Project 046 Surface Analysis to Support AEDT Aircraft Performance Model (APM) Development

Massachusetts Institute of Technology and Massachusetts Institute of Technology Lincoln Laboratory

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- P.I.(s): Hamsa Balakrishnan
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- Period of Performance: Sep. 1, 2017 to Aug. 31, 2018
- Task(s):

  Phase 1

  1.1. Assess AEDT aircraft surface performance modeling needs
  1.2. Develop enhanced aircraft surface performance models
  1.3. Validate enhanced aircraft surface performance models
  1.4. Recommend AEDT APM enhancements

  Phase 2

  2.1. Extend analysis to broader range of aircraft types that serve US domestic operations
  2.2. Extend analysis on airport-specific differences that significantly impact surface fuel burn to more US airports
  2.3. Identify AEDT surface APM enhancements to support emissions and noise inventories
  2.4. Recommend AEDT APM enhancements & Coordination with AEDT APM Developers

Project Funding Level

$75,000 FAA funding and $75,000 matching funds. Source of match is approximately $75,000 all from MIT.

Investigation Team

Prof. Hamsa Balakrishnan, Co-Principal Investigator (MIT)
Dr. Tom Reynolds, Co-Principal Investigator (Lincoln Laboratory, via separate contract)
Yashovardhan Chati (Graduate student)
Sandeep Badrinath (Graduate student)

Project Overview

The current taxi phase models in the Aviation Environmental Design Tool (AEDT) make a number of simplifying assumptions that reduce the accuracy of their fuel burn and emissions predictions. First, AEDT's current model assumes a constant engine specific thrust level (and resulting fuel flow rate) during taxi, determined from engine manufacturer certification data [1]. However, this assumption can be significantly different than actual characteristics during operational conditions for a given aircraft because of factors such as the age of the engine (as the engine gets older the amount of fuel it burns changes), as well as pilot technique (chosen taxi thrust level or "riding the brakes" instead of throttling down the engines when coming to a stop). Second, default taxi times are often assumed to be consistent with the standard certification Landing and Take-Off (LTO) cycle which assumes 26 minutes of taxi time on the airport surface, typically broken into 19 min taxi-out and 7 min taxi-in. Clearly different airports may have very different taxi times depending on topology, configuration, congestion levels, etc., that can lead to a large range of different taxi times. Using empirical data to determine realistic taxi time distributions can be effective, but these distributions need to be updated regularly to capture evolving airport conditions. Finally, the fuel burn contribution in the non-movement area from the gate time, pushback and engine start events (including engine and auxiliary power unit (APU) contributions) are typically neglected but can be quite significant. This project addresses these three issues by leveraging empirical data to build statistical and predictive models of fuel flow for a given airport and aircraft type. These analyses are designed to capture "first order" enhancements to provide recommendations for future development of tools such as AEDT.

Task Progress and Plans

Objectives

The objective of this research project is to identify and evaluate "first order" methods for improving taxi performance modeling in AEDT in order to better reflect actual operations. This objective will be met through analyses using surface surveillance (ASDE-X) and ASPM taxi time datasets, in combination with a statistical analysis of Flight Data Recorder (FDR) archives and other operational fuel burn data. Subsequent research phases may address potential higher order enhancement areas. Phase 1 of the work identified key gaps in the AEDT aircraft performance models and enhancements were developed in the areas of improved baseline fuel flow modeling, updated airport-specific taxi times and addition of pre-taxi fuel burn components. Phase 2 activities are refining and expanding and these areas. Tasks 2A.1-4 listed below correspond to the Tasks which were carried out between September 2017-Aug 2018 which are the main focus of this report. Subsequent Tasks 2B.1-4 correspond to the on-going activities in these task areas, which are discussed in the following section.

Research Approach

Task 2A.1 -Extend Phase 1 analysis to broader range of aircraft types: Phase 1 of ASCENT 46 (Jul 2016-Aug 2017) extended this approach by synthesizing such statistical models with surface traffic models obtained through the analysis of ASDE-X data [9]. A particular focus of this phase was the analyses needed to identify and extract first-order vs. higher-order effects on the fuel burn. To do so we considered fuel consumed in the non-movement area (including gate, push-back and engine start events that have previously not been studied in detail, as well as accounting for Auxiliary Power Unit (APU) fuel during these events), as well as the movement areas, including the relative effects of acceleration events on fuel burn, when compared to the baseline fuel flow rates.

Through a synthesis of prior work in ACRP 02-27 [10], ACRP 02-45 [11], AEDT documentation, stakeholder input, and data analysis, the following gaps were identified: (1) Need for improving/refreshing taxi times at different airports; (2) Absence of a surface-specific regression model, even for modeling the baseline fuel burn index; (3) No evaluation of the magnitude of non-movement area, engine-startup and/or APU fuel burn impacts; and (4) No consideration of acceleration events, and the resulting increase in the fuel flow rate. In addition, it was noted that the existing surface APM models were deterministic in nature and did not evaluate the uncertainty or variability associated with real operations.

Figure 1 shows a typical fuel flow rate profile (post-pushback and engine start) during taxi-out. It can be seen that the fuel flow rate profile (red curve) can be divided into two distinct regions: a baseline region and a fuel flow spike region. The baseline region is characterized by an almost constant (low variation) fuel flow rate having a low value. The fuel flow spike region is characterized by spikes in the fuel flow rate with values greater than the baseline fuel flow rate. Therefore, these two fuel flow rate regions need to be modeled separately.

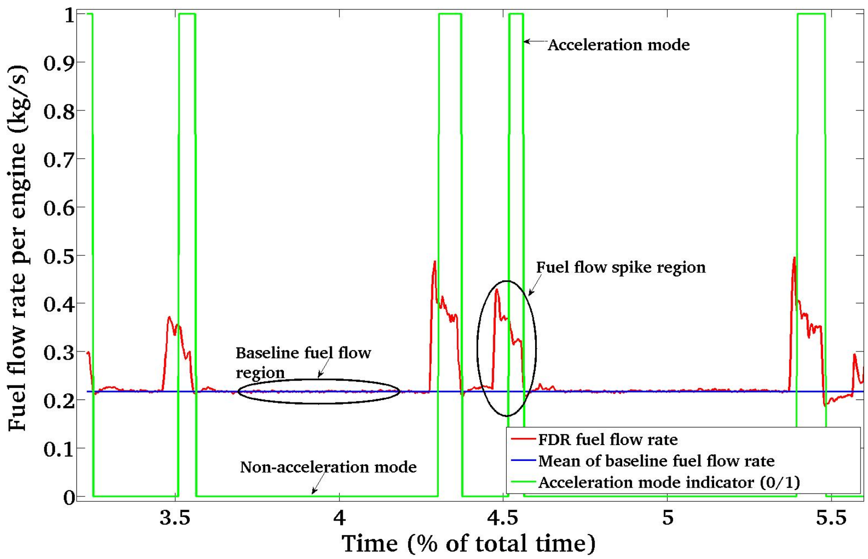

Figure 1. Typical fuel flow rate profile in taxi-out.

Phase 1 also analyzed different characteristics of the baseline fuel flow region for two example aircraft types: the A330-343 and the B777-300ER extracted from operational FDRs data and found that, on an average, more than 90% of the taxi-out fuel consumption occurs during the baseline fuel flow region. Therefore, in the current work, only the baseline fuel flow region is modeled and the fuel flow spikes are neglected. Figure 1 also shows a mean baseline fuel flow rate (in blue) obtained by averaging the baseline fuel flow rates for a particular taxi-out operation.

The values of aircraft acceleration during taxi are generally not explicitly recorded in the trajectory data. Hence, the raw trajectory data are smoothed in order to estimate the variables of interest (such as acceleration mode, shown in green in Figure 1). Finally, the mean baseline fuel flow rate per engine in taxi-out (blue curve in Figure 1) was regressed against the mean values of the selected predictor variables. An Ordinary Least Squares (OLS) regression approach is found to be sufficient to develop this simplistic model (which is still based on the same functional form as the current AEDT model). Table 2 shows the OLS-derived equations for modeling the fuel flow rate in taxi-out for the six aircraft types.

Table 1. OLS regression equations to model fuel flow rate per engine during taxi-out, along with the number of observations (flights) in the training dataset.

A/C Type	Engine Type	# Training Obs.	OLS Model Equation
A320-214	2 × CFMI CFM56-5B4/2	103	$0.812 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty^{-0.123} \cdot \theta_\infty^{-0.483}$
A321-111	2 × CFMI CFM56-5B1/2	46	$0.796 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty \cdot \theta_\infty^{0.209}$
A330-343	2 × RR Trent 772B-60	117	$0.779 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty \cdot \theta_\infty^{0.350}$
A340-313	4 × CFMI CFM-56 5C4/P	37	$1.019 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty^{-6.690} \cdot \theta_\infty^{0.597}$
B777-300ER	2 × GE GE90-115BL	81	$0.753 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty \cdot \theta_\infty^{0.717}$
C Series 100 (RJ)	2 × PW PW1542G	95	$0.966 \cdot \dot{m}_{f_{ICAO}} \cdot \delta_\infty \cdot \theta_\infty^{0.186}$

We also compare the predictions from such baseline fuel flow modeling with the estimates provided by AEDT, which uses the ICAO fuel burn indices in conjunction with the Boeing Fuel Flow Correction. Since the pressure and temperature ratios are approximately one for taxi operations, the multiplicative factor in Table 2 is the key differentiator from AEDT, which uses a constant value of 1.1 for all aircraft types. The results are shown in Table 3, and suggest that significant benefits may be achieved through such a data-driven methodology.

Table 2. Performance of the OLS-based baseline fuel flow rate models and the AEDT model to predict fuel flow rates on unseen test data during taxi-out. The number of flights in the test data are also shown.

A/C Type	# Test Observations from FDR	Mean error (%)		Mean absolute error (%)	
		OLS Model	AEDT	OLS Model	AEDT
A320-214	34	1.0	36.3	13.3	39.4
A321-111	14	3.8	47.1	14.9	50.1
A330-343	37	-3.0	36.4	5.8	39.1
A340-313	12	-0.7	7.8	9.1	12.5
B777-300ER	25	-2.2	42.3	3.1	43.1
C Series100 (RJ)	30	0.1	17.7	5.5	19.3

Task 2A.2- Extend Phase 1 findings on airport-specific differences that significantly impact surface fuel burn to more US airports: Airport-specific taxi out times are available in AEDT but have been found to be outdated. For this part of the study, taxi times were collected from the FAA's Aviation System Performance Metrics (ASPM). This dataset contains flight-specific taxi out times, available to the nearest minute. ASPM data from flights across 25 major U.S. airports was aggregated for dates between October 2016 and September 2017, to provide a more recent model of the distribution of taxi out times at a given airport. This analysis could be extended to other U.S. or international airports as needed.

Figure 2 below shows the updated taxi out time distributions for three sample airports: New York LaGuardia (LGA), Charlotte Douglas (CLT) and Washington Reagan (DCA). As expected, the times vary significantly within and between airports. For this particular set of airports, LGA is seen to have the largest peak and broadest spread in taxi-out time; this is not surprising given the high congestion levels at LGA. The peak in the total taxi-out time distributions for LGA, CLT, and DCA are 18, 15, and 13 minutes, respectively. Compared to the standard 19 minutes of taxi-out time assumed from the LTO cycle (shown by the dashed magenta line in Figure 2), these correspond to errors of 5.3%, 26.7%, and 46.2% of the typical taxi out times for these particular airports. This is indicative of the impact the LTO 19-minute taxi time has on the accuracy of the calculated fuel burn based on the simplified taxi time.

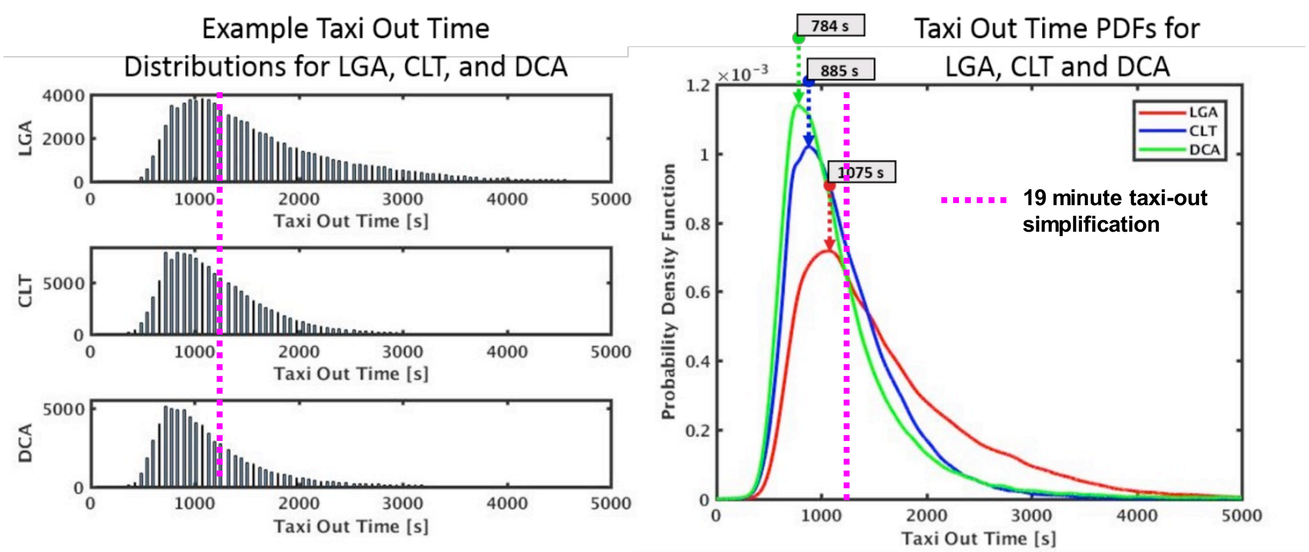

Figure 2. Example ASPM taxi-out time distributions for LGA, CLT and DCA airports

A similar comparison was conducted across the top 25 U.S. airports. Sometimes it is beneficial to reduce the number of taxi time distributions to a few clusters which capture the spectrum of differences seen in the taxi-out distributions for all airports. To this end, each of the airport distributions were fitted to a cumulative distribution function (CDF) and the resulting curves were clustered. Since the CDF is a cumulative function, differences in the shape of the distributions will accumulate, and therefore better results are achieved by clustering on the CDFs instead of the probability density functions (PDFs). Clustering the data was accomplished through implementing a Mean Shift algorithm but other techniques could also be applied. The resulting number of clusters can be modified by changing the bandwidth parameter for the Mean Shift algorithm. There is a trade-off between the number of clusters and the error between each of the actual distributions and the corresponding cluster approximations. Fewer clusters allows for a simpler categorization of the different distributions, but results in higher error. A larger number of clusters will decrease this error, but at the cost of defeating the purpose of clustering. To determine the optimal number of clusters for the taxi-out distributions at these airports, the relationship between the error and the number of clusters was investigated. It was seen that the error continued to decrease steadily until around 6 clusters, at which point adding additional clusters had a reduced incremental impact on the total error, with zero error when there were as many clusters as airports. The box plot in Figure 3 allows a side-by-side comparison of all the airport taxi-out distributions across the 25 airports studied, as well as the differences between the six resulting clusters. The 19-minute taxi-out simplification is provided as a reference, along with the error between this assumption and median of each of the distributions. It is seen that for some clusters (such as cluster 1), the 19-minute approximation is relatively accurate. However, for other clusters (such as cluster 5), such an estimate would introduce significant error compared to the actual taxi-out time at the airports in this group. It is also interesting to note which airports are paired together. For example, JFK and LGA have been identified as airports with similar taxi-out characteristics. Both distributions have a higher spread and higher mean compared to the other airports. By contrast, Chicago Midway (MDW) is dissimilar enough from any of the other airports that it has been placed into a cluster by itself.

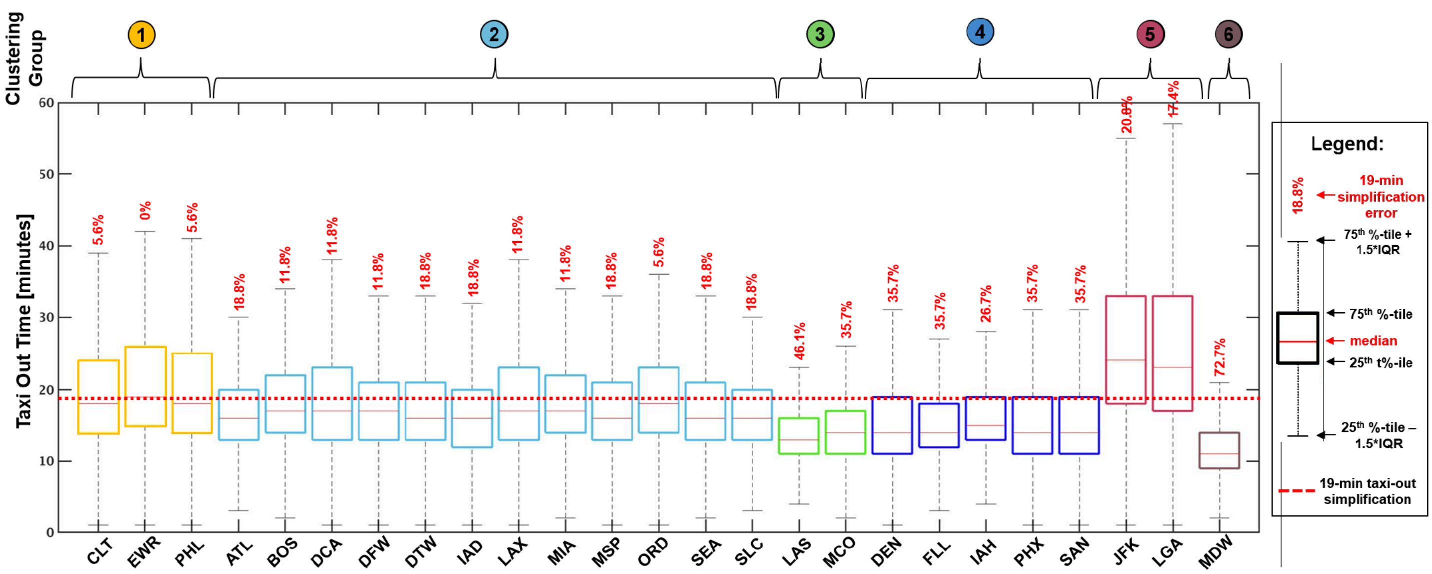

Figure 3. Boxplot of airport distributions by clustering group (outliers removed).

The 19-minute default taxi-out time assumption is intended to represent average airport taxi time. This chart shows that the errors in this estimate vary from 0% to 72.7% for these particular airports, which is one reason why users typically do not use the 19-minute default taxi time. By using recent historical data at an airport, the error resulting from predicting the taxi-out time for a given flight can be decreased drastically. In addition, if it is better to have fewer groups of airports, much of the error can still be reduced by clustering airport taxi-out data and using the respective cluster centroid as an estimation for the flight's taxi-out time.

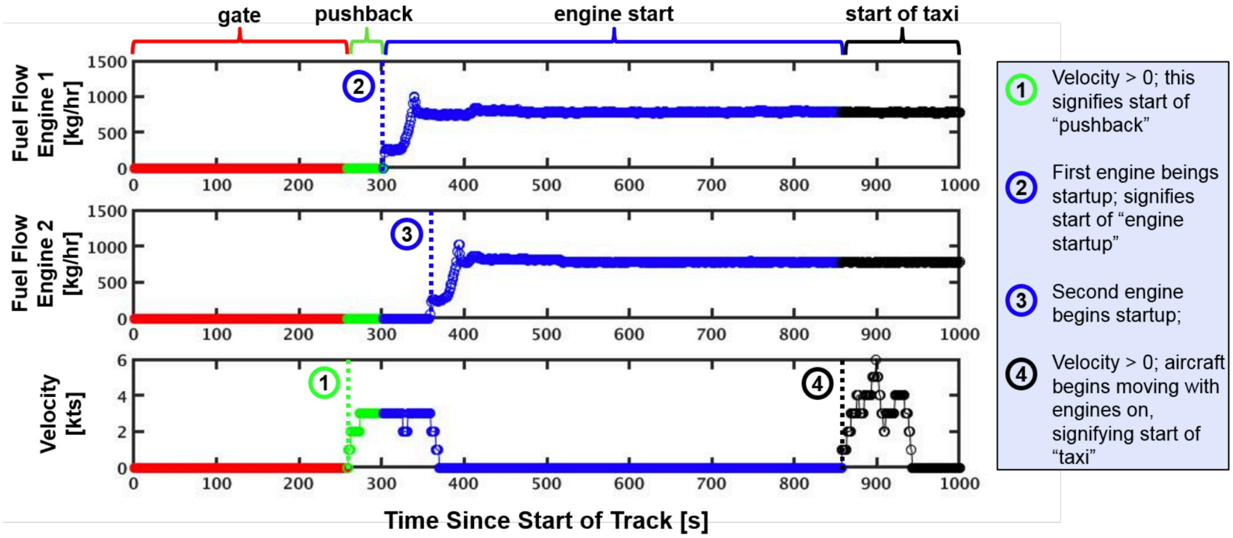

Figure 4. Example FDR data for a single flight gate, engine and push-back events.

Adding Gate, Push-back & Engine Start Fuel Estimates: In order to establish a more accurate model of the fuel burn at a given airport, the fuel consumed during engine startup up, as well as the APU contribution at the gate, pushback, and engine startup is also investigated in this study. Differences in fuel burn for these phases across different airports were found to be negligible, however the fuel burn distributions were found to vary significantly between different aircraft types. For this analysis, data from FDR was available for a European carrier for a selection of aircraft types. This contains a record over time of information specific to a flight, including fuel burn and velocity.

Figure 4 above shows the raw FDR data for a sample flight. For this part of the analysis, the flight was broken up into multiple segments, as the gate, pushback, and engine start have different APU and engine fuel burn settings. APU fuel burn rates were obtained from the ACRP 02-25 guidance document [3], which groups aircraft into categories (Narrow Body, Wide Body, Jumbo Wide Body, Regional Jet, and Turbo Prop) and gives the APU settings for the "no load" (gate), "environmental control systems" (pushback), and "main engine start" conditions for each aircraft category. The APU is turned on while still at the gate in the "no load" condition, after the aircraft has been disconnected from the gate's electricity. Through discussion with an experienced commercial pilot, it was determined that the APU is first turned on typically between 10-15 minutes before pushing back from the gate at large U.S. airports. Therefore, for all aircraft, the gate time was assumed to be 12.5 minutes, although different assumptions may be appropriate at other airports, for example where off-gate stands are more common. Pushback was defined from the point at which the aircraft began to move back from the gate, until the point at which one of the engines began burning fuel. As can be seen in Figure 4, most aircraft begin starting the first engine while still in the process of pushback by the tug from the gate, before halting and completing engine startup with the remaining engines. Engine startup was defined from the end of pushback to when the aircraft begins to move for taxi after all engines have started up and post-engine checklists are complete.

Much of the work incorporated pre-processing the data before performing the statistical analysis, as many of the flights had corrupted data, such as non-zero fuel or velocity at the beginning of the track. Once tracks had been corrected for these issues, the fuel burn totals for the gate/pushback/engine start processes were aggregated over all the flights of a given aircraft type available in the FDR data as a statistical approach to building the fuel burn histograms from historical data. The resulting fuel burn distributions for the types studied are shown in Figure 5 (left). The relationship between fuel burn and aircraft size was then investigated as a means to predict the fuel burn of the flights not within the FDR dataset. The maximum takeoff weight was used for each data type, pulled from the BADA 3.6 dataset. The total fuel burned during gate/pushback/engine start was seen to be linearly related to the weight of the aircraft type, and this correlation was used to then predict the approximate fuel burn for aircraft types not available in the FDR data set. Estimates for some example types using the observed correlation are presented as dashed lines in Figure 5 (left), and also on Figure 5 (right).

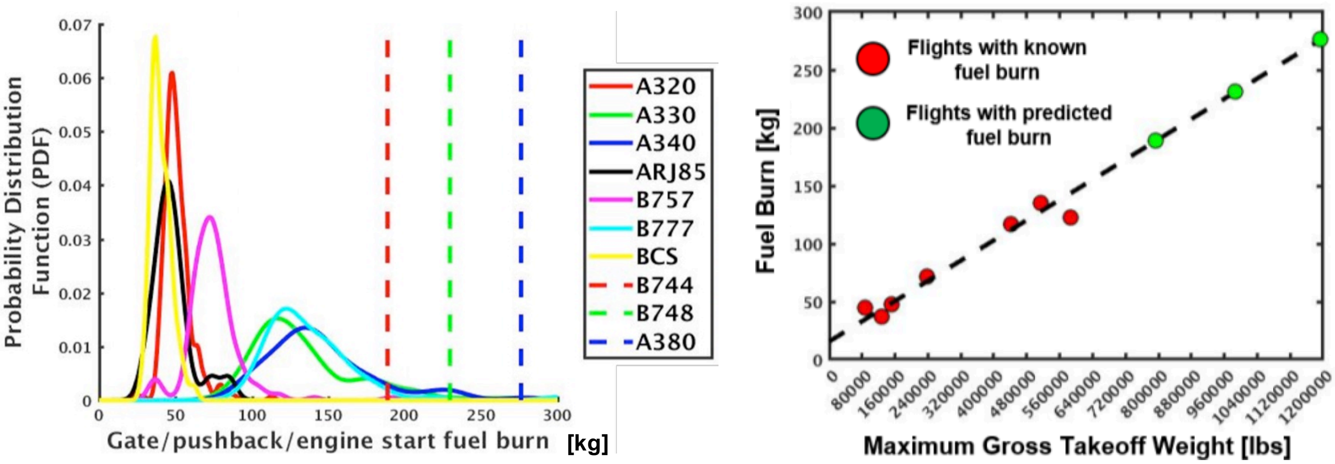

Figure 5. PDF curves for gate, pushback, and engine start fuel burn by aircraft type.

The total fuel burn between the gate to the point at which an aircraft begins to taxi is seen to vary significantly between aircraft types, and can be a significant fraction of total surface fuel burn. Figure 6 shows the percentage of pre-taxi fuel burn relative to total surface fuel burn from the types analyzed from the FDR data. For narrow body aircraft, this percentage of total fuel burn is seen to be higher than the larger body aircraft, as seen in the left plot of Figure 6. The right plot of the figure shows that the typical contribution of the pre-taxi fuel in comparison to the total fuel burned on the aircraft surface is between 10-40% on average, reinforcing the need to carefully consider this component of surface fuel burn.

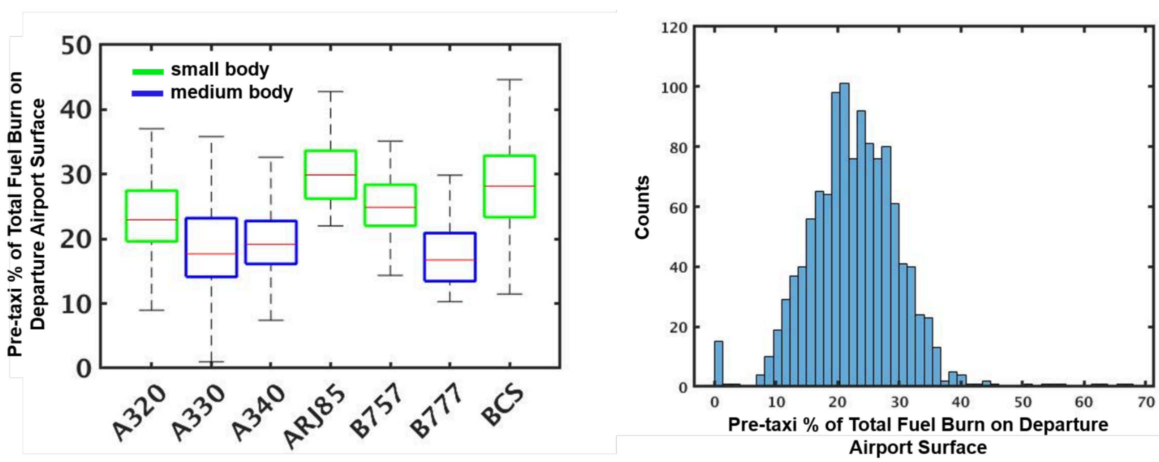

Figure 6. Pre-taxi fuel burn as a percentage of total fuel burned during departure from gate to wheels-off, per aircraft type (left) and aggregate distribution (right).

Task 2A.3- Identify AEDT surface APM enhancements to support emissions and noise inventories

The work to date has focused on the enhancement of AEDT surface APM to support fuel burn models. We have begun to conduct a preliminary study (based on prior literature) to identify potential first-order effects in the modeling of emissions and noise. Our literature survey for emissions modeling has considered literature on NOx (e.g., 'P3-T3' methods), HC, CO, and soot emissions. References [4]-[15] have been the primary sources reviewed for emissions modeling. In ongoing work, we are undertaking a similar exercise on noise modeling, beginning with ACRP 02-27 [16, 17].

Task 2A.4- Recommend AEDT APM enhancements & Coordination with AEDT APM Developers
Based on the modeling enhancements developed from this process, specific targeted recommendations for AEDT APM improvements for the surface domain will be made. Coordination will be required throughout with the primary AEDT APM developers—i.e., Volpe and ATAC—to ensure that the research is practical and will directly inform enhancements to the APM.

Milestone(s)

Phase 2A (Tasks 1-4) were carried out between September 2017-Aug 2018. Phase 2B (Tasks 1-4) are now ongoing. These tasks include:

Task 2B.1: Refine analyses in "1st order" improvement areas
Refine "1st order" AEDT surface fuel burn improvements initiated in prior phases in the areas of: (1) **Pre-taxi operations** (gate and engine start operations), e.g., extending fuel estimates to a wider range of aircraft types, more refined modeling of APU fuel burn rates and usage times to reflect differences between airports, airlines, etc. (2) **Baseline fuel flow rates**, e.g., extending estimates and correlation techniques to a wider range of aircraft types, operating conditions, etc. In particular, develop techniques that can leverage the A4A data, accounting for identified data-quality issues on the surface fuel burn components. (3) **Airport-specific taxi times**, e.g., extending to a wider set of airports (potentially the Core 30) and operating conditions, such as taxi time distributions conditioned on factors such as weather (VMC, IMC), airport congestion level, airport runway configuration, etc.

Task 2B.2: Extend surface fuel burn analyses to align with planned additional AEDT development aligned with different user classes
Based on engagement with AEDT developers in the prior phase of the work, investigate the functionality needed by different user classes, ranging from **basic users** wanting the ability to select "pre-canned" options representative of typical operating conditions, to **advanced users** who may want complete control over all aspects of aircraft and airport dynamics. In addition, the needs may vary depending on whether a user is interested in modeling inventories (i.e., the aggregate) or dispersions at an airport.

Task 2B.3: Undertake initial studies to extend AEDT capabilities to model surface noise and emissions impacts
Appropriate literature sources and the modeling enhancements initiated in the prior phase will be leveraged and extended to explore AEDT surface noise and emissions modeling enhancements. AEDT currently calculates surface emissions as the product of the taxi time, fuel flow rate, and emissions index. The refinements of taxi times and fuel flow rates, as conducted in Task 1, will therefore improve the emissions models within AEDT. The locations and times at which emissions occur are a necessary input for dispersion modeling in AEDT. In other words, 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), have a direct impact on the modeled pollutant concentrations. For surface noise impacts, we are using the findings of ACRP 02-27 as a starting point to identify the aircraft performance modeling needs.

Task 2B.4: Continued coordination with AEDT developers to transition key findings into development plan. Conduct regular analysis status and results review with FAA sponsors and AEDT developers. Based on relevant modeling enhancements identified in the tasks above, discuss specific targeted recommendations for AEDT improvements with developers. Coordinate to align research plans with AEDT development schedule as required.

Publications

E. Clemons, T.G. Reynolds, S. Badrinath, Y. Chati and H. Balakrishnan. Enhancing Aircraft Fuel Burn Modeling on the Airport Surface. AIAA Aviation 2018 Conference, Atlanta, June 2018.

Outreach Efforts

Presentation at the AIAA AVIATION 2018 Conference.

Awards

None

Student Involvement

Graduate students have been involved in all aspects of this research.

Plans for Next Period
Completion of Tasks 2B.1-4.

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