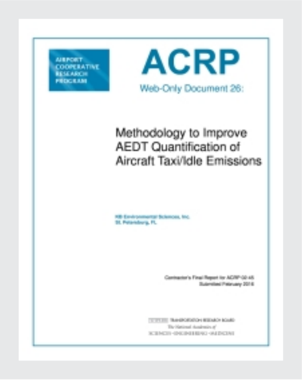

Methodology to Improve AEDT Quantification of Aircraft Taxi/Idle Emissions

DETAILS

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Executive Summary

Within the current framework of the Federal Aviation Administration (FAA) Aviation Environmental Design Tool (AEDT) is the simulation of commercial jet engine taxi/idle conditions, producing an estimate of the emissions that would result under these low-thrust conditions. Presently, the model defines the standard thrust setting for this operational mode at seven percent of full thrust, based on International Civil Aviation Organization (ICAO) engine test conditions. However, relevant research and observations suggest that the thrust settings in actual practice may differ from this value. Other factors that may also affect taxi/idle emissions include aircraft size, engine type, airport layout, and meteorological conditions.

Based on these factors, the primary objectives of this ACRP Research Project was to develop and provide the following:

Primary Objectives

- A prioritized list of potential improvements to AEDT that will improve the predictive accuracy for estimating jet aircraft emissions during the taxi/idle phase of operation; and
- Detailed documentation of select near-term, high-priority improvements to AEDT.

For the purposes of this research, the Research Team targeted three fundamental elements (i.e., factors) within the current AEDT framework that the model uses to calculate aircraft engine emissions during the taxi/idle mode. These factors are identified and represented as follows:

Taxi/idle emissions = TIM x FFR x EI *Where*:

- Time-in-mode (TIM) = the time aircraft engines are operating in the taxi/idle mode (seconds);
- Fuel flow rate (FFR) = the rate of fuel intake (kilograms (kg) per second); and
- Emission index (EI) = the emissions generated per mass of fuel burned (grams (g) per kg of fuel burned).

Based upon the outcomes of the research, the following improvements to AEDT are proposed:

Proposed AEDT Improvements

Factors	Parameter(s)	Improvement Option(s)	Priority (Near-/Long-Term)
Time-in-mode (TIM)	Default taxi time	1) Change default taxi in and taxi out times to values derived for all airports. --*7 minutes taxi in / 16 minutes out*	Near-term
		2) Provide user query for type of airport and number of runways in GUI – link to new database.	Long-term
		3) Default to average of five years of data for specific airport being evaluated.	Long-term
	Default taxi speed	1) Change default assumption to weighted average value based on FDR data. -- *11 knots (12.66 mph)*	Near-term
		2) Allow users to indicate whether a taxiway is used for aircraft taxiing in or out. -- *13 knots (14.96 mph) for taxi in taxiways and 10 knots (11.51 mph) for taxi out taxiways*	Long-term

Factors	Parameter(s)	Improvement Option(s)	Priority (Near-/Long-Term)
Fuel Flow Rate (FFR)	--	1) Adjust FFRs in databases only for those aircraft for which there are FDR data.	*
		2) Adjust the FFRs for those aircraft for which there are Flight Data Recorder (FDR) data or for which the data are representative.	*
		3) Use a single, global adjustment to all commercial jet engines.	Near-term
Emission Indices (EI)	Carbon monoxide (CO) and hydrocarbons (HC)	1) Apply a global adjustment factor assuming all engines CO and HC EIs follow same temperature/FFR dependence as the CFM56-7B family of engines.	Near-term
		2) Apply an engine specific adjustment factor.	*
		3) Apply adjustment factors only to the CFM56 family of engines.	*
	Nitrogen oxides (NOx)	There is only one option to adjust emissions of NOx. To what engines it would be applied would depend on the FFR adjustment option described above.	Near-term
Additional considerations	Assumptions regarding single/reduced engine taxi procedures to be included in modeling	When selected by user, apply factor of 0.995 to FFRs for taxi in operations and 0.96 to FFRs for taxi out operations.	Near-term
	Allow for e-taxi procedures to be included in modeling	Allow users to specify the percentage that taxi-related emissions should be reduced.	Long-term
	Emission distribution across airfield	Allow users to define areas other than the runway queue area where aircraft are delayed.	Long-term

* This improvement is considered to be an alternative to the recommended near-term improvement.

With the exception of the improvements to the emission indices for carbon monoxide (CO) and hydrocarbons (HC) and only if this improvement is considered in isolation, all of the near-term improvements listed above would reduce estimates of the emissions associated with commercial jet engine taxi/idle conditions. The magnitude of the reduction would depend on the number of (i.e. combination of) improvements incorporated in to the AEDT.

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Initialisms and Acronyms

AAFEX	Alternative Aviation Fuel Emissions Experiment
AAM	Aircraft Acoustic Module
ACRP	Airport Cooperative Research Program
AEDT	Aviation Environmental Design Tool
AEE	Office of Environment and Energy
AEM	Aircraft Emissions Module
APE	Aerospace Particulate Emissions
APEX	Aircraft Particulate Emissions Experiments
APM	Aircraft Performance Module
APU	Auxiliary Power Unit
ASIF	AEDT Standard Input Format
ASPM	Aviation Policy's Aviation System Performance Metrics
ATC	Air Traffic Control
AWP	Amplified work plan
BTS	Bureau of Transportation Statistics
C_2H_4	Ethene
CAA	Clean Air Act
CRUD	Create, Read, Update, Delete
CO	Carbon monoxide
ECAC	European Civil Aviation Conference
EDMS	Emissions and Dispersion Modeling System
EGTS	Electric Green Taxiing System
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FID	Flame Ionization Detection
FSC	Fuel sulfur content
GSE	Ground support equipment
GUI	Graphical Users Interface
HAPs	Hazardous air pollutants
HC	Hydrocarbons
HCHO	Formaldehyde
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
ISA	International Standard Atmosphere
LTO	Landing-Takeoff Cycle
MAGENTA	Model for Assessing Global Exposure to the Noise of Transport Aircraft
NAAQS	National Ambient Air Quality Standard
NEPA	National Environmental Policy Act
NIRS	Noise Integrated Routing System
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen oxides
PMFO	Fuel organics particulate matter
PMNV	Nonvolatile particulate matter
PMSO	Volatile sulfates particulate matter
ROG	Reactive organic compounds
RPM	Revolutions per minute
SAGE	System for Assessing Aviation's Global Emissions
SO_2	Sulfur dioxide

SOx	Sulfur oxides
THC	Total hydrocarbons
TIM	Time-in-mode
TOG	Total organic gases
UHC	Unburned hydrocarbons
UK	United Kingdom
US	United States
VOC	Volatile organic compounds

1. Introduction

Over the past two decades, considerable emphasis has been placed on the potential effects of airport-related air emissions on ambient (i.e., outdoor) air quality. In response to this concern, an increased reliance on computer models has emerged as a means of assessing this impact. The most commonly relied-upon computer model is the Federal Aviation Administration's (FAA's) Aviation Environmental Design Tool (AEDT), which officially replaced the FAA's previous model – the Emissions and Dispersion Modeling System (EDMS) - on May 29, 2015.

NOTE: The reviewer should note that the initiation of this research pre-dated the sunset of the FAA EDMS model and, therefore, the research title still contains reference to EDMS. Since the sunset of EDMS has now occurred, this Final Report refers only to the AEDT model tool, unless the specific reference requires noting some aspect of the no-longer-in-use EDMS model.

Within the current framework of AEDT is the simulation of commercial jet engine taxi/idle conditions, producing an estimate of the emissions that would result under these low-thrust conditions. Presently, the model defines the standard thrust setting for this operational mode at seven percent (7%) of full thrust, based on International Civil Aviation Organization (ICAO) engine test conditions. However, other research and observations suggest that the thrust settings in actual practice may differ from this value. Other factors that may also affect taxi/idle emissions include aircraft size, engine type, airport layout, and meteorological conditions.

Based on the above, the primary objectives of the ACRP 02-45 (*Methodology to Improve EDMS/AEDT Quantification of Aircraft Taxi/Idle Emissions*) Research Project was to develop and provide the following:

Primary Objectives

- A prioritized list of potential improvements to AEDT that will improve the predictive accuracy for estimating jet aircraft emissions during the taxi/idle phase of operation; and
- Detailed documentation of select near-term, high-priority improvements to AEDT.

To achieve these primary goals, three main areas of research were considered important to the successful outcome of the project. They were as follows:

Main Areas of Research

- An assessment of "real-world" in-service engine performance data compared to AEDT modeling assumptions;
- An evaluation of model inaccuracies and the implications to emissions inventories; and
- Collection and evaluation of stakeholder feedback from subject matter experts on modeling, aircraft emissions, and airport operations.

In order to accomplish the goals and cover the intended research areas of the ACRP 02-45 project, the Work Plan was subdivided into an 11-task assignment, the first three of which were entitled as follows:

Initial Tasks

- Task 1: *Literature Review*,
- Task 2: *Review of AEDT Modeling Inputs*, and
- Task 3: *Task 1 and 2 White Paper* (originally published in 2013 as a separate document and included in this *Final Report* as **Appendix A**).

The findings and results from those first three tasks were intended to serve as the basis and guidance for developing the scope of work and methodology for the subsequent research tasks, as described in later sections of this *Final Report*.

By way of background, it is noteworthy that the 02-45 Research Project was aimed principally at addressing emissions resulting from the operation of commercial jet aircraft during the taxi/idle mode.[1,2] The primary emphasis is on the emissions inventory components of AEDT, although the dispersion modeling capabilities of the model were also considered.

The pollutant types (and their precursors) addressed in the research primarily comprise the following:

- Carbon monoxide (CO),
- Nitrogen oxides (NO_x), and
- Volatile organic compounds (VOCs).[3]

Emissions of sulfur oxides and carbon dioxide (CO_2) were considered, but only with respect to the emission rates of these pollutants as they relate to fuel flow. Similarly, emissions of hazardous air pollutants (HAPs) were also considered, but only as they relate to emissions of VOCs. Finally, because aircraft-related emissions of particulate matter (PM) equal to, or less than 10 micrometers (PM_{10}), and PM equal to, or less than 2.5 micrometers ($PM_{2.5}$), are being studied by others (i.e., E-31, the SAE International Aircraft Exhaust Emissions Measurement Committee, and the European Aviation Safety Agency), emissions of PM were not addressed as part the ACRP 02-45 project.

2. Task 1 & 2 Results: Literature Search and Review of AEDT Model Inputs

The initial two tasks conducted to help address the ACRP 02-45 research objectives were to (i.) review and summarize relevant scientific and industry literature, published guidance, and other pertinent research on the combined topics of aircraft taxi/idle emissions and AEDT (i.e., the Task 1, *Literature Review*) and to (ii.) review the relevant assumptions, algorithms, database coverage, and outputs of AEDT (the Task 2, *AEDT Review*). The outcomes from these tasks were published in a separate *Working Paper* and accompanied by a comprehensive annotated bibliography prepared under Task 3.[4]

The information from Tasks 1 and 2, as summarized in the working paper at **Appendix A**, served as the foundation upon which the ACRP 02-45 research proceeded. Importantly, the Research Team was mindful of the following questions during the course of the literature and AEDT reviews, because the corresponding answers were necessary to develop a prioritized list of potential improvements to AEDT:

Guiding Research Questions

- What are the factors that affect an aircraft departing an airport from the time the aircraft leaves the airport's gate until the aircraft reaches a runway (i.e., the taxi out process)?
- What are the factors that affect an aircraft arriving at an airport from the time the aircraft exits a runway until the aircraft reaches a gate (i.e., the taxi in process)?
- What thrust settings do pilots use for aircraft engines during the taxi out/in process?
- Are there readily available air pollutant/pollutant precursor emission indices for low engine thrust settings other than those already in the AEDT databases?

---

[1] Other aircraft operational modes included in AEDT comprise take-off, landing, and cruise, which are not addressed as part of the 02-45 research.

[2] Other airport-related emission sources, such as ground support equipment (GSE), auxiliary power units (APUs), fuel storage facilities, motor vehicles, and stationary sources (i.e., boilers, emergency generators, incinerators, etc.) are also not included as part of the 02-45 research.

[3] For the purposes of this document, the terms VOCs and hydrocarbons (HC) are used interchangeably.

[4] That working paper is included in its original form as *Appendix A* to this *Final Report*.

- Do the current databases, input variables, algorithms and sub-models of AEDT provide a reasonable estimate of taxi-related emissions?

To answer these questions, the literature review focused on the following four categories of information:

Information Categories

- *Aircraft Performance Characteristics* – including aircraft taxi/idle times-in-modes under alternative airfield conditions, single-engine taxi procedures, flight data recorder (FDR) data, etc.;
- *Aircraft Engine Emissions* – including ICAO reference fuel flows and emission indices, aircraft engine emissions and ambient measurements, etc.;
- *AEDT Performance and Development* – including model architecture, development programs and timeframes, model accuracy and sensitivity tests, etc.; and
- *Regulatory Framework* – including the FAA's rules/regulations that relate to the taxi process and the requirements of the National Environmental Policy Act (NEPA), the federal Clean Air Act (CAA), and other state/local requirements as they pertain to airport emissions and ambient air quality.

Based on the findings of the literature search and review of model inputs in Tasks 1 and 2, some additional issues, or research "gaps," in need of resolution were also identified. In addition to these research "gaps," the Task 3 *White Paper* identified potential model inaccuracies revealed in the review. **Table 1** below summarizes those findings relative to potential model inaccuracies and their possible impact on taxi/idle emission predictions. For detailed discussion of those issues, the reviewer is referred to the complete Task 3: *(Working Paper)* included as **Appendix A**.

Table 1
Summary of AEDT Shortcomings Related to Taxi/Idle Emissions

Shortcoming	Impact
AEDT assumptions regarding the duration of taxi/idle modes are not representative of actual conditions.	Differences in actual emissions and AEDT emissions are (at least) directly proportional to differences in the duration of taxi/idle modes.
AEDT assumes fixed fuel flow rates during taxi/idle based on seven percent thrust.	Actual fuel flow rates vary considerably and emission indices are a function of fuel flow rate.
AEDT uses one emission index value for each pollutant.	Actual emission indices are complex functions of fuel flow rate, ambient temperature, and other factors.
AEDT does not account for variations in operational practice, including tug assisted single-engine (i.e., reduced engine) or electric taxiing.	Discrepancies between actual and AEDT assumed operating patterns directly impact the accuracy of model estimates.

3. Research Approach and Findings

Based largely upon the outcomes of the Task 1 *Literature Search* and Task 2 *AEDT Review*, the subsequent research tasks were entitled and performed as follows:

Subsequent Tasks

- Task 4: *Analysis of In-service Engine Performance Data*
- Task 5: *Evaluate the Implications of Model Inaccuracies*

- Task 6: *Develop List of Potential AEDT Improvements*
- Task 7: *Stakeholder Outreach*
- Task 8: *Interim Report*
- Task 9: *Identification of Near-Term Model Improvements*
- Task 10: *Steps Needed for Implementation*
- Task 11: *Final Report*

Notably, for the interrelated Tasks 4, 5 and 6 designed to develop the initial list of potential model improvements, the Research Team targeted three fundamental elements (i.e., factors) within the current AEDT framework that the model uses to calculate aircraft engine emissions during the taxi/idle mode. These factors are identified and represented as follows:

Targeted Aircraft Taxi/Idle Emission Variables

Taxi/idle emissions = TIM x FFR x EI

Where:

- Time-in-mode (TIM) = the time aircraft engines are operating in the taxi/idle mode (seconds);
- Fuel flow rate (FFR) = the rate of fuel intake (kilograms (kg) per second); and
- Emission index (EI) = the emissions generated per mass of fuel burned (grams (g) per kg of fuel burned).

The remainder of this section discusses each of these factors in detail, including how the Research Team evaluated options for improving the model's treatment or consideration of each one. There is also a discussion of potential model improvements not directly related to the three factors which are discussed under a fourth category termed "Additional Considerations." For ease of review, **Table 2** provides a summary of this information.

3.1 Time-in-Mode

In its current configuration, AEDT considers aircraft taxi/idle time-in-mode two different ways, depending on whether the model is being used to (i.) only prepare an emissions inventory or to (ii.) perform atmospheric dispersion modeling (which also provides an emissions inventory). These two methods are summarized as follows:

- **Emissions Inventory** – When only an emissions inventory is being prepared, model users are instructed to input airport/aircraft-specific values (or use default values) of taxi times (i.e., taxi-in and taxi-out), defined as the amount of time required for an aircraft to taxi to/from an airport's terminal gate and/or runway. These values include periods of aircraft delay encountered along the way.
- **Dispersion Modeling** – When dispersion analysis is performed, model users are required to input a value (or use default) for the aircraft taxi speed. Under this option, the model performs Delay and Sequence Modeling which uses airport operational schedules, runway configurations, and the airport's capacity to estimate taxi/idle times and delay periods.

Because the AEDT default taxi/idle time-in-mode represents a potential source of inaccuracy in computing aircraft taxi/idle emissions, this parameter was the focus of further analysis, as discussed below.

3.1.1 Default Taxi Times

Presently, the AEDT default aircraft taxi/idle (i.e., taxi-in, taxi-out and delay) times-in-mode are set to 7 minutes for taxi in and 19 minutes for taxi out (a total of 26 minutes). These values, dating back to the

1980s, were derived from the U.S. Environmental Protection Agency's (EPA's) *AP-42, Compilation of Air Pollutant Emission Factors* as being typical durations for civil aircraft (i.e., commercial jumbo, long-range, and medium-range jets) operating within the standard landing/take-off (LTO) cycles at large congested metropolitan airports.

In search of an alternative to these default values, it is instructive to know that AEDT also has an internal database containing airport-specific taxi-in and taxi-out times. While there are a substantial number of airports included in the list (i.e., 75 airports), the number of years for which taxi data are provided varies by airport and the values are also somewhat out of date, with the most recent data being from 2006.

To improve modeling taxi times, the Research Team extracted five years of taxi data for the 74 commercial service airports contained in the FAA's Aviation System Performance Metrics (ASPM) Database that have these data. For the purposes of this analysis, the ASPM's actual taxi times from this database, which include unimpeded taxi times and delay periods (i.e., impeded taxi times), were used.

Based on the outcome of this analysis, three options were developed that, if implemented, could improve the simulation of aircraft taxi/idle times in AEDT and thus also improve the accuracy of an emissions inventory computed using these data.[5] These taxi time options are described below.

Aircraft Taxi Time Options

- **Option 1** – Update the AEDT default values using the average taxi in/out times computed from the ASPM data. As shown in **Table 3**, these values vary somewhat by airport size (i.e., large, medium, small) and number of runways, but trend toward overall averages of 7 minutes for taxi in and 16 minutes for taxi out. This option would reduce the default taxi/idle times (and the resultant emissions) by 12 percent when compared to the current default values and would apply to all aircraft, not just those equipped with commercial jet engines.

- **Option 2** – Under this option, AEDT users would select default taxi in/out times based on an array of airport-specific design characteristics, including: (i.) the number of runways, (ii.) whether an airport is a hub or non-hub, and/or (iii.) for hub airports, the size of the airport (i.e., large, medium, and small). Again, as shown in **Table 3**, while taxi/idle times and the resultant emissions would increase at several airports (i.e., 5 of the 75 airports) and remain the same at several more (5 to 6, depending on the selected method), taxi/delay times and the resultant emissions would decrease from 4 percent to 50 percent at the majority of the airports when compared to the current AEDT default values.
- **Option 3** – The current version of AEDT apparently does not use the airport-specific database of taxi in/taxi out times from the EDMS database that are out-of-date. Under this option, that database would be expanded to include more airports and updated using average taxi times (including delay periods) obtained from the most recent five years of data from the ASPM. These data are listed in **Table 4**, where they are compared with the current default values. With the exception of six airports, these data would decrease aircraft taxi/idle times (and the resultant emissions predictions) from 4 percent to 50 percent at the majority of the airports, when compared to the current default values.

Notably, although the 02-45 Research Project is only addressing taxi/idle emissions that result from the operation of commercial jet aircraft, the taxi time options described above can be assumed for all aircraft operating at an airport (i.e., jets, turboprops, and props).

---

[5] When conducting dispersion modeling using AEDT, aircraft taxi times are computed based on input values of taxi speed and aircraft delay which is calculated using an internal Delay and Sequence Modeling mechanism.

Table 2
AEDT Taxi/Idle Emission Improvement Research Approach

Taxi/Idle Emissions Computational Factors	Research Parameter(s)	Research Accomplishments	Improvement Option(s)
Time-in-mode	Default taxi time (criticall for AEDT users that use the default time-in-mode option) *- Currently 7 minutes taxi in and 19 minutes taxi out.*	Extracted five years of taxi data for the 74 commercial service airports for which there is data in the ASPM. Using this data, the following were derived: ▪ Averages for taxi in and out for 1) all airports (hub plus non-hub) and 2) based on the number of runways. ▪ Averages by 1) type of airport (hub, non-hub) and 2) type of airport based on the number of runways. ▪ Averages by size of hub airport (large, medium, and small). ▪ Five year averages for each of the 74 airports.	1) Change default taxi in and taxi out to values derived for all airports. *--7 minutes taxi in / 16 minutes out*
			2) Provide user query for type of airport and number of runways in GUI – link to new database. -- *Values in Table 3*
			3) Default to average of five years of data for specific airport being evaluated. -- *Values in Table 4*
	Default taxi speed (important for AEDT users that evoke the dispersion modeling option) *- Except for queue area before departure, AEDT assumes aircraft taxi at one speed (default 15 knots (17.26 mph)). Users may also enter aircraft specific speeds.*	Reviewed 258,824 data samples from FDR data (1,800 aircraft operations—mostly Airbus from European carrier).	1) Change default assumption to weighted average value based on FDR data. -- *11 knots (12.66 mph)*
			2) Allow users to indicate (or the model to distinguish) whether a taxiway is used for aircraft taxiing in or out. -- *13 knots (14.96 mph) for taxi in taxiways and 10 knots (11.51 mph) for taxi out taxiways*
Fuel Flow Rate (FFR)	FFR *- Actual FFRs can be higher or lower than those listed in engine-specific ICAO datasheets for operation at 7 percent thrust. Rates are positively correlated with thrust setting and bleed flow. Furthermore, a range of FFRs is used during idle, not just a fixed single value.*	Reviewed 258,824 data samples from FDR data (1,800 aircraft operations--mostly Airbus from European carrier) and data from APEX2, APEX3, and ACRP 02-03a.	1) Adjust FFRs in databases only for those aircraft for which there are FDR data (varies between 80 and 111 percent of ICAO idle value for taxi in and between 90 and 113 percent for taxi out). -- *Values in Table 6* 2) Adjust the FFRs for those aircraft for which there are FDR data or for which the data are representative. -- *Values in Table 6 and list of engines in Table B-4* 3) Use a single, global adjustment to all commercial jet engines. -- *92 percent of an engine's ICAO idle value*
Emission Indices	CO and HC *- Note: EIs should be adjusted only if FFRs are adjusted.*	Reviewed studies that address dependence of CO and HC on FFR and ambient temperature including: ACRP Report 63, Project 02-03a. (*Measurement of Gaseous HAP Emissions from Idling Aircraft as a Function of Engine and Ambient Conditions*). Yelvington, P. E.; Herndon, S. C.; Wormhoudt, J.; Jayne, J. T.; Miake-Lye, R. C.; Knighton, W. B.; Wey, C., Chemical Speciation of Hydrocarbon Emissions from a Commercial Aircraft Engine. Journal of Propulsion and Power 2007, 23 (5), 912-918.	1) Apply a global adjustment factor assuming all engines CO and HC EIs follow same temperature/FFR dependence as the CFM56-7B family of engines. -- *Factor varies depending on ambient temperature (Figure 1)* 2) Apply an engine specific adjustment factor. -- *Factors vary depending on engine (Table 6 and Figure 1)* 3) Apply adjustment factors only to the CFM56 family of engines. -- *Factor varies depending on ambient temperature (Figure 1)*
	NOx	Reviewed studies that address the dependence of NOx on fuel flow and ambient temperature, including documentation for Boeing Fuel Flow Method 2.	There is only one option to adjust emissions of NOx. To what engines it would be applied would depend on the FFR adjustment option described above.
Additional	Assumptions regarding single/reduced engine taxi procedures to be	Discovered very few documents or sources to address the extent to	When selected by user, apply factor of 0.995 to FFRs for taxi in

considerations	included in modeling.	which reduced taxi procedures are in use or provide data to indicate the percentage of time or frequency when aircraft are taxied with fewer than all engines.	operations and 0.96 to FFRs for taxi out operations.
	Allow for e-taxi procedures to be included in modeling.	Discovered very few documents to address the emissions benefit, or provide data to support the emissions benefit, of alternative taxi systems.	Allow users to specify the percentage that taxi-related emissions should be reduced.
	Emission distribution across airfield. *Constant thrust assumption (i.e., should the taxi/idle thrust values vary across airfield idle/taxi phase (e.g., x min @ 4 percent thrust and y min @ 12 percent thrust) or is a single thrust assumption sufficient?)*	Not applicable	Allow users to define areas other than the runway queue area where aircraft are delayed (e.g., crossing active runways, ramp area where aircraft are held waiting for gate, deicing area).

Table 3
ASPM Aircraft Taxi Times

Airport Size	No. of Runways	No. of Airports	Average Time (min.)		Percent Change in Taxi/Idle Times (and Emissions)[a]
			Taxi In	Taxi Out	
All	1-8	74	7	16	-12
	1	2	4	13	-35
	2	20	5	15	-23
	3	21	6	14	-23
	4	21	7	16	-12
	5	5	9	17	0
	6	3	8	17	-4
	7	1	9	15	-8
	8	1	9	17	0
Hub (All)	1-8	71	7	16	-12
	1	2	4	13	-35
	2	17	5	15	-23
	3	21	6	14	-23
	4	21	7	16	-12
	5	5	9	17	0
	6	3	8	17	-4
	7	1	9	15	-8
	8	1	9	16	-4
Hub – Large Airport[b]	1-8	29	8	17	-4
	1	1	4	13	-35
	2	2	6	21	+4
	3	5	7	16	-12
	4	13	7	17	-8
	5	3	9	18	+4
	6	3	8	17	-4
	7	1	9	15	-8
	8	1	9	16	-4
Hub – Medium Airport[c]	1-5	32	5	12	-35
	1	1	5	12	-35
	2	10	5	11	-38
	3	13	5	12	-35

	4	7	6	13	-27
	5	1	5	13	-31
Hub – Small Airport[d]	2-5	10	5	12	-35
	2	5	4	12	-38
	3	3	5	12	-35
	4	1	4	9	-50
	5	1	5	13	-31
All Non-hub	2	3	5	12	-35

[a] When compared to the current default taxi in/out values of seven and 19 minutes, respectively.

[b] Large airport = Airports that account for at least one percent of the total U.S. passenger enplanements (see Table 4 for a list of these airports).

[c] Medium airport = Airports that account for between 0.25 percent and one percent of the total U.S. passenger enplanements (see Table 4 for a list of these airports).

[d] Small airport = Airports that account for between 0.05 percent and 0.25 percent of the total U/S. passenger enplanements (see Table 4 for a list of these airports).

Table 4
ASPM Aircraft Taxi Times by Airport

Airport Code	Airport Name	Hub Type	No. of Runways	Average Taxi Time (min.)		Percent Change in Taxi/Idle Times (and Emissions)[a]
				In	Out	
ABQ	Albuquerque Intl. Sunport	Medium	3	5	10	-42
ANC	Ted Stevens Anchorage Intl.	Medium	3	4	12	-38
ATL	Hartsfield-Jackson Atlanta Intl.	Large	5	11	20	19
AUS	Austin-Bergstrom Intl.	Medium	2	5	12	-35
BDL	Bradley Intl.	Medium	3	5	13	-31
BHM	Birmingham-Shuttlesworth Intl.	Small	2	4	12	-38
BNA	Nashville Intl.	Medium	4	6	12	-31
BOS	General Edward Lawrence Logan Intl.	Large	6	7	18	-4
BUF	Buffalo Niagara Intl.	Medium	2	4	12	-38
BUR	Bob Hope	Medium	2	3	11	-46
BWI	Baltimore Washington Intl.	Large	4	6	13	-27
CLE	Cleveland-Hopkins Intl.	Medium	3	6	13	-27
CLT	Charlotte/Douglas Intl.	Large	4	8	18	0
CVG	Cincinnati/Northern Kentucky Intl.	Medium	4	6	15	-19
DAL	Dallas Love Field	Medium	3	4	10	-46

DAY	James M Cox Dayton Intl.	Small	3	5	13	-31
DCA	Ronald Reagan Washington National	Large	3	5	16	-19
DEN	Denver Intl.	Large	6	8	14	-15
DFW	Dallas/Fort Worth Intl.	Large	7	9	15	-8
DTW	Detroit Metropolitan Wayne County	Large	6	9	19	8
EWR	Newark Liberty Intl.	Large	3	9	22	19
FLL	Fort Lauderdale/Hollywood Intl.	Large	2	5	16	-19
GYY	Gary/Chicago Intl.	Non-hub	2	4	11	-42
HNL	Honolulu Intl.	Large	4	6	13	-27
HOU	William P Hobby	Medium	4	6	9	-42
HPN	Westchester County	Small	2	5	13	-31
IAD	Washington Dulles Intl.	Large	4	7	16	-12
IAH	George Bush Intercontinental	Large	5	8	17	-4
IND	Indianapolis Intl.	Medium	3	6	13	-27
ISP	Long Island MacArther	Small	4	4	9	-50
JAX	Jacksonville Intl.	Medium	2	5	13	-31
JFK	John F Kennedy Intl.	Large	4	10	27	42
LAS	McCarran Intl.	Large	4	6	14	-23
LAX	Los Angeles Intl.	Large	4	9	15	-8
LGA	La Guardia	Large	2	7	24	19
LGB	Long Beach Daugherty Field	Small	5	5	13	-31
MCI	Kansas City Intl.	Medium	3	5	11	-38
MCO	Orlando Intl.	Large	4	7	13	-23
MDW	Chicago Midway Intl.	Large	5	6	11	-35
MEM	Memphis Intl.	Medium	4	7	16	-12
MHT	Manchester	Small	2	4	12	-38
MIA	Miami Intl.	Large	4	8	16	-8
MKE	General Mitchell Intl.	Medium	5	5	13	-31
MSP	Minneapolis-St Paul Intl	Large	4	7	17	-8
MSY	Louis Armstrong New Orleans Intl.	Medium	2	5	11	-38
OAK	Metropolitan Oakland Intl.	Medium	4	6	10	-38
OGG	Kahului	Medium	2	6	8	-46
OMA	Eppley Airfield	Medium	3	4	12	-38
ONT	Ontario Intl.	Medium	2	4	10	-46
ORD	Chicago O’Hare Intl.	Large	8	9	16	-4

PBI	Palm Beach Intl.	Medium	3	4	13	-35
PDX	Portland Intl.	Medium	3	4	11	-42
PHL	Philadelphia Intl.	Large	4	6	19	-4
PHX	Phoenix Sky Harbor Intl.	Large	3	7	15	-15
PIT	Pittsburgh Intl.	Medium	4	5	14	-27
PSP	Palm Springs Intl.	Small	2	5	12	-35
PVD	Theodore Francis Green State	Small	2	4	12	-38
RDU	Raleigh-Durham Intl.	Medium	3	5	14	-27
RFD	Chicago/Rockford Intl.	Non-hub	2	4	10	-46
RSW	Southwest Florida Intl.	Medium	1	5	12	-35
SAN	San Diego Intl.	Large	1	4	13	-35
SAT	San Antonio Intl.	Medium	3	4	11	-42
SDF	Louisville Intl-Standiford Field	Small	3	5	12	-35
SEA	Seattle-Tacoma Intl.	Large	3	6	15	-19
SFO	San Francisco Intl.	Large	4	6	17	-12
SJC	Norman Y Mineta San Jose Intl.	Medium	3	4	10	-46
SJU	Luis Munoz Marin Intl.	Medium	2	6	13	-27
SLC	Salt Lake City Intl.	Large	4	6	18	-8
SMF	Sacramento Intl.	Medium	2	4	10	-46
SNA	John Wayne Airport-Orange County	Medium	2	6	12	-31
STL	Lambert-St Louis Intl.	Medium	4	5	11	-38
SWF	Stewart Intl.	Non-hub	2	5	14	-27
TPA	Tampa Intl.	Large	3	5	12	-35
TUS	Tucson Intl.	Small	3	4	11	-4

[a] Percent increase/decrease when compared to the current default value.

3.1.2 Default Taxi Speed

When AEDT computes aircraft taxi/idle times for the purpose of performing dispersion analysis, model users are instructed to input an airport-specific value (or use a default value) for the aircraft taxi speed. Under this selection, the model performs Delay and Sequence Modeling which uses airport operational schedules, runway configurations, and the airport's capacity to estimate taxi/idle times and delay periods. In its current configuration, the AEDT default aircraft taxi speed is set to 15 knots (17.26 miles-per-hour (mph)) for these computations.

For the purposes of this assessment, the Research Team evaluated available Flight Data Recorder (FDR) data for a number of aircraft types. Notably, the FDR dataset is similar, but not identical, to the dataset used for ACRP Project 11-02 /Task 8 (*Enhanced Modeling of Aircraft Taxiway Noise – Scoping*). Among the 100+ available parameters contained in the FDR dataset is the aircraft groundspeed data during taxi operations.

Listed in **Table 5**, these FDR groundspeed data were evaluated for seven high-bypass turbofan jet aircraft engines from four engine families, which included the following:

- Rolls-Royce Trent series,
- Rolls-Royce RB211 series,
- PW4000 by Pratt & Whitney, and the
- CFM56 by CFM International.

As shown in **Table 5**, the FDR data for these "Test Data Engines" (representing approximately 68,000 taxi in and 111,000 taxi out events) indicate that the average unimpeded aircraft taxi in and taxi out aircraft ground speeds are 13 knots (14.96 mph) and 10 knots (11.51 mph), respectively. Importantly, when aircraft were stationary (i.e., when groundspeed was equal to zero), these data were not considered.

Table 5
FDR Unimpeded Aircraft Taxi Speeds (knots)

Engine	Taxi In			Taxi Out		
	No. of Samples	Average	Standard Deviation	No. of Samples	Average	Standard Deviation
Trent 772	389	13	9.0	641	10	5.4
RB211-535E4	7,079	13	6.7	12,101	9	4.4
PW4168A	15,382	12	7.3	25,162	10	6.2
CFM56-5C4	14,564	12	6.8	21,367	9	5.9
CFM56-5B5/P	10,675	14	7.8	16,917	10	7.0
CFM56-5B4/2P	13,835	14	7.8	23,131	9	6.1
CFM56-5B1/2P	6,324	13	7.4	11,944	10	6.8
All Operations	68,248	13	7.4	111,263	10	6.2

The relevance of these "Test Data Engines" to the aircraft fleet being operated in the U.S. by international and U.S. domestic airlines is discussed in **Appendix B** of this document.

Based on the outcome of this analysis, two options were developed that, if implemented, could improve the simulation of aircraft taxi speeds in AEDT, thereby improving the accuracy of an emissions inventory computed using these data. These options are described below.

Taxi Speed Options

- **Option 1** – As stated above, currently the AEDT default aircraft taxi in and out speed is 15 knots (17.26 mph). Based on FDR data (**Table 5**), a weighted average speed of 11 knots (12.66 mph) could replace the current value. This change would decrease predicted emissions associated with unimpeded taxi times by 27 percent, as compared to the current AEDT.
- **Option 2** – Under this option, AEDT users would indicate (or the model would distinguish) whether a taxiway is used for aircraft that are taxiing in, taxiing out, or both. For example, if a taxiway is used by aircraft arrivals, the model would default to an aircraft speed of 13 knots (14.96 mph). Similarly, if a taxiway is used for departures, the model would default to a speed of 10 knots (11.51 mph). In this case, the revision in aircraft speeds would also decrease the predicted non-delayed, taxi-related emissions, with the level of decrease dependent on the

number and length of the taxiways and whether they are assigned for arrivals, departures, or both.

3.2 Fuel Flow Rates (FFRs)

The FFRs currently used by AEDT during the idle/taxi phase of an LTO cycle are those listed in engine-specific ICAO certification sheets. These rates nominally correspond to an engine thrust equal to seven percent of each engine's maximum rated thrust. Several studies, however, have demonstrated that actual FFRs can differ significantly from the ICAO values. Besides the direct impact of these deviations on calculated emissions (the 2^{nd} term in TIM × FFR × EI equation), there are also indirect impacts due to the dependence of EIs on FFR. This is especially the case for CO and VOCs EIs, which increase measurably with corresponding decreases in thrust settings.

The Research Team consulted the following sources of information that discuss/document FFRs during actual aircraft operations:

- The FDR data discussed previously in this document that includes data for 1,800 aircraft operations of aircraft equipped with engines from four engine families; [6]
- Published papers that document FFRs established directly from FDR data or indirectly by comparing EIs observed downwind of aircraft to those determined during staged engine tests; and
- JETS/Aircraft Particle Experiment2 (APEX2) and APEX3 studies data.[7]

The FFR data from the above sources are summarized in **Table 6**. Notably, the data emphasis is on FFRs rather than engine thrust setting because, as stated previously, FFRs are one of the three fundamental elements within the current AEDT framework that are involved in the calculation of aircraft engine emissions during the taxi/idle mode. FFRs are also used by the Research Team to suggest adjustments to pollutant and pollutant precursor EIs (discussed in the next section). Additional data/information (e.g., histograms of FFRs from the FDR dataset) are included in **Appendix C**.

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[6] The relevance of these test data engines to the fleet of aircraft being operated in the U.S. by international and domestic airlines is discussed in **Appendix B** of this document.

[7] JETS/APEX2 and APEX3 were studies of aircraft emissions sponsored by the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration, the California Environmental Protection Agency (EPA), and the California Air Resources Board, conducted by researchers from the U.S. EPA, NASA, Aerodyne Research, Inc., the University of California-Riverside, University of Missouri-Rolla, and Arnold Air Force Base.

Table 6
Fuel Flow Rates (FFRs)

Method	Study	Engine (Airframe When Provided)	FFR/ICAO FFR (Percent)
FDR Data	ACRP 02-45	CFM56-5B1/2P	91 (in), 94 (out)
		CFM56-5B4/2P	87 (in), 89 (out)
		CFM56-5B5/P	111 (in), 113 (out)
		CFM56-5C4	85 (in), 91 (out)
		PW4168A	95 (in), 98 (out)
		RB211-535E4	80 (in), 84 (out)
		Trent772	87 (in), 85 (out)
	ACRP 02-03a, Figure V-4 of Final Report (ACRP Report 63)	CFM56-5B4-2 (A320)	90 (83 percent of time 0.1 kg/s, 17 percent of time 0.15 kg/s) ICAO = 0.121
	Turgut et al, 2013	CFM56-7B	89
	Khadilkar 2012, based on 2300 flights	CFM56-5 (A319)	82
		CFM56-5 (A320)	92
		CFM56-5 (A321)	92
		GE CF6-80E1A4 (A330-202)	91
		RR Trent 772B-70/772C-60 (A330-243)	87
		Trent 553 (A340-500)	74
		ARJ85	100
		RB211 (B757)	94
		GE90/PW4084/Trent877 (B777)	98
Comparison of Staged and in-use NOx EIs	JETS/APEX2, Wood et al. 2008	CFM56-3B1, -7B22	~80 to 85 percent (taxi/idle), >100 percent during acceleration
Comparison of Stated and in-use HCHO EIs	JETS/APEX2, Herndon et al. 2009	CF6-50C2, -80C2A5F; CFM56-7B22, -7B26, -3C1; JT8D-15; V2527-A5	HC EI 1.5 – 2.2 times higher at real-world operation compared to 7 percent
Staged Engine Tests, FFR	JETS/APEX2	CFM56-7B22	67 (aircraft 1), 79 (aircraft 2)

Read from Cockpit		CFM56-3B1	84
		CFM56-3B2	87
	APEX3	CFM56-3B1	73 (aircraft 1), 88 (aircraft 2)
		AE3007-A1E	106
		AE3007-A	110
		PW-4158	NA
		RB211-535E4-B	61 (aircraft 1), 73 (aircraft 2)
Average Normalized FFR			*92*

Rather than list the absolute FFRs (in kg/s), the values in **Table 6** provide the ratio of the actual FFR to the engine-specific ICAO idle/taxi FFR. An important distinction between the FDR data and the JETS/APEX2-3 listings relates to the scope of the two sets of data. The FDR data can be considered "complete" for the engines studied, in that the full distribution of FFRs (comprising operations while stationary, while accelerating, and while moving at a constant speed, etc.) is accounted for in the average. These distributions of rates are provided in **Appendix C**.

In contrast, the data from the JETS/APEX2 and APEX3 studies only reflect the FFR used during "ground idle" operation, and thus do not reflect FFRs at any other setting (e.g., acceleration). For these reasons, the average normalized FFR listed was calculated using only the FDR. The average normalized actual FFR for the engines in the ACRP 02-45 FDR dataset is approximately 92 percent of the ICAO FFR.

As extensive as this list is, there are some important data gaps. For example, there are no entries for several types of engines (e.g., CF6, PW-x, etc.). Furthermore, it is not known how representative these data are of the seasonal dependence of emissions, since the FDR data evaluated for the purpose of the ACRP 02-45 project were only acquired during the spring and fall. Use of air conditioning or de-icing also increases the FFR due to bleed air demand and may be unaccounted for in this dataset.[8]

From the Research Team's evaluation and analysis of actual rather than test rates, three options were developed to improve the FFRs in AEDT:

Fuel Flow Rate Options

- **Option 1** – Use the engine-specific FFR adjustment only for the engines listed in **Table 6**.
- **Option 2** – Use the engine-specific FFRs for the test data engines and engines determined to have "like" fuel flows and EIs (discussed and listed in **Appendix B**).
- **Option 3** – Use a single, global adjustment to all commercial jet engines based on the average normalized FFR of approximately 92 percent, as reported in **Table 6**.

3.3 Emission Indices (EI)

Similar to FFR, the EIs that are used to calculate emissions of CO, total hydrocarbons (HC), and NOx are from the ICAO certification data for each engine. These EIs are affected by FFR and ambient conditions (especially temperature) and respond differently, depending on the pollutant or pollutant precursor. Since the vast majority of total CO and HC emissions occur during the idle/taxi phase of an LTO, use of appropriate EIs during idle/taxi is considered important for accurately calculating emissions.

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[8] The FDR data was collected during the months of April and October.

The Research Team reviewed studies that address the dependence of CO, HC, and NOx EIs on FFR and ambient temperature. Among others, this dependence has been studied as part of the following projects: APEX (1), JETS/APEX2, APEX3, ACRP Project 02-03a (*Measurement of Gaseous HAP Emissions from Idling Aircraft as a Function of Engine and Ambient Conditions*).

Figure 1 summarizes the CO and HC results for the CFM56-7B22 engine from ACRP 02-03a, a study that focused on the CFM56-7B family of engines. Calculated EIs/temperature adjustment factors (defined below) to the ICAO EIs are plotted on **Figure 1**, based on ambient temperature. Six variants in the FFR are provided, expressed in both absolute values (kg/s) and as percentages of the ICAO idle/taxi FFR for the CFM56-7B22 engine (0.105 kg/s).

Using the values in **Figure 1**, the ICAO EIs in AEDT for CO and HC would be adjusted as shown below:

EI (temperature, FFR) = Adjustment factor × EI (ICAO idle)

The following provides an example of how the EI for HC emitted from a CFM56-7B22 engine would be adjusted using the values in **Figure 1**.

- A CFM56-7B22 engine is operating at 0.095 kg/s and the ambient temperature is 283 K (10 °C). At this FFR, the engine is idling at 90 percent of the ICAO FFR for seven percent thrust. In **Figure 1**, the adjustment factor is obtained from the blue line with triangles (i.e., the 90 percent line). At the ambient temperature of 283 K, the adjustment factor is 1.8. The ICAO HC EI for the CFM56-7B22 is 2.5 g/kg. Therefore, the adjusted HC EI is 4.5 g/kg (2.5 g/kg x 1.8 = 4.5 g/kg).

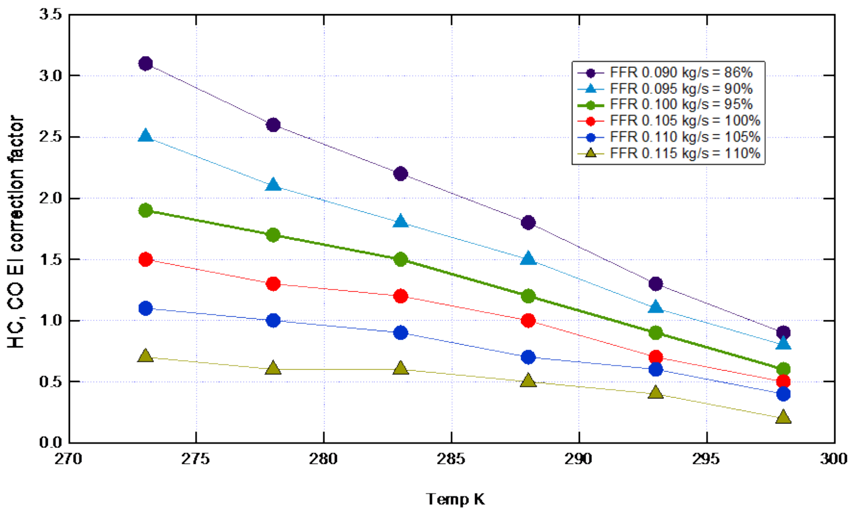

Figure 1
CFM56-7B22 Fuel Flow/Temperature Adjustment Factors for CO and HC EIs

From the Research Team's evaluation and analysis of actual rather than test rates, three options were developed to improve the CO and HC EIs in AEDT:

CO/HC EI Options

- **Option 1** – Use a global FFR adjustment factor and assume that all engines' (CFM56s, RB211s, CF6s, etc.) CO and HC EIs follow the same temperature and FFR dependence as the CFM56-7B family of engines. In other words, assume that all engines operate at the same average normalized FFR (approximately 92 percent of the ICAO idle FFR), and that the CO and HC EIs can be adjusted based on this FFR just as they can for the CFM56-7B engines.
- **Option 2** – Apply an engine-specific FFR adjustment factor (using values from **Table 6**), and then use the appropriate curve from **Figure 1**, again assuming the EI adjustment factor is the

same as that observed for the CFM56-7B family of engines. For engines that idle at intermediate FFRs (e.g., 88 percent of the ICAO FFR instead of 85 percent or 90 percent), interpolated traces have been added to the figure in **Appendix C.** These interpolated lines are based on the observed FFRs from the FDR dataset. Explicit formulas for the specific engines from the FDR dataset are also listed in **Appendix C**.

- **Option 3** – Only apply adjustment factors to CFM56 family of engines.

In contrast to CO and HC, NOx EIs increase with FFR and ambient temperature. In AEDT, the ICAO NOx EIs are adjusted to ambient conditions from the standard ICAO conditions of 15°C, one atmosphere pressure using the Boeing Fuel Flow Method 2. The reduced FFRs observed in actual aircraft operation (summarized in **Table 6**) warrant a concomitant reduction in the NOx EI. The relationship between FFR and NOx EI is approximated as being linear as demonstrated in **Figure 2**, which displays the relative NOx EI at "ground idle" versus the relative FFR during the JETS/APEX2 and APEX3 engine tests. Relative NOx EI is computed by the ratio NOx EI (ground idle) / NOx EI (ICAO idle setting). Relative FFR is computed by the ratio FFR (actual) / FFR (ICAO idle setting). The blue dots are the JETS/APEX2 and APEX3 data, for the following engines: CFM56-7B22, CFM56-3B1, CFM56-3B2, and RB211-535E4-B. The grey line is for comparison and has a slope of 1.

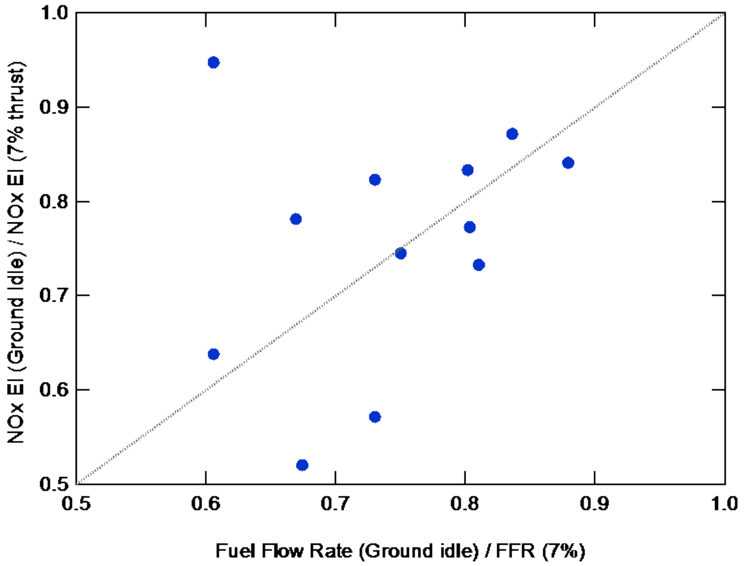

Figure 2
Relationship of NOx Emissions to FFR

From the Research Team's evaluation and analysis, the following model improvement option was developed to improve the NOx EIs in AEDT:

- **NOx EI Option** – In addition to applying the ambient condition (temperature and relative humidity) adjustment to NO_X EIs according to the Boeing Fuel Flow Method 2, an additional FFR adjustment would be applied as follows:

$$\textit{Adjusted } EI_{NOx} = (FFR/FFR_{ICAO}) \times EI_{NOx}\ (\textit{ICAO idle})$$

Where:

- FFR/FFR_{ICAO} = Ratio of actual FFR to ICAO FFR and
- EI_{NOx} (ICAO idle) = ICAO Idle NO_x EI

For example, consider a CFM56-7B22 operating at 0.095 kg/s. The ICAO FFR is 0.105 kg/s. The EI adjustment factor is equal to FFR/FFR_{ICAO} = 0.095/0.105 = 0.9, and so the ICAO NO_X EI of 4.5 g/kg is reduced to 4.05 g/kg. Note that the final NO_X emission *rate (in g/s)* - which is equal to the product of the FFR and the NO_X EI - is 81 percent of the ICAO emission rate, since both the FFR and the EI decrease to 90 percent of their original values (and 0.9 × 0.9 = 0.81). Importantly, although there is only one option to adjust emissions of NOx, to what engines it would be applied would depend on which FFR adjustment was assumed (see **Section 3.2** of this *Report*).

3.4 Additional Considerations

In addition to the assessment of EIs to improve how AEDT computes aircraft taxi/idle emissions, the ACRP 02-45 research also addressed how the model could be improved to include consideration of some aircraft operational parameters that could reduce emissions, including reduced engine taxiing and alternative-power aircraft taxi systems. Also considered were potential improvements that could enhance AEDT use for dispersion analyses of aircraft emissions. Each of these is discussed further below.

3.4.1 Reduced Engine Taxiing

As discussed in the Task 3: *(White Paper)* of the Task 1 *Literature Search* results (see **Appendix A**), many airlines promote the practice of taxiing with less than all of an aircraft's engines operating as a method of reducing fuel-burn (and emissions). Although this practice is generally referred to as "single engine taxiing," it can involve more than one of an aircraft's engines. For this reason, the practice is referred to in this document as "reduced engine taxiing."

Notably, reduced engine taxiing is performed only at the discretion of an aircraft's pilot. Factors considered by pilots include meteorological conditions (if wet, the surface of the taxi path could be slippery) and the need for full power for runway crossings. Very few documents address the extent to which reduced taxi procedures are in use or provide data to indicate the percentage of time or frequency when aircraft are taxied with fewer than all engines.

One source of information is a document published from the ACRP 11-02 project (Task 8: *Enhanced Modeling of Aircraft Taxiway Noise*). This document provides the percentage of time each engine on that project's test data aircraft was operating. The percentages of time were reported for periods when the aircraft were both stationary and moving and when they were arriving and departing. Most of the aircraft evaluated for this project were equipped with two engines (e.g., A319, B757). Because it is not known how many samples were considered in the evaluation of aircraft with more than two engines, these aircraft were not included in this evaluation. When considering just the two-engine jets and an equal amount of time when the aircraft were stationary and moving, pilots taxied aircraft in with just one engine operating an average one percent of the time and taxied out with just one engine operating an average eight percent of the time.

Presently, AEDT does not provide a direct method of considering any reduction in taxi-related emissions that would be realized by the practice of reduced engine taxiing (there are ways to do so, but they are time consuming and data intense). As such, the following model improvement was considered by the Research Team to allow such an option:

- **Reduced Engine Option** – Allow users to indicate whether reduced engine taxiing procedures should be considered in the calculation of emissions from jet aircraft equipped with two (or more) engines. If they should be considered, apply emission reduction factors to the calculated emissions. For taxi in operations, the factor would be a minimal value of 0.995 (a 0.5 percent reduction). For taxi out operations, the factor would be 0.96 (a four percent reduction).

3.4.2 Alternative Taxi Systems

Recognizing that the reduced use of an aircraft's engines on the ground could result in significant fuel savings, at least two manufacturers/joint ventures are developing methods to taxi aircraft on the ground with no engines operating. Honeywell, and the aerospace firm Safran, have been working together to develop an electric motor that would power an aircraft's main wheels, the motor being powered by an aircraft's auxiliary power unit (APU). The Honeywell/Safran product is known as the Electric Green Taxiing System (EGTS) and it is reported by the joint venture that the product will be available in 2017.[9] Wheeltug, a system being developed by a subsidiary of Borealis Exploration Limited, involves an electric motor in the hub of the nose wheel.[10] This motor would also be powered by an aircraft's APU. As recently reported by Wheeltug, they expect to begin installing their system onto aircraft belonging to eleven airlines, including six flagship carriers, in the near term.[11]

As stated above, very little documentation is available addressing reduced engine taxiing. Even fewer address the emissions benefit, or provide data to support the emissions benefit of these alternative taxi systems.

Currently, AEDT does not provide direct methods to consider/account for any reduction in taxi-related emissions that would be realized by the use of alternative taxi systems. As such, the following improvement was considered by the Research Team to allow for such a consideration:

- **Alternative Taxi Option** – Because the benefits of these systems are not yet well defined but data may be available in the near future, allow users to enter a percentage by which taxi-related emissions would be reduced to account for the type of alternative taxi system in use at an airport.

3.4.3 Airfield Emission Distribution (Dispersion Analysis Only)

When preparing an emissions inventory, the emission totals are not location-specific; thus, it is not necessary for an analyst to know, or for the computer model to simulate, where delay periods (or delay areas) occur on an airfield. However, when performing dispersion analysis, the location at which emissions are generated, as well as the distance between the emission source(s) and a receptor (i.e., locations for which the model will derive estimated concentrations of pollutants), will have a direct impact on the modeled pollutant concentrations.

When performing dispersion analysis, the AEDT Delay and Sequence Modeling is used to simulate taxi operations. The Delay and Sequence Modeling takes into account aircraft operational schedules, active runway configurations, and the delays that are associated with airport capacity. To use the Delay and Sequence Modeling, analysts must define the location(s) of receptors, airport gates, taxiways, runways, taxi paths (i.e., defined taxiway/runway connections), and runway configurations (i.e., weather dependent runway usage). The following was considered by the Research Team as an option to more realistically model aircraft taxiing at an airport:

- **Airfield Emission Distribution Option** – The modeling of aircraft queues (i.e., areas at which aircraft are delayed) are only considered for departing flights. All arrivals are assumed to have unimpeded taxi conditions from an airport's runway to a gate. In reality, and for reasons that may include an insufficient number of gates, arrivals could be "held" (i.e., delayed) in ramp areas before parking at a gate. To better define these areas, the computer model could be modified to provide an option for analysts to define where areas of delay occur and the extent of the delay.

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[9] Electric Green Taxiing System overview - www.greentaxiing.com/overview.html

[10] Wheeltug - www.wheeltug.gi/

[11] Royal Aeronautical Society, Toulouse, 13 September 2013. Delivered by Isaiah Cox, WheelTug Chief Executive Officer

4. Stakeholder Outreach

Upon the completion of the Task(s) 4, 5 and 6, the Research Team implemented Task 7: (*Stakeholder Outreach*) as a means of further evaluating the recommended improvements to computing aircraft taxi/idle emissions using AEDT. Each of four Stakeholder representatives were provided with a summary report describing the research completed in the previous tasks, much to the same detail as provided in the previous sections of this *Final Report*. Although the number of Stakeholders from which feedback was obtained was minimal, each of the participants is considered to be a subject-matter expect. The low number of participants is in part due to the relatively few Stakeholders on the subject of aircraft taxi/idle emissions and/or a reluctance of others to participate in the Project.

The four Stakeholder reviewers that did participate were selected to include a perspective from each of the following stakeholder categories:

- Model architecture expert (i.e., model developer)
- Model user (i.e., airport air quality consultant),
- Airline ground operations and engine performance expert (i.e., representative from active airline company), and
- Airport operations expert (i.e., representative from a working airport).

The Stakeholder review was focused particularly on receiving feedback on the results of Task 6: (*Develop List of Potential AEDT Improvements*), that being the identification of potential model improvement options considered in the research, within each of the following categories:

- Taxi time and taxi speed
- Fuel flow rates (FFRs)
- Emission Indices (EIs)
- Reduced engine taxiing options
- Alternative taxi systems
- Airfield emission distribution

The Stakeholder feedback received from each of the reviewers on each of the above categories is summarized in **Table 7** below. As can be expected with a group of reviewers - each with a different perspective - there was not complete consensus as to the best or most appropriate options for improvement within most of the categories. The following generally summarizes the results, by category:

4.1 Taxi Time

Stakeholders generally agreed that existing model default values for taxi time should be revised, with most comments suggesting that an option other than just using ASPM averages would be preferred. If/when more accurate or airport-specific information on taxi times is available, the reviewers feel that should be used.

4.2 Taxi Speed

The four Stakeholder reviewers generally agreed that the preferred option for taxi speed would be to allow model users to specify taxiway use (i.e., arrival or departure) and have corresponding default speeds.

4.3 Fuel Flow Rates (FFRs)

The Stakeholder reviewers were generally apprehensive about the potential improvement options in this category, which would involve adjustments to currently-used ICAO FFR average values, based on actual measured performance data for specific engines, and possibly also including “like engines” along with those for which actual performance data are available. Points raised by the reviewers included concern that the identified options for improvement would use data from (i.) too small a database and from (ii.) engine test data from a group of engine types that may not be transferable to other engine types. As the current model values are ICAO values and accepted worldwide, it was further recommended that any FFR changes should be coordinated with ICAO.

4.4 Emission Indices (EIs)

The model developer and model user reviewers had much the same comments as they provided for the options considered for FFRs - specifically, that potential changes should be coordinated with ICAO and caution regarding transferability of test engine data to other engine types. The airport and airline stakeholder reviewers offered no comment(s) on this category, apparently because it is outside their realm of expertise.

4.5 Reduced Engine Taxiing

The Stakeholder reviewers generally agreed that some allowance for considering reduced engine taxing in emissions prediction would be appropriate. The airport representative suggested use of this operation mode would be easier to predict at airports with one major carrier. There was no agreement among the reviewers regarding how much of a reduction in emissions should be applied when this operation mode is used.

4.6 Alternative Taxi Systems

Generally, the reviewers thought there should be a method by which model users could adjust (by applying a percentage) to account for potential use of alternative taxi systems. Comments also included uncertainty as to the ability of airports to supply the necessary data and the complication that some of the alternative systems would use fuels that would also be emission sources.

4.7 Airfield Emission Distribution

This option would allow some modification to the model to define where areas of delay occur and the extent of the delay. The reviewers were generally uncertain that this would be implementable or, if it were, that it would be useful or accurate. Comments included that events were too random and changeable. There were also questions as to quality control of the application of the option and how the model could be modified to consider it.

Table 7
Stakeholder Review and Feedback Summary

Research Parameter	**Option**	**Stakeholders**			
		Airport	**Model Developer**	**Model User**	**Airline**
Taxi time	1 – Update default values using average taxi in/out times computed from ASPM data.	At the least.	Each airport is unique. Use of the default values should be discouraged for the larger airports where more accurate information is either available or can be determined. In the case where defaults are used, a margin of safety is needed since the analyses are for health-based reasons. Simple averages are not enough.	Seems like as an overall 7 and 16 minutes only a 12 percent reduction, however if I am looking at the airport sizes correctly, the refinement could yield greater reductions for large and medium airports. However, this would be a conservative approach to refining the current assumptions.	Our airline's average taxi out time is approx. 5.5 minutes taxi out and 4.5 minutes taxi in so we believe the default values are greatly overestimated.
	2 – Allow users to select default taxi in/out times based on array of airport-specific design characteristics.	Better.	This should be the "default" mode. But again, larger airports should be encouraged to provide data specific for their airport.	Seems like the better way to go if you could refine the times based on airport size. I would be interested in the criteria for selecting airport design characteristics.	--
	3 – Update current database to include recent data.	ACI has adopted European carbon reduction program and assuming more [sic] AEDT may be more frequently used for inventory use than dispersion. These times are more readily available for airports that don't now calculate taxi times.	Care should be taken to make sure of final answers before any updates to databases are made. For example, it is recommended that taxi speeds be decreased leading to greater taxi times and greater emissions. But then recommendations are made to reduce the emission indices. What is the final result? It seems like a wash. The evaluations stop short of going the final step to determine what these changes really mean.	This could also be a viable alternative to Option 1 based on actual data. Could this also be used in Option 2? I am a fan of using more recent available data. I assume the revised data includes a variation of aircraft type? Do you have this broken down by aircraft type?	Regarding default taxi times, **we suggest option 3**. For all airports in our system, we have data available specific to each airport that include taxi times. Is there a way the new AEDT model could prioritize actual times gathered from air carriers? Our airline has been able to provide this data for several airport emissions inventories resulting in significant reductions in emissions from this parameter.
Taxi speed	1 – Update default taxi in/out speed.	Good to update the speed, but I would be more interested in seeing a set speed established and not changed over scenario or time so changes in taxi time and fuel flow resulting in updating airport facilities and aircraft engines will show what changes to both of these will do. As an airport I can control stop and start but not speed.	These times are unique to taxi in/out, airport layouts, aircraft type in use, and even airlines. If implemented it needs to be implemented based on these variables and not just an overall average which may not necessarily be better for each airport.	If I read this data correctly, there does not seem to be a lot of variability in the engines and taxi speeds evaluated in the 7 engine types? What representation is this to the total fleet? Reading in the back, maybe 448 test engines in the U.S.?	Our average taxi speed is higher than the one mentioned in the study and we can provide you with an exact number if you like. Guidance mentions a taxi speed of 35kts except in congested areas. Looking at average taxi speeds we could provide this data for specific airports, including or excluding delay times. The default speeds mentioned seem to be low. Again, our airline prefers option 2 where airports use actual taxi speeds. This information can be obtained by contacting carrier environmental staff.
	2 – Allow users to specify (or have the model distinguish) whether a taxiway is used for arrivals or departures. Use corresponding default aircraft speeds.	As above.	This should be included if changes made, but again there are more variables than just this one (see comment above). Taxi speeds can change on departure as an aircraft approaches the runway and queues up. Taxi speeds can also change on arrival as an aircraft approaches the tarmac/gate area.	If possible, this seems to me to be more accurate compared to the default Option 1	--
Fuel flow rates	1 – Apply engine-specific FFR adjustment only for engines for	Sounds reasonable	While on the surface this is a good idea, the ICAO values are based on worldwide acceptance.	In the test engine data, looking at Table A-1, perusing at the list of airlines,	--

Research Parameter	**Option**	**Stakeholders**			
		Airport	**Model Developer**	**Model User**	**Airline**
(FFR)	which test data are available.		Before any changes are made, this should go through ICAO and not just implemented without any concerns for the overall practice.	nothing is represented for JetBlue and Southwest airlines which seem to be a large percentage of U.S. operations. Will these aircraft and large operations be adequately addressed?	
	2 – Apply engine-specific FFR adjustment to engines for which test data are available and engines determined to have like fuel flows and emission indices.	--	(See previous comment). In addition, this now starts to add in uncertainty. A practice to change by ratio of the measured fuel flows from ICAO may reduce this uncertainty.	This would be a great benefit, but are you confident you can assimilate existing engine data into the ones for which test data are available. Have you mapped out a methodology for assigning like fuel flows?	Our airline's configuration is not addressed in this research: Our classic fleet are equipped with CFM56-3B1 engines and CFM56-7B24 engines. Fuel flow during taxi is dependent not only on temp but also on breakaway thrust to get the a/c rolling. Once rolling the a/c will have the engines back in idle. For this we need to consider the weight of the a/c as well. As reference for engine thrust settings, we don't use % of maximum thrust. We usually call it engine speed. The engines usually idle at about 22-25% N1. As breakaway thrust, we use an average of 35% N1. Depending on fleet type the following fuel flow in average can be seen: -300: Idle at the gate 800 lbs/hr, taxi 1,874 lbs/hr -500: Idle at the gate 804 lbs/hr, taxi 1,913 lbs/hr -700: Idle at the gate 788 lbs/hr, taxi 1,954 lbs/hr, APU fuel flow 194 lbs/hr -800: Idle at the gate 818 lbs/hr, taxi 1,977 lbs/hr, APU fuel flow 180 lbs/hr
	3 – Apply a global adjustment to all commercial jet engines based on average normalized FFR.	It may be worthwhile taking a quick look at the percentage of aircraft engine variants in-use worldwide before we make a final decision.	Again, this is an ICAO process. Additionally, for all options associated with FFR, even though data shows a reduction in idle FFRs, any time an aircraft comes to a complete stop during taxi they need and will apply thrust significantly over the 7% power setting. When analyzing the FDR data, this should have been observed. How will this be applied for taxi?	Could be a good compromise, but may run into the same issues identified above for assimilating like engine data. Have you mapped out a methodology yet?	The project used 258,824 flights (data samples) from mostly European carriers, which is approx. 5 years' worth of data. This is the amount of flights our airline collects in 3 months. Five years of data would be about 4 million flights in our system. As a result, we don't think use of this small data set from European carriers would adequately represent all commercial jet engines.
Emission Indices (EI)	1 – Apply a global EI/FFR adjustment factor.	Beyond my understanding.	Again an ICAO process. How much will uncertainty be reduced? Need to go the next step in process to recommend. For example, will defaults be used or will each engine be known?	No specific comments to EI, just similar to the above	--
	2 – Apply an engine-specific EI/FFR adjustment factor.	Beyond my comprehension.	Same comment as above.	--	--
	3 – Apply adjustment factor to	No on principle.	This is based on sufficient data but again, with the	--	--

Research Parameter	Option	Stakeholders			
		Airport	Model Developer	Model User	Airline
	CFM56 engines only.		worldwide acceptance and use of ICAO, should again go through this process.		
Reduced engine taxiing	Allow users to indicate if reduced engine taxiing procedures should be considered. If so, apply minimal reduction factor.	Taxi in, maybe we should apply minimal reduction, if practiced. Taxi out no. Airports with one major carrier are easier to predict what the pilots will do. Taxi out by a 380 on two engines is preferred by operators but not by airports as spooling up two engines to turn a 90 degree corner can knock over signs and can peel grass off.	This would seem to be justified. The question not answered is that when reduced engine procedures are used, how much more fuel flow and increase in emissions occur for the engines used.	If I understand correctly, reduced engine taxiing only results in a 4 to 5 percent reduction? How did you arrive at this?	Single engine taxi is a procedure we utilize for taxi out and taxi in. For taxi in and out, our airline has a compliance rate of more than 70%. We have calculated a savings of around 12 gallons of jet fuel per taxi event, and are concerned that the reduction factor may be too low, but don't have the details of your calculation in order to determine that.
Alternative taxi systems	Allow users to enter a percentage by which emissions would be reduced to account for a specific type of alternative taxi system in use at an airport.	Good idea.	Airports would be hard pressed to supply adequate data.	Would you also do this for alternative fuels?	Agreed. However, some of the alternative taxi systems under development utilize hybrid diesel engines (Taxibot), which would be considered an emissions source. I do think it is important that future models account for systems such as those mentioned in the stakeholder feedback report.
Airfield emission distribution	Modify model to provide an option for analysts to define where areas of delay occur and the extent of the delay.	Arrival queuing no, too random. Departure yes. The offsite data available for dispersion modeling is so inaccurately apportioned as to make fine improvements to the airport data not needed.	This could be an option that some larger airports could use. How will it be quality controlled?	I like this flexibility and seems much more realistic when conducting dispersion modeling. Do you have some ideas for how you would make such modification to the model?	Not sure if this can be quantified or modeled. Most delays on the tarmac are due to weather or construction on the airfield, both of which constantly change. Regulatory changes have required carriers to return to the gate for major delays, otherwise they face fines. In addition, delays can result in engine shut-down while the APU powers the aircraft.

5. Recommended Near-Term Model Improvements and Implementation Steps

With completion of Tasks 1 through 7, an *Interim Report* was prepared under Task 8, and provided to the Research Panel summarizing the outcomes of this work. Following the Panel's review and discussions with the Research Team, the Panel instructed the Team to proceed with the following final three research tasks:

- Task 9: *Identification of Near-Term Model Improvements*
- Task 10: *Steps Needed for Implementation*
- Task 11: *Final Report*

The Panel also suggested enhancements to the methodology the Research Team used to evaluate the relevance of the FDR data from the Test Data Engines. That improved methodology was implemented by the Research Team and the Test Data Engine information incorporated into this *Final Report* is based this recommendation (see **Appendix B)**.

Table 8 provides a concise summary of the model improvements recommended by the 02-45 Research, including an estimate of the level of effort needed to implement the improvements and a recommendation as to the priority (i.e., near-term or long-term). For each recommended improvement, the table also includes a summary of required changes to the model and the likely effect of the improvement on the model's emissions predictions. For each of the recommended near-term improvements, the following sections of this report discuss in greater detail the steps required for the implementation of those recommendations.

It must be noted that the discussions of implementation steps do not include any explicit steps that would be required to provide support to the user to make AEDT preserve its current treatments. It should also be noted that every implementation step would also require efforts to deal with any unanticipated interactions, unit test development, system-level testing, and updates to technical documentation and model user guidance.

5.1 Near-term Model Improvements for Time-in-Mode (TIM) Factor

As indicated in **Table 8**, there are two recommended near-term model improvements related to the TIM factor of the taxi/idle emissions equation in AEDT. The required steps to implement each of the improvements into the model are discussed below:

5.1.1 Default Taxi Time

The recommended near-term improvement is to change the default taxi in and taxi out times in AEDT to values computed from ASPM data representing all airports. While these values vary somewhat by airport size and number of runways, they trend toward overall averages of 7 minutes for taxi in and 16 minutes for taxi out. To make the necessary model changes to adapt this improvement, the following steps/sub steps would be required:

AEDT Improvement Implementation Steps

- Implement air operation Create, Read, Update, Delete (CRUD) support that includes taxi-out duration:
    - Create a graphical user interface (GUI) dialog to edit air operations.
    - Add value control and check-box (for null vs. non-null) to GUI dialog and implement coordination with database.
    - Have dialog set value control to 16 minutes when check-box is activated.
    - Add property to the AEDT Standard Input Format (ASIF) import-file schema and implement persistence support.
    - Implement database coordination with GUI and ASIF.

- Repeat for taxi in, but with seven minutes as default value in GUI dialog.
- Repeat for taxi in and taxi out, but for airport layout CRUD support.

5.1.2 Default Taxi Speed

The recommended near-term improvement is to change the default taxi speed in AEDT to 11 knots (12.66 mph), based on a weighted average speed derived from FDR data taken from actual aircraft operations. To make the necessary model changes to adapt this improvement, the following steps would be required:

AEDT Improvement Implementation Steps

- Change default speed value to 11 knots in GUI dialog for editing taxiway points.
- Change taxi network construction algorithm's default speed value to 11 knots.

5.2 Near-Term Model Improvements for Fuel Flow Rate (FFR) Factor

The recommended near-term improvement for this factor is to consider the FFR for each engine as that engine's ICAO FFR value, times a global factor of 0.92, derived from comparing actual FDR data with the ICAO data. To make the necessary AEDT changes to adapt this improvement, the following steps would be required:

AEDT Improvement Implementation Steps

- Create a method to determine whether or not an airplane is a commercial jet.
- Change fuel flow rate calculations to result in 92 percent of the ICAO idle value in cases where the aircraft is a commercial jet:
    - In the performance calculation algorithm for monolithic taxi segments, and
    - In the performance calculation algorithm for sequenced taxi segments.

5.3 Near-Term Model Improvements for the Emissions Index (EI) Factor

There are two recommended near-term improvements in the way AEDT considers the EI factor, one regarding the model's prediction of HCs and CO; the other regarding NOx. They are discussed individually below.

5.3.1 Prediction of HCs and CO

The recommended near-term improvement is to apply a global adjustment factor assuming all engines' CO and HC EIs follow the same temperature/FFR dependence as the CFM56-7B family of engines.

To make the necessary model changes to adapt this improvement, the following steps would be required:

AEDT Improvement Implementation Steps

- Create a method to determine whether or not an airplane is a commercial jet.
- Gather parameter values required to encode the 92 percent adjustment factor curve from **Figure 1** (either as a set of coordinates for interpolation, or the equation of a line).
- Create a method that calculates and returns the CO/HC adjustment factor for a given temperature, based on encoded data.
- Create methods that calculate CO and HC emissions indices as the product of the engine's corresponding ICAO idle EI with the adjustment factor for the local ambient temperature.
- Update the overall emissions calculation algorithm to detect taxi segments and call the new CO/HC EI calculators for taxi segments when the airplane is a commercial jet.

5.3.2 Prediction of NOx

The recommended near-term improvement is to use the fuel flow rate fraction to scale the NOx EI for commercial jets. This model improvement would require the following steps:

AEDT Improvement Implementation Steps

- Create a method to determine whether or not an airplane is a commercial jet.
- Create a method that calculates a NOx EI as the product of the BFFM2 NOx EI with the fuel flow rate fraction.
- Update overall emissions calculation algorithm to detect taxi segments and call the new NOx method for taxi segments when the airplane is a commercial jet.

5.4 Near-Term Model Improvements for Additional Considerations

The recommended near-term improvement is to add to the model the capability for users to indicate whether reduced engine taxiing procedures should be considered in the calculation of emissions from jet aircraft equipped with two (or more) engines. If they are to be considered, emission reduction scaling factors would be applied to FFRs—0.995 for taxi in FFRs and 0.96 for taxi out FFRs. To make the necessary model changes to adapt this improvement, the following steps would be required:

AEDT Improvement Implementation Steps

- To all classes representing air operations at some level of specificity, add a boolean property indicating whether or not to apply these scaling factors.
- For air operations, implement CRUD support that includes the new property:
  - Create a GUI dialog box to edit air operations.
  - Add a check-box corresponding to the new property to the GUI dialog and implement coordination with database.
  - Add a corresponding property to ASIF import-file schema and implement persistence support.
  - Add a corresponding column to the database and implement coordination with GUI and ASIF.
- Propagate the values assigned to the new property air operations to the more specific representations.
- Update the performance calculation algorithms to apply the scaling factors to the fuel flow rates calculated for monolithic taxi segments when requested for the event.
- Update the performance calculation algorithms to apply the scaling factors to the fuel flow rates calculated for sequenced taxi segments when requested for the event.

Table 8
Prioritized List of Potential Improvements to AEDT

Taxi/Idle Emissions Computational Factors	Research Parameter(s)	Improvement Option(s)	Required Revision to Model(s)	Effect on Predicted Emissions	Cost (Ease) of Implementing Improvement[a]	Priority (Near-/Long-Term)
Time-in-mode	Default taxi time (crucial for EDMS/AEDT users that use the default time-in-mode option) - *Currently 7 minutes taxi in and 19 minutes taxi out*	1) Change default taxi in and taxi out to values derived for all airports. --*7 minutes taxi in / 16 minutes out*	Update values in dbo. SCENARIO_AIRPORT_LAYOUT (DEF_TAXI_TIME_A (arrivals) and DEF_TAXI_TIME_D (departures)).	Reduction of 12 percent.	Minimal Cost	Near-term
		2) Provide user query for type of airport and number of runways in GUI – link to new database. -- *Values in Table 3*	Modification to GUI, algorithms, and a new database.	Reduction of four to 50 percent depending on airport.	Moderate Cost	Long-term
		3) Default to average of five years of data for specific airport being evaluated. -- *Values in Table 4*	Modification to algorithms and a new database (or addition to existing databases above).	No change or increase from eight to 42 percent at six airports. Reduction of four to 50 percent at all other airports.	Moderate Cost	Long-term
	Default taxi speed (important for EDMS/AEDT users that evoke the dispersion modeling option) - *Except for queue area before departure, EDMS assumes aircraft taxi at one speed (default 15 knots (17.26 mph)). Users may also enter aircraft specific speeds)*	1) Change default assumption to weighted average value based on FDR data. -- *11 knots (12.66 mph)*	Requires a change to a value in the model code.	Reduction of 27 percent.	Minimal Cost	Near-term
		2) Allow users to indicate (or the model to distinguish) whether a taxiway is used for aircraft taxiing in or out. -- *13 knots (14.96 mph) for taxi in taxiways and 10 knots (11.51 mph) for taxi out taxiways*	Algorithm modifications to derive total emissions using adjustment factors.	Reduction that would depend on an airports number and length of taxiways and taxi mode being modeled (i.e., taxi in or taxi out).	In/out distinction already present in AEDT. Re-assignment of values is only task necessary. Minimal cost	Long-term
Fuel Flow Rate (FFR)	FFR - *Actual FFRs can be higher or lower than those listed in engine-specific ICAO datasheets for operation at idle/taxi. Rates are positively correlated with thrust setting and bleed flow. Furthermore, a range of FFRs is used during idle, not just a fixed single value.*	1) Adjust FFRs in databases only for those aircraft for which there are FDR data (varies between 80 and 111 percent of ICAO idle value for taxi in and between 90 and 113 percent for taxi out). -- *Values in Table 6*	Algorithm modification to derive total emissions using adjustment factors.	Without considering the more important effect of FFR on the EIs themselves, decreasing FFR decreases emissions of all compounds (including CO_2). *See below for combined effect on emissions when considering the impact of reduced FFR on EIs.*	Moderate cost	*

Taxi/Idle Emissions Computational Factors	Research Parameter(s)	Improvement Option(s)	Required Revision to Model(s)	Effect on Predicted Emissions	Cost (Ease) of Implementing Improvement[a]	Priority (Near-/Long-Term)
		2) Adjust the FFRs for those aircraft for which there are FDR data or for which the data are representative. -- *Values in Table 6 and list of engines in Table B-4*	Algorithm modification to derive total emissions using adjustment factors.	Same comment as Improvement Option 1	Moderate Cost	*
		3) Use a single, global adjustment to all commercial jet engines. -- *92 percent of an engine's ICAO idle value*	Algorithm modification to derive total emissions using adjustment factors.	Same comment as Improvement Option 1	Minimal Cost	Near-term
Emission Indices	CO and HC - *Note: EIs should be adjusted only if FFRs are adjusted*	1) Apply a global adjustment factor assuming all engines CO and HC EIs follow same temperature/FFR dependence as the CFM56-7B family of engines. -- *Factor varies depending on ambient temperature (Figure 1)*	Algorithm modification to derive total emissions using adjustment factors.	At 92 percent of the ICAO idle FFR, HC and CO emission EIs increase by 40 percent at 15 degrees centigrade. The combined effect accounting for both the reduction in FFR and increase in EIs is an increase of 30 percent at 15 degrees centigrade.	Minimal cost	Near-term
		2) Apply an engine specific adjustment factor -- *Factors vary depending on engine (Table 6 and Figure 1)*	Algorithm modification to derive total emissions using adjustment factors.	Same comment as Improvement Option 1	Moderate cost	*
		3) Apply adjustment factors only to the CFM56 family of engines -- *Factor varies depending on ambient temperature (Figure 1)*	Algorithm modification to derive total emissions using adjustment factors.	Same comment as Improvement Option 1	Moderate cost	*
	NOx	There is only one option to adjust emissions of NOx. To what engines it would be applied would depend on the FFR adjustment option described above.	Algorithm modification to derive total emissions using adjustment factors.	NOx EIs decrease by 8 percent and combined with the decrease in FFR lead to a 15 percent decrease in NOx emissions.	Minimal cost assuming same choice for CO and HC already implemented	Near-term
Additional considerations	Assumptions regarding single/reduced engine taxi procedures to be included in modeling	When selected by user, apply factor of 0.995 to FFRs for taxi in operations and 0.96 to FFRs for taxi out operations.	Algorithm modification to derive total emissions using adjustment factors.	Reduction in emissions.	Minimal cost	Near-term
	Allow for e-taxi procedures to be included in modeling	Allow users to specify the percentage that taxi-related emissions should be reduced.	Modification to GUI and algorithms to derive total emissions using adjustment factor.	Reduction in emissions.	Minimal cost	Long-term

Taxi/Idle Emissions Computational Factors	Research Parameter(s)	Improvement Option(s)	Required Revision to Model(s)	Effect on Predicted Emissions	Cost (Ease) of Implementing Improvement[a]	Priority (Near-/Long-Term)
	Emission distribution across airfield *Constant thrust assumption (i.e., should the taxi/idle thrust values vary across airfield idle/taxi phase (e.g., x min @ 4 percent thrust and y min @ 12 percent thrust) or is a single thrust assumption sufficient?)*	Allow users to define areas other than the runway queue area where aircraft are delayed (e.g., crossing active runways, ramp area where aircraft are held waiting for gate, deicing area).	Modification to GUI and algorithms.	Increase or reduction in emissions depending on location being evaluated.	High cost	Long-term

[a] Minimal cost – up to 2 person weeks of effort
Moderate cost – up to 6 person weeks of effort
High cost – Up to 24 person weeks of effort

* This improvement is considered to be an alternative to the recommended near-term improvement.

APPENDIX A
TASK 3 WORKING PAPER:
Literature Review and Review of EDMS/AEDT Modeling Inputs

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Initalisms and Acronyms

AAFEX	Alternative Aviation Fuel Emissions Experiment
AAM	Aircraft Acoustic Module
ACRP	Airport Cooperative Research Program
AEDT	Aviation Environmental Design Tool
AEE	Office of Environment and Energy
AEM	Aircraft Emissions Module
APE	Aerospace Particulate Emissions
APEX	Aircraft Particulate Emissions Experiments
APM	Aircraft Performance Module
APU	Auxiliary Power Unit
ASPM	Aviation Policy's Aviation System Performance Metrics
ATC	Air Traffic Control
AWP	Amplified work plan
BTS	Bureau of Transportation Statistics
C2H4	Ethene
CAA	Clean Air Act
CO	Carbon monoxide
ECAC	European Civil Aviation Conference
EDMS	Emissions and Dispersion Modeling System
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
FID	Flame Ionization Detection
FSC	Fuel sulfur content
GSE	Ground support equipment
GUI	Graphical Users Interface
HAPs	Hazardous air pollutants
HC	Hydrocarbons
HCHO	Formaldehyde
ICAO	International Civil Aviation Organization
INM	Integrated Noise Model
ISA	International Standard Atmosphere
LTO	Landing-Takeoff Cycle
MAGENTA	Model for Assessing Global Exposure to the Noise of Transport Aircraft
NAAQS	National Ambient Air Quality Standard
NEPA	National Environmental Policy Act
NIRS	Noise Integrated Routing System
NMHC	Nonmethane hydrocarbons
NO_x	Nitrogen oxides
PMFO	Fuel organics particulate matter
PMNV	Nonvolatile particulate matter
PMSO	Volatile sulfates particulate matter
ROG	Reactive organic compounds
RPM	Revolutions per minute
SAGE	System for Assessing Aviation's Global Emissions
SO2	Sulfur dioxide
SOx	Sulfur oxides
THC	Total hydrocarbons

TOG	Total organic gases
UHC	Unburned hydrocarbons
US	United States
VOC	Volatile organic compounds

1. Introduction

Consistent with the Amplified Work Plan (AWP) approved by the Project Panel, this Task 3 White Paper outlines the scope and preliminary results for the Task 1 *Literature Review* and Task 2 *Emissions Dispersion Modeling System (EDMS)/Aviation Environmental Design Tool (AEDT) Review* elements of the Airport Cooperative Research Program (ACRP) 02-45 Research Project. For both tasks, an overview of the collected literature and information are provided and discussed in the context of how the collected material will aid the completion of subsequent research tasks. An annotated bibliography is also provided after Section 5 (Plan Going Forward) of this Working Paper.

2. Problem Statement Objectives

There is a need to improve the current method of estimating air pollutant and pollutant precursor emissions from aircraft engines during the taxi/idle mode of operation. More specifically, there is a need to evaluate whether the emissions indices (i.e., factors) that are used to derive emissions inventories and used by EDMS and AEDT appropriately reflect real world emission rates. To address this need, the following two objectives were developed by the Project Panel for this ACRP 02-45 Research Project:

- Develop a prioritized list of potential improvements to EDMS and AEDT that will increase the predictive accuracy of these tools to estimate commercial jet aircraft emissions during the taxi/idle phase of operation; and
- Prepare documentation that highlights and describes high priority improvements that should be accomplished in the near term.

The initial two tasks to meet the above objectives were to review and summarize relevant scientific and industry literature, published guidance, and pertinent research on the combined topics of aircraft taxi/idle emissions and EDMS/AEDT (i.e., the *Literature Review*) and to review the relevant assumptions, algorithms, database coverage, and outputs of both EDMS and AEDT (the *EDMS/AEDT Review*) The results of these tasks are presented in this Working Paper with the intent that the information will serve as the foundation from which the ACRP 02-45 project will proceed.

3. Results of the Literature and EDMS/AEDT Reviews

Because the corresponding answers are necessary to develop a prioritized list of potential improvements to EDMS/AEDT, the Research Team was mindful of the following questions during the course of the literature and EDMS/AEDT reviews:

- What are the factors that affect an aircraft departing an airport from the time the aircraft leaves the airport's gate until the aircraft reaches a runway (i.e., taxi out)?
- What are the factors that affect an aircraft arriving at an airport from the time the aircraft exits a runway until the aircraft reaches a gate (i.e., taxi in)?
- What thrust settings do pilots use for aircraft engines during the taxi process?
- Are there readily available air pollutant/pollutant precursor emission indices for engine thrust settings other than those already in the EDMS/AEDT databases?
- Do the current databases, input variables, algorithms and sub-models of EDMS/AEDT provide a reasonable estimate of taxi-related emissions?

The following summarizes the Research Team's knowledge and findings from the Task 1 *Literature Review* and Task 2 *EDMS/AEDT Review*.

3.1 Relevant Literature and Research

The literature review focused on the following four categories of information:

- *Aircraft Performance Characteristics* – including aircraft taxi/idle times-in-modes under alternative airfield conditions, single-engine taxi procedures, flight data recorder (FDR) data, etc.;
- *Aircraft Engine Emissions* – including International Civil Aviation Organization (ICAO) reference fuel flows and emission indices, aircraft engine emissions and ambient measurements, etc.;
- *EDMS/AEDT Performance and Development* – including model architecture, development programs and timeframes, model accuracy and sensitivity tests, etc.; and
- *Regulatory Framework* – including the Federal Aviation Administration's (FAA's) rules/regulations that relate to the taxi process and the requirements of the National Environmental Policy Act (NEPA), the federal Clean Air Act (CAA), and other state/local requirements as they pertain to airport emissions and ambient air quality.

The literature and research review results are discussed below. The results were also compiled in an annotated bibliography that is provided at the end of this Working Paper. Within this text, references to the literature included in the bibliography are enclosed inside brackets ([…]).

3.1.1 Aircraft Performance Characteristics

Aspects of an aircraft's performance while in the taxi mode that are relevant to emissions include factors which affect the amount of time an aircraft spends on taxiways and in hold areas, and airfield/aircraft operational procedures that reduce aircraft engine emissions. These aspects are discussed in the following subsections. A source of real-world aircraft performance data (i.e., FDRs) is also discussed.

3.1.1.1 Taxi Process/Time in Mode

Without considering environmental influences (e.g., temperature), an aircraft's total taxi-related emission load depends on aircraft type, the amount of time the aircraft spends in taxi, the duration of aircraft delay and the power settings (i.e., thrust) of each of the aircraft's engines. Several of the literature sources describe the aircraft taxi out and taxi in process. From these sources, the following taxi process descriptions were developed [FAA, 2013b; Khadilkar et al, 2012; Bhadra et al, 2011; Page, 2013; Grinspun, 2002; Boeing, 2002]:

- **Taxi out** – The taxi out process begins in one of two ways–1) an aircraft's engine(s) is started at a gate and a pilot begins taxiing using the aircraft's own power or, 2) for nose-in gates, a pushback tug is used to back the aircraft out of the gate, the engines are started and the aircraft begins taxiing after it is disconnected from the pushback tug. These initial activities occur in what is referred to as the nonmovement area of an airport. The movement of aircraft in the nonmovement area is the responsibility of the pilot, the airport operator or airport management. When exiting the nonmovement area, Air Traffic Control (ATC) issues an aircraft's pilot a route that is to be followed to the departure end of an airport's runway (i.e., the movement area). Along this route, the pilot may be instructed to "hold short" at any point (e.g., a runway other than the departure runway, a taxiway). Depending on the departure demand rate at an airport, pilots may also be instructed to hold short of the departure runway in a "departure queue". Key influences on the taxi out process include the taxi path, the taxi distance (i.e., as the taxi distance increases, the chances of having more holds increases because of the likelihood of a taxiing aircraft having to negotiate intersections and other taxiing aircraft), the weather (which could include the time spent to deice an aircraft), and required separation distances between departures. Generally, the taxi out process is comprised of the following five components:

  - Pushback
  - Unimpeded taxi
  - Route delay
  - Runway queue delay
  - Deicing (when applicable)

- **Taxi in** – The taxi in process begins when an aircraft exits a runway and a pilot begins taxiing along an assigned taxi route. Along this route, a pilot may also be instructed to hold short at any point due to factors such as airfield congestion or the weather. An aircraft may also be delayed in the nonmovement area as pilots are instructed to hold short of an assigned gate that is occupied by another aircraft. The taxi in process is comprised of three components:
  - Unimpeded taxi
  - Route delay
  - Gate hold delay

Throughout the taxi out and taxi in processes, pilot's will turn an aircraft, decelerate and accelerate an aircraft's taxi speed, move at a constant speed, brake, and stop with the thrust settings for the aircraft's engine(s) varying according to the process component. For commercial service jets, aircraft manufacturers recommend taxi procedures and speeds in Flight Crew Training Manuals. A manual prepared for the Boeing 737-300/400/500 series aircraft states the following regarding taxi speeds, thrust and braking:

- "To begin taxi, release brakes, smoothly increase thrust to minimum required for airplane to roll forward, then reduce thrust to idle."
- "Normal taxi speed is approximately 20 knots, adjusted for conditions. On long straight taxi routes, speeds up to 30 knots are acceptable…"
- "Because of additional operational procedural requirements and crew workload, taxiing out for flight with an engine shut down is not recommended."

Taxi-out and taxi-in delays are metrics reported by the FAA's Office of Aviation Policy's Aviation System Performance Metrics (ASPM). The taxi delays are computed as the difference between the taxi-out (or in) duration and the unimpeded taxi time. For the purpose of the ASPM, the unimpeded taxi time is estimated by regression equations (i.e., the times are not directly observed from surveillance data).

3.1.1.2 Airfield/Aircraft Operational Procedures that Reduce Emissions

As a method of reducing fuel-burn, airlines promote the practice of taxiing with less than all of an aircraft's engines operating. Although this practice is generally referred to as "single engine taxiing", it can involve more than one of an aircraft's engines operating.

There are three categories of considerations for pilots making a decision to single-engine taxi. The categories are crew workload, aircraft systems implications and breakaway thrust levels. These categories are briefly described below [UK Dept. of Transport, 2012]:

- **Crew workload** – So that airfield congestion is avoided, an aircraft taxiing with fewer engines must be able to taxi at the same speed that would be possible with all engines operating. In order to do so, additional systems checks requiring the attention of the flight crew may be necessary.
- **Systems implications** – Taxiing with fewer engines can provide less or degraded power to some systems on an aircraft which would require the operation of an aircraft's auxiliary power unit (APU). Even if all systems have sufficient power, use of an APU may be necessary in case there is a systems failure.

- **Breakaway thrust levels** – The thrust level necessary to start moving or to move a heavy aircraft cannot be such that it creates a jet blast risk to other aircraft. The increased thrust of the operating engine may also increase the potential for debris to be picked up from the ground.

Other considerations include the surface condition of the taxipath (e.g., it could be slippery), excessive taxiway slopes, congested maneuvering areas, and the need for full power for runway crossings. Notably, although promoted by most airlines, single-engine taxiing is performed only at the discretion of an aircraft's pilot and, all engines typically need to be running for three to five minutes prior to an aircraft's departure and for up to five minutes after arriving to cool down.

Recognizing that the reduced use of an aircraft's engines on the ground could result in significant fuel savings, at least two manufacturers/joint ventures are developing methods to taxi aircraft on the ground with no engines operating. Honeywell, and the aerospace firm Safran, have been working together to develop an electric motor that would power an aircraft's main wheels that would be powered by an aircraft's APU. The Honeywell/Safran product is known as the Electric Green Taxiing System (EGTS) and it is reported by the joint venture that the product will be available in the year 2017[1] [AOPA 2011; Franc24, 2013]. Wheeltug, a system being developed by a subsidiary of Borealis Exploration Limited, involves an electric motor in the hub of the nose wheel.[2] This motor would also be powered by an aircraft's APU. As recently reported by Wheeltug, they expect to begin installing their system onto aircraft belonging to 11 airlines, including six flagship carriers, in the near term.[3]

An airlines acceptance of an electric taxi system could depend on the cost of the system and whether or not the taxi-related fuel savings offsets the increased fuel consumption to carry the systems added weight during flight. A study performed to evaluate the operational and environmental benefits of electric taxi excluded heavy aircraft (i.e., aircraft heavier than an Airbus A321) because the analysts expected that the additional weight of the motors and resultant fuel consumption during a long cruise would more than offset the reduction in fuel usage during these aircraft's ground movements. And, while the analysts concluded that the electric motors would make a valuable contribution to reducing emissions, they report that the greatest benefit would result from the systems being installed on aircraft that connect large airports that are located close to each other but have long taxi times [Wollenheit et. al., 2013].

At congested airports, ATC may use procedures that also result in emission savings. These procedures are often referred to as virtual queuing procedures because they control the rate at which aircraft are pushed backed from a gate on departure (i.e., departure management) without an aircraft losing its place in an airport's departure queue. Assuming another aircraft does not need a gate, keeping a departing aircraft at a gate, as opposed to the aircraft waiting in the movement area, saves fuel and reduces emissions [Bhadra et al, 2011; Simaiakis et al, 2010; Baik, UNK].

3.1.1.3 Flight Data Recorder Data

The best source of aircraft performance data are FDRs which are also known as "black boxes". FDRs record any instructions (i.e., thrust settings) that are sent to any electronic system on an aircraft. Unfortunately, due to the proprietary nature of the data on FDRs, the data is not readily available for research purposes. However, Research Team members have FDR data from which summary results can be used for the purpose of the Project. Team members also have access to the raw data that has been collected as part of several field campaigns, including Aircraft Particulate Emissions Experiments (APEX), JETS-APEX2, APEX3, ACRP 02-03A, and the Alternative Aviation Fuel Experiment (AAFEX)

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[1] Electric Green Taxiing System overview - www.greentaxiing.com/overview.html

[2] Wheeltug - www.wheeltug.gi/

[3] Royal Aeronautical Society, Toulouse, 13 September 2013. Delivered by Isaiah Cox, WheelTug Chief Executive Officer

projects. Notably, much of the data has been published in peer-reviewed literature [e.g., Yelvington et al. 2007] or as an ACRP report [Herndon et al. 2012].

ACRP's 11-02 Task 8 Research Project, *Enhanced Modeling of Aircraft Taxiway Noise* (Page et al. 2009) examined FDR information from a major European airline and the airline's affiliate regional carriers from which statistical generalities were developed regarding aircraft taxi operations [Page et al, 2013b]. The FDR data included one year of operational data from "gate to runway to air to runway to gate", for a multitude of international airport pairs. Although from a European airline, the data is reported to have included information for some United States (U.S.) airports and was considered generally applicable to U.S. airports.

The 11-02 research project assessed the taxi out and taxi in components separately. Operations at a gate while engines were spooling down were not included in the arrival taxi segment and stationary segments were defined as those with reported ground speed less than one knot. Data from Tables 1 through 4 of the Volume 1 (Scoping) report for ACRP's 11-02 are provided below in **Tables 1 through 6** of this Working Paper. Notably, there are currently no RJ100 aircraft and only one RJ85 aircraft registered to a domestic airline. This fact will be considered by the Research Team in the evaluation/use of this available FDR information.

Table 1
Ground Speeds for Taxiing Operations

	Departures		Arrivals	
Aircraft	**Average Speed (knots)**	**Standard Deviation (knots)**	**Average Speed (knots)**	**Standard Deviation (knots)**
A319	9.26	3.34	11.72	3.27
A320	9.10	2.92	11.08	3.27
A321	9.39	3.31	11.28	4.67
A330	10.05	3.32	13.07	3.21
A340	9.26	2.98	9.88	2.92
B757	8.87	2.28	13.23	2.68
B767	11.13	3.13	12.65	2.60
B777	8.97	3.18	11.45	2.26
RJ100	9.14	3.57	14.10	4.44
RJ85	8.23	3.08	14.67	4.77
Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009				

Table 2
Engine Use - Taxi Out

	Percent of Time Number of Engines Were Operating							
	One Engine		Two Engines		Three Engines		Four Engines	
Aircraft	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stationary								
A319	2.4	5.47	97.4	5.68	--	--	--	--
A320	3.3	7.62	96.6	7.85	--	--	--	--
A321	2.1	3.56	97.8	3.85	--	--	--	--
A330	9.6	14.93	90.3	15.12	--	--	--	--
A340	1.2	7.25	7.1	15.86	3.2	5.7	88.2	21.51
B757	5.1	5.58	94.7	5.86	--	--	--	--
B767	17.1	15.24	82.7	15.38	--	--	--	--
B777	7.3	14.01	92.5	14.14	--	--	--	--
RJ100	0.0	--	0.0	--	0.0	--	100.0	0.00
RJ85	0.0	--	0.0	--	0.0	--	100.0	0.00
Moving								
A319	11.2	19.54	88.6	19.41	--	--	--	--
A320	9.3	18.39	90.6	18.27	--	--	--	--
A321	8.7	16.10	91.1	15.99	--	--	--	--
A330	11.3	14.72	88.5	14.75	--	--	--	--
A340	1.8	2.98	7.2	8.74	1.4	1.88	89.2	10.83
B757	2.8	4.51	97.1	4.76	--	--	--	--
B767	6.6	9.73	93.3	9.90	--	--	--	--
B777	10.5	10.87	89.4	10.92	--	--	--	--
RJ100	0.0	--	0.0	--	0.0	--	100.0	--
RJ85	0.0	--	0.0	--	0.0	--	100.0	--

Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009 Note: -- = Not applicable

Table 3
Engine Use - Taxi In

	Percent of Time Number of Engines Were Operating							
	One Engine		Two Engines		Three Engines		Four Engines	
Aircraft	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Stationary								
A319	3.0	15.13	98.9	15.21	--	--	--	--
A320	1.1	7.63	98.8	7.77	--	--	--	--
A321	0.0	0.00	100.0	0.00	--	--	--	--
A330	4.4	19.42	95.5	19.50	--	--	--	--
A340	1.0	8.60	1.7	10.36	1.2	10.7	95.9	19.35
B757	1.2	10.87	98.7	10.87	--	--	--	--
B767	0.6	5.39	99.3	5.44	--	--	--	--
B777	0.0	--	100.0	0.00	--	--	--	--
RJ100	0.0	--	0.0	--	0.0	--	100.0	--
RJ85	0.0	--	0.0	--	0.0	--	100.0	--
Moving								
A319	0.4	2.85	99.5	2.99	--	--	--	--
A320	1.1	6.28	98.7	6.46	--	--	--	--
A321	0.0	0.53	99.9	0.62	--	--	--	--
A330	1.7	11.23	98.2	11.36	--	--	--	--
A340	0.5	3.05	1.7	10.09	0.1	0.68	97.5	11.04
B757	0.4	3.60	99.5	3.72	--	--	--	--

B767	0.5	7.36	99.4	7.36	--	--	--	--
B777	0.0	0.18	99.9	0.25	--	--	--	--
RJ100	0.0	--	0.0	--	0.0	--	100.0	--
RJ85	0.0	--	0.0	--	0.0	--	100.0	--

Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009 Note: -- = Not applicable

Table 4
Engine Operating Parameters - Taxi Out

Aircraft	Average N1 average	Standard Deviation N1average	Average Percent Thrust	Stnd Dev Percent Thrust	Average EMS Thrust	Stnd Dev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
Stationary								
A319	19.42	1.41	8.41	1.18	1975.24	278.42	1975.24	278.42
A320	19.16	1.29	7.45	1.34	2011.77	361.01	2011.77	361.01
A321	20.06	1.55	6.15	1.15	1843.61	345.29	1843.61	345.29
A330	21.16	3.08	N/A	N/A	3845.13	2484.18	N/A	N/A
A340	19.50	4.73	N/A	N/A	2210.70	1027.83	N/A	N/A
B757	20.47	1.51	2.68	0.67	1077.75	268.58	1077.75	268.58
B767	23.78	2.66	5.74	1.24	3565.83	772.65	N/A	N/A
B777	19.89	2.30	4.86	0.86	5615.41	989.00	N/A	N/A
RJ100	22.67	1.80	21.70	1.99	1518.85	139.30	N/A	N/A
RJ85	22.32	1.59	21.44	1.71	1500.55	120.04	N/A	N/A
Moving								
A319	19.56	3.34	9.20	1.92	2162.66	451.69	2162.86	451.69
A320	19.71	3.29	8.22	1.85	2220.48	498.40	2220.48	498.40
A321	20.32	3.13	6.89	1.43	2066.97	429.37	2066.97	429.37
A330	22.28	3.30	N/A	N/A	4261.80	2792.32	N/A	N/A
A340	20.45	4.08	N/A	N/A	2407.10	1008.95	N/A	N/A
B757	23.28	2.20	3.73	1.01	1500.41	405.07	1500.41	405.07
B767	26.14	1.71	6.58	1.14	4085.75	708.94	N/A	N/A
B777	20.08	1.94	5.16	0.77	5960.23	884.92	N/A	N/A
RJ100	25.49	2.45	24.61	2.47	1722.56	172.80	N/A	N/A
RJ85	24.59	2.11	23.85	2.38	1669.50	166.76	N/A	N/A

Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009
N/A = Not available (Source states that some A330/A340 departure values were erroneous in the FDR database.

Table 5
Engine Operating Parameters - Taxi In

Aircraft	Average N1 average	Standard Deviation N1average	Average Percent Thrust	Stnd Dev Percent Thrust	Average EMS Thrust	StndDev EMS Thrust	Average EMS Enhanced	Standard Dev EMS Enhanced
Stationary								
A319	17.37	3.98	8.62	2.20	2026.47	516.45	2026.47	516.45
A320	17.51	3.04	7.72	1.89	2086.66	510.60	2083.66	510.60
A321	18.21	3.82	6.78	1.97	2034.77	591.40	2034.77	591.40
A330	21.51	4.25	5.80	4.46	3947.56	3035.05	2815.96	3582.02
A340	19.20	3.93	6.38	2.85	2590.74	839.84	1516.45	1520.39
B757	19.64	2.50	1.39	0.87	560.33	347.74	560.33	347.74
B767	26.79	1.56	6.09	4.47	3781.28	2777.72	N/A	N/A
B777	21.41	0.91	5.46	0.43	6312.84	496.08	N/A	N/A
RJ100	17.51	6.52	16.54	6.41	1157.97	449.01	N/A	N/A
RJ85	18.03	5.69	17.06	5.45	1194.22	381.76	N/A	N/A

Moving								
A319	19.94	1.05	9.89	0.70	2323.04	164.33	2323.04	164.33
A320	19.62	1.38	8.70	1.32	2350.02	355.09	2350.02	355.09
A321	20.72	1.55	7.62	0.57	2284.95	169.66	2284.95	169.66
A330	23.15	2.23	6.56	4.26	4459.99	2892.61	2886.91	3742.11
A340	20.03	2.55	7.04	2.54	2862.06	555.44	1672.96	1585.15
B757	22.29	1.79	3.34	0.61	1341.46	245.01	1341.46	245.01
B767	27.17	2.13	6.65	0.89	4130.46	549.77	N/A	N/A
B777	21.53	0.45	5.48	0.31	6336.52	359.74	N/A	N/A
RJ100	23.84	6.19	22.85	6.16	1599.68	431.08	N/A	N/A
RJ85	23.44	6.67	22.55	6.63	1578.58	463.89	N/A	N/A

Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009
N/A = Not available (The source reports that some A330/A340 departures values were erroneous in the FDR database.

Table 6
Engine Operating Parameters – Accelerating Aircraft

Arrival/ Departure	Aircraft	Avg Accel Time (s)	Avg N1 average	Avg N1 Max	Avg Avg Percent Thrust	Avg max Percent Thrust	Avg. Max Long Accel (g)	# Events
Burst								
Arrival	A319	5.00	14.88	15.58	8.01	8.50	0.29	2
	A320	8.33	18.40	20.45	7.21	8.44	0.03	6
	A321	7.00	18.56	18.71	6.88	6.94	0.03	5
	A330	7.31	21.89	23.80	5.82	6.27	0.01	13
	A340	9.50	22.77	25.88	8.07	9.69	0.03	10
	B757	6.68	18.85	20.50	N/A	N/A	0.02	95
	B767	8.00	26.10	27.31	4.61	11.88	0.01	25
	B777	9.27	21.04	22.10	5.23	5.73	0.01	41
Departure	A319	6.63	28.24	36.07	13.74	21.24	0.20	92
	A320	7.07	27.93	35.79	13.74	18.68	0.20	121
	A321	6.07	28.80	35.45	12.74	16.69	0.18	61
	A330	8.00	40.07	54.75	10.44	16.58	0.15	95
	A340	7.50	29.52	41.41	8.57	14.04	0.14	34
	B757	7.27	35.58	44.34	10.29	14.30	0.15	75
	B767	8.17	41.16	57.39	14.19	28.82	0.18	71
	B777	8.17	31.14	40.96	9.45	13.02	0.15	101
Gentle								
Arrival	A319	104.41	17.85	26.12	8.71	14.17	0.02	17
	A320	115.47	15.32	23.89	6.64	11.30	0,03	43
	A321	54.76	22.08	27.72	7.89	11.41	0.03	21
	A330	32.20	24.32	29.84	8.76	11.49	0.02	25
	A340	29.44	23.28	29.09	8.50	11.40	0.02	18
	B757	12.41	19.70	21.94	N/A	N/A	0.02	106
	B767	41.84	21.94	27.73	4.55	16.35	0,02	98
	B777	17.50	21.19	22.66	5.24	5.89	0.01	54
Departure	A319	71.53	23.07	27.90	10.87	14.49	0.02	334
	A320	70.02	22.46	26.77	9.42	12.22	0.03	547
	A321	70.63	23.39	28.18	8.22	11.53	0.03	248
	A330	59.65	27.27	32.93	6.46	9.18	0.02	103
	A340	48.94	23.38	31.10	5.22	8.68	0.03	17
	B757	67.99	27.38	33.84	5.14	8.95	0.04	296
	B767	74.26	27.64	29.86	6.84	22.62	0.02	291

	B777	68.46	22.89	25.80	5.98	7.16	0.02	343

Source: Web-Only Document 9: ACRP Project 11-08 Task 8, June 2009
N/A = Not available (The source reports that some A330 and A340 Departures values were erroneous in the FDR database and were removed).

Table 1 lists the ground speed of the departing and arriving aircraft for which FDR data were reviewed. As shown, during taxi out the large jet taxi speed ranged from 8.87 to 11.13 knots (10.21 to 12.81 miles per hour) and during taxi in the speed of these aircraft ranged from 9.88 to 13.23 knots (11.37 to 15.2 miles per hour). Additionally, while the speed of the RJs was similar during taxi out (an average of 8.69 knots (10 miles per hour)) the taxi in speed of these aircraft was higher than the large jets (14.39 knots (16.56 miles per hour)).

Tables 2 and 3 provide the percentage of time that each aircraft operated with all (or less than all) engines operating during taxi out and taxi in, respectively. As shown, during taxi out the A319 aircraft had both engines operating 97.4 percent of the time while the B767 only had both engines operating 82.7 percent of the time. Of note also is that the RJs had all four engines operating at all times during the taxi out process.

Tables 4 and 5 report engine operating parameters for the taxi out and in process when the aircraft were both stationary (i.e., moving less than one knot) and moving. The parameters include the average rotational speed of the engine spool, the average engine thrust, the average absolute thrust measurement and the recommended average thrust to ensure the most efficient operation at the time of the measurement. As shown, during stationary departure operations, the engines on the A319 had an average rotational speed of 19.42 revolutions per minute (RPM)[18] plus or minus 1.41 percent and the engines operated at 8.41 percent thrust (plus or minus 1.18 percent). During the measurement period, the absolute thrust of the engines was 1,975.24 kilonewtons (plus or minus 278.42 kilonewtons) and a different thrust was not recommended.

Table 6 provides the engine operating parameters for the aircraft during acceleration. As shown, these data are available for both taxi out and taxi in and for two distinct operation types: 1) short bursts of acceleration (i.e., 15 seconds or less) and 2) gentle, longer and slower accelerations.

The documentation for ACRP's 11-02 research project also provides the following aircraft taxi speed information for which the source was FDR information:

- The taxi study conducted for the ACRP 11-02 indicates that typical ground speeds range from 9 to 16 knots with a standard deviation of 3 to 5 knots [Page et al, 2013].
- Analysis of data published by the University of Madrid indicates that most measured aircraft move at a constant speed ranging from 15 to 23 knots with an average taxi speed of 19.8 knots [Page et al, 2013b].
- The ACRP 02-27 project for which results were published in January of 2013 indicates a reference ground taxi speed of 16 knots [Page et al, 2013b].

Other studies are available that use FDR information [e.g., Khadilkar et al, 2012] but the reported values are not relevant to the ACRP 02-45 Research Project.

3.1.2 Aircraft Engine Emissions

The ICAO aircraft LTO cycle comprises four modes: idle/taxi, take-off, and climb-out approach. Total emissions of a particular pollutant (e.g., carbon monoxide) per engine per LTO mode are calculated by the product of the fuel-based emission index (grams of pollutant emitted per kilogram of fuel burned), the

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[18] This value may instead represent a percentage of thrust. Additional research is needed to confirm which unit is appropriate when interpreting the values in Tables 4 and 5.

fuel flow rate (kilogram of fuel per second), and the total time in mode (in seconds). For example, CO emissions from an engine during the idle/taxi component of an LTO are calculated by the following equation:

$$\text{CO Emissions}_{\text{IDLE}}\ (\text{g}) = \text{CO EI}_{\text{IDLE}}\ (\text{g/kg}) \times \text{FFR}_{\text{IDLE}}\ (\text{kg/s}) \times \text{TIM}_{\text{IDLE}}\ (\text{s})$$

where:

EI = emissions index
FFR = fuel flow rate
TIM = time-in-mode
g = grams
kg = kilograms
s = seconds

Total CO emissions from this engine during an entire LTO are then calculated by adding the emissions from each of the four LTO modes.

The aircraft emission indices in the current EDMS database that are used to create emission inventories are based on ICAO certification tests performed at four thrust levels corresponding to the four components of a LTO cycle: idle/taxi (7 percent thrust), take-off (100 percent thrust), climb-out (85 percent thrust) and approach (30 percent thrust). Each thrust setting corresponds to an engine-specific fuel flow rate (with variations determined, among other variables, by “bleed flow” used for auxiliary uses such as air conditioning). For example, using the ICAO default fuel flow rates, time-in-modes, and emission indices, each CFM56-7B24 emits 3,741 grams of CO during the idle/taxi mode: (22 g CO per kg of fuel) × (0.109 kg fuel / second) × (1560 seconds idling).

As discussed further below, a general trend common to all engines is that CO and hydrocarbon (HC) emission indices are highest at low thrust settings (because CO and HC result from incomplete combustion of fuel) while nitrogen oxide (NO_x) emission indices are highest at high thrust settings (because NO_x is mainly created from the high temperature oxidation of atmospheric nitrogen). **Figure 1** depicts the CO and NO_x emission indices at each of the four components of a LTO cycle for a CFM56-7B24 engine, one of the most common engines in the commercial fleet.

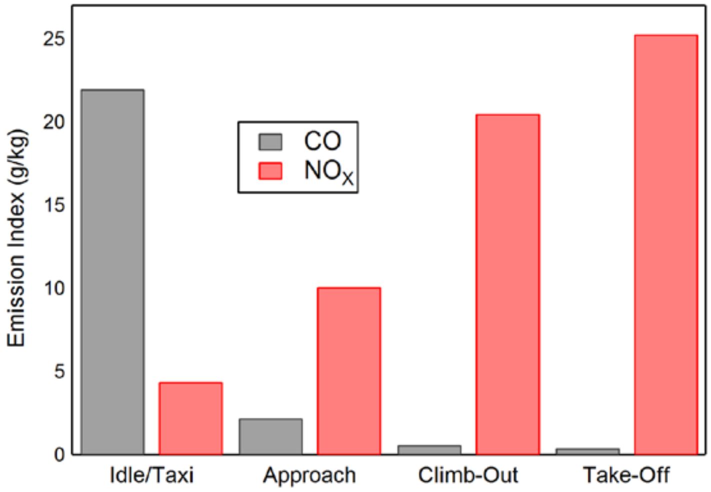

Figure 1. ICAO Emission indices for CO and NOx for the CFM56-7B24 engine. HC emission indices show the same general trend as CO – highest during idle/taxi (low thrust, low fuel flow rate) and lowest at take-off (high thrust and fuel flow rate).

Because the emission indices, fuel flow rates, and time-in-modes all vary with LTO phase, all three must be considered when calculating total emissions per LTO as per above equation (total LTO emissions being calculated using the appropriate emissions index, fuel flow rates, and time in mode for each of the operational modes). **Figure 2** shows the total LTO emissions of CO, NO_x, and HC from a CFM56-7B24 engine using the default ICAO values for fuel flow rate, emission indices, and time-in-mode. Evident from **Figure 2** is that the idle/taxi mode is responsible for the largest portion of CO and HC emissions by far – because both the emission indices and time-in-mode are highest during idle/taxi, even though the fuel flow rate is lowest. Conversely, most NO_x emissions result from the take-off and climb-out phases since both the fuel flow rate and NO_x emission indices are highest at high fuel flow rates, even though the total time spent during these two modes is small compared to the idle/taxi mode. The idle/taxi mode accounts for approximately 15 percent of total NO_x emissions.

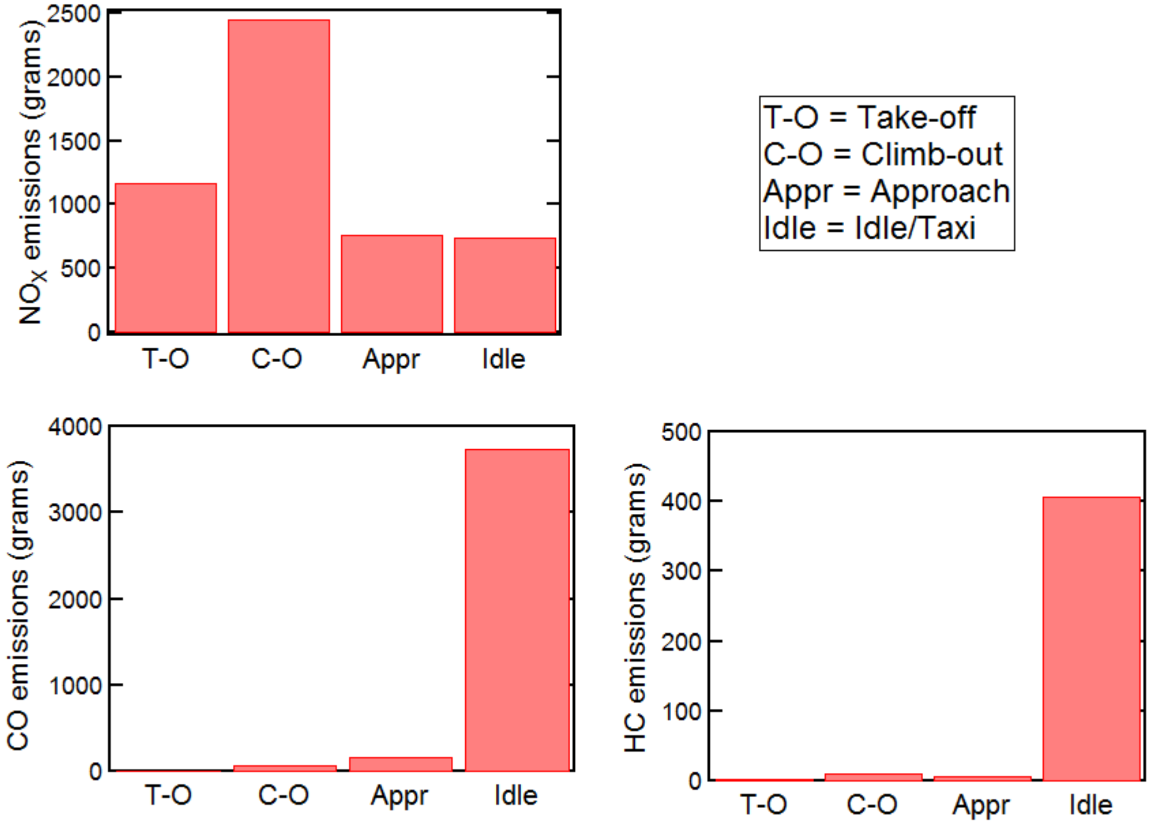

Figure 2. Total emissions of NO_x, CO, and HC emitted by a single CFM56-7B24 engine during a LTO cycle, calculated using the default time-in-modes and ICAO fuel flow rates and emission indices. The vast majority of CO and HC emissions occur during the taxi/idle mode.

These numbers all vary in actual use, however, so using these default numbers can lead to inaccuracies in emission inventories. Time-in-mode values can vary significantly from the default values, and airport-specific values based on actual data and/or the Delay and Sequence module can be input into EDMS. The only way to deviate from the default flue flow rates and emission indices is to create "custom aircraft" (discussed further in Section 3.2.1 of this Working Paper). As initially discussed in **Section 3.1.1** and repeated below, actual thrust settings and fuel flow rates can actually vary significantly from 7 percent thrust for the idle/taxi phase. The emission indices for CO and HC depend on the fuel flow rate, and are much greater at lower thrust settings (e.g., 4 percent versus 7 percent thrust). Additionally, CO and HC emission indices are very sensitive to the ambient temperature (i.e., low temperatures lead to increased

CO and HC emission indices). The rest of this section describes our understanding of emissions from the idle/taxi phase with an emphasis on HC and CO emissions.

3.1.2.1 Idle Thrust Setting (Fuel Flow Rate): ICAO Versus Actual Operation

Although unburned HC (UHC) / volatile organic compound (VOC) emissions are currently based on certification tests performed at 7 percent thrust, there is strong evidence that this single thrust value does not accurately reflect true operating conditions. This evidence is based both on FDR data, which directly records fuel flow rate, and comparison of pollutant emission indices from advected plumes of in-use aircraft to emissions data collected at known thrust and fuel flow rate settings. Evidence to date (partially listed below) indicates that while stationary or moving at a constant speed, aircraft operate at thrust values closer to ~4 percent thrust ("ground idle") and accelerations / turning are associated with higher values that at times exceed 7 percent thrust.

- ***FDR data*** - Examination of FDR is the most straightforward method to assess what thrust settings / fuel flow rates are actually used in day-to-day practice. For example, FDR data from an A320 during the idle/taxi phase show that during most of the idle/taxi period, the engines operated at a fuel flow rate of ~0.10 kilograms/second, punctuated by occasional "bursts" of 0.14 to 0.17 kilograms/second. The value of 0.10 kilograms/second is 20 percent lower than the ICAO 7 percent fuel flow rate of 0.12 kilograms/second (Figure V-4 of ACRP report 63, project 02-03a), and the higher values are 17 to 40 percent higher. Similarly, FDR data from a CFM56-7BX engine in Turkey [Turgut et al, 2013] show that fuel flow rate during the idle phase was usually 0.09 kilograms/second with occasional bursts up to 0.17 kilograms/second, compared to the ICAO 7 percent value of 0.11 kilograms/second. Additional corroborating evidence can be found in the work of Patterson et al [1999], Khadilkar and Balakrishnan [2012], and Nikoleris et al. [2011] among others.

- ***Comparison of Staged to In-Use Emission Indices*** - During several aircraft emissions measurements studies (e.g., the Aircraft Particulate Emissions eXperiments – APEX), emissions were characterized in two different experimental set-ups: 1) with a stationary aircraft operating at exactly known parameters (e.g., fuel flow rate), and 2) measuring diluted advected plumes downwind of the actual in-use aircraft. The first method provides well defined relationships between pollutant emission indices (e.g., for CO, NO_x, individual VOCs, etc) that can be used during the second method to infer the actual fuel flow rate. For example, NO_x emission indices decrease with increasing thrust value. During the JETS-APEX2 study, [Wood et al, 2008) it was observed that NO_x emission indices from idling B737 aircraft at Oakland International Airport were usually lower than the NO_x emission indices for 7 percent thrust operation observed during staged tests. The observed emission indices were more consistent with operation at 4 percent thrust with occasional bursts at approximately 15 percent thrust, in agreement with the FDR findings described above. Similar results have been presented by several research teams [Herndon, 2009; Mazaheri, 2009; Schäfer, 2003].

3.1.2.2 Inter-Engine Variability in Unburned Hydrocarbon Emissions

Differences in the 7 percent ICAO HC emission indices between different types of engines (e.g., CFM56 vs. RB211) can easily exceed a factor of 10. As shown, **Figure 3** compares the ICAO HC emission indices for three different engines: a V2527 (commonly used in the Airbus A320), a CFM56-7B24 (commonly used in Boeing B737), and the CF6 (commonly used on McDonnell Douglas DC-10).

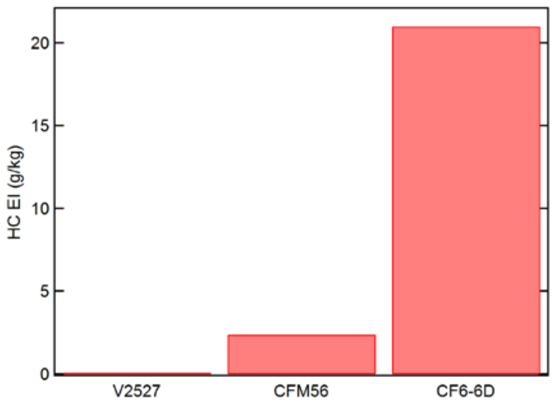

Figure 3. ICAO 7 percent HC emission indices for three common aircraft engines.

3.1.2.3 Near-Idle Unburned Hydrocarbon Emissions Sensitivity to Fuel Flow Rate and Ambient Temperature.

Thrust settings lower than the ICAO certification value (7 percent thrust) and temperatures lower than the certification temperature (15 degrees Celcius) lead to increases in CO and HC emission indices. This was observed during the first APEX project [Yelvington et al, 2007] and studied in great detail during ACRP 02-03a, *Measurement of Gaseous HAP Emissions from Idling Aircraft as a Function of Engine and Ambient Conditions*. These two effects are described separately in the two following sections:

- **Fuel Flow Rate -** As described earlier, evidence to date suggests that 7 percent thrust overestimates the true thrust levels used most of the time by idling aircraft. True “ground” idle appears to be lower than 7 percent thrust (approximately 4 percent), and accelerations result in thrusts that exceed 7 percent. Although these differences in thrusts are associated with seemingly small changes in fuel flow rates, the effects on HC and CO emissions are large. **Figure 4** shows the fuel flow rate effect on the emission indices of three pollutants for the CFM56-7B24 engine using data from ACRP 02-03a: CO, formaldehyde (HCHO) and total HC. Although 0.09 kilograms/second is only 14 percent lower than 0.105 kilograms/second, it approximately doubles the emission index for all three pollutants. Note that this does not mean that the emission rate (in grams per second) is twice as high – the decrease in the fuel flow rate partially offsets the higher emission index. Rather, the increase in emission rate is approximately a factor of approximately 1.7.

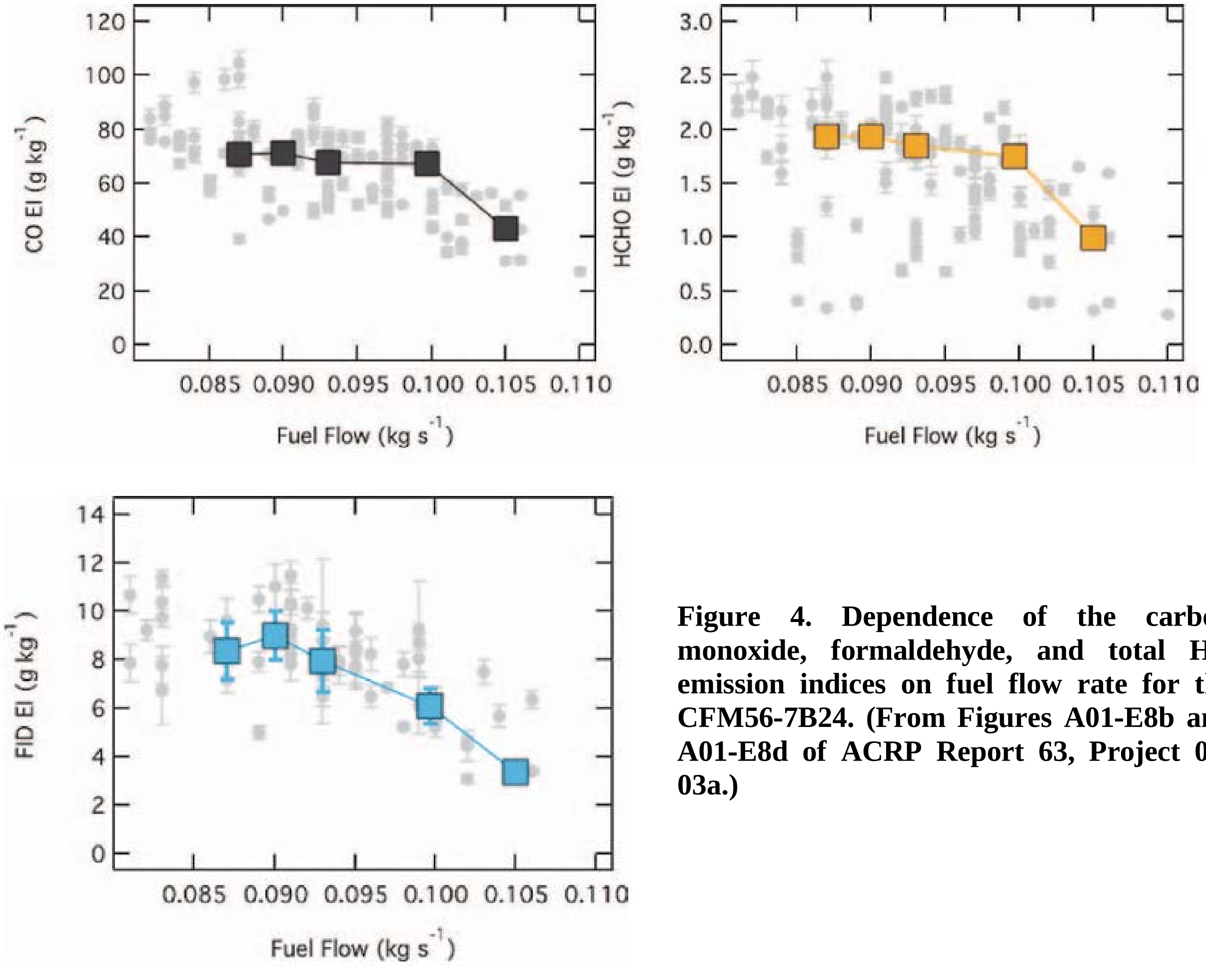

Figure 4. Dependence of the carbon monoxide, formaldehyde, and total HC emission indices on fuel flow rate for the CFM56-7B24. (From Figures A01-E8b and A01-E8d of ACRP Report 63, Project 02-03a.)

- **Ambient Temperature** - The ICAO "reference temperature" for engine certification is 15 degrees Celsius. Ambient temperatures at airports, of course, span a large range of values. **Figure 5** summarizes the *relative* emission indices for HCHO and ethene (C_2H_4) – two important and representative components of total HC – as a function of ambient temperature, using data from the ACRP 02-03a and APEX1 projects. The relative increase of both pollutants is approximately a factor of two at temperatures just below freezing (i.e., the true HCHO and C_2H_4 emission indices are twice as high at approximately -2° C as they are at 15 degrees Celsius). Conversely, the emission indices at 27 degrees Celcius (80 degrees Fahrenheit) are approximately half the 15 degrees Celsius values.

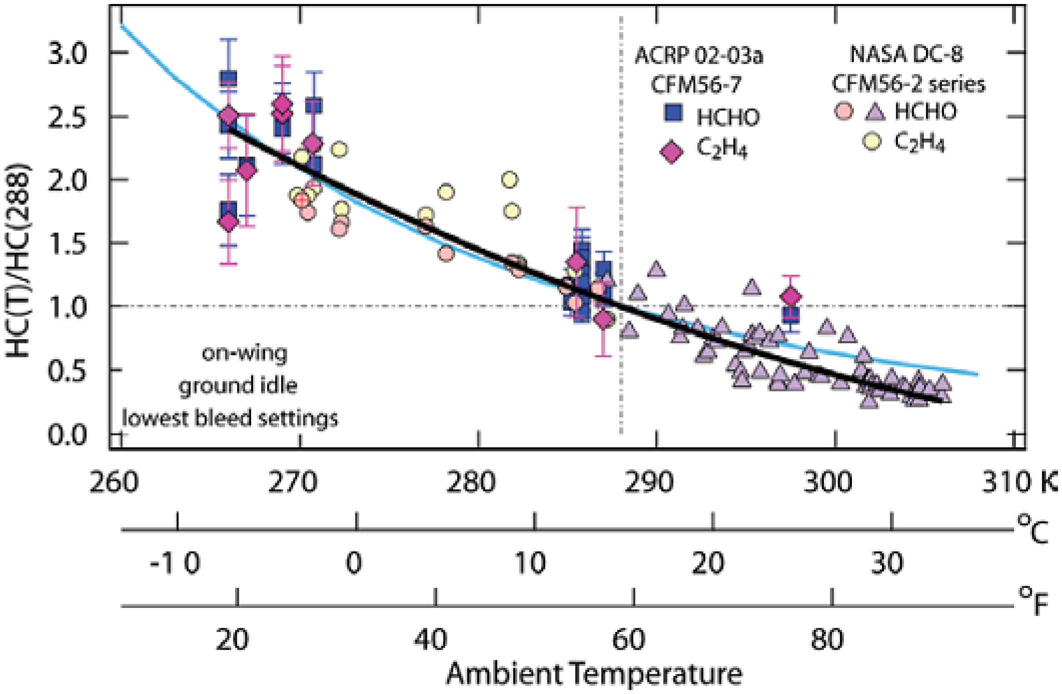

Figure 5. Normalized emission indices as a function of ambient temperature (from Figure IV-3 of ACRP report 63, Project 02-03a). Compared to the ICAO certification emission indices (at 15 °C), actual HC emission indices are doubled at ~-2 degrees Celsius and halved at 27 degrees Celsius.

These relationships between HC emission index and ambient temperatures and fuel flow rates held true for the limited but representative sample of engines studied during the ACRP 02-03a and APEX campaigns. These two parameters (i.e., temperature and fuel flow rate) both act simultaneously – the true HC emission index for an engine that is idling both at very cold temperatures and at sub-7 percent thrust is determined both by the "temperature effect" and by the "fuel flow rate effect". For example, for a CFM56-7B22 engine, operation at 0.09 kilograms/second (versus the ICAO value of 0.105 kilograms/second) and operation at an ambient temperature of 2 degrees Celsius (versus the ICAO 15 degrees Celsius value) results in a factor of three increase in HCHO emission index.

3.1.2.4 Hydrocarbon Speciation into Individual Compounds

There are ICAO certification emission indices for CO, NO_x, sulfur dioxide (SO_2,) total HC, and smoke number, but not for individual VOCs or hazardous air pollutants (HAPs). Similarly, EDMS/AEDT generate total HC emissions but not speciated VOC emissions. Nevertheless, given the importance of

HAPs from a regulatory perspective, a discussion of the differences between HC and individual VOCs is warranted. The term “total HC” is actually a misnomer since the measurement technique for quantifying “HC” – flame ionization detection (FID) – does not detect all HC compounds. Most importantly, FID is most sensitive to large HC compounds (present in unburned fuel) and less sensitive to compounds with carbon-oxygen bonds (which are usually produced by incomplete combustion). The FID also does not detect HCHO. EPA’s SPECIATE module (EPA 2008) can be used to derive the speciation of HC emissions from aircraft (based on data collected in the past decade).

3.1.2.5 Single (Reduced) Engine Taxi Considerations

As stated in **Section 3.1.1** (*Aircraft Performance Characteristics*), airlines promote the practice of single-engine taxiing to reduce fuel burn. However, while shutting down one or more engines during taxi out would on the surface appear to reduce emissions, the engines that are operating may need to operate at a higher thrust to maneuver an aircraft. This practice can also be counterproductive if a departing aircraft has to wait at the end of a runway while an engine(s) is warmed up (typically between three to five minutes) [Kumar et al, 2008].

One study [Kim et al, 2008] reports that where only one engine (out of two) was used to taxi, the increase in the power setting for the running engine ranged between 1.5 to three percent. Similar results were observed for the power settings of aircraft with more than two engines (i.e., the thrust level for the running engines was increased to compensate for one or more engines being off).

3.1.3 EDMS/AEDT Performance and Development

This section of this Working Paper summarizes the Research Team’s knowledge and findings on the subjects of the architecture of the EDMS and AEDT computer models, the historical and future development programs for the models, and steps that have been taken to insure the accuracy of the models.

3.1.3.1 Model Architecture

Figure 6 (Figure 1-2 of the *EDMS User’s Manual*) [FAA, 2013] illustrates the interaction of the various components and modules of the EDMS model that are used to process both emission inventories and to perform dispersion analysis. The manual also provides the following description of the model’s components and modules:

- The back-end of the inventory and dispersion analysis functions is the databases that contain system data and user-created sources. The front-end of the model is the Graphical User Interface (GUI).
- Users of EDMS enter data through the GUI.
- Between the GUI and the databases the model contains the set of classes and functions that represent each emissions source and dispersion object along with the source/object associated properties.
- The external interfaces to the EDMS include AERMAP (Version 12345), AERMET (Version 12345), AERMOD (Version 11103) and MOBILE (Version 6.2).
- EDMS contains an Aircraft Performance Module (APM) and an Aircraft Emissions Module (AEM) that are common to components in AEDT.
- EDMS’s view modules permit users to view output, receptor concentrations and system data that are stored in the databases. They also allow users to view a graphical representation of the various sources in an airport-specific input file.
- EDMS also incorporates certain utilities for importing and exporting some types of data.

The EDMS provides three options for modeling aircraft-related taxi operations: 1) default taxi/delay times, 2) user-specified taxi times for each aircraft and 3) delay and sequence modeling. User-specified taxi times can be based on ICAO default values of 26 minutes or based on measurements from FAA's ASPM [19] and Bureau of Transportation Statistics (BTS) *Airline On-time Statistics* databases.[20] The EDMS Delay and Sequence Module simulates each aircraft's ground movements using user's input for an aircraft operations schedule, the assigned aircraft speed on taxiways, the overall capacity of the airport, and the airfield layout associated with runways, aprons, and taxiways. The module then estimates the time it takes each individual aircraft to taxi between apron and runway endpoints, based on airport-specified taxipaths. Notably, the use of sequence modeling is required when performing dispersion analysis using EDMS. For discussion purposes, **Figure 7** depicts the aircraft taxi/delay datasets used by the EDMS.

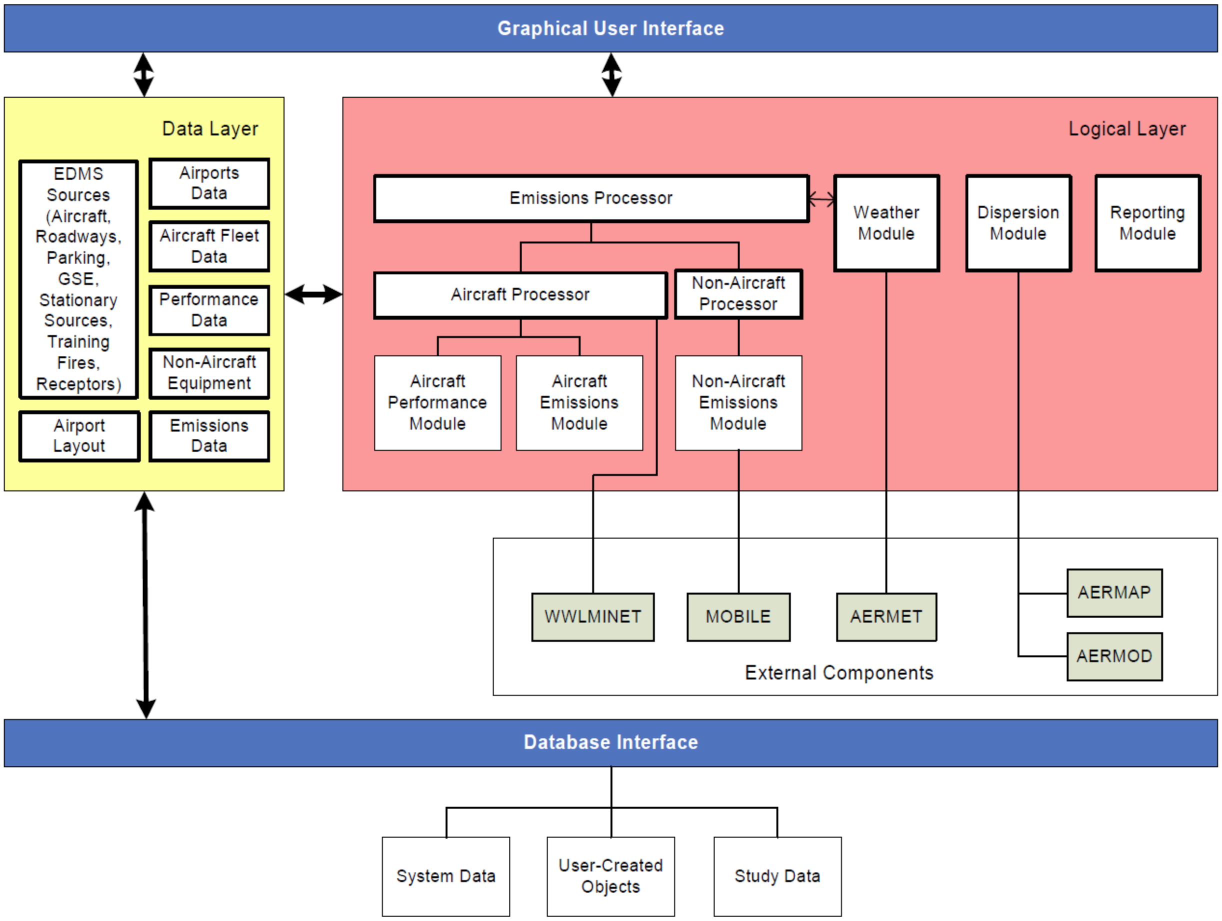

Figure 6. Figure 1-2 of the EDMS User's Manual which illustrates the architecture of the model.

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[19] The **Aviation System Performance Metrics (ASPM)** online access system provides detailed data on flights to and from the ASPM airports (currently 77); and all flights by the ASPM carriers (currently 22), including flights by those carriers to international and domestic non-ASPM airports. All instrument flight rules (IFR) traffic and some visual flight rules (VFR) traffic are included. ASPM also includes airport weather, runway configuration, and arrival and departure rates. This combination of data provides a robust picture of air traffic activity for these airports and air carriers.

[20] BTS reports taxi information for 16 U.S. air carriers that have at least one percent of total domestic scheduled-service passenger revenue, as well as two other carriers that report their schedule information voluntarily.

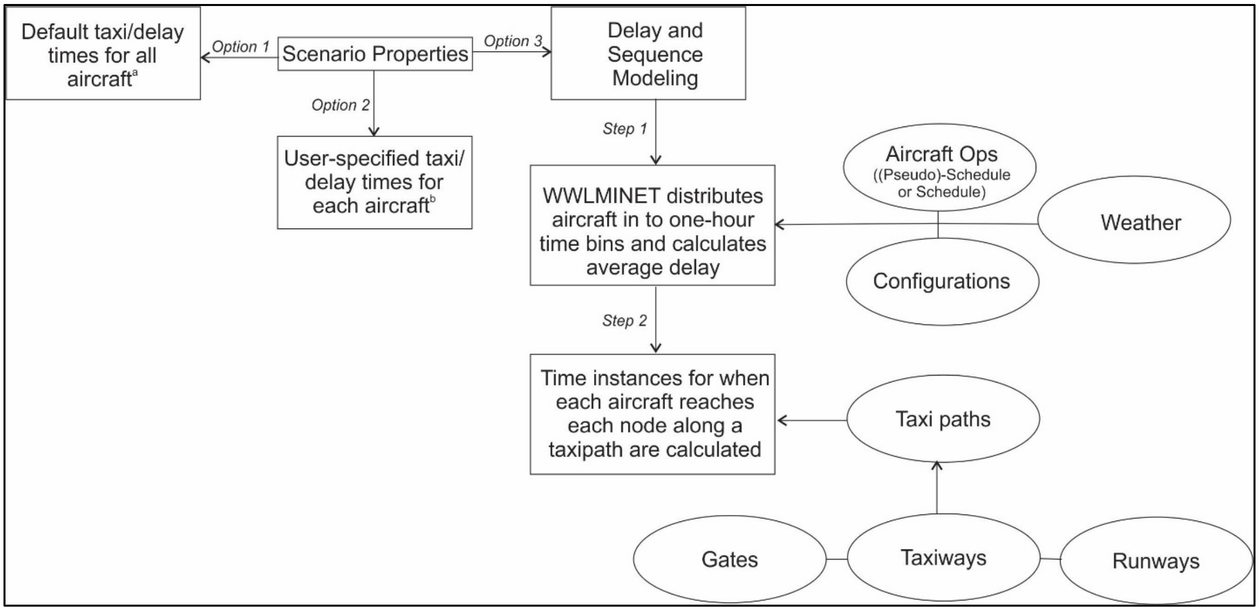

Figure 7. EDMS Taxi/Delay Datasets

The architecture of the AEDT is depicted in **Figure 8**. The AEDT system is anticipated to incorporate the functionality of four noise and emissions modeling applications: 1) the Integrated Noise Model (INM), 2) the EDMS, 3) the Model for Assessing Global Exposure to the Noise of Transport Aircraft (MAGENTA), and 4) the System for assessing Aviation's Global Emissions (SAGE). As shown, the third party components that are identified for EDMS--AERMAP, AERMET, and AERMOD—will also be components of AEDT (the FAA considered the release of EDMS Version 5.1 as a transition to AEDT) [Iovinelli et al, 2009].

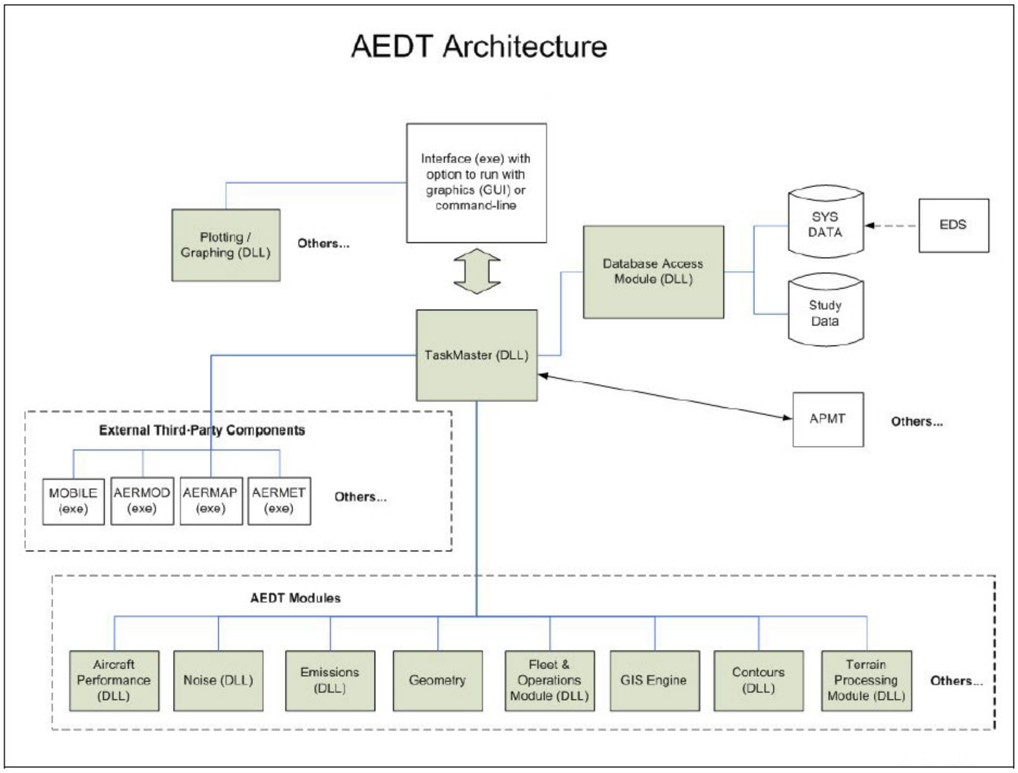

Figure 8. Figure 2 of AEDT-AD-01 AEDT Architecture.

3.1.3.2 Development Programs/Timeframes

The current version of the EDMS was released in August of this year (Version 5.1.4.1). The current version of the AEDT was released in June of 2012 (Version 2a (AEDT2a), Service Pack 1). AEDT2a replaces the Noise Integrated Routing System (NIRS) model, a model used to evaluate the potential environmental impacts of air traffic airspace and procedure actions. The FAA intends to release AEDT2b in 2014. AEDT2b will replace (i.e., sunset) both the FAA's Integrated Noise Model (INM) and EDMS [Cointin, 2011].

3.1.3.3 Model Accuracy/Sensitivity Tests

There are typically three steps to producing models to predict real-world conditions: calibration, verification, and validation:

- Calibration – Models are calibrated by adjusting available parameters to adjust how a model operates and simulates a process.
- Verification – Tests are run to verify that a model is operating as it is expected to.
- Validation **-** This step involves comparing the output from a model to historical data for a study area.

As stated above, the current version of the EDMS was released in August of this year (Version 5.1.4.1). The FAA's Office of Environment and Energy (FAA/AEE) and the Environmental Measurement and Modeling Division at the U.S. Department of Transportation's John A. Volpe National Transportation Systems Center (i.e., the Volpe Center) conducted a validation study for a version of the EDMS that was released in October of 2002 (Version 4.1). The validation was performed to evaluate the addition of EPA's AERMOD dispersion model. At the time, AERMOD had been validated for stationary sources but not for the varied sources found at an airport (particularly aircraft). Field measurements of CO were obtained at 25 sample positions over several days at a major international airport within the U.S. Airport operational activity for aircraft, ground support equipment (GSE), stationary sources, and motor vehicles on airport roadways were input to the EDMS. The comparisons between measured and modeled results were intended for use in an uncertainty assessment of the EDMS [Wayson et al, UNK].

In 2006, the verification of the EDMS's ability to predict concentrations of CO was the subject of a thesis prepared by a student at the University of Central Florida [Martin, 2006]. This verification study was performed on Version 4.21 of the model. Two separate modeling exercises were performed (one using general airport information and the other using very detailed data) and the results of each were compared to measured data. The aircraft-related input values including taxi and queue times and taxiway assignments. For each hour of the study, the known arrival taxi and queue times were averaged and the average was applied to arriving aircraft with unknown taxi/queue times. The departure taxi and queue times were also averaged and applied to the departing aircraft with unknown taxi and queue times. The modeling exercises also included input for GSE, stationary sources, mobile lounges, and motor vehicles on airport roadways and in parking lots. The findings of the study were that measured concentrations of CO were overall higher than the model's predictions. Notably, because this study did not attempt to isolate the various sources of CO for comparison to the measured levels, a single source or process was not identified as being the primary cause of the under prediction.

FAA/AEE, the Volpe Center and staff of the Massachusetts Institute of Technology Department of Aeronautics & Astronautics are collaborating to assess a suite of tools that includes AEDT. As part of the development of the tools, tests are being performed to evaluate the sensitivity of the output from the models to uncertainties in model input and assumptions. There are four elements to the assessment program: 1) parametric sensitivity and uncertainty analyses, 2) comparisons to gold standard data, 3) expert reviews and 4) capability demonstrations/sample problems. In 2009, at the Eighth USA/Europe Air Traffic Management Research and Development Seminar, the preliminary results of the parametric sensitivity and uncertainty analyses were presented. Three main modules within AEDT were assessed—

the APM, the AEM, and the Aircraft Acoustic Module (AAM). Although the study evaluated aircraft emissions of CO2, NO_x, CO, SO_x, H_2O and UHC below 3,000 feet, it does not appear that emissions resulting from ground level taxi operations were included in the assessment [Noel et al, 2009].

3.1.4 Regulatory Framework

The regulations that are most relevant to the 02-45 Research Project are those that mandate the maximum level of pollutants and pollutant precursors that can be emitted from the engine(s) on an aircraft. For aircraft manufactured in the U.S., the U.S. Environmental Protection Agency (EPA) establishes these rates for commercial jet engines.

14 CFR Part 34, *Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes* and 40 CFR Part 87, *Control of Air Pollution from Aircraft and Aircraft Engines; Emission Standards and Test Procedures*, specify exhaust emission rates for new and in-use aircraft that vary depending on the date that an engine is manufactured. These regulations also prescribe that the test procedures used to demonstrate whether an engine meets the standards be performed using equipment and procedures specified in ICAO's Annex 16 [ICAO, 2008].

EPA's initial regulations for gaseous exhaust emissions from aircraft were promulgated in 1973. In 1997, the agency aligned the emissions standards with those established by ICAO (generally referred to as the CAEP/2 standards). In 2005, the agency promulgated more stringent NO_x emissions standards for newly-certified engines. These standards brought the U.S. allowable emission rates closer to the ICAO rates that were effective in 2004 (referred to as the CAEP/4 or Tier 4 standards). Since that time ICAO has adopted two additional standards focused on the reduction of NO_x (referred to as the CAEP/6 and CAEP/8 standards). In 2012, the EPA modified 40 CFR Part 87 such that engine models certified on or after July 18, 2012 had to meet the CAEP/6 standards (also referred to as the Tier 6 standards) and engines certified on or after January 1, 2014 must meet the CAEP/8 standards (also referred to as the Tier 8 standards) [EPA, 2012, 2012b, 2013].

3.1.4.1 National Environmental Policy Act Requirements

Enacted in 1970, the NEPA, was created as a result of public concerns about the human impact on the environment. The Act ensures that environmental factors are weighted equally in all the factors used by a federal agency in their decision making process. There are three levels of analysis that an improvement subject to the NEPA may undergo: 1) a Categorical Exclusion, 2) an Environmental Assessment and Finding of No Significant Impact, or 3) preparation of an Environmental Impact Statement. Airport-related projects subject to the NEPA that would involve aircraft taxi emissions include new airports and additional or extended taxiways to access existing runways.

3.1.4.2 Clean Air Act

One of the purposes of Title I, *Air Pollution Prevention and Control*, of the CAA, is the protection and enhancement of the quality of the nation's air resources so as to promote the public health and welfare. To this end, the CAA requires EPA to establish National Ambient Air Quality Standards (NAAQS). Mitigation measures may also be required under the CAA if it cannot be demonstrated that emissions from a proposed airport activity (i.e., aircraft taxiing on a new or expanded taxiway) would not cause or contribute to a new violation of any of the NAAQS.

For the purpose of identifying activities/actions which would result in an increase in emissions that would be clearly de minimis, the EPA established rates which are referred to as the "de minimis levels". These rates vary depending on whether an area is designated as "non-attainment" or "maintenance" for any of the NAAQS and the air pollutant for which the area has the designation.

3.2 EDMS/AEDT Review

The Research Team conducted a review of the modeling inputs, assumptions, algorithms, database coverage and outputs required by EDMS and AEDT. As previously stated, the current version of AEDT (2a) replaces the NIRS model, a model used to evaluate the potential environmental impacts of air traffic airspace and procedure actions. As also stated, when released by the FAA, Version 2b of the AEDT will sunset the EDMS model. Notably, while AEDT2a does provide fuel burn and emissions data, use of the model is only intended for actions for which the study area is larger than the immediate vicinity of an airport, those that incorporate more than one airport, and/or those that include actions above 3,000 feet above ground level [Marks, 2012].

EDMS was specifically designed by the FAA to estimate emissions of CO, VOC, total organic gases (TOG), nonmethane hydrocarbons, (NMHC), reactive organic compounds (ROG), NO_x, and sulfur oxides (SO_x). EDMS also provides estimates of particulate matter equal to or less than 10 micrometers (PM_{10}) and particulate matter equal to or less than 2.5 micrometers ($PM_{2.5}$). However, because aircraft-related emissions of PM are being addressed by studies being performed by others (i.e., E-31, the SAE International aircraft exhaust emissions measurement committee and the European Aviation Safety Agency), emissions of this pollutant are not being addressed in the ACRP 02-45 project.

Through the use of AERMOD, EDMS can also be used to perform atmospheric dispersion modeling to determine ambient (i.e., “outdoor”) pollutant concentrations of CO, NHMC, VOC, TOG, NO_x, and SO_x (PM also).

3.2.1 Input

For the purpose of estimating/dispersing aircraft-related taxi and queue delay emissions, users have three options for EDMS input:

- Use the ICAO/EPA default taxi/delay times (7 minutes for taxi-in and 19 minutes for taxi out),
- Specify taxi/queue times for each aircraft of interest, or
- Allow EDMS to calculate the times by invoking the model’s “delay and sequence” option.

Estimating aircraft taxi-related emissions by using the EDMS sequencer requires users to specify additional airport layout information, including at least one gate, taxiway, taxipath, and runway. The following describes the required delay and sequence modeling input for an airport’s gates, taxiways, and taxipaths and discusses how a user’s input could affect the resultant level of taxi-related emissions:

- Gates – The location of a gate(s) as specified by a user can affect taxi-related emissions because the model calculates the distance an aircraft traverses from a gate to a runway.
- Taxiway – The coordinates of a taxiway identify a series of areas sources through which an aircraft travels to/from a gate and to/from a runway. Unless airport-specific data are entered, EDMS uses a default taxi speed for aircraft on taxiways of 15 knots (17.26 miles per hour).
- Taxipath – Taxipaths are defined separately for departing and arriving aircraft and the sequence model determining the time-location coordinates of an aircraft as the aircraft moves along the assigned path.

Other EDMS study elements that are used by the sequencer to more accurately estimate taxi-related emissions are:

- User specified operational profiles – These profiles indicate the relative activity at an airport by the quarter-hour, day-of-the-week, and by the month.
- Airport schedule data – Users can "attach" a schedule file to the EDMS that contains scheduled pushback and landing times for every aircraft. If not provided, the sequence modeler will derive a schedule based on the annual operations and input (or default) operational profiles.
- Configurations – EDMS uses configurations to assign aircraft to a runway based on weather conditions (wind direction, wind speed, hour of the day, ceiling, visibility, and temperature).

Other user input that can affect aircraft taxi-related emissions include:

- Reference values for temperature, pressure, and relative humidity can be changed by a user for each airport and scenario combination.
- The airport's elevation which redefines the altitude from which the reference thermodynamic conditions are lapsed can be changed.
- By creating custom aircraft, users can set their own values for the reference idle emissions indices E_{CO}, E_{HC}, and E_{NO_x}, as well as reference fuel flow rate $f_{r_{ID}}^{0}$.

All of the overrides and improved fidelities mentioned above are available for both emission inventories and dispersion analysis. However, dispersion analysis requires a minimum level of fidelity. The time-in-mode basis must be performance-based (though this does not require additional inputs affecting taxi). Taxi time must be sequence-based, requiring airfield configuration and layout definitions. Meteorological data must be hourly, requiring the full set of preprocessed reference data.

Using configuration input, the sequence module of EDMS assigns an appropriate runway configuration for each hour of a year based on the meteorological data for each hour. The module then calculates an airport's capacity for each hour. This capacity data and the calculated airport demand information (which is based on default or user input operational profiles or a schedule) are "fed" to a delay/queuing model—WWLMINET—which calculates an airport's throughput. Modeling of taxi delay/queuing is performed only for departing aircraft. The departing aircraft are also assumed to form queues only along the taxiways that are assigned to a runway.

3.2.2 Algorithms

An algorithm is a detailed sequence of actions that accomplish a task. EDMS's emissions processing algorithms for the taxi mode are detailed in the model's Technical Manual [FAA, 2009]. In general, EDMS develops a schedule of aircraft operations then "simulates" each aircraft flight using the calculations in the APM assuming the weather conditions specified by the model user to occur at the same time as the flight. Resulting emissions are then computed by the model using the AEM.

The smallest unit of emissions calculations in EDMS is the trajectory segment. A trajectory segment represents some portion of an aircraft's trajectory, characterized by temporal and spatial ranges, and select associated aspects of environmental and operational conditions. Emissions calculations for a trajectory segment utilize some of these characteristics, along with aircraft properties, to estimate the amounts of pollutants created over the course of the segment. The characteristics of a trajectory segment considered in calculating its emissions are duration, fuel flow rate, temperature, pressure, relative humidity, Mach number, operating mode, and altitude relationship to mixing height (that is, whether or not the aircraft is below the mixing height).

For the purpose of emissions calculations, EDMS represents the entire taxi portion of an aircraft operation as a single trajectory segment. That is, taxi is characterized using fixed values for fuel flow rate, weather, Mach number, operating mode, and altitude relationship to mixing height, through the duration of the taxi mode These characteristics, combined with emissions parameters specific to the associated aircraft, are used to determine taxi emissions. Some of these characteristics are always the same, whereas others are determined in manners that depend on the selected levels of fidelity. For example, Mach number is always zero, operating mode is always "idle" (though this only relevant to PM calculations), and the aircraft is always assumed to be below the mixing height (also only relevant to PM). Certain emissions parameters are also consistently employed (CO_2 factor of 3,155, water factor of 1,237), and others are always used for jets (conversion factors of 1.0 for NMHC, 1.156234049 for TOG, and 0.9947855 for VOC, as well as the entire spectrum of mass ratios for speciated hydrocarbons).

The value used for relative humidity is taken directly from the reference weather conditions associated with the air operation. The values used for pressure and temperature are also taken from reference conditions when using ICAO/USEPA performance, but are lapsed to the runway end elevation when using the European Civil Aviation Conference (ECAC) Doc29 performance (this is the only effect flight performance fidelity has on taxi emissions).

3.2.3 Databases

EDMS has a database of emission indices (e.g., kilograms of pollutant per kilogram of fuel) and fuel flow rates (e.g., kilograms of fuel per second) for a variety of aircraft/engine combinations and representative operating conditions. These emission indices and fuel flow rates coupled with the amount of time an aircraft spends within the operating mode and the number of engines per aircraft, provides the basis for the emissions estimates.

***CO, HC, NOx* -** The calculation of aircraft taxi CO, HC, and NO_x emissions requires species-specific emissions indices E_{CO}, E_{HC}, and E_{NO_x} for idle engine operation at reference conditions. The calculation of taxi fuel flow rate requires a reference fuel flow rate $f_{r_{ID}}^{0}$ gathered under the same conditions. These quantities come primarily from the ICAO Aircraft Engine Emissions Databank [ICAO, 2013], though some come directly from engine manufacturers or from the EPA's AP-42 Volume II Section 1. They are based on measurements taken from engines running in their test bed, at conditions outlined in a certification standard put forth by ICAO [ICAO, 2008].

EDMS stores the emissions indices and fuel flow rates in the database table ENG_EMIS.DBF for standard system aircraft, and in USER_AIR.DBF for user-defined aircraft (AEDT currently stores them in its FLEET database, table FLT_ENGINES). The associated field names, which are consistent between EDMS and AEDT, are CO_REI_ID, HC_REI_ID, and NOX_REI_ID.

The maximum values, and minimum non-zero values, specified for each of these parameters in the EDMS and AEDT system databases, are tabulated below. For both models, the lowest value for each of these modeling parameters for commercial jet engines is zero. Such values arise when no measurement is available, or when the measured value was small enough to round to zero. In the case where a value is zero, there is no indication (i.e., a note) of which was the case. Notably, however, the emissions modeling process in both EDMS and AEDT overrides zero values with a value of 0.0001.

Table 7
Maximum and Minimum Modeling Parameters

Modeling parameter	AEDT min	AEDT max	EDMS min	EDMS max
E_{CO}	5.74	1294	5.74	897
E_{HC}	0.002	302.36309	0.08	280.73
E_{NO_x}	0.39	8.53181	0.45	7.35
$f_{r_{ID}}^{0}$	0.00098	0.421	0.00102	0.38

***SOx* -** The calculation of sulfur oxides emissions requires fuel sulfur content (FSC) and sulfur conversion efficiency ($\boldsymbol{\varepsilon}$). EDMS and AEDT use hard-coded conservative values of 0.068 percent for FSC and 5 percent for $\boldsymbol{\varepsilon}$ when modeling sulfur according to FOA3a. For EDMS, this is whenever the airport associated with the operation is in the U.S., whereas for AEDT it is determined by a setting in the application configuration file. When not modeling sulfur according to FOA3a, EDMS reads FSC from AC_MAIN.DBF, and $\boldsymbol{\varepsilon}$ from SCENARIO.DBF, both of which are populated by the user in defining their study.

***CO_2* *and Water Emissions Modeling Data* -** The calculation of CO_2 and water emissions requires species-specific emissions indices $\boldsymbol{E_{CO_2}}$ and $\boldsymbol{E_{H_2O}}$. Reviews of available fuel composition data and a first-principles analysis on an assumption of complete HC burn lead to the development of such values based on average composition [Hadaller et al, 1989 and 1993]. For EDMS, the values of these indices are hard-coded into the software as $\boldsymbol{E_{CO_2} = 3155}$ and $\boldsymbol{E_{H_2O} = 1237}$. For AEDT, the values are specified in the application configuration file, and can be modified by the user.

***TOG, VOCs, and NMHC Emissions Modeling Data* -** The calculation of TOG, VOC, and NMHC emissions requires species-specific emissions indices that depend on the emissions index for HC and species-specific conversion factors $\boldsymbol{C_{TOG}}$, $\boldsymbol{C_{VOC}}$, and $\boldsymbol{C_{NMHC}}$. The determination of these factors is based on an estimated value of 0.0052145 for ethane content in TOG, and an assumption that no methane is produced. For EDMS, the values of these indices for jets are hard-coded into the software at $\boldsymbol{C_{TOG} = 1.1571}$, $\boldsymbol{C_{VOC} = 0.0052145}$, and $\boldsymbol{C_{NMHC} = 1}$. For AEDT, the values are specified in the application configuration file.

***Speciated Organic Gases Emissions Modeling Data*-** The calculation of speciated organic gases' emissions requires species-specific emissions indices that depend on the emissions index for HC and species-specific mass fractions. In EDMS, these mass fractions are specified in the database table MASSFRAC.DBF, with values ranging from 0.00002 to 0.15461. For AEDT, the values must be specified by the user in the application configuration file.

3.2.4 Output

The EDMS generates an emissions inventory for CO_2, CO, total hydrocarbons (THC), NMHC, VOC, TOG, NO_x, SO_x, and 394 speciated organic gases. Of note, emissions of CO_2 are calculated only for aircraft and THC is calculated only for aircraft and APUs. Total fuel consumption is also calculated only for aircraft and is provided separately for taxi out and taxi in.

The results of an inventory can be viewed in either summarized or detailed reports. For aircraft, the emission inventory results can be viewed for all aircraft in a "run" (e.g., total CO emissions for all aircraft operating in all modes within an input file) or by aircraft type/engine combination and mode (e.g., total CO for all MD-88 aircraft operating in each of the following modes: startup, taxi-out, takeoff, climb-out, approach, and taxi-in).

As previously stated, using AERMOD, EDMS also generates pollutant concentration estimates for CO, NHMC, VOC, TOG, NO_x, and SO_x ($PM_{2.5}$ and PM_{10} also).

3.2.5 AEDT

The FAA's AEDT is currently a work in progress and is being developed to replace all of the FAA's existing regulatory and policy environmental models including SAGE, MAGENTA, IRS, INM, and the EDMS - essentially in that order.

The first public version of AEDT, version 2a, was released in March of 2012. This version was created to replace NIRS for regulatory purposes and as such includes functionality focused on the needs of users performing regional noise analyses in the context of airspace re-design efforts. While it does include the ability to calculate fuel burn and emissions, it has no provisions for the modeling of aircraft taxi operations.

AEDT2a provides totals for aircraft fuel burn and for aircraft emissions of CO, THC, TOG, VOC, NMHC, NO_x, CO2, H2O, and SO_x (the nonvolatile component of PM (PMNV), PM from sulfur (PMSO), PM from unburned fuel organics (PMFO),, and $PM_{2.5}$ also). Emission totals can be aggregated in four ways: 1) for each mode, 2) for each flight, 3) for each mode on each flight, or 4) for each performance segment of each flight. Modes include taxi out, takeoff ground roll, airborne departure for three altitude ranges (below 1,000 feet, below mixing height, and below 10,000 feet), airborne above 10,000 feet, and airborne approach for the same three altitude ranges.

The emissions result capabilities of AEDT2a are closely aligned with those of EDMS, but there are some important differences. AEDT2a does not calculate any emissions or fuel burn contributions from non-aircraft sources (e.g., GSE, APUs, stationary sources, or vehicular sources), nor does it include aircraft startup or taxi. AEDT2a also does not support emissions dispersion modeling, or provide emissions results for speciated organic gases (or PM_{10}). Conversely, the H_2O emissions provided by AEDT2a are not provided in EDMS results (emissions of PMNV, PMSO, and PMFO are also not provided).

The next public version of AEDT, version 2b, is currently under development and is scheduled for completion in 2014. When released, AEDT2b will replace the INM and EDMS for regulatory purposes - and as such will meet or exceed the capabilities of those two tools. It will therefore include the ability to calculate fuel burn, emissions, and potentially aircraft taxi-related noise - depending on available resources, funding, development priorities, and the output and schedule of the ACRP 02-27 Research Project for which the focus is taxi noise modeling. The implementation of taxi modeling functionality has just begun within the last few months for AEDT2b and so far the model only has simple time-in-mode capability (as in EDMS) for taxi emission calculations which are intended to serve the needs of global emissions inventories users of AEDT at the Volpe center.

While initial planning has taken place regarding potential improvements to aircraft taxi modeling, firm decisions have yet to be made with respect to the scope of such improvements in the context of AEDT2b. Some of the primary reasons for this are schedule and resource constraints that are affecting AEDT developments. Due to these constraints, the focus for the next 12 months or so of AEDT2b development will be on supporting the functionality that currently exists in the legacy EDMS tool for taxi modeling. As a result, and for the purpose of the ACRP 02-45 Research Project, it is currently assumed that the AEDT capability will match the EDMS capability as described above in all areas, including allowable inputs, assumptions, database coverage, and outputs.

4. Issues in Need of Resolution

Based on the findings of Tasks 1 and 2 discussed above, several additional issues, or research "gaps", in need of resolution are now evident and will be addressed during the subsequent tasks of this research project. These issues are described as follows along with some preliminary recommendations on how they will be addressed:

- **ACRP 02-03a Findings** - First, ACRP 02-03a focused mainly on the CFM56 family of engines and though these results for a few other engines fit the same data, a large number of engine types were not characterized. Secondly, ACRP 02-03a focused on gas-phase HAP emissions, largely comprising individual VOCs like HCHO and benzene. However, aircraft engines are certified for NO_x, CO, and HC and EDMS/AEDT outputs emissions for these three gas-phase pollutants - but not for individual HAPs. Finally, the relationship between NO_x, HC, and CO emissions on fuel flow rate and ambient temperature was not analyzed in great detail by ACRP 02-03a.

It is recommended that the NO_x, CO, and HC data from ACRP Project 02-03a could be further analyzed to help address these shortcomings listed above.

- **Taxi/Idle Sub-Phases -** Given the scope of the dependence of true HC emission rates on actual fuel flow rates and ambient temperatures, it is apparent that the current method used by EDMS to compile HC and CO emissions (i.e., fuel flow rate and emission indices based on the ICAO 7percent value) can lead to inaccurate emission inventories.

  Recommendations to address this shortcoming of EDMS/AEDT are included as elements of later tasks of this project and two possible suggestions are briefly described below:

  - **Multiple Sub-Phases -** Based on the evidence that the idle/taxi phase cannot be well described by a single fuel flow rate and concomitant emission indices (especially for CO and HC), the idle/taxi phase could be sub-divided into multiple sub-phases. This approach was used by Stettler et al. [2011] based on data presented in Patterson et al [2009]. In that study, the idle/taxi phase was divided into the following components (w/ mean time-in-mode and percent thrust in parentheses): landing roll (46 seconds, 4 – 7 percent), reverse thrust (15 seconds, 30 percent), taxi in (371 seconds, 4 – 7 percent), taxiway in acceleration (10 seconds, 7 – 17 percent), taxi out (780 seconds, 4 – 7 percent), taxiway out acceleration (10 – 20 seconds, 7 – 17 percent), and hold (341 seconds, 4 – 7 percent). The true values for each sub-phase vary among airports and are affected by numerous parameters including aircraft type, time-of-day, weather conditions, etc.

  - **Corrected Emission Indicies -** For each sub-phase, a "corrected" emission index appropriate for the actual fuel flow rate and ambient temperature could be used. For example, ACRP 02-03a presented a model by which HAP emission indices for 7 percent thrust can be multiplied by a correction factor that is determined by the actual fuel flow rate, the 7 percent fuel flow rate, and the ambient temperature, as follows:

    $$\text{EI HAP "corrected"} = \text{EI HC}_{(7\text{ percent, 15 degrees Celcius})} \times (\text{Fuel flow rate correction factor}) \times (\text{ambient temperature correction factor})$$

    Although this approach is geared toward individual gas-phase HAP compounds and cannot be blindly applied to CO or HC emissions (both of which show the same overall trends as individual HAP compounds), it is likely that an analogous model applicable to CO and HC could be developed.

5. Go Forward Plan

At the end of December, 2013 or first of January 2014, a web-based meeting will be held with both the Project Panel and Research Team. During this meeting, the Panel/Team will discuss the findings of the Task 1 literature and Task 2 EDMS/AEDT reviews presented in this Working Paper and the next two tasks that will be performed in January and February of 2014. The next two tasks involve the following:

- *Task 4 – Analyze Engine Performance Data* - KBE Team members have FDR data from which summary results can be used for the purpose of this ACRP Reseach Project. Team members also have access to the raw data that has been collected as part of several field campaigns, including APEX, JETS-APEX2, APE3, ACRP 02-03A, and the AAFEX projects. Notably, much of the data has been published in peer-reviewed literature (e.g., Yelvington et al. 2007) or as an ACRP report [Herndon et al. 2012]. By leveraging a broader ASDE-X data set covering taxi operations, enhancements can be better applied within EDMS/AEDT through improved knowledge as to when to apply them. Better knowledge of the prevalence and nature of accelerations and decelerations, hold times, and other operational details are crucial to making good use of the knowledge of how those situations impact taxi fuel flow and emissions.

- Task 5 – Evaluate Model Inaccuracies – This task represents one of the most important elements of the ACRP 02-45 Research Approach as it will help pave the way forward to improving how EDMS/AEDT quantifies aircraft taxi/idle emissions. Although additional inaccuracies with EDMS/AEDT taxi/idle emissions estimates are likely to be identified during the course of Task 4, the Task 1 and 2 Literature and EDMS reviews confirmed what the Research Team believed are major faults with EDMS/AEDT taxi/idle emissions estimates. These shortcomings (presented in the Work Plan) and a general description of their impact on taxi/idle emissions are summarized below:

Table 8
Summary of EDMS/AEDT Shortcomings Related to Taxi/Idle Emissions

Shortcoming	Impact
EDMS/AEDT assumptions regarding the duration of taxi/idle modes are not representative of actual conditions.	Differences in actual emissions and EDMS/AEDT emissions are (at least) directly proportional to differences in the duration of taxi/idle modes.
EDMS/AEDT assumes fixed fuel flow rates during taxi/idle based on 7 percent thrust.	Actual fuel flow rates vary considerably and emission indices are a function of fuel flow rate.
EDMS/AEDT uses one emission index value for each pollutant	Actual emission indices are complex functions of fuel flow rate, ambient temperature, and other factors.
EDMS/AEDT does not account for variations in operational practice including tug assisted single-engine (i.e., reduced engine) or electric taxiing.	Discrepancies between actual and EDMS/AEDT assumed operating patterns directly impact the accuracy of model estimates.

The purpose of Task 5 is to put the relative importance and implications of these inaccuracies in EDMS/AEDT related to emission estimates into perspective both in terms of airport emission inventories as well as potential impacts on local and regional air quality planning. Work under Task 5 will begin with development of a spreadsheet model that can be used to quantify the impacts of taxi/idle related inaccuracies in EDMS/AEDT identified during the course of Tasks 1, 2 and 4. The primary focus will be on THC, CO, and NO_x, and, to the extent possible, HAPs where suitable data are available. Given that fuel usage rates will also be directly calculated, impacts on CO_2 emissions will also be reported using standard carbon content factors applicable to jet fuel.

The spreadsheet model will then be used in combination with appropriate data and assumptions including the actual operating data obtained under Task 4 to analyze the potential impact that the flaws in EDMS/AEDT have on estimated taxi/idle emissions at the individual aircraft level.

Annotated Bibliography — Literature Search
ACRP 02-45: Methodology to Improve EDMS/AEDT Quantification of Aircraft Taxi/Idle Emissions

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Aircraft Owners and Pilots Association	2011	Taxi Green in 2016	Aircraft Owners and Pilots Association. n.p. Web. October 2, 2013.	Describes a system being developed by Honeywell and Safran that would allow aircraft to taxi to and from gates using electric motors powered by auxiliary power units.
Alternative Emissions Methodology Task Group, CAEP7	2006	Results from a Number of Surveys of Power Settings Used During Taxi Operations	CAEP7-WG3-AEMTG-WP7-08	The results of a number of surveys that were carried out to investigate the actual power settings used during taxi operations.
Anderson B.E., Chen, G., Blake, D.	2006	Hydrocarbon Emissions from a Modern Commercial Airliner	Atmospheric Environment 2006: 40(19): 3601 - 3612	Emissions from the RB211-535-E4 engine during the EXCAVATE project. Numerous speciated hydrocarbons measured. Idle thrust is listed as “4 – 7 percent”.
Baik, H., Sherali, H., Trani, A.	UNK	Time-Dependent Network Assignments Strategy for Taxiway Routing at Airports	Transportation Research Board, Paper No. 02-3660	A time-dependent network assignment strategy is proposed for efficiently handling aircraft taxiway operations at airports.
Balakrishna, P., Ganesan, R., Sherry, L.	2010	Accuracy of Reinforcement Learning Algorithms for Predicting Aircraft Taxi-out Times: A Case-Study of Tampa Bay Departures	Transportation Research Part C 18 (2010) 950-962	Presents the results of a taxi-out time case study performed at Tampa International Airport. Investigates the accuracy of taxi out time prediction using a nonparametric reinforcement learning (RL based method.
Beyersdorf, A., Thornhill K., Winstead, E., Ziemba, L., Blake, D., Timko, M., Anderson, B.	2012	Power-Dependent Speciation of Volatile Organic Compounds in Aircraft Exhaust	Atmospheric Environment 61 (2012): 275-82.	APEX3 measurements of speciated VOCs. Found that the universal VOC scaling didn’t apply at high powers - the X / C2H4 ratios varied. Quantified speciated VOC EIs at 4 percent and 7 percent.
Bhadra, D., Knorr, D., Levy, B.	2011	Benefits of Virtual Queuing at Congested Airports using ASDE-X: A Case Study of JFK Airport	Presented at Ninth USA/Europe Air Traffic Management Research and Development Seminar, 2011	Discusses the potential for delay management by using departure data recorded by the ASDE-X system at JFK Airport before runway reconstruction in 2010 began. Lays out concepts, data, metrics, and a framework to estimate benefits from virtual queuing, a departure management system that allows an aircraft to maintain a rolling spot in the queue without physically joining a queue.
Buttress, Jenna and Kevin Morris	2005	An Estimation of the Total NO_x Emissions Resulting from Aircraft Engine Ground Running at Heathrow Airport	British Airways Technical Paper ENV/KMM/1127/14.18	Results of a study performed to evaluate the levels of NO_x emissions during three categories of ground operations--check starts, runs at no more than ground idle, and runs at powers greater than ground idle

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Clare, B., Richards, A.	UNK	Optimization of Taxiway Routing and Runway Scheduling	University of Bristol	Describes an optimization method for the combined issues of airport taxiway routing and runway scheduling.
Clewlow, R., Simaiakis, I., Balakrishnan, H.	UNK	Impact of Arrivals on Departure Taxi Operations at Airports	American Institute of Aeronautics and Astronautics	Through an analysis of departures at JFK International and Boston Logon International, the effect of arrivals in delaying departure operations, is evaluated.
Cointin, R.	2011	Aviation Environmental Design Tool: Interdependencies of Aircraft Noise, Emissions and Fuel Burn	Accessed at http://www.fican.org/pdf/Roadmap2011/2011_1020_Cointin_AEDT_Briefing_Noise_Workshop.pdf. November 26, 2013	Topics included were 1) why AEDT, 2) What is AEDT, 3) AEDT Timelines, and 4) Uncertainty Quantification
Collins, B.	1982	Estimation of Aircraft Fuel Consumption	Journal of Aircraft 19, 969-975	Describes an algorithm for estimating the fuel consumption of commercial aircraft from path profile data.
Deonandan, I., Balakrishnan, H.	UNK	Evaluation of Strategies for Reducing Taxi-out Emissions at Airports	American Institute of Aeronautics and Astronautics	Evaluates the effects of single engine taxiing and operational tow-outs
Diana, Tony.	2013	An Application of Survival and Frailty Analysis to the Study of Taxi-out Time: A Case of New York Kennedy Airport	Air Transport Management 26 (2013) 40-43	Evaluates how selected operational factors affect the duration of aircraft taxi-out times at John F. Kennedy Airport.
DuBois, D., Paynter, G.	2006	Fuel Flow Method 2 for Estimating Aircraft Emissions	Society of Automotive Engineers Paper: 01-1987	Presents derivation, updates, and clarifications of the fuel flow method methodology known as "Fuel Flow Method 2".
European Civil Aviation Conference	2005	Report on Standard Method of Computing Noise Contours around Civil Airports, Volume 1: Applications Guide, 3rd Edition	ECAC.CEAC Doc 29	Guidance for the best practice methodology for aircraft noise contour modelling.
European Civil Aviation Conference	2005	Report on Standard Method of Computing Noise Contours around Civil Airports, Volume 2: Technical Guide, 3rd Edition	ECAC.CEAC Doc 29	The technical companion to the Applications Guide.
Federal Aviation Administration	2013	Emissions and Dispersion Modeling System (EDMS) User's Manual	FAA-AEE-07-01	Detailed information on the functionality of the EDMS model.
Federal Aviation Administration	Unknown	Runway Safety A Best Practices Guide to Operations and Communications	Federal Aviation Administration, n.p. Web, October 2, 2013.	Describes the common tasks that pilots should incorporate in to their taxi procedures.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Federal Aviation Administration	2013b	Order JO7110.65U	Air Traffic Organization Policy, Order JO7110.65U, Air Traffic Control, August 22, 2013	Prescribes air traffic control taxi and ground movement control procedures.
Federal Aviation Administration	2009	Emissions and Dispersion Modeling System (EDMS) Version 5 Technical Manual	FAA-AEE-07-07	Technical support documentation for Version 5 of the EDMS.
Federal Aviation Administration	2013	Aeronautical Information Manual	FAA, 2013	The official guide to basic flight information and Air Traffic Control Procedures
Federal Aviation Administration	2007	Environmental Desk Reference for Airport Actions	Federal Aviation Administration. Office of Airports. Environmental Desk Reference for Airport Actions. October, 2007. http://www.faa.gov/airports/environmental/environmental_desk_ref/.	Regulatory guidance document. The Desk Reference summarizes applicable special purpose laws in one location for convenience and quick reference. Its function is to help FAA integrate the compliance of NEPA and special purpose laws.
Federal Aviation Administration	1997	Air Quality Procedures for Civilian Airports & Air Force Bases	Federal Aviation Administration. Office of Environment & Energy. Air Quality Procedures for Civilian Airports & Air Force Bases, prepared by EEA Inc. and CSSI, Inc., April 1997.	Regulatory guidance document. Procedures for the preparation of air quality assessments for proposed Federal actions are required for compliance with the National Environmental Policy Act, the Clean Air Act and other environment-related regulations and directives.
Federal Aviation Administration	2004	Air Quality Procedures for Civilian Airports & Air Force Bases - Addendum	Federal Aviation Administration. Office of Environment & Energy. Air Quality Procedures for Civilian Airports & Air Force Bases, Addendum, 2004.	Regulatory guidance document. Addendum to the 1997 version. Procedures for the preparation of air quality assessments for proposed Federal actions are required for compliance with the National Environmental Policy Act, the Clean Air Act and other environment-related regulations and directives.
Federal Aviation Administration	2012	Vision 100 - Century of Aviation Reauthorization Act	Public Law 108–176 (enacted December 12, 2003) as Amended through Public Law 112–95 (enacted February 14, 2012)	One part of the Vision 100—Century of Aviation Reauthorization Act was to establish a legal framework to reduce emissions from airport vehicles, ground support equipment (GSE) and infrastructure at commercial service airports in air quality nonattainment and maintenance areas. The Act defines a program and procedures for determining emission reduction credits for voluntary early reduction measures that could be counted towards transportation conformity determinations or new source review requirements at airports.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Federal Aviation Administration	2006	Environmental Impacts: Policies and Procedures.	Federal Aviation Administration. Order 1050.1E. Effective March 20, 2006.	Agency Order. This order updates the FAA agency-wide policies and procedures for compliance with the National Environmental Policy Act (NEPA) and implementing regulations issued by the Council on Environmental Quality (40 CFR parts 1500-1508). Order 1050.1E cancels Order 1050.1D.
Federal Aviation Administration	2006	National Environmental Policy Act (NEPA) Implementing Instructions for Airport Actions	Federal Aviation Administration. Order 5050.4B. Effective April 28, 2006.	Agency Order. Order 5050.4B supplements FAA Order 1050.1E, “Environmental Impacts: Policies and Procedures.” Order 5050.4B substantially updates and revises Order 5050.4A, “Airports Environmental Handbook.” ARP’s issuance of Order 5050.4B cancels Order 5050.4A.
Federal Aviation Administration	2007	Voluntary Airport Low Emission (VALE) Program Technical Report	Federal Aviation Administration. Office of Airports. Voluntary Airport Low Emission (VALE) Program Technical Report, Version 7. December 2010.	Regulatory guidance document. FAA technical guidance to support VALE applications. Version 7 is the latest of the series of reports.
Federal Aviation Administration	2002	General Conformity Guidance for Airports, Questions and Answers	Federal Aviation Administration and US Environmental Protection Agency. General Conformity Guidance for Airports, Questions and Answers. September 25, 2002.	Regulatory guidance document. Joint FAA and USEPA technical guidance based on a stakeholders group to address airport air quality improvements - focusing on NO_x reductions.
Fleuti, E. et al	2009	Air Quality Assessment Sensitivities - Zurich Airport Case Study	Fleuti et al. 2009	The case study is based on Zurich airport's 2008 activity data and examined the emissions variability of the LTO cycle based on the sophistication of the data inputs. The inventory analysis begins with ICAO default methods and successively adds increasing details including ambient temperature impacts, altitude impacts and airline specific thrust settings. The model used for the study is LASPORT version 2.0 (aka LASAT for airports) developed by Janicke Consulting (one of the co-authors); it is not clear if the model's methods for ambient, altitude and trust impacts on emissions are published in the public domain. If the methods are not public, the resulting impacts on the inventories by level of detail is still a useful point of comparison. Pollutants covered are NO_x, HC, CO, PM, and CO2.

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Franc24	2013	Electric Taxiing Unveiled at Paris Air Show	France24. n.p. Web. June 18, 2013.	An article on the electric taxi system developed by Honeywell and Safran. States that the system was demonstrated on an A320, the companies planned on marketing the system in 2016 with the intent of equipping approximately 2,600 aircraft with their Electric Green Taxiing System (EGTS).
Goldberg, B., Chesser, D.	2008	Sitting on the Runway: Current Aircraft Taxi Times Now Exceed Pre-9/11 Experience	Bureau of Transportation Statistics, SR-008, May 2008.	Figures illustrate average taxi-in/taxi-out times for the period 1995-2007. Also analyzes ground time by size of airport and flight volume.
Grinspun,Y., Miller, E.	2002	A Survey-Based Approach to Measure Taxiway Delay and Predictability at Lester B. Pearson International Airport	Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.	A study of taxiway delay and taxi-in/out times at this airport in Toronto.
Hadaller, A. M. Momenthy	1989	The Characteristics of Future Fuels	Boeing, D6-54940	
Hadaller, A. M. Momenthy	1993	Characteristics of Future Aviation Fuels	Report to American Council of ran Energy-Efficient Economy, Washington D.C., 1993	
Herndon, S. C., Wood, E., Northway, M., Miake-Lye, R., Thornhill, L., Beyersdorf, A., Anderson, B., Dowlin, R., Dodds, W., Kinghton, W.	2009	Aircraft Hydrocarbon Emissions at Oakland International Airport	Environmental Science and Technology 43 (6):1730-1736	Characterization of VOC EIs measured from in-use aircraft during the JETS-APEX2 campaign (at OAK). Showed that even for a single engine type EIs are variable (reflecting changes in ambient temperature and fuel flow rate), but most emission ratios (e.g., propene / formaldehyde) are fairly constant. This supports a “universal” VOC scaling profile – i.e., regardless of total VOC emissions, the portion accounted for by formaldehyde, propene, etc. is constant. Analysis suggests OAK idle VOC emissions are underreported by 16 – 45 percent.
Herndon, S., Jayne, J., Lobo, P., Onasch, T., Fleming, G., Hangem, D., Whitefield, P., Miake-Lye, R.	2008	Commercial Aircraft Engine Emissions Characterization of in-Use Aircraft at Hartsfield-Jackson Atlanta International Airport	Environmental Science & Technology 42 (2008): 1877-83.	Emission indices of in-use aircraft at Hartfield-Jackson Atlanta International Airport inferred from advected plumes. The CO emission index observed in ground idle plumes was greater (up to 100 percent) than predicted by engine certification data for the 7 percent thrust condition, consistent with actual idle operation being at thrusts lower than 7 percent. Plenty of CF34, JT8D, CFM56, PW2037, and CF6 engines observed.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Herndon, S., Rogers, T., Dunlea, E., Jayne, J., Miake-Lye, R., Knighton, B.	2006	Hydrocarbon Emissions from In-Use Commercial Aircraft during Airport Operations	Environmental Science & Technology 40 (14):4406 - 4413.	Advected plumes at Boston Logan International Airport, May 2003. Found that the sum of individual VOCs and projected total VOCs were higher than ICAO 7 percent UHC (consistent with aircraft idling at lower thrusts with higher UHC emissions)
Herndon, S., Wood, E., Franklin, J., Miake-Lye, R., Knighton, W.B, Babb, M., Nakahara, A., Reynolds, T., Balakrishnan, H.	2012	Measurement of Gaseous HAP Emissions from as a Function of Engine and Ambient Conditions (ACRP Project 2-03a)	ACRP Report 63.	In depth analysis of dependence of VOC emissions on engine condition (i.e., fuel flow rate) and ambient temperature. Temperatures ranged from -8 °C to 25 °C, fuel flow rate ranged from ground idle (approximately 3 percent) to 15+ percent (above the “idle” regime). A simple model tool was developed that can be used to “correct” the ICAO UHC EI based on ambient temperature and fuel flow rate. i.e., the temperature and fuel flow rate determine the appropriate factor by which to multiply the ICAO values. This model is the frontrunner model for how to “fix” the EDMS/AEDT default 7 percent values. Engine covered: numerous CFM56-7B24 and -3B1’s, a V2527 and a PW4090.
International Civil Aviation Organization	2013	Engine Exhaust Emissions Databank, Issue 19.	ICAO, April 15, 2013.	Contains exhaust emissions for those aircraft engines that have entered production. The information is provided by engine manufacturers.
International Civil Aviation Organization	2008b	International Standards and Recommended Practices, Annex 16, Environmental Protection: Aircraft Engine Emissions	ICAO, Annex 16, Vol 2, Montreal, 3rd ed., 2008	Adopted by the Council of ICAO it achieves "the highest practicable degree of uniformity in regulations, standards, procedures and organization in relation to aircraft, personnel, airways, and auxiliary services in all matters in which such uniformity will facilitate and improve air navigation."
International Civil Aviation Organization	2008	ICAO Annex 16: Environmental Protection, Volume II - Aircraft Engine Emissions	ICAO, Annex 16 2008	Provides all provisions that relate to the environmental aspects of aircraft engine emissions for aircraft engaged in international civil aviation.
International Civil Aviation Organization	2011	Airport Air Quality Manual	ICAO, Doc 9889, 2011	Discusses the reference emissions/trust settings of each aircraft operational phase, the operational flight cycle (i.e., engine start, taxi to runway, hold, etc.) and approaches to emissions calculations (inventories and dispersion)
Iovinelli, Ralph and Mohan Gupta	2009	FAA's Airport Air Quality Model: Aviation Sector's Tool for Analysis of Criteria and Hazardous Pollutants	In the U.S. Environmental Protection Agency 18th Annual International Emissions Inventory Conference Proceedings, April 14-17, 2009, Baltimore, Maryland..	Discusses the development of AEDT and the enhancements that were included in Version 5.1 of the EDMS.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Jung, Y.	2010	Fuel Consumption and Emissions from Airport Taxi Emissions	Presentation at NASA Green Aviation Summit, Washington DC	A presentation regarding a method to calculate fuel consumption and emissions of phases of taxi operations.
Khadilkar, K., Balakrishnan, H.	2012	Estimation of Aircraft Taxi Fuel Burn Using Flight Data Recorder Archives	Transportation Research Part D (2012) 532-537	Creates a model for estimating fuel consumption of a taxiing aircraft using flight data recorder information from operational aircraft.
Kim, B., Rachami, J.	2008	Aircraft Emissions Modeling Under Low Power Conditions	Report to Observatory of Sustainability in Aviation	Presents the results from different analysis levels involving a single aircraft and engine and aggregated fleet levels to illustrate the range of errors in the thrust setting at idle.
Kumar, Vivek, Lance Sherry and Terry Thomspon	2008	Analysis of Emissions Inventory for "Single-Engine Taxi-out" Operations	In the International Conferences on Research in Air Transportation 3rd Conference Proceedings, June 1-4, 2008, Fairfax, Virginia, edited by Vivek Kumar, 1-6.	Examples the sensitivity of emission factors (number of engines, engine efficiency, and fleet mix, taxi-out time) through case study of departure operations at Orlando International Airport and LaGuardia Airport.
Legge, J., Levy, B.	2008	Departure Taxi Time Predictions Using ASDE-X Surveillance Data	Presented at 26th International Congress of the Aeronautical Sciences, 2008	Analyzes the utility of the Airport Surface Detection Equipment, Model X (ASDE-X) surface surveillance data using data from March 2008 at ATL.
Levine, Brian, H. Oliver Gao	2006	Aircraft Taxi-Out Emissions at Congested Hub Airports and the Implications for Aviation Emissions Reductions in the United States	Levine, Brian. Presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C., 2007.	Discusses and describes the aircraft taxi process at a congested hub airport (Newark Liberty Intl)
Lobo, P. et al	2007	The Development of Exhaust Speciation Profiles for Commercial Jet Engines	Lobo et al. 2007	This study reports the emissions of CO, CO_2, NO_x, and speciated HC at six thrust settings: 4 percent, 7 percent, 30 percent, 40 percent, 65 percent and 85 percent measured from both engines on four parked 737 aircraft at the Oakland International Airport. The engine types were selected to represent both old and new technologies. Sponsored by CARB, this collaboration between University of Missouri – Rolla, Aerodyne Research and University of California - Riverside forms the basis of the California agency's speciation for commercial aircraft exhaust. Germane to the ACRP study at hand are the emissions data collected by thrust setting. There was some data loses noted in the Executive Summary related to specific HC compounds.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Marks, Julie	2012	FAA Order 1050.1E, Change 1 Guidance Memo #4: Guidance on Using AEDT2a to Conduct Environmental Modeling for FAA Air Traffic Airspace and Procedure Actions	Prepared by Rebecca Cointin and Steve Urlass, March 21, 2012.	Provides guidance on the use of AEDT2a to conduct aircraft noise, fuel burn, and emissions modeling for air traffic airspace and procedure actions under the National Environmental Policy Act.
Martin, A.	2006	Verification of FAA's Emissions and Dispersion Modeling System (EDMS)	Thesis (M.S.E) -- University of Central Florida, Dept. of Civil and Environmental Engineering, 181 p.	Presents the results of a study conducted by the FAA, the Volpe Center, and CSSI to verify EDMS's ability to predict CO concentrations in the vicinity of an airport.
Mazaheri, M., Johnson, G., Morawska, L.	2009	Particle and Gaseous Emissions from Commercial Aircraft at Each Stage of the Landing and Takeoff Cycle	Environ. Sci. Technol. 43 (2009): 441-46	Australian measurements of in-use aircraft. Found that “idle” thrust was lower than “taxi” thrust and less than the ICAO value, meaning that idle is not at 7 percent thrust.
Miller, Bruno, Kenneth Minogue and John-Paul Clarke	2010	Constraints in Aviation Infrastructure and Surface Aircraft Emissions	Accessed at http://www. areco. org/AQ% 20Aircraft% 20Surface%20Constrants%20Miller. pdf, January 18, 2010.	Discusses the growth of aviation emissions from 1995 to 2000 and investigates potential methods to reduce emissions including single-engine taxiing.
Nikoleris,T., Gupta, G, Kistler, M.	2011	Detailed Estimation of Fuel Consumption and Emissions During Aircraft Taxi Operations at Dallas/Fort Worth International Airport	Transportation Research Part D 16 (2011) 302-308	Estimates fuel consumption and emissions during taxi operations using aircraft position data from actual operations at Dallas-Ft. Worth International Airport. Uses assumptions for the thrust level during each taxi state, fuel flow and emission index values from ICAO's databank.
No information	2012	Air Quality Assessment Sensitivities - Zurich Airport Case Study	Zurich Airport 2012	A second version of SR1002, updated to include a section (3.7) on "Effect of Emissions on Regional Concentrations."
Noel, George, Doug Allaire, Stuart Jacobson, Karen Willcox and Rebecca Cointin	2009	Assessment of the Aviation Environmental Design Tool	In the USA/Europe Air Traffic Management Research and Development 8th Seminar, June 29-July 2, 2009, Napa, California, edited by George Noel. Unpaginated document.	Presents a summary of an assessment of the AEDT component of the FAA's Tool Suite.
Page, J., Bassarab, K., Hobbs, C., Robinson D., Schultz, T., Sharp, B., Usdowski, S., Lucic, P.	2009	Enhanced Modeling of Aircraft Taxiway Noise, Volume 1 Scoping	ACRP Web-Only Document 9	Presents the results of a study to determine the best way to model airport noise from aircraft taxi operations and to create a plan for implementation of noise prediction capability in to the INM in the near term and the AEDT in the long term.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Page, J., Hobbs, C., Gliebe, P.	2013b	Enhanced Modeling of Aircraft Taxiway Noise, Volume 2	ACRP Web-Only Document 9	Summarizes taxi-related data from ACRP Project 11-02 Task 8 (Enhanced Modeling of Aircraft Taxiway Noise - Scoping), a number of surveys of power settings used in normal taxi operations that are being considered by ICAO, and data from the ICAO Best Practices Certification Database (BPDB-IACO/CAEP8) which lists nominal percentage taxi thrusts.
Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER)	2009	Aircraft Impacts on Local and Regional Air Quality in the United States	PARTNER Project 15 final report	Documents the findings of a study to evaluate ways to promote fuel conservation measures and opportunities to reduce air traffic inefficiencies that increase fuel burn and emissions.
Roof, C., Hansen, A., Fleming, G., Thrasher, T., Nguyen, A., Hall, C., Dinges, E., Bea, R., Grandi, F., Kim, B., Usdrowski, S., Hollingsworth, P.	2007	Aviation Environmental Design Tool (AEDT) System Architecture	Federal Aviation Administration, Document AEDT-AD-01	Describes the "building blocks" that form AEDT's architecture (i.e., EDMS, INM, MAGENTA, SAGE), timelines, and development specifications.
Santoni, G., Lee, B., Wood, E., Herndon, S., Miake-Lye, R., Wofsy, S., McManus, J., Nelson, D., Zahniser, M.	2011	Aircraft Emissions of Methane and Nitrous Oxide During the Alternative Aviation Fuel Experiment	Environmental Science & Technology (2011): 110720130733026.	Emission indices of the greenhouse gases methane and nitrous oxide during the AAFEX project. CH4 EIs are ~500 to 50 mg/kg fuel for the CFM56-2C1 engine at idle (and negative at high power).
Schäfer, K., Jahn, C., Sturm, P., Lechner, B., Bacher, M.	2003	Aircraft Emission Measurements by Remote Sensing Methodologies at Airports	Atmospheric Environment 37, no. 37 (2003): 5261-71.	Remote sensing of EIs from in-use aircraft at a few European airports. Actual observed EIs are higher (CO) and lower (NO_x) than ICAO 7 percent values, suggesting actual idle operation is usually at sub-7 percent thrusts.
Senzig, D., Fleming, G., Iovinelli, R.	2009	Modeling of Terminal-Area Airplane Fuel Consumption	Journal of Aircraft 46 (4)	Presents a method of modeling fuel consumption that was developed using data from a major airplane manufacturer.
Simaiakis, I., Balakrishnan, H.	2010	Impact of Congestion on Taxi Times, Fuel Burn, and Emissions at Major Airports	*Transportation Research Record: Journal of the Transportation Research Board, No. 2184*, 2010, pp 22-30	Assesses the impact of surface congestion on taxi times, fuel burn, and emissions through analysis of departing traffic from four major U.S. airports

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Simaiakis, I., Khadilkar, H., Balakrishnan, H., Reynolds, T.G., Hansman, R.J., Reilly, B., Urlass, S.	2001	Demonstration of Reduced Airport Congestion Through Pushback Rate Control	American Institute of Aeronautics and Astronautics	Presents the results of field tests to evaluate control strategies to airport congestion at Boston Logan International. The approach determines a suggested rate to meter pushbacks from gates in order to prevent surface congestions and reduce the time that aircraft spend with their engines on while taxiing to the runway.
Spicer, C.W., Holdren, M., Riggin, R., Lyon, T.	1994	Chemical-Composition and Photochemical Reactivity of Exhaust from Aircraft Turbine-Engines	Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences 12, no. 10-11 (1994): 944-55.	One of the first studies to quantify speciated VOCs in aircraft exhaust (CFM56 and TF39). Also looked at photochemical reactivity and showed that carbon mass balance was mostly closed (i.e., sum of speciated VOCs = UHC)
Srivastava, Amal	2011	Improving Departure Taxi Time Predictions Using ASDE-X Surveillance Data	In the Digital Avionics System Conference IEEE/AIAA 30th Proceedings, October 16-20, 2011, Seattle, Washington, edited by Arnal Srivastav, 2B5-1 - 2B5-14. doi:10.1109/DASC.2011.6095989	Two models that were developed to predict taxi-out time are presented. The models used data from JFK during the summer of 2010. Results are compared to values from FAA's Enhanced Traffic Management System (ETMS)
Stettler, M.E.J., Eastham, S., Barrett, S.R.H.	2011	Air Quality and Public Health Impacts of UK Airports. Part I: Emissions	Atmospheric Environment 45, no. 31 (2011): 5415-2	Generated a modified EDMS-based emission inventory for UK airports. For time-in-mode, they subdivided the idle phase into landing roll, reverse thrust, taxi in, taxiway acceleration taxi out, taxiway acceleration, hold. Used.BFFM2 and method of Kim et al 2005 to generate HC and CO EIs.
Stettler, M.E.J., Eastham, S., Barrett, S.R.H.	2011	SUPPORTING INFORMATION for Air Quality and Public Health Impacts of UK Airports. Part I: Emissions	Atmospheric Environment 45, no. 31 (2011): 5415-2	Contains detailed information on how they (Stettler et al) generated time-in-modes based on # of runways, etc.
The Boeing Company	2002	737-300/400/500 Flight Crew Training Manual	Document No.FCT 737 CL revision 2. October 31, 2002.	Provides information and recommendations for maneuvers and techniques for the Boeing 737-300/400/500 series aircraft
Thrasher, T., Nguyen, A., Hall, C. Fleming, G., Roof, C., Balasubramamian, S., Grandi, F., Usdrowski, S., Dinges, E., Burleson, C., Maurice, L., Iovinelli, R.	2007	AEDT Global NO_x Demonstration	USA/Europe ATM R&D Seminar 2007	Provides results of a demonstration of the capabilities of AEDT and concludes that that the dynamic gate-to-gate aircraft performance element of the model is "successful"

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Timko, M. T., Herndon, S.C, Wood, E., Onasch, T., Northway, M., Jayne, J., Canagaratna, M., Miake-Lye, R.	2010	Gas Turbine Engine Emissions - Part 1: Volatile Organic Compounds and Nitrogen Oxides	J. Eng. Gas Turb. Power 132:doi: 10.1115/1.4000131.	Summarizes VOC and NO^x emission indices from the JETS/APEX2 and APEX3 projects. Covers following common engine types: CFM56-7B22, CFM56-3B1, RB211-535E4-B, PW4158, AE3007, CJ6108A. Measured HCHO EI roughly scales with ICAO UHC EI (e.g., RB211 engine have both relatively low UHC EI and low HCHO EI).
Timko, M., Herndon, S., de la Rosa Blanco, E., Wood, E., Yu, Z., Miake-Lye, R., Knighton, W., Shafer, L., DeWitt, M., Corporan, E.	2009	Combustion Products of Petroleum Jet Fuel, a Fischer–Tropsch Synthetic Fuel, and a Biomass Fatty Acid Methyl Ester Fuel for a Gas Turbine Engine	Combustion Science and Technology 183, no. 10 (2011): 1039-68.	Emission measurements from the Alt Fuels campaign. Relevant findings: speciation of VOC emissions somewhat affected by fuel content (aromatic versus oxygenates)
Transport Canada	2010	Taxi Check and Procedures	Transport Canada. n.p. Web. October 2, 2013.	Provides Standard Operating Procedures (SOPs) for taxiing aircraft on departure
Transport Canada	2010	Aircraft Icing Operations - Taxi	Transport Canada. n.p. Web. October 2, 2013.	Provides Standard Operating Procedures (SOPs) for taxiing aircraft during conditions when aircraft are deiced.
Turgut, E., Usanmaz, O., Rosen, M.	2013	Empirical model assessment of commercial aircraft emissions according to flight phases	International Journal of Energy and Environmental Engineering 4, no. doi:10.1186/2251-6832-4-15 (2013).	Secured FDR data from ten randomly selected B737-800 (CFM56-7B26) flights in Turkey. Fig 7 shows the actual fuel flow rates – looks like idle values are ~0.09 kg/s, with occasional acceleration bursts no more than 0.25 kg/s. They also present their own model for predicting true emission indices as a function of fuel flow rate for NO_x, CO, and HC.
U.S. DOT Volpe Center	2012	Aviation Environmental Design Tool (AEDT) 2a Technical Manual	DOT-VNTSC-FAA-12-09	
U.S. Environmental Protection Agency	2012	Control of Air Pollutant from Aircraft and Aircraft Engines; Final Emission Standards and Test Procedures - Summary and Analysis of Comments	EPA-420-R-12-011	EPA's responses to comments received on the July 2011 proposal for new NO_x emissions standards for aircraft turbofan and turbojet engines with rated thrust greater than 26.7 kilonewtons.
U.S. Environmental Protection Agency	2012b	EPA Adopts NO_x Emission Standards for Aircraft Gas Turbine Engines	EPA-420-F-12-027	Overview of the Tier 6 and Tier 8 standards for NO_x.

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U.S. Environmental Protection Agency	2008	Clean Air Act	42 U.S.C. §§ 7401 et seq (2008)	The Clean Air Act (CAA) is the Federal law that authorizes EPA to regulate air emissions from stationary and mobile sources, to establish National Ambient Air Quality Standards (NAAQS) to protect public health and public welfare and to regulate emissions of hazardous airborne pollutants and to coordinated all Federal noise pollution control activities. CAA was originally enacted in 1963 with significant amendments enacted in 1970, 1977 and 1990.
U.S. Environmental Protection Agency	2013	Control of Air Pollution from Aircraft and Aircraft Engines	40 C.F.R. 87 (2013)	Under the authority of 42 U.S.C. §§ 7401 et seq, 40 C.F.R. Part 87 contains the codification of the EPA rules and regulations related to the control of emissions from aircraft and aircraft engines.
U.S. Environmental Protection Agency	2013b	National Primary and Secondary National Ambient Air Quality Standards	40 C.F.R. 50 (2013)	Under the authority of 42 U.S.C. §§ 7401 et seq, 40 C.F.R. Part 50 contains the codification of the EPA rules and regulations related to establishing National Ambient Air Quality Standards (NAAQS) under Section 109 of the CAA .
U.S. Environmental Protection Agency	2013c	Requirements for Preparation, Adoptions, and Submittal of Implementation Plans	40 C.F.R. 51 (2013)	Under the authority of 42 U.S.C. §§ 7401 et seq, 40 C.F.R. Part 51 contains the codification of the EPA rules and regulations related to procedures for developing Implementation Plans to meet the NAAQS. State and Federal Implementation Plans (i.e., SIPs and FIPs, respectively) apply to areas that are not in attainment with the NAAQS. Included are the regulations related to conformity to which airports are subject and the specification of models (e.g., EDMS) required for airport air quality evaluations.
U.S. Environmental Protection Agency	2013d	Determining Conformity of Federal Actions to State or Federal Implementation Plans	40 C.F.R. 93 (2013)	Under the authority of 42 U.S.C. §§ 7401 et seq, 40 C.F.R. Part 93 contains the codification of the EPA rules and regulations related to SIP and FIP determinations of conformity resulting from federal actions.
U.S. Environmental Protection Agency	1982	National Environmental Policy Act, as Amended	42 U.S.C. §§ 4371 et seq	National Environmental Policy Act (NEPA) is the Federal law establishing the President's Council on Environmental Quality (CEQ). NEPA established procedural requirements for the preparation of environmental assessments (EAs) and environmental impact statements (EISs) with responsibility assigned to the various overseeing federal agencies. NEPA was originally enacted in 1970 and amended in 1975 and 1982.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
U.S. Environmental Protection Agency	1978	Council on Environmental Quality	40 C.F.R. Chapter V	Under the authority of 42 U.S.C. §§ 4371 et seq and § 309 of the CAA, 40 C.F.R. Chapter V contains the codification of the rules and regulations of the Council on Environmental Quality as pertaining to the procedural requirements for the preparation of environmental assessments (EAs) and environmental impact statements (EISs).
U.S. Environmental Protection Agency	2004	Guidance on Airport Emission Reduction Credits from Early Measures through Voluntary Airport Low Emission Programs	U.S. Environmental Protection Agency. Office of Air Quality Planning and Standards. Guidance on Airport Emission Reduction Credits from Early Measures through Voluntary Airport Low Emission Programs. September 2004.	Regulatory guidance document. As permitted by the Vision 100 - Century of Aviation Reauthorization Act, this document provides guidance on emission reduction credits for voluntary early emission reduction programs at airports under the General Conformity and New Source Review (NSR) programs.
Unique	2004	Aircraft NO_x-Emissions within the Operational LTO Cycle	Prepared by Emmanuel Fleuti and Juan Polymeris in cooperation with Swiss Flight Data Monitoring, CH-8058. Zurich.	Evaluates flight specific data aimed at defining an operational LTO cycle, deriving operational times in mode, fuel flow and emissions data.
United Kingdom Department for Transport	2012	Reducing the Environmental Impacts of Ground Operations and Departing Aircraft: An Industry Code of Practice	Prepared by the Departures and Ground Operations Code of Practice Working Group	Presents an interim voluntary Code of Practice for aircraft operators shutting down one or more engines during taxi-in operations
Waitz, Ian, et al	2008	ACRP Report 9: Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data	ACRP Report 9 or Waitz et al. 2008	A primer document (compendium) of various field studies including evaluating emissions by thrust setting. Should be cross-checked to make sure a pertinent reference is not omitted from our final literature review.
Watterson, J., Walker, C., Eggleston, S.	2004	Revision to the Method of Estimating Emissions from Aircraft in the UK Greenhouse Gas Inventory: Report to Global Atmosphere Division, Defra	Report to Global Atmosphere Division, Defra	Contains the methodology used by Stettler et al to derive their time-in-modes.
Wayson, R., Fleming, G., Garrity, N., Kim, B., MacDonald, J., Lau, M., Draper, J.	UNK	Validation of FAA's Emissions and Dispersion Modeling System (EDMS): Carbon Monoxide Study	United States Department of Transportation/Volpe Center, Paper 69607	A study of carbon monoxide measurements at 25 locations at a major U.S. international airport (airside and landside). The EDMS-predicted concentrations were compared to measured concentrations and a detailed statistical assessment was performed of the AERMOD dispersion algorithm.

Author(s) or Regulatory Agency	Year	Title	Citation	Annotation
Wollenheit, R., Muhlhausen, T.	2013	Operational and Environmental Assessment of Electric Taxi Based on Fast-Time Simulation	*Transportation Research Record: Journal of the Transportation Research Board, No. 2336*, pp. 36-42	Presents the findings of a fast-time simulation model at two airports to demonstrate the fuel savings of an electric taxi system
Wood, E. C., Yelvington, P.E., Timko, M.T., Herndon, S.C., Miake-Lye, R.	2008	Speciation and Chemical Evolution of Nitrogen Oxides in Aircraft Exhaust near Airports	Environmental Science & Technology. March 15, 2008	Comparison of NO_x EIs from in-use at OAK to "formal engine tests" shows that idle thrust appears to be approximately 4 percent thrust for non-accelerating aircraft and approximately 15 percent for accelerating aircraft.
Wood, E., Herndon, S., Miake-Lye, R., Nelson, D.	2008	ACRP Report 7: Aircraft and Airport-Related Hazardous Air Pollutants: Research Needs and Analysis	ACRP Report 7 or Wood et al. 2008	Summarizes the uncertainties associated with emissions from aircraft
Yaworksi, M., Dinges, E, and Iovinelli, R.	2011	High-Fidelity Weather Data Makes a Difference Calculating Environmental Consequences with FAA's Aviation Environmental Design Tool	In the USA/Europe Air Traffic Management Research and Development 9th Seminar, June 14-17, 2011, Berlin, Germany. Unpaginated document.	Examines the use of high-fidelity weather data to model aircraft performance for the purpose of quantifying environmental consequences using the AEDT model.
Yelvington, P. E., Herndon, S., Wormhoudt, J., Jayne, J., Miake-Lye, R., Knighton, W., Wey, C.	2007	Chemical Speciation of Hydrocarbon Emissions from a Commercial Aircraft Engine	Journal of Propulsion and Power 2007, 23 (5), 912-918	Description of VOC EIs measured during the APEX campaign (from a CFM56-2C1). Showed strong inverse dependence of VOC emissions on ambient temperature and fuel flow rate.
Yin, K., Tian, C., Wang, B., Quadrifoglio, L.	2012	Analysis of Taxiway Aircraft Traffic at George Bush Intercontinental Airport, Houston, Texas	*Transportation Research Record: Journal of the Transportation Research Board, No. 2266*, pp 85-94	Assesses the congestion at IAH by analyzing taxi times and flight data during different hours of the day
Yoder, Tim	2005	Development of Aircraft Fuel Burn Modeling Techniques with Applications to Global Emissions Modeling and Assessment of the Benefits of Reduced Vertical Separation Minimums	Thesis (S.M.)--Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, 50 p.	Discusses methods to improve the FAA's System for assessing Aviation's Global Emissions (SAGE) specifically focusing on the way fuel consumption is calculated and improving the algorithms to process weather information.
UNK = Unknown				

APPENDIX B
RELEVANCE OF TEST DATA ENGINES

Relevance of ACRP 02-45 Aircraft Engine Test Data to Aircraft Fleet/FFR/EIs in AEDT

1. Introduction

For the purpose of the ACRP 02-45 project, there is a need to establish the relevance of the proprietary international aircraft engine performance data from the Test Data Engines listed below to the aircraft fleet operating in the United States (U.S.) and to the data in the AEDT databases that provide aircraft airframe/engine combinations, engine fuel flow rates (FFRs) and emission indices (EI):

Test Data Engines

- 3RR028 (RB211-535E4)
- 3CM021 (CFM56-5B4/2P)
- 3CM020 (CFM56-5B1/2P)
- 4PW067 (PW4168A)
- 2RR023 (Trent 772)
- 2CM015 (CFM56-5C4)
- 3CM027 (CFM56-5B5/P)

The Test Data Engines, and other engines addressed in this report, are identified by a unique identifier (UID) assigned to the engine by the International Civil Aviation Organization (ICAO). The UIDs indicate the set of emission measurements in ICAO's databank for a particular engine (i.e., a given engine could have more than one set of emissions measurements).

2. Aircraft with Test Data Engines

During the process of developing the AEDT improvement options, the Research Team identified the number of U.S. domestic "airline-owned" aircraft equipped with the Test Data Engines. This information was presented in the project's *Interim Report* (January 31, 2015). The source used by the Research Team, *JP Airline Fleets International* (2013-2014) provided the number of each type of aircraft equipped with the Test Data Engines but not the number of operations performed by the aircraft. At the March 19th meeting, the Project Panel suggested that the Research Team contact Eastman Chemical Company to request their guide entitled *Turbine-Engine Fleets of the World's Airlines*. Information in the guide is collected by Eastman from an annual survey of the world's airlines. **Table B-1** provides a list of U.S. domestic airline-owned aircraft equipped with the Test Data Engines and the number of aircraft operations estimated to be performed annually from this data source.

As shown in **Table B-1**, the data from Eastman indicates that more than 666,000 annual operations are performed within U.S. airspace by domestic-owned aircraft equipped with the Test Data Engines.[18] When considering all of the operations performed by domestic airlines, the operations by aircraft equipped with Test Data Engines represents approximately five percent of all operations performed in the U.S. This estimated percentage of operations can be considered conservatively low because, based on data from the Bureau of Transportation Statistics for the year 2014, there were 1,263,365 international operations in the U.S. Because some of these aircraft are equipped with the Test Data Engines, the percentage of total operations in the U.S. by aircraft with Test Data Engines would be higher than five percent.

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[18] From the data provided by Eastman Chemical Company, it is not possible to identify the number of operations occurring in the U.S. airspace by aircraft owned by international airlines.

Table B-1
U.S. Domestic Airline-Owned Aircraft with Test Data Engines (2014)

Test Data Engine	Aircraft Type	Airline	Number of Aircraft	Annual Operations[a]
1RR014 (RB211-535E4)	B757-200/SF/PF	Allegiant Air	6	15,838
		FedEx	62	163,660
		United	25	65,662
		United Parcel Service	40	105,587
		US Airways	21	55,434
	Total		154	406,511
4PW067 (PW4168A)	A330-200/300	Delta	32	80,802
		US Airways	9	22,726
	Total		41	103,528
2RR03 (Trent 772)	A330-200	Hawaiian Airlines	22	34,722
		US Airways	15	23,674
			37	58,396
	Total			
3CM027 (CFM56-5B5/P)	A319	Allegiant Air	5	15,852
		Frontier	26	82,430
	Total		31	98,282
Total			263	666,717

[a] Derived based on daily average cyclic utilization rates provided by Eastman Chemical Company.

3. Aircraft with Like Engines

Because the number of Test Data Engines is relatively small, the evaluation considered whether the fuel flow rates (FFRs) and emissions indices (EIs) from the Test Data Engines could be considered similar to the FFRs and EIs from other engines ("Like Engines").

The Research Team initially developed a list of Like Engines by comparing fuel flow and total emissions of hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) from the Test Data Engines to those of other civilian jet engines. At the request of the Project Panel, the Like Engine list was revised to include engines derived with a magnitude percent deviation from the Test Data Engines, among thrust and NOx EIs, when considering the aircraft operational states of idle and approach. The idle and approach modes were selected to best approximate engine operating conditions while at "low-power" or low thrust settings.

"Similarity metrics" were calculated using the method shown below for all engines in Version 21b of the International Civil Aviation Organization (ICAO) Emissions Databank, as well as all engines in the AEDT Version 2a SP2 fleet database that are not included in the ICAO databank. The similarity metrics provide a quantitative evaluation of the similarity between the emissions of the Test Data Engines and the engines in the ICAO/AEDT databases.

$$M = 100 \times \max\left\{\Delta_F, \Delta_{NOx_{ID}}, \Delta_{NOx_{AP}},\right\}$$

$$\Delta_F = \left|\frac{F - F_R}{F_R}\right|$$

$$\Delta_{NOx_{ID}} = \left|\frac{EI_{NOx_{ID}} - EI_{NOx_{ID\,R}}}{EI_{NOx_{ID\,R}}}\right|$$

$$\Delta_{NOx_{AP}} = \left|\frac{EI_{NOx_{AP}} - EI_{NOx_{AP\,R}}}{EI_{NOx_{AP\,R}}}\right|$$

where

- M is the similarity metric (smaller values indicate greater similarity)
- F is the rated thrust of the candidate engine
- F_R is the rated thrust of the reference engine
- $EI_{NOx_{ID}}$ is the NOx emission index for the candidate engine under evaluation at the idle state
- $EI_{NOx_{ID\,R}}$ is the NOx emission index for the reference engine at the idle state
- $EI_{NOx_{AP}}$ is the NOx emission index for the candidate engine at the approach state
- $EI_{NOx_{AP\,R}}$ is the NOx emission index for the reference engine at the approach state

Table B-2 lists the Test Data Engines and the Like Engines that have calculated similarity metrics within 15 percent of the Test Data Engines.[19]

Table B-2
Test Data and Like Engines

Test Data Engine	Like Engine(s)	Similarity Metric (%)
3RR028 (RB211-535E4)	3RR034 (RB211-535E4B)	8.4
	1RR012 (RB211-535C)	8.5
	8PW086 (JT9D-7)	13.5
3CM021 (CFM56-5B4/2P)	4CM041 (CFM56-7B24/2)	10.4
	4CM042 (CFM56-7B26/2)	11.7
	7PW084 (PW6124A)	11.8
	3CM020 (CFM56-5B1/2P)	12.3
3CM020 (CFM56-5B1/2P)	4CM037 (CFM56-5B2/2P)	4.1
	4CM038 (CFM56-5B3/2P)	6.8
	4CM043 (CFM56-7B27/2)	9.0
	3CM021 (CFM56-5B4/2P)	11.0
	4CM042 (CFM56-7B26/2)	12.4
	1CM009 (CFM56-5A3)	13.7
4PW067 (PW4168A)	1PW050 (PW4168)	0.0
	1PW049 (PW4164)	5.9
	1PW059 (PW4x62)	12.8
	1PW057 (PW4x60)	14.5
	2GE044 (CF6-80C2B6)	14.7
	2GE039 (CF6-80C2A5)	14.7
	9PW095 (PW4170)	14.8
	2GE038 (CF6-80C2A3)	14.9
	4GE081 (CF6-80E1A4)	14.9
2RR023 (Trent 772)	2RR022 (Trent 768)	5.4

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[19] The choice of 15 percent as a cut-off value is arbitrary.

Test Data Engine	Like Engine(s)	Similarity Metric (%)
	8RR046 (Trent 970-84)	11.1
	13GE159 (GEnx-1B75/P2)	12.7
	9RR047 (Trent 972-84)	12.9
	9RR048 (Trent 972B-84)	12.9
	13GE160 (GEnx-1B74/75/P2)	13.1
	7PW081 (PW4164)	13.1
	5PW075 (PW4168)	13.3
	7PW082 (PW4168A)	13.3
	13GE158 (GEnx-2B67/P)	14.3
	1PW058 (PW4x62)	14.6
2CM015 (CFM56-5C4)	1CM011 (CFM56-5C3)	4.4
	7CM047 (CFM56-5C4/P)	7.2
	1CM010 (CFM56-5C2)	8.2
	3CM024 (CFM56-5B2/P)	8.8
	2CM013 (CFM56-5B2)	9.8
	3CM025 (CFM56-5B3/P)	9.8
	4PW072 (PW2037)	10.0
	7CM046 (CFM56-5C3/P)	10.0
	8CM054 (CFM56-5B3/3)	10.4
	8CM053 (CFM56-5B2/3)	11.7
	2CM012 (CFM56-5B1)	11.8
	3CM023 (CFM56-5B1/P)	11.8
	13AA008 (PS-90A2)	12.7
	7CM045 (CFM56-5C2/P)	12.8
	8CM052 (CFM56-5B1/3)	13.0
	13AA007 (PS-90A11)	15.0
3CM027 (CFM56-5B5/P)	8CM063 (CFM56-7B22/3)	4.0
	11CM068 (CFM56-7B22E)	4.0
	11CM069 (CFM56-7B22E/B1)	4.0
	1PW018 (JT8D-217 series)	5.3
	7CM049 (CFM56-5B9/P)	5.3
	1PW019 (JT8D-219)[a]	5.3
	1CM002 (CFM56-2B-1)	5.7
	1CM003 (CFM56-2-C5)	5.7
	8CM060 (CFM56-5B9/3)	5.8
	4CM035 (CFM56-5A4)	6.3
	8CM057 (CFM56-5B6/3)	6.8
	3CM022 (CFM56-5B6/2P)	6.8
	3CM028 (CFM56-5B6/P)	6.8
	8CM056 (CFM56-5B5/3)	7.7
	1CM005 (CFM56-3B-2)	7.9
	4CM039 (CFM56-7B20/2)	7.9
	11CM067 (CFM56-7B20E)	8.0
	8CM062 (CFM56-7B20/3)	8.3
	8CM059 (CFM56-5B8/3)	8.5
	1CM004 (CFM56-3-B1)	8.7
	4BR006 (BR700-715B1-30)	8.9
	8CM064 (CFM56-7B24/3)	9.9
	11CM070 (CFM56-7B24E)	9.9

Test Data Engine	Like Engine(s)	Similarity Metric (%)
	11CM071 (CFM56-7B24E/B1)	9.9
	7CM048 (CFM56-5B8/P)	10.5
	8CM061 (CFM56-7B18/3)	11.4
	4PW071 (JT8D-219)[a]	12.1
	4PW070 (JT8D-217C)	12.1
	1PW017 (JT8D-209)	12,6
	4BR007 (BR700-715C1-30)	12.6
	4CM036 (CFM56-5A5)	12.9
	1CM001 (CFM56-2A series)	13.2
	1CM007 (CFM56-3C-1)	13.2
	3CM029 (CFM56-7B18)	13.2
	3CM030 (CFM56-7B20)	13.2
	1CM008 (CFM56-5-A1)	13.6
	1PW003 (JT3D-7 series)	13.7
	11GE144 (CF34-10E5A1)	14.5
	11GE145 (CF34-10E6A1)	14.5
	11GE146 (CF34-10E7)	14.5
	11GE147 (CF34-10E7-B)	14.5
	8GE119 (CF34-10E7)	14.5
	8GE118 (CF34-10E6A1)	14.5
	8GE117 (CF34-10E5A1)	14.5
	10GE130 (CF34-10E5A1)	14.5
	10GE132 (CF34-10E6A1)	14.5
	10GE133 (CF34-10E7)	14.5
	4BR005 (BR700-715A1-30)	15.0

[a] For the JT8D-219 engine two of ICAO's engine emission measurement datasets were within 15 percent of this Test Data Engine.

Using the Eastman Chemical Company database, the number of annual aircraft operations by aircraft equipped with the Like Engines was derived. **Table B-3** provides a list of U.S. domestic airline-owned aircraft equipped with Like Engines. As shown, more than 3.3 million operations are performed annually within U.S. airspace by aircraft equipped with these engines. Again, when considering only domestic airline-owned aircraft, the operations performed by aircraft with Like Engines represents approximately 27 percent of all operations performed in the U.S. (the percentage again being higher when considering the aircraft owned by international carriers).

Table B-3
U.S. Domestic Airline-Owned Aircraft with Like Engines

Test Data Engine	Like Engine	Aircraft Type	Airline	Number of Aircraft	Annual Operations[a]
3RR028 (RB211-535E4)	3RR034 (RB211-535E4B)	757-200	American	75	197,830
			United	25	66,430
			US Airways	3	8,030
3CM020 (CFM56-5B1/2P)	1CM009 (CFM56-5A3)	A320-200	Delta	44	139,430
4PW067 (PW4168A)	2GE044 (CF6-80C2B6)	767300BCF/ER	ABX	2	4,380
			American	58	134,320
			Delta	1	2,190
			Omni Air	2	4,380
	2GE039 (CF6-80C2A5)	A300B4-600R9(f)	FedEx Express	3	7,300
2RR023 (Trent 772)	7PW082 (PW4168A)	A330-200	Delta	32	81,030
			US Airways	9	22,630
2CM015 (CFM56-5C4)	4PW072 (PW2037)	A321	US Airways	34	108,040
		757-200/SF/COMBI	Air Transport	1	2,920
			Capital Cargo	1	2,920
			Delta	148	402,230
			FedEx Express	7	18,980
	8CM054 (CFM56-5B3/3)	A321-200	US Airways	9	28,470
3CM027 (CFM56-5B5/P)	8CM063 (CFM56-7B22/3)	737-700	Southwest	5	21,900
	1PW018 (JT8D-217 series)	MD82	American	5	19,710
		MD81/82/87	Delta	5	18,980
	1PW019 (JT8D-219)	MD83/88	Allegiant Air	52	204,400
		MD82/83	American	153	603,710
		MD82/83/88	Delta	121	476,690
		MD83	Falcon Air Expr	7	27,740
	8CM057 (CFM56-5B6/3)	A319	American	16	50,370
			Frontier	2	6,570
			Virgin America	4	12,410
	3CM028 (CFM56-5B6/P	A319/A20-200	Frontier	7	21,900
			US Airways	56	178,120
			Virgin America	6	18,980
	8CM064 (CFM56-7B24/3	737-800	American	2	8,760
	4BR007 (BR700-715C1-30	717-200	AirTran	2	7,300
	4CM036 (CFM56-5A5)	A319	Delta	57	181,040
	3CM030 (CFM56-	737-700	AirTran	11	48,180

Test Data Engine	Like Engine	Aircraft Type	Airline	Number of Aircraft	Annual Operations[a]
	7B20)		Southwest	45	195,640
	4BR005 (BR700-715A1-30)	717-200	Hawaiian Air	16	57,670
Total				1,026	3,391,580

[a] Derived based on daily average cyclic utilization rates provided by Eastman Chemical Company.

4. Findings of Test Data Engine Relevance Evaluation

As previously stated, for the purpose of the ACRP 02-45 project there is a need to establish the relevance of the proprietary international aircraft engine performance data used in the research (i.e., the Test Data Engines) to the aircraft fleet operating in the U.S. and to the data in the AEDT databases. For this reason, and using data/methods suggested by the Project Panel, an estimate of the number of aircraft operations performed by aircraft with the Test Data Engines and engines identified as having similar fuel flow rates and emission indices were derived. Based on the calculations, the Test Data Engines are estimated to represent at least five percent of all jet operations in the U.S. and the Like Engines are estimated to represent at least 27 percent of all operations in the U.S.

When considering the results of this relevance evaluation, it is important to note that the FDR data from the Test Data Engines was used by the Research Team in the development of AEDT improvement options for the following aircraft taxi/idle emission computational factors:

- **Time in mode** – AEDT improvement options were developed for aircraft taxi speed.
- **Fuel Flow Rates** – AEDT improvement options were developed that would be applied to only the Test Data Engines, to the Test Data Engines and also to the Like Engines, or globally to all commercial jet engines.

5. Emissions Contribution

The second Action Item from the meeting with the Project Panel is a recommendation of the engines that should be evaluated in future studies based on their overall mass of emission contribution. The number of aircraft operations by aircraft and engine type from the Eastman Chemical Company and idle emission data from ICAO were also used for this purpose and, as for the evaluation of FDR relevance, only data for domestic airlines were considered. Additionally, for the purpose of the evaluation, a total taxi in/taxi out time of 23 minutes (one of the taxi time improvement options) was assumed.

Table B-4 lists the jet engines, and the aircraft on which they are installed, that contribute approximately 50 percent of the total HC, CO, and NOx emissions (ranked from the greatest to least contributor). As shown, the engines with the greatest contribution to emissions of these pollutants/precursors are the CF6-6D and CFM56-7BE engines (contributing 10, 9, and 8 percent of these emissions, respectively). Of note, the CFM56-7B24, CFM56-7BE, CFM56-7B26, and CFB56-7B22 engines, currently installed on 737-700, 737-800, and 737-900ER aircraft, are among the top contributors of all three ranked lists. Based on the operational data from Eastman and emissions data from ICAO, if data are available, future studies should focus on these four engines or the other engines in **Table B-4**. Assessment of this data also indicates that operations performed by aircraft equipped with the Test Data Engines result in approximately 1, 1.5, and 2 percent of total HC, CO, and NOx idle emissions within the U.S., respectively, while operations performed by aircraft equipped with Like Engines result in approximately 5, 11, and 11 percent of total HC, CO, and NOx idle emissions, respectively.

Table B-4
Engines/Aircraft With Greatest Emission Contribution[a]

HC			CO			NOx		
Engine Model	**Aircraft**	**%[b]**	**Engine Model**	**Aircraft**	**%[b]**	**Engine Model**	**Aircraft**	**%[b]**
CF6-6D	DC10-10CF/(F)	10%	CFM56-7BE	737-700/800/900ER	9%	CFM56-7BE	737-700/800/900ER	8%
CFM56-7B24	737-700/800	7%	CFM56-7B24	737-700/800	6%	CFM56-7B24	737-700/800	6%
PW4060	767-300/ER/BCF	6%	CF34-3B1	CRJ200/440	5%	CFM56-7B26	737-700/800/900ER	6%
CF34-3B1	CRJ200/440	6%	JT8D-219	MD-82/83/88	5%	V2527-A5	MD90-30, A320-200	5%
CFM56-7BE	737-700/800/900ER	6%	CFM56-7B26	737-700/800/900ER	4%	JT8D-219	MD-82/83/88	4%
CFM56-7B26	737-700/800/900ER	5%	CFM56-3B1	737-300/500	4%	CFM56-7B27	737-800/900ER	4%
CFM56-7B22	737-700	3%	V2527-A5	MD90-30, A320-200	3%	CFM56-7B22	737-700	3%
CF6-6K	DC10-10(F), 737-700	3%	CFM56-7B22	737-700	3%	PW2037	757-200/SF/COMBI	2%
CF34-10E6	ERJ190-100	3%	CF34-10E6	ERJ190-100	3%	V2533-A5	A321-200	2%
			CFM56-7B27	737-800/900ER	2%	PW4090	777-200B	2%
			CF6-6D	DC10-10CF/(F)	2%	CFM56-3B1	737-300/500	2%
			PW4060	767-300/ER/BCF	2%	CF34-8E5	ERJ170-100/200	2%
			PW2037	757-200/SF/COMBI	2%	CF6-80C2B6F	767-300BCF/ER/FER	2%
						RB211-535E4B	757-200	2%

[a] Contribute approximately 50 percent of total emissions occurring within the U.S. airspace.

[b] Columns headed with "%" show the percent emission contribution for the corresponding engine/aircraft type.

Note: Shaded cells indicate engines/aircraft included in each list (HC, CO, and NOx).

APPENDIX C

EMISSION INDEX ADJUSTMENT FACTORS FOR CO AND HC

Emission Index Adjustment Factors for CO and HC

Figure C-1 below is reproduced from **Figure 1** in the main body of this document, with the addition of interpolated traces corresponding to the relative fuel flow rates (FFRs) at which the engines from the flight data recorder (FDR) dataset used in the ACRP 02-45 project operated. The equations for these added lines are presented below the graph.

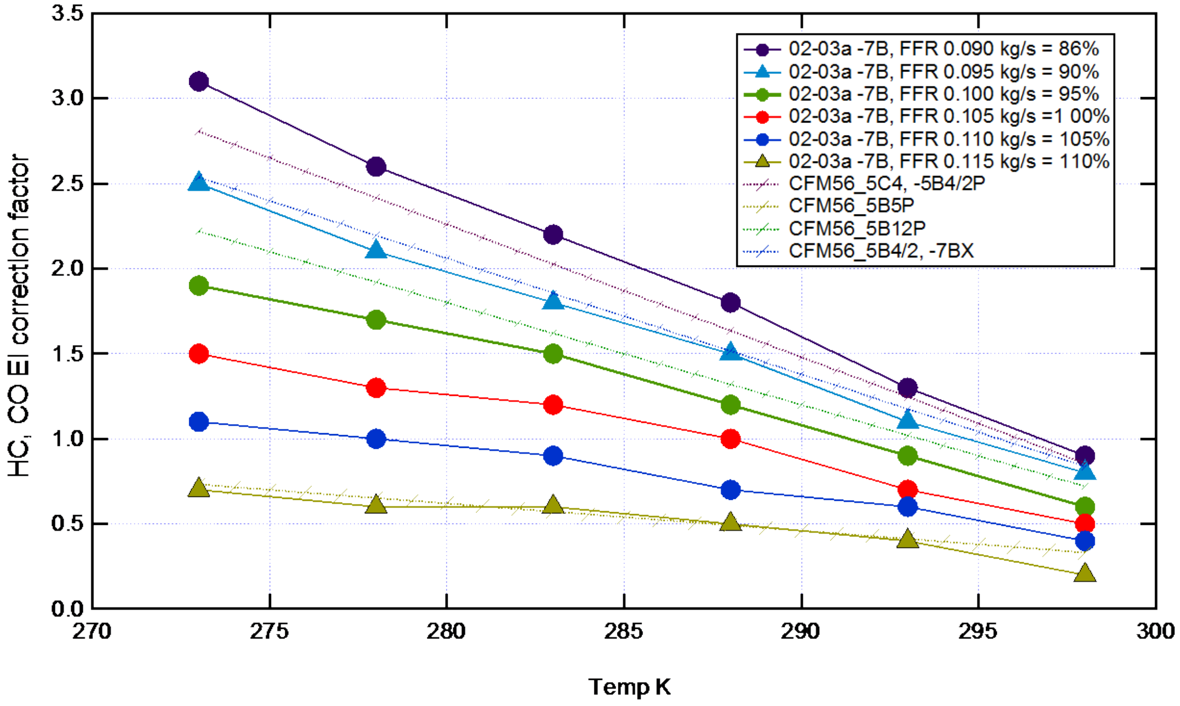

Figure C-1

- **CFM56-5B1/2P**
  European FDR shows FFR = 91 – 94 percent of ICAO (-5B1/2P)
  $EI(T)/EI_{ICAO} = -0.060 * Temp(K) + 18.6$

- **CFM56-5B4/2P, -5C4**
  FFR = 87 percent - 89 percent of ICAO (-5B4/2P)
  FFR = 85 percent - 91 percent of ICAO (-5C4)
  $EI(T)/EI_{ICAO} = -0.078 * Temp(K) + 24.1$

- **CFM56-5B5/P**
  FFR = 111 – 113 percent of ICAO
  $EI(T)/EI_{ICAO} = -0.016 * Temp(K) + 5.1$

- **CFM56-5B4/2, -7BX, -3B1**
  90 percent of ICAO
  $EI(T)/EI_{ICAO} = -0.068 * Temp(K) + 21.1$