# Project 046 Surface Analysis to Support AEDT APM Development

## Massachusetts Institute of Technology and Massachusetts Institute of Technology Lincoln Laboratory

## Project Lead Investigator

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- P.I.(s): Hamsa Balakrishnan
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- 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. Firstly, 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). Secondly, 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. which 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.

### Research Approach

**Task 1.1: Assess AEDT aircraft surface performance modeling needs:** This task included soliciting input from stakeholders (including FAA AEE sponsors, AEDT developers, users, etc.) and related research (e.g., ACRP studies 02-45 [2] and 02-27 [3]) on known gaps and associated needs in current aircraft surface modeling capabilities. We conducted a discussion with AEDT developers and users (at the FAA and Volpe) to discuss gaps identified during the literature review and from ACRP studies 02-45 and 02-27. We also familiarized ourselves with the AEDT APM's current capabilities. In addition, prior research into high fidelity aircraft surface modeling was, and will continue to be, assessed and leveraged as appropriate. The three specific need areas identified were (1) enhanced models of fuel flow rates during taxi; (2) refined airport taxi time estimates; and (3) improved estimates of gate, pushback and engine start fuel burn.

**Task 1.2: Develop enhanced aircraft surface performance models:** This task involves developing refined models that account for the three needs identified in Task 1.1.

**Enhancing fuel flow modeling:** 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.

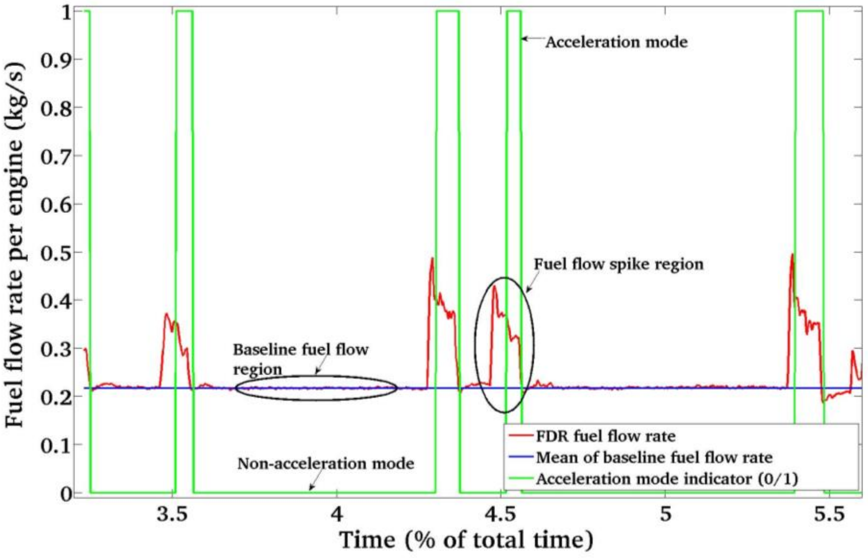

**Figure 1.** Typical fuel flow rate profile in taxi-out.

Table 1 shows 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. It can be seen 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.

**Table 1.** Characteristics of the baseline fuel flow region. The table shows the mean and the range of time spent and fuel mass consumed in the baseline fuel flow region, as a percentage of the total time and fuel burn in taxi-out.

| **Aircraft type** | **Time (%)** | | **Fuel burn (%)** | |
|---|---|---|---|---|
| | **Mean** | **Range** | **Mean** | **Range** |
| A330-343 | 94.1 | 76.1 – 100.0 | 91.0 | 68.0 – 100.0 |
| B777-300ER | 93.0 | 77.4 – 100.0 | 91.0 | 73.0 – 100.0 |

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) is 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 two example aircraft types, the A330-343 and the B777-300ER. The training sets used to determine these equations comprised of 118 A330s and 83 B777s.

**Table 2.** OLS regression equations to model fuel flow rate per engine during taxi-out.

| **A/C Type** | **Baseline-1 Model Equation** |
|---|---|
| A330-343 | $\dot{m}_{f_{\text{taxi}}} = 0.779\dot{m}_{f_{\text{ICAO,taxi}}}\delta_\infty\theta_\infty^{0.350} \approx 0.779\dot{m}_{f_{\text{ICAO,taxi}}}$ |
| B777-300ER | $\dot{m}_{f_{\text{taxi}}} = 0.753\dot{m}_{f_{\text{ICAO,taxi}}}\delta_\infty\theta_\infty^{0.717} \approx 0.753\dot{m}_{f_{\text{ICAO,taxi}}}$ |

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. The model evaluation is conducted using an independent test set comprising of the entire taxi-out trajectory (i.e., the time elapsed between pushback and takeoff) of 37 A330s and 25 B777s. The results are shown in Table 3, and suggest that significant benefits may be achieved through such a data-driven methodology.

**Table 3.** 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.

| A/C Type | Mean error (%) | | Mean absolute error (%) | |
|---|---|---|---|---|
| | OLS Model | AEDT | OLS Model | AEDT |
| A330-343 | -3.3 | 36 | 6.3 | 39.4 |
| B777-300ER | -1.8 | 42.6 | 2.7 | 43.2 |

**Enhancing taxi time estimates:** 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 US 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 US 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 longest peak and most varied 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.

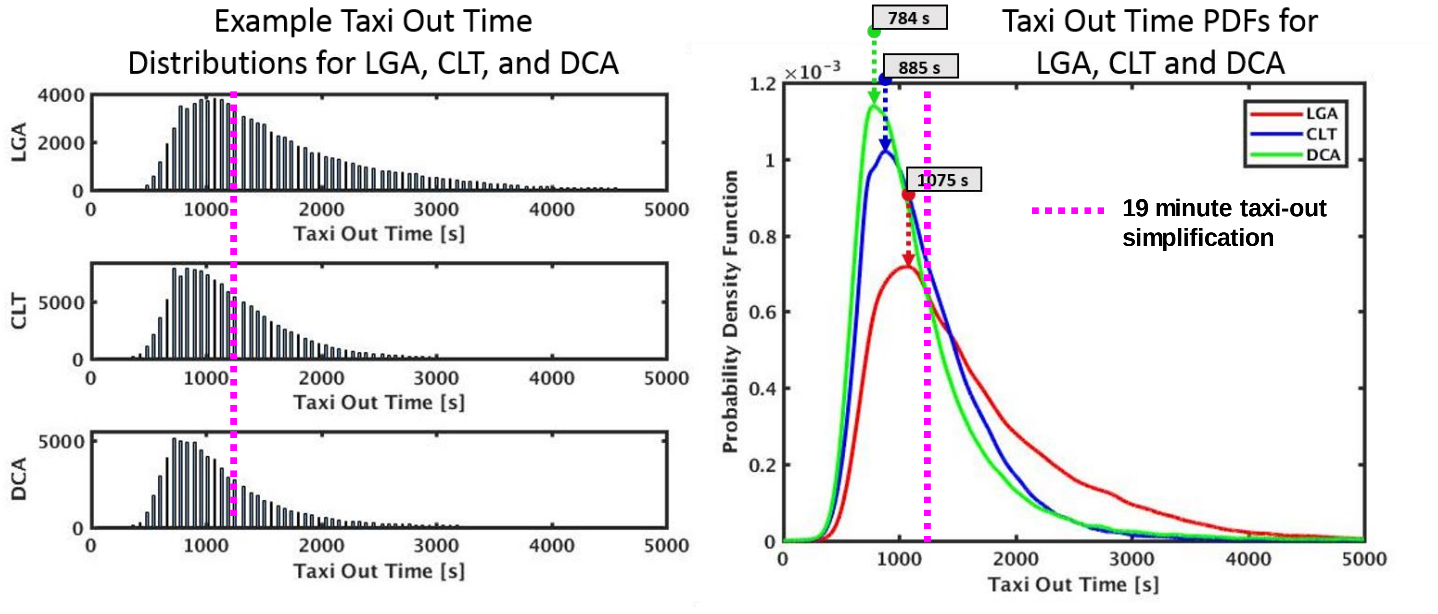

**Figure 2.** Example ASPM taxi-out time distributions for LGA, CLT and DCA airports

**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.

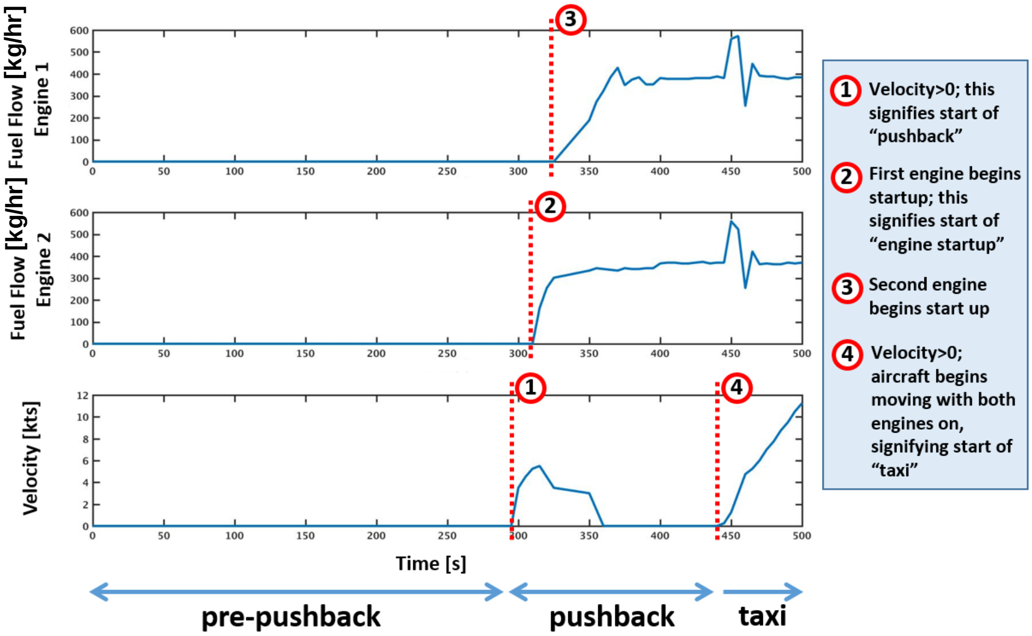

**Figure 3.** Example FDR data for a single flight gate, engine and push-back events

Figure 3 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 US 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 3, 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 4.

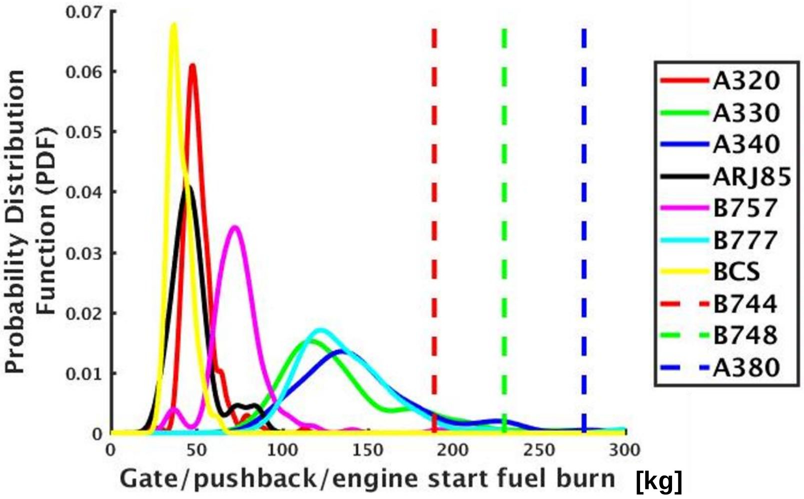

**Figure 4.** PDF curves for gate, pushback, and engine start fuel burn by aircraft type

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 4.

**Task 1.3: Validate enhanced aircraft surface performance models:** A subset of the ASDE-X and FDR data archives were held back from the enhanced model development activity in the previous step so it can be used as independent validation data. For example, fuel burn profiles (and baseline fuel flow rates) were estimated using the enhanced models developed from the previous step and compared to the estimates direct from FDR data. Table 3 showed the model performance on the independent training sets. This analysis also demonstrated that the incorporation of fuel flow spikes corresponding to acceleration events during taxi contribute to a second-order impact on the fuel burn.

**Task 1.4: Identify and recommend "first order" AEDT APM enhancements:** As mentioned earlier, this phase identified and recommended the incorporation of the three first-order impacts mentioned above, namely, (1) enhancing models of fuel flow rates during taxi; (2) refining airport taxi time estimates; and (3) improving estimates of gate, pushback and engine start fuel burn.

**Task 2.1: Extend Phase 1 analysis to broader range of aircraft types that serve US domestic operations:** The Phase 1 analysis has shown how an aircraft's fuel flow profile can be estimated from the ASDE-X surveillance data, if available. A key finding was that significant improvements would be had by refining the taxi time estimates, as well as by improving the baseline fuel flow rate.

These models to-date were built using fuel flow rate data from a European carrier, including its operations at 6 US airports. However, these US operations correspond only to flights of the Airbus A330/340 and the Boeing 777. In the next phase, we will extend these approaches to analyze the A4A data obtained by the AEE, which includes the total surface fuel consumption for each of nearly 3.3 million domestic US flights between 2012-2015. This data set is also more representative of US operations, with 38% of the flights being flown by the Boeing 737. We therefore propose to use this dataset in Phase 2 to develop and validate baseline fuel burn indices for these different aircraft types. In addition, we hope to consider the typical fleet mixes at various airports to produce a lookup table that would reflect the fuel burn indices. Such a table, in combination with a table of average taxi times under different meteorological conditions, will enable the estimation of taxi fuel burn even in the absence of ASDE-X data. When such ASDE-X data is available, it can be used directly with the revised baseline fuel burn indices to obtain improved estimated of taxi fuel consumption.

**Task 2.2: Extend to more US airports Phase 1 findings on airport-specific differences that significantly impact surface fuel burn:** Phase 1 analysis has shown that there can be significant differences between airports which impact fuel burn prediction methods and hence potential recommendations for AEDT. For example, these differences between airports include surveillance coverage, pushback operations and airport topology. The first phase of analysis has highlighted differences at a small number of airports and for a limited set of gates at those airports. In Task 1, we have described how this analysis can be extended to airports with different aircraft fleet mixes.

Another key finding in Phase 1 was that the gate, push-back and engine start events do have a significant impact on the surface fuel burn. While this analysis was based on a limited number of airports, it suggested that the engine-startup fuel and times, and pushback times, are primarily dependent on aircraft-specific standard operating procedures and not airport-dependent (although APU fuel burn may be more airport dependent given gate procedure differences). This suggests that the existing analysis can be extended to cover a broader range of aircraft types and airports in Phase 2.

Figure 5 gives an initial proposal of tasking to make proposed enhancements. FDR archives and appropriate regressions will be used to establish look-up tables of push-back and engine start fuel burn for different aircraft types. These data can be used together with the fleet mix at any given airport under investigation to get the total push-back and engine start fuel burn. The FDR and ASDE-X data can be used to develop enhanced taxi fuel flow models for the main aircraft types of interest as previously discussed. These can be multiplied by updated taxi-out/in time distributions based on updated ASPM analysis.

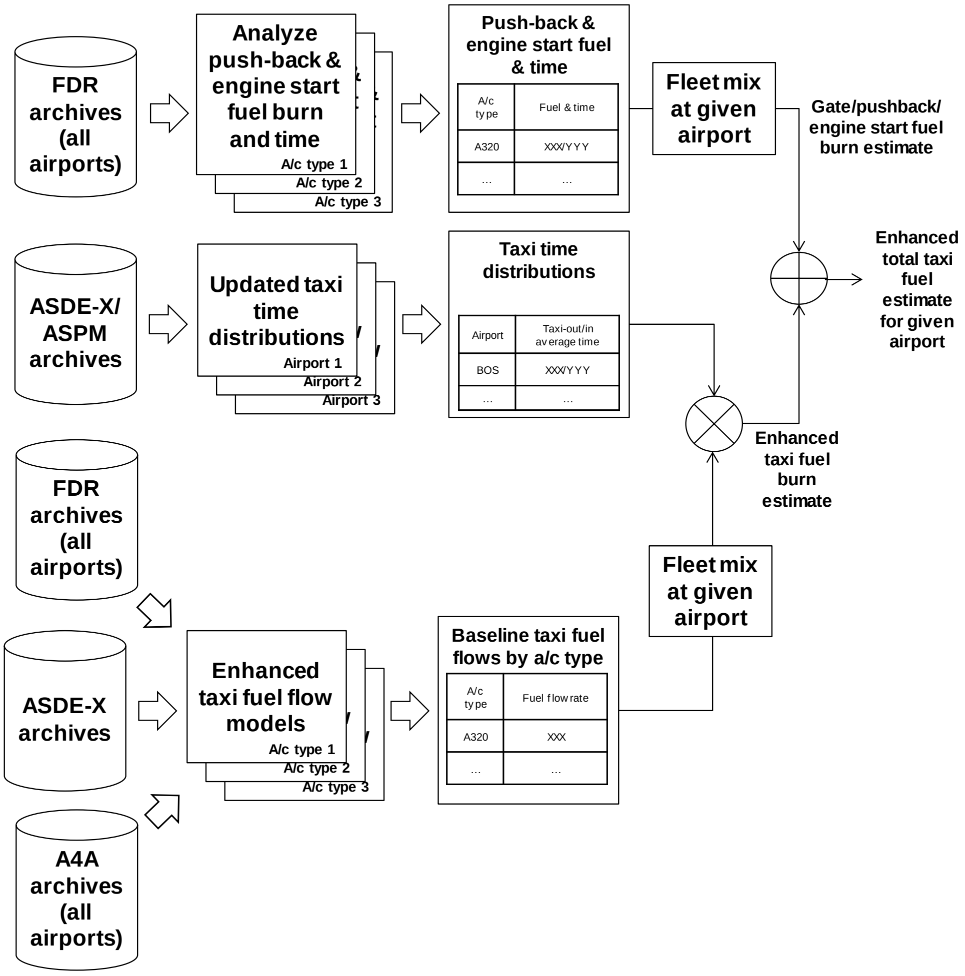

**Figure 5.** Proposed Phase 2 analysis activities.

**Task 2.3: 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 will conduct a preliminary study (based on prior literature) to identify potential first-order effects in the modeling of emissions and noise. For example, the spikes in fuel burn caused by acceleration events (and the modeling of the corresponding variations in thrust) are expected to be of particular interest in this task.

**Task 2.4: 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 1 (Tasks 1.1-1.4) was carried out between July 2016-Aug 2017. Phase 2 (Tasks 2.1-2.4) are now ongoing.

## Publications

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

## Outreach Efforts

Presentations at the FAA-AEE Tools/Analysis Coordination Meetings.

## Awards

Yashovardhan Chati and Hamsa Balakrishnan. Best Paper in Trajectory and Queue Management Track, ATM R&D Seminar 2017, Seattle, WA.

## Student Involvement

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

## Plans for Next Period

Completion of Tasks 2.1-2.4.

## References

[1] International Civil Aviation Organization (ICAO), “ICAO aircraft engine emissions databank.” [Online database], cited 12 February 2014.

[2] ACRP 02-45, “Methodology to Improve EDMS/AEDT Quantification of Aircraft Taxi/Idle Emissions”, Transportation Research Board, 2016.

[3] ACRP 02-25, “Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems”, Transportation Research Board, 2012.