008**	**347,790**	**410,431**	**269,992**	**313,770**	**355,105**	**453,609**	**564,787**	**698,773**
% Change from IP13	**-27%**	**-30%**	**-32%**	**-36%**	**-38%**	**-41%**						
Percent of Total NOx												
20 - 99	11%	12%	12%	13%	14%	15%	5%	5%	5%	6%	6%	6%
100 - 210	55%	54%	53%	51%	48%	45%	55%	53%	51%	46%	43%	39%
211 - 650	34%	34%	35%	36%	38%	41%	40%	42%	44%	48%	51%	55%
LTO Counts												
20 - 99	11,389,659	12,072,458	12,784,766	14,242,075	15,784,100	17,483,371	3,615,302	4,500,883	5,448,739	7,608,327	9,735,241	11,911,474
100 - 210	12,753,038	13,734,367	14,741,056	16,636,700	18,241,168	19,325,300	13,596,379	14,764,100	15,700,006	17,746,231	19,926,451	22,284,635
211 - 650	2,173,776	2,540,231	2,871,883	3,613,505	4,605,716	6,082,047	2,986,015	3,534,049	4,045,619	5,299,321	6,812,078	8,693,656
Total	**26,316,473**	**28,347,056**	**30,397,705**	**34,492,280**	**38,630,984**	**42,890,718**	**20,197,696**	**22,799,032**	**25,194,364**	**30,653,879**	**36,473,770**	**42,889,765**
% Change from IP13	**30%**	**24%**	**21%**	**13%**	**5.90%**	**0.00%**						
Percent of Total LTOs												
20 - 99	43%	43%	42%	41%	41%	41%	18%	20%	22%	25%	27%	28%
100 - 210	48%	48%	48%	48%	47%	45%	67%	65%	62%	58%	55%	52%
211 - 650	8%	9%	9%	10%	12%	14%	15%	16%	16%	17%	19%	20%
Pounds of NOx per LTO	15	15.5	16	16.9	18	19.1	26.7	27.5	28.2	29.6	31	32.6
% Change from IP13	-44%	-44%	-43%	-43%	-42%	-41%						

Table 8 not only repeats the NOx emissions below 3,000 ft from Table 7, but expands it by including emissions within the terminal area defined as below 10,000 ft, as well as the total NOx from the entire flight, including cruise. The NOx emissions above 10,000 ft were calculated using the Boeing curve fitting methodologies used for computations in the terminal area. Even though the numbers presented in this table are draft and should not be quoted, it does illustrate possible trends that were not previously available. Some observations are:

- NOx emissions from aircraft below 3,000 ft account for approximately 10 percent of the total NOx from the entire flight. Of which, half of the NOx emissions below 3,000 ft is from 100-210 seat aircraft for local air quality impacts.
- There are less 211-650 seat aircraft than 100-210 seat aircraft, yet the larger aircraft spend more time enroute, thereby producing the most NOx emissions from the entire flight.

Table 8. Baseline NOx emissions according to altitude and entire flight, reported as metric tons and percentage of entire flight for the *entire world fleet*.

NOx Emitted below 3,000 ft AFE – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric Tons	%	Metric Tons	%
20 – 99	14,526	1%	17,779	1%	21,359	1%	28,750	1%	36,760	1%	46,075	1%
100 – 210	87,415	5%	95,254	5%	103,169	4%	119,683	4%	135,531	4%	147,128	4%
211 – 650	55,810	3%	63,168	3%	70,311	3%	86,262	3%	107,074	3%	135,730	4%
Total	157,750	8%	176,201	8%	194,839	8%	234,695	9%	279,364	9%	328,933	9%
NOx Emitted below 10,000 ft AFE – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric Tons	%	Metric tons	%
20 – 99	27,009	1%	32,971	2%	39,519	2%	53,044	2%	67,683	2%	84,659	2%
100 – 210	151,244	8%	164,814	8%	178,691	8%	207,721	8%	235,619	7%	256,061	7%
211 – 650	95,275	5%	108,094	5%	120,573	5%	148,478	5%	184,845	6%	234,966	6%
Total	273,528	15%	305,879	15%	338,783	15%	409,243	15%	488,148	15%	575,687	16%
NOx Emitted during Entire Flight – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric Tons	%	Metric tons	%
20 – 99	80,252	4%	92,459	4%	106,248	5%	134,715	5%	165,407	5%	200,957	6%
100 – 210	775,516	41%	833,527	40%	899,067	39%	1,035,410	38%	1,167,627	36%	1,272,087	35%
211 – 650	1,029,453	55%	1,156,272	56%	1,288,886	56%	1,571,232	57%	1,875,945	58%	2,176,668	60%
Total	**1,885,221**	100%	**2,082,258**	100%	**2,294,201**	100%	**2,741,357**	100%	**3,208,978**	100%	**3,649,713**	100%

Table 9. Baseline NOx emissions according to altitude and entire flight, reported as metric tons and percentage of entire flight for aircraft with *ICAO-certified engines only*.

NOx Emitted below 3,000 ft AFE – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric tons	%	Metric Tons	%
20 – 99	11,589	1%	14,807	1%	18,373	1%	25,740	1%	33,733	1%	43,028	1%
100 – 210	87,404	5%	95,243	5%	103,157	5%	119,671	4%	135,519	4%	147,116	4%
211 – 650	55,810	3%	63,168	3%	70,311	3%	86,262	3%	107,074	3%	135,730	4%
Total	154,802	8%	173,217	8%	191,842	8%	231,674	9%	276,326	9%	325,874	9%
NOx Emitted below 10,000 ft AFE – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric tons	%	Metric tons	%
20 – 99	20,044	1%	25,922	1%	32,438	1%	45,912	2%	60,520	2%	77,471	2%
100 – 210	151,212	8%	164,781	8%	178,658	8%	207,688	8%	235,586	7%	256,028	7%
211 – 650	95,275	5%	108,094	5%	120,573	5%	148,478	5%	184,845	6%	234,966	6%
Total	266,532	14%	298,797	14%	331,669	15%	402,078	15%	480,951	15%	568,466	16%
NOx Emitted during Entire Flight – Baseline												
Seat Class	**2002**		**2006**		**2008**		**2012**		**2016**		**2020**	
	Metric Tons	%	Metric tons	%	Metric tons	%	Metric Tons	%	Metric tons	%	Metric tons	%
20 – 99	64,084	3%	76,069	4%	89,776	4%	118,114	4%	148,737	5%	184,247	5%
100 – 210	775,313	41%	833,320	40%	898,859	39%	1,035,199	38%	1,167,415	37%	1,271,876	35%
211 – 650	1,029,453	55%	1,156,272	56%	1,288,885	57%	1,571,232	58%	1,875,945	59%	2,176,668	60%
Total	**1,868,850**	100%	**2,065,661**	100%	**2,277,520**	100%	**2,724,545**	100%	**3,192,097**	100%	**3,632,791**	100%

The CAEP/6-IP/13 analysis consisted of six increased NOx certification stringencies ranging from 5% to 30%. The implementation for each stringency was evaluated for the years 2008 and 2012. Tables 10 and 11, as well as Figure 5, illustrate the impact of imposing various NOx stringencies at these future years. As expected and in agreement with conclusions from CAEP/6-IP/13, the sooner that a large NOx stringency is imposed (in this case 2008 instead of 2012), the greater the cumulative benefit.

To assist the reader with understanding Tables 9 and 10, and Figure 5, the following brief summary is a refresher of the calculations used in CAEP/6-IP/13. Cumulative change from the Baseline scenario is defined as the sum of the differences in emissions over all years from the implementation year to the given future year, in this case 2020. Years prior to implementation have no difference in emissions, and can therefore be ignored. Emissions for intermediate years were derived from linear interpolation of the emissions for the two nearest years for which emissions were modeled. The baseline has no stringency applied, but includes the effects of traffic growth for the future years. For stringencies implemented in 2008, cumulative change through 2020 can be summarized by equation 3:

Equation 3.
$$\boxed{\begin{aligned} C = &\left[(2.5)S_{2008} + (4)S_{2012} + (4)S_{2016} + (2.5)S_{2020}\right] \\ &-\left[(2.5)B_{2008} + (4)B_{2012} + (4)B_{2016} + (2.5)B_{2020}\right] \end{aligned}} \qquad (3)$$

where:

C = cumulative change,

S_y = total emissions for a given stringency in year y, and

B_y = total emissions for the baseline in year y.

For stringencies implemented in 2012, cumulative change through 2020 can be summarized by equation 4:

Equation 4.

$$\boxed{\begin{aligned} C = & \left[(2.5)S_{2012} + (4)S_{2016} + (2.5)S_{2020}\right] \\ & -\left[(2.5)B_{2012} + (4)B_{2016} + (2.5)B_{2020}\right] \end{aligned}} \tag{4}$$

where:

C = cumulative change,

S_y = total emissions for a given stringency in year y, and

B_y = total emissions for the baseline in year y.

Beyond the comparisons with CAEP/6-IP/13 results and because the NOx Demonstration Round 2 uses common databases and methodologies also used in global analyses, Table 3 also shows how imposing a larger NOx stringency, which likely requires a greater technology level, has a potential tradeoff with CO_2 and water vapor emissions. CO_2 and water vapor are not typically reported in a local air quality analysis; therefore these results only appear relative to the entire flight. Note that the CO_2 and H_2O values for the 15% and 20% stringencies are identical: This is an artifact of the replacements database that slated the same aircraft to be replaced and highlights the need for an updated replacements database.

Table 10. Cumulative NOx reductions according to altitude and for the entire flight.

Cumulative Change in Emissions 2002 through 2020
(Thousands of Metric Tons)

Emissions Below 3,000 ft AFE

	CAEP/6-IP/13		***AEDT NOx Modeling Demonstration***	
Implementation Date	**2008**	**2012**	**2008**	**2012**
Stringency	**NO_x**	**NO_x**	**NO_x**	**NO_x**
5%	(49)	(26)	(17)	(13)
10%	(146)	(78)	(29)	(21)
15%	(197)	(105)	(40)	(27)
20%	(217)	(116)	(43)	(29)
25%	(292)	(157)	(57)	(37)
30%	(321)	(173)	(64)	(41)

Emissions Below 10,000 ft AFE

Implementation Date	**2008**	**2012**
Stringency	**NO_x**	**NO_x**
5%	(28)	(20)
10%	(50)	(33)
15%	(68)	(44)
20%	(74)	(47)
25%	(96)	(60)
30%	(109)	(67)

Emissions for Entire Flight

Implementation Date	**2008**			**2012**		
Stringency	**NO_x**	**CO_2**	**H_2O**	**NO_x**	**CO_2**	**H_2O**
5%	(173)	(1)	(1)	(100)	(3,290)	(1,290)
10%	(323)	(1)	(1)	(181)	(3,290)	(1,290)
15%	(439)	1,077	422	(245)	(2,729)	(1,070)
20%	(481)	1,077	422	(268)	(2,729)	(1,070)
25%	(676)	14,749	5,783	(376)	4,833	1,895
30%	(772)	22,897	8,978	(429)	9,307	3,649

Table 11. Effects of stringency implementation ranked by amount of total NOx reduction.

	Below 3,000 ft AFE		**Below 10,000 ft AFE**	**Entire Flight**
RANK	**CAEP/6-IP/13**	**AEDT NOx Modeling Demonstration**	**AEDT NOx Modeling Demonstration**	**AEDT NOx Modeling Demonstration**
	Stringency	**Stringency**	**Stringency**	**Stringency**
Highest	-30% in 2008	-30% in 2008	-30% in 2008	-30% in 2008
2nd	-25% in 2008	-25% in 2008	-25% in 2008	-25% in 2008
3rd	-20% in 2008	-20% in 2008	-20% in 2008	-20% in 2008
4th	-15% in 2008	**-30% in 2012**	-15% in 2008	-15% in 2008
5th	-30% in 2012	**-15% in 2008**	-30% in 2012	-30% in 2012
6th	-25% in 2012	-25% in 2012	-25% in 2012	-25% in 2012
7th	-10% in 2008	**-20% in 2012**	-10% in 2008	-10% in 2008
8th	-20% in 2012	**-10% in 2008**	-20% in 2012	-20% in 2012
9th	-15% in 2012	-15% in 2012	-15% in 2012	-15% in 2012
10th	-10% in 2012	-10% in 2012	-10% in 2012	-10% in 2012
11th	-5% in 2008	-5% in 2008	-5% in 2008	-5% in 2008
Lowest	-5% in 2012	-5% in 2012	-5% in 2012	-5% in 2012

A sensitivity-type check of the results presented in Table 11 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 12 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 12. 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 5. NOx percent change in cumulative emissions from baseline between 2002-2020 according to altitude

To demonstrate the functionality offered by the NOx Demonstration Round 3 to report emissions by geographic area, Table 13 provides a detailed look at the impact of a 15% stringency imposed in 2008 on annual NOx emissions for a subset of ICAO regions. This table highlights the ability to show differences in traffic levels and fleet mix observed in the different regions. A map of the ICAO regions shown is provided in Figure 6.

Table 13. NOx emissions by year and ICAO region for a 15% stringency implemented in 2008.

Emissions Below 10,000 ft AFE (thousands of metric tons)

Year	Region K	Region C	Region E
2008	97	6.8	45
2012	112	8.0	57
2016	131	9.3	72
2020	153	11	87

Emissions for the Entire Flight (thousands of metric tons)

Year	Region K	Region C	Region E
2008	667	49	314
2012	769	57	383
2016	884	65	451
2020	1,017	72	502

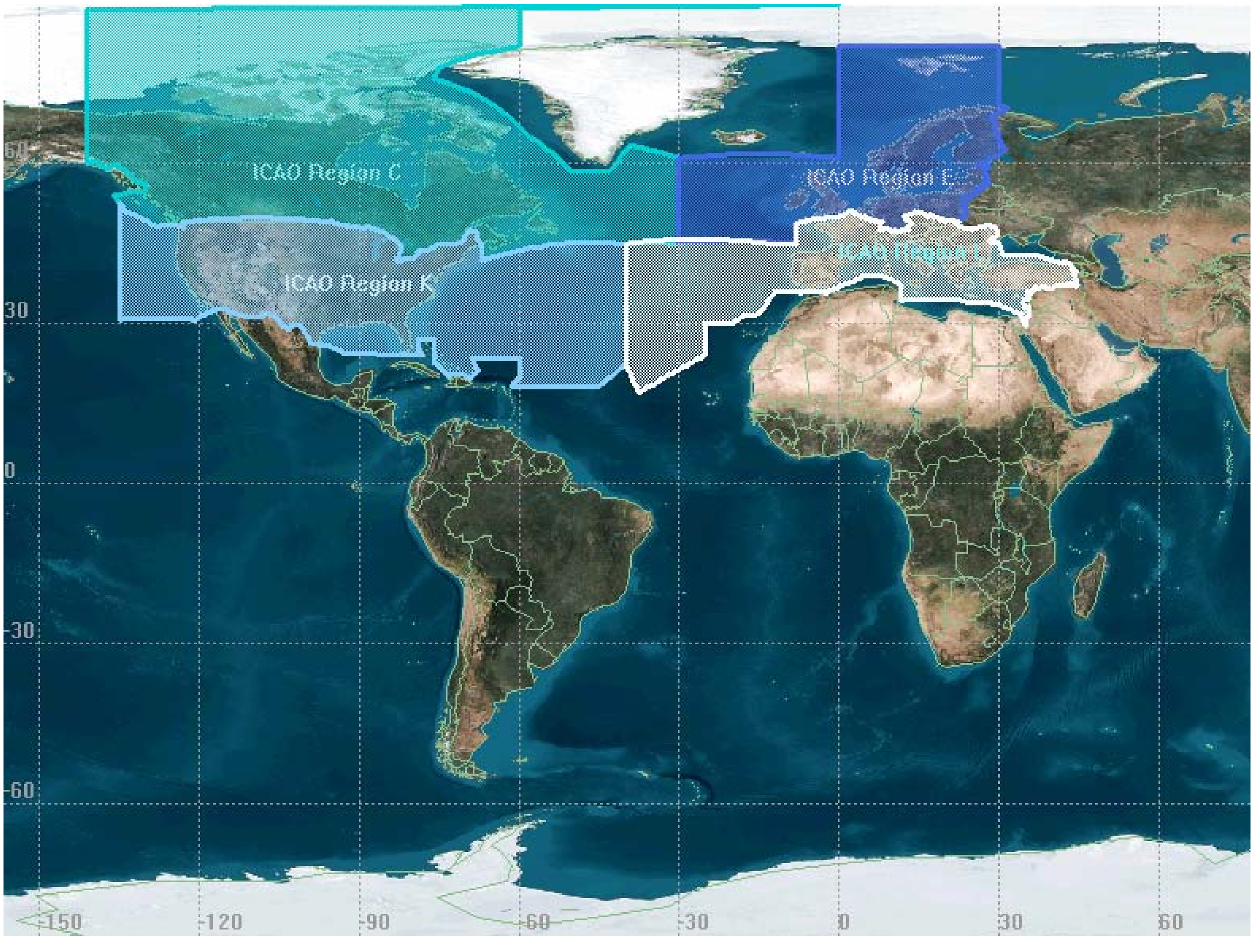

Figure 6. Map of ICAO regions C, E, K, and L

5 Improvements over the CAEP/6 Study

This analysis significantly improves on the analysis performed in support of CAEP/6, IP/13. These enhancements are described in detail in Task Group 2 (TG2) Working Paper 10 (WP10) and are also summarized here.

In this analysis, the BFFM2 was implemented with specific enhancements detailed in ICAO[f]. BFFM2 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 Engine Exhaust Emissions Databank.

The source of the fleet mix and operations has also been improved by applying the IOAG and ETMS data to the FESG forecast. In the past, the total BACK cycles were normalized to FESG levels. By moving to the IOAG and ETMS, it is now possible to aggregate the results in multiple ways, since the origin and destination airports are known. Since the number of operations from the IOAG and ETMS was scaled to match the FESG levels, the total number of operations remains the same for both approaches, but the fleet mix definition is more precise, since unscheduled commercial operations within the ETMS coverage area were also included. Also, the derivation of the fleet and operations data for each stringency scenario using the forecasting engine developed for MAGENTA represents a more methodical and open technique of generating such data.

In addition to these important technical enhancements, significant administrative enhancements are also included. The entire analysis process is being thoroughly documented so that future studies can begin exactly where this study finishes.

In an effort to understand why the results from Round 3 were so dramatically different from the results in CAEP/6-IP/13, a sample of the Round 3 scenarios were run using the ICAO default times in mode. As Table 14 illustrates, the time in mode has a significant influence on the results, but is not the only cause of the differences. The next largest likely source of the differences is the fleet mix that was used. The impact of using meteorological data in conjunction with the performance module was also evaluated. A sensitivity analysis was also performed by looking at the impact on NOx emissions from aircraft at both high and low elevation airports for a variety of temperatures. For most airports, the resultant change in NOx emissions ranged from 1.5% to 3%, with the highest elevation airports experiencing a delta of up to 5%. These results suggest that the use of annual average meteorological data is sufficient and that applying the standard temperature lapse rate based on field elevation for a global analysis is adequate.

Further analysis is required to fully understand how each of the variables contributes to the overall results.

Table 14. Initial quantification of the differences.

Baseline NOx (short tons)*	**2002**	**2006**	**2008**	**2012**	**2016**	**2020**
Performance-based TIM	197,082	219,537	242,531	292,008	347,790	410,431
IP-13	297,615	345,872	391,435	500,018	622,570	770,265
	-34%	**-37%**	**-38%**	**-42%**	**-44%**	**-47%**
ICAO Default TIM	243,151	273,201	302,499	366,433	439,288	521,930
IP-13	297,615	345,872	391,435	500,018	622,570	770,265
	-18%	**-21%**	**-23%**	**-27%**	**-29%**	**-32%**
Contribution to difference	-46%	-42%	-40%	-36%	-33%	-31%

6 *Lessons Learned*

In the hopes of streamlining both the NOx and CDA demonstration processes, the AEDT Development Team has assembled a list of lessons learned from the NOx Demonstration. It is anticipated that these lessons will be leveraged in support of future AEDT demonstrations and development.

1. Some airport codes that were included in the Operations database could not be found in the Airports database during Round 2. In the process of developing the Airports database for Round 3, it was discovered that there were 2 causes of this problem: 1) joint-use airports have separate

identifiers for military operations at the airport vs. civilian operations and 2) typographical errors exist within the ETMS data and it is not practical to correct all of them.

2. Enhanced memory management was implemented for EDMS in Round 2 since reading the operations files required significantly more memory than was required for the IP/13 analysis due to the added level of detail. Since the data was simply too large to be processed on a single PC, 12 computers were used to complete the analysis runs for Round 2. Between Round 2 and Round 3 SAGE and EDMS implemented common aircraft performance and emissions modules. This allowed the Round 3 runs to be completed using the SAGE software and hardware, which was intended for a run of this magnitude.
3. The data contained in the fleet database is currently only intended to support the NOx analysis and does not contain the full fleet data required to support the existing EDMS user base. This needs to be corrected prior to finalizing EDMS 5.0. In the process of developing the EDMS 5.0 fleet database following Round 3, it was discovered that limitations exist in the current aircraft performance data that prevent the aircraft performance module from being able to calculate thrust for certain military aircraft and helicopters. By not fully exercising the data available to the aircraft performance module during the NOx Demonstration phase, this limitation went unnoticed until EDMS 5.0 beta testing was ready to begin.
4. The development of the retirement factors database should be automated for ease of use and quality assurance. Ideally, these retirement curves would be a product of FESG in the future.

5. The forecasting module should determine which aircraft replacement scheme to apply (i.e., use an all new aircraft fleet or a new and old aircraft fleet) depending on each airport regional classification. In previous CAEP studies, airports were grouped based on the replacement scheme they required, and then the two groups were processed separately. During CAEP 5, Mr. Larry Grey assisted in developing percentages to represent the combination of Used and New aircraft commercial carriers in the RoW regions would acquire to cover growth and aircraft retirement. During modeling, the used aircraft replacement fleet was determined by each airport's current fleet. Similar to #4, ideally, guidance and data would be provided by FESG.

6. The 2% fuel burn penalty applied to TL5b aircraft in Round 2 was not entirely consistent with the methodology used in CAEP6 IP/13. This is a result of incomplete documentation of the process used in CAEP6. Although the additional fuel burn was included in the analysis, the associated increase in aircraft weight due to the additional fuel requirement was not considered. Insufficient time is available to correct

this deficiency prior to Round 3, but it will need to be corrected prior to any policy analysis.

7. Microsoft Visual Studio 6 and Visual Studio .NET 2005 are not compatible. MAGENTA, INM, and EDMS have been developed in the Visual Studio 6 environment, but SAGE was developed in the more modern .NET 2005 environment. This has required the shared emissions and performance modules to be maintained in both environments, resulting in additional workload and software development inefficiency. The solve this issue, future versions of MAGENTA, INM, and EDMS will be updated to the .NET 2005 environment.

8. Round 2 of the NOx Demonstration provided results to ICAO that illustrated AEDT's ability to model the entire world fleet of aircraft, including those with turboprop and piston engines. While the demonstration was impressive, it failed to consider the target audience. ICAO does not certify or develop emissions standards for engines with less than 26.2 kN thrust, therefore ICAO is not interested in modeling capabilities outside of their domain.

7 Conclusions

This report shows that the NOx Demonstration successfully confirmed that harmonized databases and methodologies can be used to assess noise and emission simultaneously. During this initial demonstration, many lessons were learned, and the AEDT Development Team can benefit from this enhanced knowledge in preparation for the next modeling capability demonstration.

8 Model Validation and Review of Uncertainties

The uncertainties associated with this NOx assessment can be viewed at varying levels. At the lowest level are the parameters/variables that are used to set conditions and control attributes of the models/tools. At a higher level are the modules that are used to perform certain calculations such as the aircraft performance modules. At the highest level is the AEDT system that includes the contributions from all parameters and modules, and where the uncertainties of the final outputs (e.g., NOx emissions) represent the system uncertainties. Each of these levels needs to be addressed in order to obtain a comprehensive understanding of the uncertainties associated with this NOx Demonstration work. The following sections provide suggestions on the uncertainties at varying levels including a discussion of the relative contributions of the various components.

8.1 Uncertainties Associated with Selected Key Parameters

The starting point for assessing the uncertainties of a modeling system is to understand the sources of uncertainties at the parameter/variable levels. Various work has been performed in the past to try and summarize the errors associated with each of the main parameters [Lee 2005]. Some of these parameters are indicated below:

- Atmospheric parameters include head and tail winds with an estimated sigma value of 12.5 m/s and cruise altitude temperatures with a sigma value of 3.3 K. These types of statistics assume the error distributions are normal.
- Aircraft performance parameters include the BADA aerodynamic coefficients (L/D) with sigma values of about 14% and engine coefficients (TSFC) with sigma values of about 11%.
- Operational parameters include the BADA speed schedules with sigma values of about 5%.
- The uncertainties associated with the certification data for emissions indices (EI) of NOx have been estimated to be about 24% for one sigma.

In general, the higher the uncertainty values (e.g., one sigma), the greater the contribution of uncertainties to the overall system. This is true for the NOx EI values, which after being corrected for atmospheric effects are multiplied by fuel, burn to obtain NOx emissions. But in other cases, a parameter with a high sigma value may have little effect on the overall system uncertainties because of their usage within the modeling scheme. Therefore, to fully understand the relative contributions of the various parameters to system uncertainty, detailed sensitivity and error analyses need to be conducted.

8.2 Uncertainties Associated with Selected Key Modules

8.2.1 Fuel Burn Module

The various AEDT modules used for this NOx Demonstration work can be assessed individually as if they were complete models themselves. The uncertainties of the modules can then be compared to determine relative contributions to the system as a whole. Some of the traditional type of validation work conducted in the past includes efforts to assess the aircraft performance through fuel flow comparisons. Based on a comparison against fuel flow values from NASA and a major US airline, the cruise performance module in AEDT was found to have a mean error of about 7% with a standard deviation of 37% [FAA^b 2005]. Since these comparisons were made using the trajectories and speed data from NASA and the US airline to model within the performance module, the differences are a reflection of just the performance assessment rather than including the effects of different trajectories and operations.

8.2.2 Emissions Module

Unlike the performance-related comparisons, assessments of other modules are more difficult due to the difficulty of obtaining measured data. For example, little at altitude measured emissions data exists. And those that may be available need to be quality checked since measurement are usually conducted at a distance away using a chase aircraft. Hence the measurements are usually in concentration units that need to be verified for accuracy and converted to emission rates using appropriate assumptions. Such data would have the potential for both modular and system level uncertainty assessments.

However, even with no measured at-altitude emissions data, the module could still be assessed through comparisons of modeled EI values to measured values from an engine manufacturer. An indication of this assessment is provided in CAEP 2003 where the accuracy of the curve-fitting method in BFFM2 was found to be within +/-10%.

8.2.3 Flight Schedules

A potential source of significant error in modeling all flights worldwide is the module that handles flight schedules. Mainly because of unscheduled flights, IOAG-based schedules may not account for about 5%-10% of total flights in North America or about 10%-15% of flights over Western Europe. On an airport level, these errors could be significantly higher at some predominantly cargo airports. Therefore, the inclusion of ETMS data allows for the accounting of much of the 5%-10% of unscheduled flights, especially in North America. For other parts of the world that ETMS does not cover, the incorporation of the airport-level scaling factor allows for an artificial accounting of unscheduled flights [FAA[a] 2005]. Even though such accounting of unscheduled flights is a moot point for the overall global number of flights due to the normalization to FESG data, it still allows a better distribution of flights by airports and by region as well.

8.2.4 Forecasting Module

Because forecasting is an inexact science involving many assumptions, any attempts to validate the results will be dubious. However, some cursory comparisons could still be conducted to provide sanity checks of flight counts on global or large-scale regions. Forecasting for CAEP is generally accomplished using the latest FESG projections that start with 2002 as the baseline. Using this baseline, forecasted schedules for 2003, 2004, etc., could be compared against the corresponding historical IOAG data. As an indication of this assessment, a previous comparison check using a week's worth of schedules showed a difference in flight counts of about 1%-4% on a global level for years 2003 and 2004 [FAA[b] 2005]. In these checks, the forecasted schedules for 2003 and 2004 were generated using growth factors derived from FESG projections. Even though normalizations to FESG data were not conducted, the growth factors should have reflected similar effects. Additional years, longer time spans, and fleet comparisons should be conducted to provide better assessments of the forecasting methodologies.

8.2.5 Trajectories and Operations Modeling

Due to the multi-dimensional nature of trajectories and operational parameters (e.g., speed schedules), conducting validation assessments for these modules can be difficult. The current modules use standard-condition procedures for modeling departure and approach movements that tend to be in line with airline-accepted rules. However, issues such as derate can have significant effects on both modular and overall results, especially the LTO portions. For example, the 100% thrust currently employed by the performance module in modeling takeoff to 1,000 ft could be in error by 10% or 20%, depending on the derate level actually employed by airlines [Lee, 2005]. That error would generally propagate proportionally to fuel flow, fuel burn, and ultimately to NOx emissions. Errors in speed and rate of climb would also need to be assessed to obtain a more complete picture of the errors associated with aircraft performance and operations, especially during departure and approach movements. For cruise, since the altitudes and horizontal tracks are assigned from distributions developed from statistically analyzing about a million radar flights, the errors associated with these tracks are reflected within the distributions. Overall, on large-scale modeling (e.g., global), the distributions will provide reasonably accurate representations of the effects of actual trajectories. However, the assumptions concerning constant cruise altitude (i.e., no step climbs) and constant cruise speed need to be assessed.

8.3 Uncertainties of the System

System-level assessments include contributions from various modules and parameters used within the system. Partly because of a lack of at-altitude measured emissions data, the traditional system assessments have involved comparing against fuel burn as this is essentially just one step removed from the emissions calculations. Since a "gold standard" emissions inventory is not available, two surrogates have been used in the past to assess the uncertainties of the system: (1) compare flight-by-flight fuel burn; and (2) compare aggregated airline fuel consumptions. In this regard, past studies have shown that when comparing against fuel burn data from a major US airline and two major Japanese airlines on a flight-by-flight basis, a gate-to-gate system using INM and BADA methodologies show overall mean errors within 3% and standard deviations within about 22% [FAA[b] 2005]. Aggregated comparisons conducted by Boeing using US-DOT's FORM41 fuel consumption data for the top ten US carriers showed that their modeled results (1999 inventory) were an underestimate by about 21% for the aforementioned carriers [Sutkus 2001]. It is expected that this bias could be alleviated to a certain extent by accounting for unscheduled flights and deviations from the Great Circle trajectories that were used by Boeing.

A deeper investigation on a flight-by flight level showed that shorter range flights tended to have higher errors [FAA[b] 2005]. The reason for this is partly due to the fact that the aircraft types used on shorter flights tend to have less-than-exact matches with those within the INM and BADA performance databases. Also, trajectory modeling for shorter flights tend to be less accurate due to the greater variability of tracks for such flights.

8.4 Assessment of Relative Contributions of Component Uncertainties

While the system-level assessments provide an understanding of the accuracy of the end results (e.g., fuel burn as a surrogate for lack of measured emissions data), further assessments can be conducted to determine the relative contributions of uncertainties by the various system components.

Sensitivity assessments can provide an indication of the significant contributors to uncertainty by the relative change to the end results when a parameter or module output is varied. As an example, a previous study has shown that a 1% increase in TSFC can cause a 2% increase in NOx emissions. Approximately similar results can be seen for aerodynamic drag, takeoff weight, and flight speed. However, a 1% increase in ambient temperature appears to cause roughly a 3.5% increase in NOx. By contrast, a 1% increase in cruise altitude results in a 1% decrease in NOx emissions likely due to less fuel use. These results provide an indication of the level of sensitivity for several parameters, but they are specific to a modeled scenario. Specifically, the scenario corresponding to these results involved the use of BADA at a cruise altitude of 35,000 ft with a Mach number of 0.8 for a variety of larger aircraft types [Lee 2005].

Another type of assessment that has previously been conducted to assess relative contributions to uncertainty involved the use of Monte Carlo simulations [Lee 2005]. In these assessments, uncertainty values such as the previously discussed sigma values are first assigned to key parameters, and then allowed to propagate through the system (e.g., AEDT, etc.). By running the simulation multiple times (e.g., thousands of times), a distribution of the system errors can be developed to show that the uncertainty assignments to the key parameters reflect the actual uncertainties and these chosen parameters are the most significant sources of uncertainty. After this confirmation, the end results (fuel burn or emissions) can be regressed on the various input parameters to determine relative contributions to the overall system uncertainty. The preliminary results of analyzing a gate-to-gate model using INM and BADA methodologies have shown that the first and second most significant contributors to system uncertainty for full mission flights are likely the NOx EI values and aerodynamic drag coefficients with the NOx EI accounting for about 45% of the total uncertainties [Lee 2005].

8.5 Applicability to the NOx Demonstration Work

The NOx stringency assessments provide an excellent case study for assessing how model uncertainties in contribute to uncertainties of distinguishing the effects of two stringency levels. Once the emissions benefits of the various stringency options are determined (i.e., as compared to a baseline scenario), the uncertainties of these benefits (or differences) can be estimated. A natural outcome of analyzing differences between scenarios is that the impacts of the large system uncertainties are reduced. Although large uncertainties exist in aircraft performance and trajectories on a flight-by-flight basis, it is possible to distinguish small differences in emissions (a percent or less) for different policy options.

To exemplify such an assessment, a previous study was conducted using smaller, representative datasets as a precursor to the current NOx Demonstration work [Lee 2005]. It was assumed that the following uncertain parameters were common between the two fleets: aerodynamic coefficients and aircraft operations. However, the engine fuel consumption and emissions indices were assumed to be independent between the two fleets.

A Monte Carlo simulation was used to estimate the uncertainty in the prediction of the difference in fleet NOx between the baseline and stringency scenarios. The aircraft types of B727-200, B737-800, B757-200, B767-200, B767-300, B777-200, A300-600, DC10, MD80, MD90 and F100 were included in the simulation. These aircraft types were assumed to represent the NOx emissions characteristics and associated uncertainties in the FESG fleet in part because they represent a good mix of small versus large aircraft and old versus new aircraft.

The variance (σ2) in flight-by-flight NOx delta was calculated for a population of 2000 flights using the 11 aircraft types. To calculate the uncertainty in the change in fleet average NOx emissions, it was assumed that the variance in the flight-by-flight NOx_delta determined for the representative fleet is valid for all aircraft in the fleet. Furthermore, it was assumed that each flight of each aircraft type is an independent random variable. The uncertainty in the change in NOx emissions of a given flight is zero when the aircraft-engine did not have to be replaced under the stringency scenario. The propagated uncertainty is estimated using the square root of the sum of squared σ's of only those aircraft-engine combinations that are replaced due to the stringency option.

The uncertainty in flight-by-flight NOx_delta was propagated for the entire fleet for each combination of stringency level and implementation year. The resulting 95% confidence intervals were attached to each scenario value (% NOx reduction point), as exemplified in Figure 7 for the 2020 forecasts.

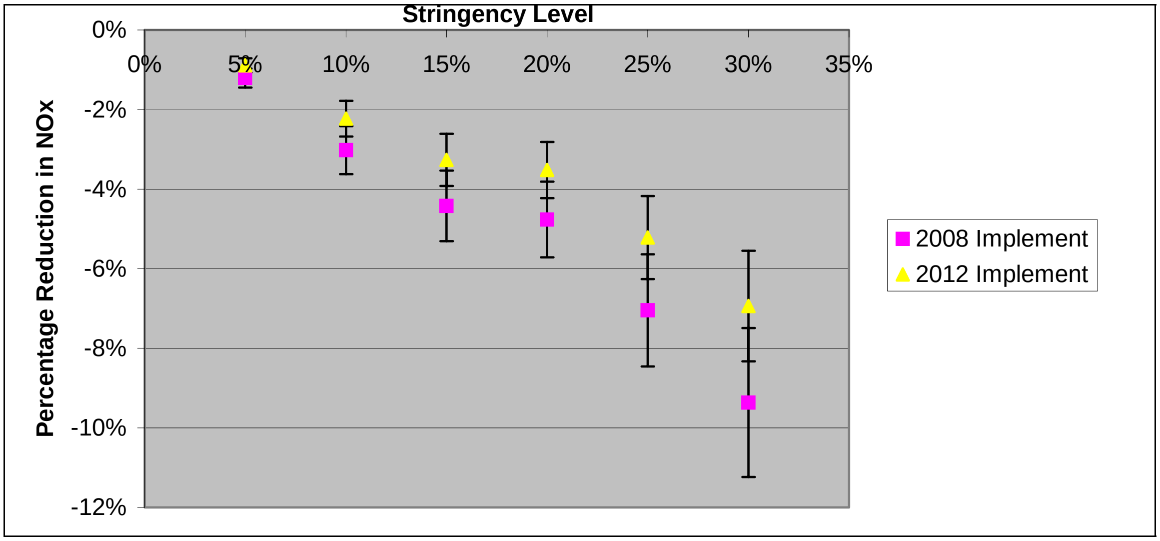

Figure 7. NOx Stringency Scenarios for 2020

The usefulness of such a plot is readily apparent, as it shows that each of the stringency levels results in reductions in NOx that are statistically different from zero based on the 95% confidence intervals. The confidence intervals also indicate that some scenario estimates may not be statistically different from each other given knowledge of the uncertainties inherent in the modeling tool. Such conclusions are important to communicate to policy makers to help make informed decisions. This example assessment illustrates how the absolute uncertainties may not be as important when assessing the relative differences between different scenarios.

8.6 Summary

Although there have been some preliminary assessments that have provided suggestions on the levels of uncertainties at various model levels, the abundance of parameters and modules make it difficult to provide any conclusive statements regarding the uncertainties associated with this NOx Demonstration work. However, educated statements of relative contributions to system uncertainty by model components can be made based on a preponderance of the type of information discussed in the previous sections.

Overall, the larger scale modeling (e.g., global flights) will tend to decrease the mean errors associated with NOx modeling. Therefore, the specific errors associated with more specific items such as the aforementioned shorter flights will tend to have less of an effect, since they generally burn less fuel, produce less NOx, and, as a result, get averaged into the overall results. A general understanding appears to be that the NOx EI values are a significant source of uncertainties, if not the most significant. As such, gaining a greater understanding of the uncertainties associated with this parameter will help to better describe the uncertainties of the end results.

Other significant sources of uncertainty are the flight schedules and fleet mixes. Although the normalization to FESG forecasts indicate that the global number of flights will match the FESG numbers, the indirect coverage of unscheduled flights through the use of airport-level scaling factors will provide a better distribution of the world's fleet. Aircraft performance and operations have also been shown to be potentially significant contributors to uncertainties. But again, on an overall flight level, these errors will likely decrease through the averaging effect. The comparison to data from NASA and the US airline have shown mean errors within 7%.

Because the NOx Demonstration work depends so much on the forecasted projections from FESG, any errors associated in deriving that dataset would be propagated through AEDT. Again, as previously discussed, forecasting is a dubious process and cannot be validated until historical data (e.g., flight schedules) becomes available.

Lastly, although large uncertainties may exist in the various model components, very small differences in fleet emissions (a percent or less) for different policy options can be distinguished. This is possible because the impacts of the system uncertainties are reduced when assessing differences between scenarios. The usefulness of such assessments is evident in being able to identify whether or not the benefits of each stringency level is statistically different from zero and from each other.

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Appendix A. Comparison of EDMS 5.0 Alpha 3 and SAGE 1.5 Predictions

While the focus of the first NOx analysis has been the overall system of software modules and databases required to undertake an integrated and fully documented NOx stringency analysis, an additional benefit is that in some cases multiple sets of data have been developed for similar scenarios. Table A.1 presents a comparison of EDMS and SAGE results below 3000 ft, as well as aggregate SAGE data above 3000 ft. Differences in the assumed weight of the aircraft between EDMS and SAGE are the likely culprit. Analysis of these differences is ongoing using NASA 757 flight recorder data. For analysis round 2, SAGE and EDMS will assume the same departure and arrival weights.

Table A.1. Comparison of EDMS and SAGE Predictions

		Baseline		Stringency	
		EDMS	**SAGE**	**EDMS**	**SAGE**
Below 3,000 Ft	**NOx (kg)**	797,954,262	755,740,302	696,201,754	651,124,999
	SAGE % Diff re EDMS		-5.3		-6.5
Above 3,000 Ft	**NOx (kg)**	(n/a)	6,634,362,209	(n/a)	6,337,193,636
	Stringency % Diff re Baseline				-4.5