

Aircraft Emissions Modeling Under Low Power Conditions

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Abstract

The International Civil Aviation Organization (ICAO) defines standard power settings for jet engines at 7%, 30%, 85%, and 100% corresponding to the idle, approach, climbout, and takeoff modes, respectively. These modes define the Landing and Takeoff (LTO) cycle developed as part of the jet engine certification process started in the 1970s. The cycle serves as the international basis for airport emissions modeling and inventory development. Although the 7% power setting has been widely adopted as the standard for modeling taxi and idling activities, the common understanding is that the actual power used will be noticeably lower than this nominal 7%. The resulting error in fuel burn and nitrogen oxide (NO_x) calculations will be relatively proportional to the amount of difference in power settings. However, the exponential relationship between emissions indices (EI) and fuel flow at the lower power settings for total hydrocarbons (THC) and carbon monoxide (CO) could result in much greater errors for these pollutants. With greater emphasis being increasingly placed on health impacts from aircraft emissions, it is important to understand the potential errors associated with emissions predictions. To illustrate the range of errors involved, this paper presents the results from different analysis levels involving a single aircraft and engine and aggregated fleet levels involving an airport and the top 100 United States (US) commercial airports. The few published references appear to indicate that actual average taxi power may be somewhere between 3% and 6%. Using a nominal 5% power setting, the results for the different levels were similar and they all indicate that as power settings are decreased below 5%, THC and CO emissions increase

dramatically. The 100 airport analysis revealed that taxi THC and CO emissions would increase by 132% and 58%, respectively, if the 5% power setting is modeled.

Introduction

For airport air quality assessments, the Emissions and Dispersion Modeling System (EDMS), currently at Version 5.0.2, is the FAA required tool¹. In the last few years, the FAA has embarked on an initiative to merge their air quality and noise tools into a modeling suite called the Aviation Environmental Design Tool (AEDT)². The common emissions module used in the suite is based on the Boeing Fuel Flow Method 2 (BFFM2)³ which is intended for use with the emissions index (EI) data from the International Civil Aviation Organization (ICAO) emissions databank⁴. These EI values for total hydrocarbons (THC), carbon monoxide (CO), and nitrogen oxides (NO_x) are collected through an emissions certification procedure for jet aircraft at the ICAO at reference conditions (sea level static) and standard power settings of 7% (idle), 30% (approach), 85% (climbout), and 100% (takeoff).

Although emissions for idle and taxi are modeled at the nominal 7% setting in EDMS and AEDT, there are some indications (mostly unpublished) that idle/taxi power settings may be less. The BFFM2 documentation² indicates that the minimum idle may be “anywhere between 3% and 5% of takeoff thrust.” While this does not address the power used during aircraft taxi movements, it provides some indications of the errors involved in modeling idling conditions. Similarly, the findings from the Air Traffic Emissions (ARTEMIS)⁵ project indicate that based on comparing measured emissions data (especially for NO_x) to the ICAO EI data, aircraft power during idling conditions may be lower than 7%. A survey of International Air Transport Association (IATA) member carriers showed that 5% to 6% appear to be the actual power settings used for taxiing operations^{6,7}. For Rolls Royce engines, the survey found that levels were even lower at 3% to 5%.

However, in those cases where only one engine (out of two) was used for taxiing, the study found that the increase in power setting for the on-engine was increased between 1.5% and 3% resulting in total power settings of 8.5% and 10%, respectively. Similarly, the power settings for the on-engines of a four-engine aircraft (where not all were used) were also increased to compensate for the off-engines. As a result, it is advantageous to not use all engines during taxiing since it not only reduces total fuel flow, and hence total emissions, but also because it reduces the per engine EIs of THC and CO (due to higher power settings). Notwithstanding the practice of not employing all engines during taxiing, most airlines on average appear to use less than 7% power settings for taxiing and idle operations.

Since there is no clear guidance on modeling emissions below the 7% power setting, EDMS and the current AEDT emissions module places a lower cap at that 7% setting. That is, modeled EIs cannot be lower than that corresponding to the 7% power setting. Due to the lower power used in actual practice, EDMS will underpredict THC and CO emissions while NO_x emissions are overpredicted. The BFFM2 documentation indicates that care must be taken when modeling below the 7% setting so that unreasonably high emissions do not result from the use of low fuel flow rates. As such, the lower cap used in EDMS and AEDT appear to be a reasonable

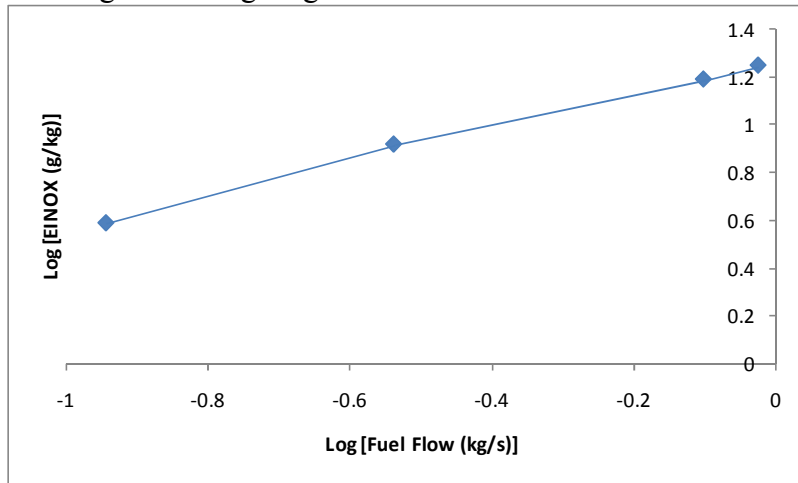
safeguard against erroneously high emissions predictions in the absence of any guidance. However, as the understanding of hazardous air pollutant (HAPs) emissions improves and the importance of airport contributions to health effects are elevated, the need for more accurate emissions are evident. In addition, the improved accuracy of these pollutant emissions would also help in the current framework to conduct General Conformity determinations and NAAQS assessments. Improving the accuracy of these emissions is important for NAAQS assessments since modeled concentrations are only as accurate as the emissions data allow.

To assess the potential errors associated with modeling idle and taxi emissions at 7%, example assessments were conducted at varying levels from one aircraft and engine combination to aggregate fleet mixes involving a single airport and a representative sample of United States (US) commercial airports. The BFFM2 emissions modeling within EDMS/AEDT was mimicked externally in a custom-built, Wyle software application to allow modifications to the power settings and facilitate the assessments. The only difference from the EDMS/AEDT methodology is that the emissions on the runway after touchdown are not included in this study; EDMS/AEDT includes those emissions as part of the taxi-in mode. Although other pollutants (e.g., particulate matter) will also be affected by the change in power settings, the scope of this study is limited to NO_x, THC, and CO.

Overview of the BFFM2 Methodology

Developed by Boeing, the BFFM2 methodology allows for the modeling of emissions at non-reference conditions (i.e., non-sea level conditions). Using data from the ICAO emissions databank, BFFM2 corrects the fuel flows for engine installation effects and also takes into account atmospheric conditions (i.e., temperature, pressure, and humidity). Emissions for non-standard power settings are determined using log-log relationships between EIs and fuel flow. Using the CFM56-3-B1 engine with an ICAO Unique Identification (UID) number of 1CM004 as an example, Figure 1 provides a typical plot of EINO_x versus fuel flow where linear interpolations between points are conducted rather than the use of an empirical fit on a log-log scales.

Figure 1: Log-Log Plot of EINO_x versus Fuel Flow



Unlike NO_x, the Log-Log plots for THC and CO are based on a bilinear fit. As shown in Figures 2 and 3, these plots are typically developed based on extending the line connecting the 7% and 30% points until it intersects with the horizontal line representing the average of the EI values at the 85% and 100% power settings.

Figure 2: Log-Log Plot of EITHC versus Fuel Flow

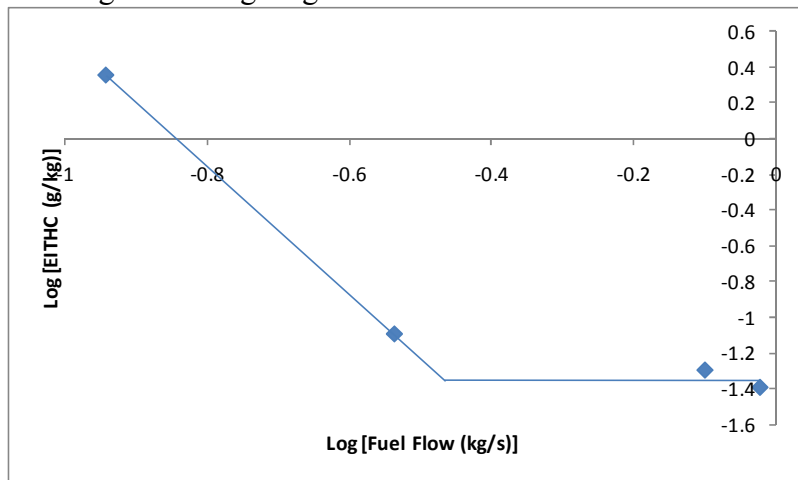
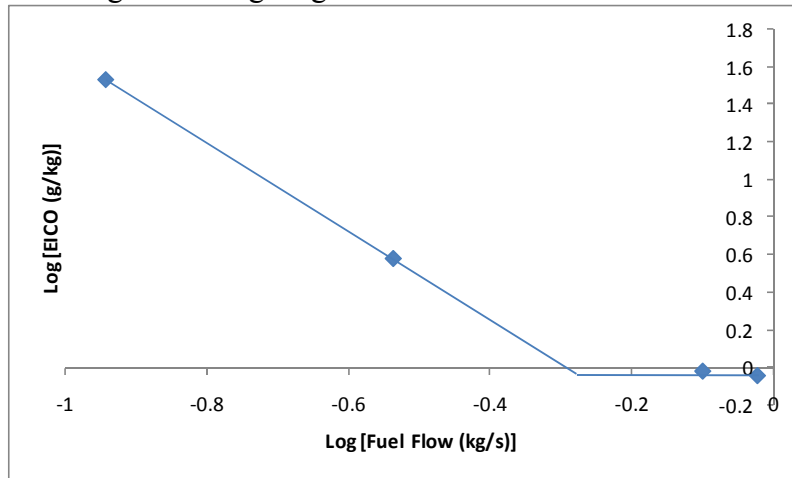


Figure 3: Log-Log Plot of EICO versus Fuel Flow



As indicated in these plots, EITHC and EICO are very sensitive and have an inverse relationship to fuel flow at the lower power settings. This is due to the asymptotic nature of the EI versus fuel flow relationship at those settings. As indicated in the BFFM2 documentation, the extrapolations below 7% can be conducted but care must be taken to ensure that very low fuel flows are not used to produce erroneously high emissions³. Due to the possibility of these large emissions, this study is mainly focused on assessing THC and CO rather than NOx emissions. The errors for NOx and fuel burn will be relatively small since their errors will be relatively proportional to the amount of difference in power settings.

In using BFFM2, additional considerations must also be given to take into account various exceptional cases including when the ICAO data has zero values and when the data do not conform to the bilinear configuration as shown in Figures 2 and 3. Procedures for handling these cases are provided in the BFFM2 documentation³. It is also worth noting that Boeing's documentation does not currently provide guidance for modeling engines with dual annular combustors (DAC)³.

Single Aircraft and Engine Analysis

To assess emissions for a single aircraft and engine, the same CFM56-3-B1 engine (ICAO UID 1CM004) was used to demonstrate the change in taxi emissions from using a lower power setting. The ICAO reference fuel flows and EIs for this engine are reproduced in Table 1.

Table 1: ICAO Reference Fuel Flows and EIs for CFM56-3-B1 (1CM004)

Mode	Fuel Flow (kg/s)	EI _{THC} (g/kg)	EI _{CO} (g/kg)	EI _{NO_x} (g/kg)
Takeoff	0.946	0.04	0.9	17.7
Climbout	0.792	0.05	0.95	15.5
Approach	0.29	0.08	3.8	8.3
Idle	0.114	2.28	34.4	3.9

For this simplified example, the International Standard Atmosphere (ISA) conditions were simulated for Atlanta Hartsfield Jackson International Airport (ATL) (i.e., airport surface temperature and pressure derived from an airport altitude of 1,026 ft) along with a relative humidity approximation of 60%. To approximate fuel flow at the lower power settings, an approximation was made using a ratio of percent power settings. Based on the previously described 5-6% settings from the IATA survey^{6,7} and the indications of 3-5% for minimum idle from the BFFM2 documentation³, a nominal 5% was used as an approximation for this analysis. As such, assuming a 5/7 ratio and applying it to the idle fuel flow (0.114) in Table 1 resulted in 0.0814 kg/s at reference conditions. Taking into account the corrections for engine installation and airport atmospheric effects as prescribed by BFFM2, the resulting non-reference fuel flow is 0.0887 kg/s as indicated in Table 2 along with the corresponding EIs.

Table 2: Non-Reference Fuel Flow and EIs at ATL Airport Conditions

Power Setting	Fuel Flow (kg/s)	EI _{THC} (g/kg)	EI _{CO} (g/kg)	EI _{NO_x} (g/kg)
7%	0.124	2.31	34.9	3.91
5%	0.0887	8.60	82.8	2.91

Future studies could potentially improve upon this approximation using either measured fuel flow data or detailed aircraft and engine performance models to more properly predict fuel flow at the lower power (or thrust) setting. Using the ICAO default total taxi time (taxi-in plus taxi-out) of 26 minutes and assuming the engine is used on the Boeing 737-300 aircraft (with 2 engines), the emissions are estimated as shown in Table 3.

Table 3: Taxi Fuel Burn and Emissions Comparisons Between 7% and 5% Power Settings

Power Setting	Fuel Burn (kg)	THC (g)	CO (g)	NO _x (g)
7%	387	896	13,520	1,520
5%	277	2,380	22,900	805
% Difference	-28.6	166	69.4	-46.9

Note: % differences may not be reproducible due to rounding.

As indicated in Table 3, a 28.6% reduction in fuel burn (FB) equates to 166% and 69.4% increase in THC and CO emissions. To provide a better understanding of the sensitivities, additional power settings were assessed as shown in Table 4.

Table 4: Percent Changes in Fuel Burn and Emissions for Various Power Settings in Comparison to the standard 7% Power Setting

Power Setting	% Difference from 7% Power Setting			
	Fuel Burn	THC	CO	NOx
6%	-14.3	56.5	27.3	-25.2
5%	-28.6	166	69.4	-46.9
4%	-42.9	408	140	-65.1
3%	-57.1	1,070	277	-79.7
2%	-71.4	3,700	612	-90.5

The percent differences in Table 4 show that at power settings below 5%, the change in emissions for THC and CO increases significantly. Modeled THC and CO emissions at 2-3% power settings may be erroneously high. And as expected, NOx emissions decrease similarly to fuel burn.

To provide some further perspective on these emissions levels, the startup emissions for THC at the 7% power setting from EDMS using the performance Times-In-Mode (TIM) values is 920 g which is slightly greater than the taxi emissions of 896 g indicated in Table 3. In EDMS, the startup mode always represents the greatest THC emissions if the ICAO default TIM values are used. This is due to the fact that EDMS estimates startup THC emissions by summing THC emissions from all other modes using the ICAO default TIM values¹. Although the startup emissions may be highest at the 7% power setting, the 5% value of 2,380 g as shown in Table 3 is more than double the startup value. Even the 6% value would exceed the startup value by a large margin (i.e., the 56.5% increase as indicated in Table 4 would result in 1,400 g of THC). This provides an indication of the significance of using more accurate taxi power settings. Additional aircraft and engines could be assessed in future studies to help further support these findings.

Fleet Mix Analysis

The fleet mix analysis was conducted at two levels: a single airport and the top 100 commercial US airports by number of operations. Although the numbers of airports are different, the methods used in both levels were identical.

For these example assessments, the 2002 Official Airline Guide (OAG) schedule of flights was used since it was readily available at Wyle. The schedule was first processed into unique operations by origin-destination (OD) and aircraft type combinations. Then it was used to identify the top 100 US airports by number of departure operations. Once these airports were identified, the operations were divided into departure and arrival sets with only operations for the top 100 US airports preserved. Although the use of scheduled flights as opposed to actual flight plans can cause some errors (e.g., due to flight cancellations, duplicate flights from code-shares, etc.), they were considered relatively small, especially since the main goal is to determine percent differences in emissions rather than actual magnitudes.

The generic aircraft types (e.g., B733, A320, etc.) in each of the OAG operations were assigned an EDMS aircraft type and ICAO (plus EDMS) UID using a combination of the EDMS “AIRCOMBO.dbf” system fleet table and various other resources (e.g., airliners.net⁸). Since only the taxi mode was being modeled with fuel flow obtained from the EDMS system tables, the aircraft assignments were not necessary for modeling purposes but provided a basis for engine assignments.

In addition to the equipment assignments, the EDMS airports system database was used to assign airport elevations to each of the top 100 airports. This elevation information was used to determine temperature and pressure at each airport based on the ISA profiles. Although it may have been possible to use the EDMS airport temperature and pressure values, it was unclear how and where this data could be extracted from the EDMS system tables. Considering the overall fidelity (e.g., assumptions associated with equipment mappings, taxi times, etc.), the use of the ISA should have provided reasonable approximations of each airport’s temperature and pressure. Similarly, the relative humidity was estimated as a constant at 60%.

Taxi times were determined from analyzing the Bureau of Transportation Statistic’s (BTS) Airline On-Time Performance (AOTP) data⁹. This database contains taxi time information for “US certified carriers that account for at least one percent of domestic scheduled passenger revenues.” Each of the monthly statistics for 2002 were obtained from BTS to correspond to the 2002 OAG schedule. This data was processed to obtain average taxi-in and taxi-out times for each of the top 100 US airports. For the 2 airports (ranked 89 and 100) that were not covered by this AOTP data, they were assigned the average taxi-in and taxi-out times of the other 98 airports. Although more accurate taxi time data could potentially have been developed (e.g., hour, weekday, etc. specific taxi times), these airport-specific averages were considered adequate for assessing emissions at the aggregate fleet levels. As previously indicated, the purpose is mainly to determine percent changes in emissions rather than actual magnitudes.

The data from the EDMS system tables and the AOTP taxi times were assigned to the OAG operations data. Table 5 exemplifies the operations data for departure segments of the LTO cycle; hence, only taxi-out data (specific to ATL airport) are shown in the table.

Table 5: Example Operations Data with Equipment Assignments and Taxi-out Times

Dep Arpt	Arr Arpt	Aircraft	Engine	ICAO UID	Num Engines	Dep Arpt Elev (ft)	Taxi-out (min)	Num Flights
ATL	DCA	B72Q	JT8D-15	1PW009	3	1026	18.7	567
ATL	DCA	B738	CFM56-7B26	3CM033	2	1026	18.7	633
ATL	DCA	B752	RB211-535E4	3RR028	2	1026	18.7	2
ATL	DCA	CRJ	CF34-3A1	1GE035	2	1026	18.7	66
ATL	DCA	MD80	JT8D-217C	4PW070	2	1026	18.7	3458
etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.

Note: EDMS-specific aircraft types are not shown since they were not used as part of the modeling work.

Each of the unique operations exemplified in Table 5 were fed into a custom-built Wyle software program to model taxiing emissions. The program uses BFFM2 in an identical manner to EDMS and can provide any level of results including single flights, individual airports, and all 100 airports. As previously indicated, the only difference from EDMS is that runway emissions after touchdown were not included as part of the taxi-in emissions as they are in EDMS. It was deemed unnecessary to include these runway emissions as they would have remained unchanged as taxi power settings were reduced below 7%. The arrival runway roll is modeled at much higher power settings and therefore, are not applicable to this taxi emissions study.

Although EDMS could have been used for these fleet assessments through modifications of fuel flows in the emissions system table, the manual entry of data through the EDMS GUI would have been tedious and hence, resource prohibitive. Batch-processing (if possible) of the EDMS study files was also not considered since it would likely not have provided the level of control required.

For the single airport-level analysis, ATL airport was arbitrarily chosen from among the airports with the highest operations and diverse fleet mix. Total taxi emissions (taxi-in plus taxi-out) are presented in Table 6 for several power settings below 7%.

Table 7: Total Taxi Emissions for ATL Airport

Power Setting (%)	Total Taxi (Taxi-In plus Taxi-Out)				% Difference from 7%			
	FB (Mg)	THC (Mg)	CO (Mg)	NOx (Mg)	FB (%)	THC (%)	CO (%)	NOx (%)
7	201,000	801	5,140	793	---	---	---	---
6	173,000	1,120	6,290	603	-14.3	40.0	22.3	-24.0
5	144,000	1,940	8,160	436	-28.6	142	58.7	-45.0
4	115,000	8,400	11,700	293	-42.9	948	127	-63.0
3	86,300	246,000	19,800	176	-57.1	3.06E+04	285	-77.8
2	57,500	4.80E+07	47,700	85.9	-71.4	5.99E+06	827	-89.2

Note: % differences may not be reproducible due to rounding.

The results in Table 7 show similar percent increases in THC and CO emissions for the different power settings as those presented for the single aircraft and engine combination in Table 4. These airport-level results also indicate that below the 5% power setting, THC and CO emissions increase dramatically. The fuel burn percent differences are identical to the single aircraft and engine results since the fuel flow reduction factors (e.g., 5/7) were applied to all operations.

Similar results are also seen when the individual airport results are summed as indicated in Table 8 for the top 100 US airports.

Table 8: Total Taxi Emissions for the Top 100 US Airports

Power Setting (%)	Total Taxi (Taxi-In plus Taxi-Out)				% Difference from 7%			
	FB (Mg)	THC (Mg)	CO (Mg)	NOx (Mg)	FB (%)	THC (%)	CO (%)	NOx (%)
7	2,960	15.3	86.7	11.3	---	---	---	---
6	2,540	21.5	106	8.55	-14.3	40.4	22.5	-24.2
5	2,110	35.6	137	6.16	-28.6	132	58.0	-45.4
4	1,690	120	192	4.13	-42.9	679	121	-63.4
3	1,270	2,800	308	2.46	-57.1	1.81E+04	256	-78.2
2	845	5.18E+05	660	1.19	-71.4	3.38E+06	662	-89.4

Note: % differences may not be reproducible due to rounding.

At the 5% power setting, Table 8 indicates that the major US airports would experience increases in THC and CO emissions by 132% and 58%, respectively. And again, these emissions increase dramatically when the power setting is lowered beyond 5%. As with the results in Table 4 and 7, the high emission values for THC and CO in Table 8 at the 2% and 3% power settings indicate they may be incorrect. Although fuel burn percent differences are identical, the emissions percent differences are not the same due to some nonlinear modeling effects for THC and CO (and to a lesser extent, NOx) as well as the fleet mix differences between the different analysis levels (e.g., single airport versus 100 airports).

Although the purpose of these assessments was mainly to determine percent differences, the overall magnitude of the fuel burn for the 7% power setting compares favorably with the FAA's more detailed inventory model, the System for assessing Aviation's Global Emissions (SAGE)¹⁰. Table 8 shows total taxi fuel burn of 2,960 Mg while the published SAGE 2002 US inventories (domestic plus international flights) show 3,539 Mg of fuel burned on the ground which results in a difference of about 16%¹¹. This difference is at least partly explainable since SAGE incorporates unscheduled flights from the Enhanced Traffic Management System (ETMS)¹². This comparison suggests that the 100 airports appear to be a good representation of total US operations.

The ramifications of improved taxi emissions modeling is that it could affect decisions regarding airport regulations. For example, if an airport improvement project results in increased aircraft operations, the higher emissions for THC and hence, volatile organic compounds (VOCs), along with CO could cause either a delay or stop to the project. These higher emissions could potentially exceed the de minimis thresholds when previously they may have been below those levels. This is especially important since unlike NOx, the taxi/idle modes account for the vast majority of THC and CO emissions in an LTO cycle.

Similarly, higher emissions could also result in higher modeled concentrations which would need to be carefully compared against the National Ambient Air Quality Standards (NAAQS). With all of the uncertainties surrounding atmospheric dispersion and chemical transformation models, it is important to improve the emissions input data to such models. These models are only as accurate as the emissions data will allow. Therefore, improved estimates of taxi emissions could lead to better health impact assessments.

Conclusions

This study provides a first-order assessment of the effects of modeling more accurate aircraft taxi emissions. The findings from the study show that results at different levels were overall similar with the differences attributed to nonlinear effects in the modeling THC and CO as well as fleet mix differences. Unlike NO_x which decreases as the power setting (fuel flow) is decreased, THC and CO increases exponentially. At the 5% power setting, the major US airports are expected to experience increases in THC and CO emissions by 132% and 58%, respectively. As emissions increase dramatically below this power setting, care must be taken so that erroneously high emissions are not predicted.

The 5% power setting promulgated in this study is an approximation based on the few published indications of the actual, average power used during taxiing operations. Future studies could potentially assess large sets of data from flight data recorders (FDR) to more accurately determine taxi power settings. Ultimately, the improvements in taxi emissions could lead to better airport air quality assessments under regulatory and/or scientific projects.

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