



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

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

### Project Lead Investigator

Hamsa Balakrishnan  
William E. Leonhard (1940) Professor  
Aeronautics and Astronautics  
Massachusetts Institute of Technology  
77 Massachusetts Ave., 33-207  
Cambridge, MA 02139  
617-253-6101  
hamsa@mit.edu

### University Participants

#### Massachusetts Institute of Technology (MIT) and MIT Lincoln Laboratory

- PI: Hamsa Balakrishnan
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 021, 035, 044, 047, 063, and 068
- Period of Performance: July 7, 2016 to August 10, 2021
- Tasks:
  1. Undertake more detailed studies to extend Aviation Environmental Design Tool (AEDT) capabilities to model surface noise and emissions impacts.
  2. Identify representative application scenarios and estimate the impact of improved surface movement modeling capability.
  3. Develop implementation plan to transition appropriate surface modeling enhancements into the operational AEDT product.

### Project Funding Level

FAA provided \$625,000 in funding and \$625,000 matching funds are from MIT.

### Investigation Team

- Prof. Hamsa Balakrishnan, co-PI (MIT)
- Dr. Tom Reynolds, co-PI (MIT Lincoln Laboratory)
- Sandeep Badrinath (graduate student)
- Emily Joback (MIT Lincoln Laboratory staff)

### Project Overview

The objective of this research project is to identify and evaluate methods for improving taxi performance modeling in the Aviation Environmental Design Tool (AEDT) in order to better reflect actual operations. This objective is being met through the analysis of relevant data sources, including surface surveillance (Airport Surface Detection Equipment, ASDE-X), Aviation System Performance Metrics (ASPM) taxi time, Flight Data Recorder (FDR), and air quality monitor datasets. Prior phases of the ASCENT Project 46 have identified first order enhancements to the AEDT Aircraft Performance Model (APM) for surface operations. Specific improvement areas include enhanced baseline taxi fuel flow models; improved taxi times at different airports; and estimation of pre-taxi engine and auxiliary power unit (APU) fuel burn. These enhancements were described in the 2019 annual report. This phase of the work has extended and refined fuel burn modeling in these areas, as well as

undertaking initial studies to explore whether improved surface emissions models can leverage these enhanced fuel models. In particular, the research team has undertaken a detailed assessment of surface operations and associated air quality impacts at Los Angeles International Airport (LAX) due to extensive data availability at that location. The next focus is on expanding the LAX findings to more airports and exploring the impacts of findings on the current implementation of the Delay, Sequence, and Queuing Model (DSQM). We will make recommendations on AEDT improvements from all these analyses.

## Task Progress and Plans

This report summarizes the latest accomplishments in each of the ASCENT46 task areas.

### Task 1 – Undertake More Detailed Studies to Extend AEDT Capabilities to Model Surface Noise and Emissions Impacts

Massachusetts Institute of Technology

In prior phases of the work, relevant literature sources and other modeling approaches were identified and reviewed with respect to surface noise and emissions modeling (e.g., ACRP 02-27, (Martin et al., 1996), ACRP 02-45, (Kyprianidis et al., 2015), and P3-T3 emissions models (Doppelheuer & Lecht, 1998)). Based on these activities, a roadmap has been developed of how researchers will use the enhanced surface fuel flow models to benefit noise and emissions modeling in AEDT. The work on this Task to date has focused on leveraging the enhanced surface fuel burn models to determine taxi emissions on the airport surface for any given airport operating condition (fleet mix, demand profile, etc.) and meteorological conditions using the approach presented in Figure 1. It comprises two elements: a statistical model of emissions dispersion patterns built on the enhanced surface fuel burn models from prior phases of the work, and a model of the queuing areas on the airport surface.

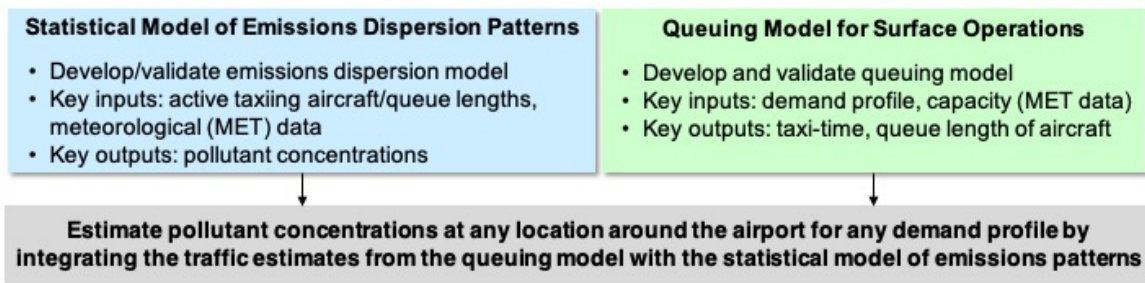


Figure 1. Enhanced air quality modeling approach.

Implementation of these models has been demonstrated initially for LAX due to the availability of detailed airport Performance Data Analysis and Reporting System (PDARS) surface surveillance and associated high resolution air quality monitor measurements over a six-week period from February 1 to March 16, 2012. Over this period, the airport was operating in west-flow configuration (i.e., taking off and landing to the west) for over 90% of the time, and hence was the focus for the analysis. Air pollutant measurements for CO, NO, NO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, and ultra-fine particulate (UFP) were available from four air quality monitor locations termed Community North, East, and South (CN, CE, and CS respectively) and AQ to the north located 500-5,000 ft from the airport boundary as illustrated in Figure 2. Because of their location in the urban environment in communities around LAX, these monitors measured both airport and non-airport pollutant sources, and this needed to be carefully considered in the analysis.

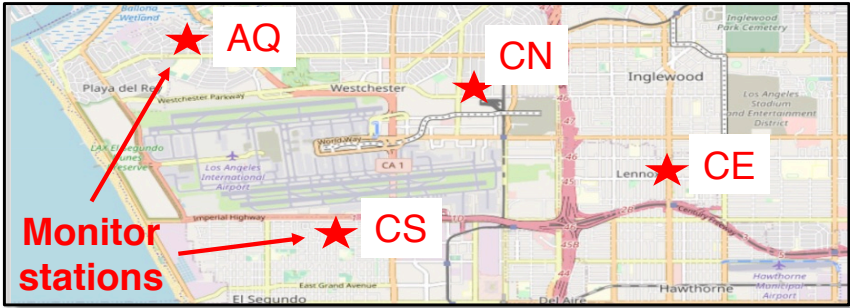


Figure 2. LAX air quality monitor locations.

Each monitor recorded measurements of CO, NO, NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>2.5</sub>, and UFP concentrations every minute. The median measurements over the six-week measurement period for some of these species as a function of local time are presented in Figure 3. It is seen that variations in the species are influenced greatly by diurnal photochemical reactions which makes their dynamics as a function of airport traffic very hard to discern.

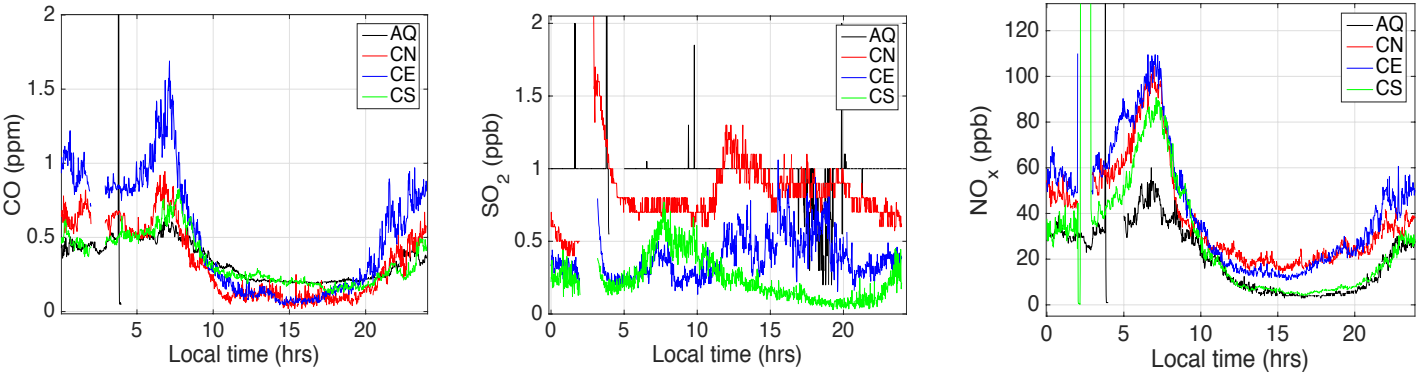


Figure 3. Sample air quality monitor median measurements of CO, SO<sub>2</sub>, and NO<sub>x</sub> species as a function of local time over the six-week test period.

Therefore, there was a need to consider other pollutants in order to identify good correlations with airport activity. UFPs are aerosols with an aerodynamic diameter of 0.1 μm (100 nm) or less. There is a growing concern in the public health community about the contribution of UFPs to human health. Despite their modest mass and size, they dominate in terms of the number of particles in the ambient air. Figure 4 presents a plot of median 100 nm UFP measurements from a representative monitor (the CE site, in this example) relative to aircraft movements as a function of local time. These UFP concentrations are seen to be a very good signature for airport traffic: PM particle diameter depends on the thrust setting of the engine which helps isolate taxi emissions from other phases of flight, and particle diameter from aircraft emissions is much lower than vehicular emissions or other sources.

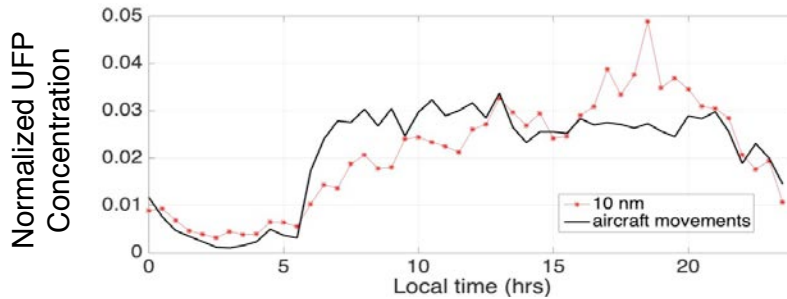


Figure 4. 100 nm UFP and aircraft movement correlation.

Given this strong UFP correlation to aircraft traffic on the airport surface, we built a preliminary statistical model of emissions dispersion patterns that estimates the UFP concentration (i.e., what the monitor observes) as a function of the aircraft traffic on the surface and meteorological conditions (winds, temperature, and solar irradiance). We developed two classes of models: a temporal one that only focuses on each monitor location (and does not try to generalize to all locations on the surface), and another spatial model that tries to infer the spatial impacts as well (which is a much harder problem, especially given we had data from only four monitor locations, and there are a lot of effects at play). Time-delays are found to be important, since the advection of the pollutants is not instantaneous. We investigated both linear regression and Gaussian Process Regression (GPR) models (which are non-parametric, can capture nonlinear effects, and estimate the probability distribution of the dependent variable).

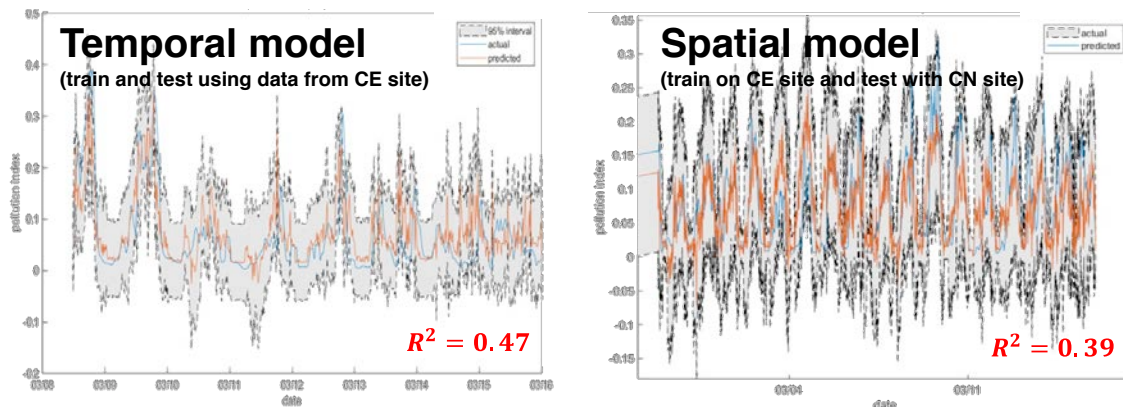


Figure 5. Preliminary emissions model based on GPR (left) temporal and (right) spatial models.

Figure 5 shows sample results from the temporal and spatial GPR models. The blue lines are the mean predicted values, the grey regions are the 95% confidence intervals, and the red lines are the observed values of a weighted UFP concentration. As expected, the temporal model performs better than the spatial model, as shown by the respective  $R^2$  scores. We also find that the performance of the spatial model varies by monitor (location), with better performance at the downwind sites (which makes sense since the pollutants are being transported and dispersed towards them).

The second element of Figure 1 is the development of a model of airport surface queuing locations. For LAX, PDARS and FAA Aviation System Performance Metrics (ASPM) data was available for the same six-week period as the air quality monitor data. This was used to identify the taxi time distributions for departures from the airport, as shown in Figure 6 for the case of taxi-out time.

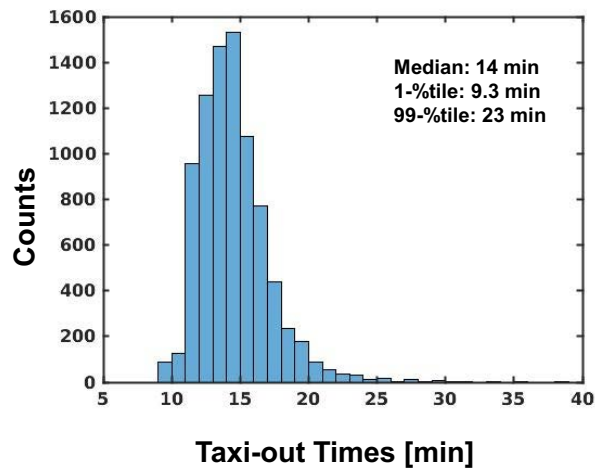


Figure 6. LAX taxi-out time distribution for a 6-week test period.

The time periods making up the 99th percentile taxi-out times were taken to be representative of periods when the airport was most congested. These were then used to identify heat maps of queueing locations on the airport surface, as shown in Figure 7. The hypothesized causes of the observed queueing locations are also presented, which fall into general “queue building block” categories of:

- departure runway queues
- terminal/spot queues
- runway crossing queues
- other areas (e.g., remote/corporate pad queues)

These results are now being used to develop queueing models for the various parts of the LAX airport surface. A particular finding in our initial analysis relates to the need to calibrate the unimpeded taxi times of aircraft, rather than relying on the ASPM calculated values, while building the queueing models. We use the ASPM records of gate and runway times to infer various parameters of the queueing model, such as the service times of different runway queues, as well as the unimpeded taxi times. By estimating the time spent idling in different queues (corresponding to hotspots on the surface), we can estimate the emissions that occur at different locations on the airport surface.

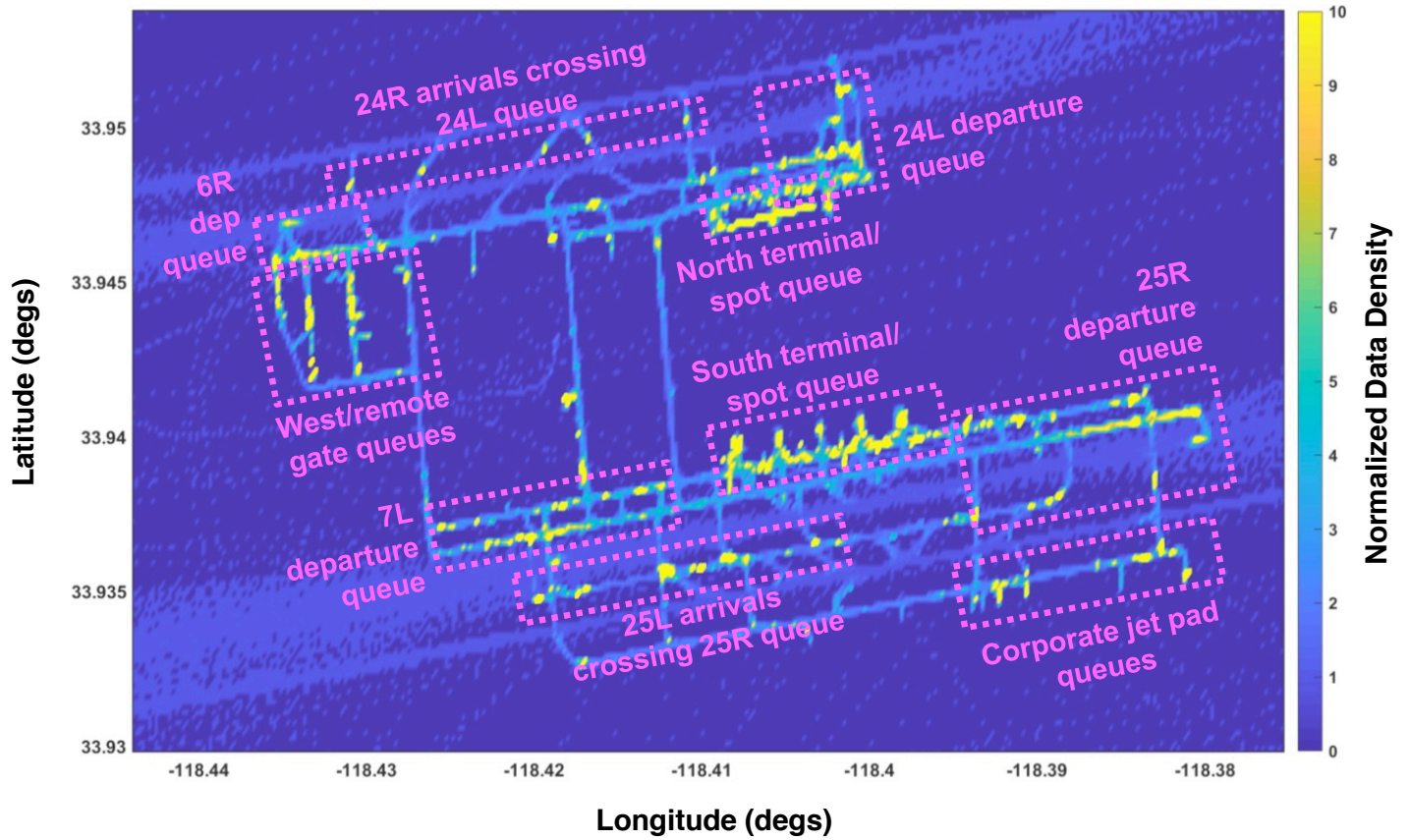


Figure 7. LAX queuing location heat map and hypothesized causes.

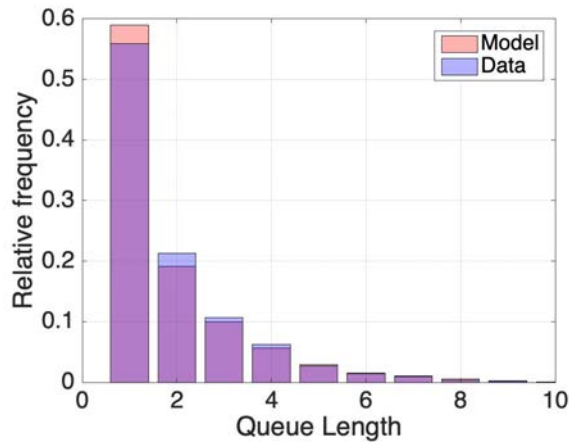


Figure 8. LAX queuing model preliminary results, showing a comparison of modeled and observed runway queue length frequency distributions. The purple regions correspond to an overlap of the model estimates and observed values, while light red regions correspond to the model estimates exceeding the observed values, and the blue regions correspond to the observed values exceeding the model estimates.

Figure 8 shows a comparison of the queuing model-predicted runway queue lengths and the observed values for an independent training set. The mean error is 0.02 aircraft and the mean absolute error is 0.64 aircraft. Next, we propose to validate the queuing model by comparing the queue lengths with those estimated from ASDE-X data (i.e., the heat map in Figure 7).

## Task 2 – Identify Representative Application Scenarios and Estimate the Impact of Improved Surface Movement Modeling Capability

Massachusetts Institute of Technology

Plans for this Task moving forward include:

- Improve the performance of emissions model by:
  - Exploring other input features
  - Different machine learning methods
- Develop and validate queuing model for LAX
  - Model will be developed using larger quantities of historical ASDE-X and ASPM operational data
  - Capable of estimating surface traffic based on demand, capacity (meteorological data)
- Integrate the queuing model with the statistical model of emissions dispersion patterns to evaluate the performance of the resulting emissions estimate
- Explore generalizing results to other airports
  - Develop lookup table of queue building blocks for a set of different classes of airports and runway configurations
  - Leverage prior ASCENT-funded efforts to inform this task (e.g., CLT, DFW, PHL, BOS, and LGA airports)
- Evaluate implications for AEDT/DSQM

Priorities for extensions will be established through continued engagement with FAA sponsors, AEDT developers, and other appropriate stakeholders.

## Task 3 – Develop Implementation Plan to Transition Appropriate Surface Modeling Enhancements into the Operational AEDT Product

Massachusetts Institute of Technology

The research team conducts regular analysis status and results review with FAA sponsors and AEDT developers. This will continue moving forward, with the intent to identify an implementation plan and schedule to transition specific surface modeling enhancements into appropriate versions of the operational AEDT product given their developmental maturity and programmatic priorities.

### Milestones

Task 1 has been the primary focus in CY2020. Tasks 2 and 3 will be the focus of the next three months of the current period of performance. In particular, based on discussions with FAA sponsors and AEDT developers, we plan to develop a lookup table that identifies the components of queuing network models for different types of airports.

### Publications

N/A

### Outreach Efforts

N/A

### Awards

None

## **Student Involvement**

MIT students have been involved in this research. Sandeep Badrinath is currently a PhD candidate in Aeronautics and Astronautics at MIT. We also had an undergraduate student, James Abel, involved in this project over the summer.

## **Plans for Next Period**

The ongoing phase of work involves enhancing AEDT's surface performance modeling to augment its dispersion modeling capabilities for airport air quality analysis, using a statistical model of emissions dispersion patterns. In particular, the research team will assess the current implementation of the DSQM and associated issues, will make recommendations on improvements, and if appropriate, develop a new/improved surface queuing model that would address these issues. The next extension to this work focuses on maturing the surface fuel, noise, and emissions models to a point they are suitable for implementation in the operational AEDT. Implementation pathways into the operational AEDT product will then be created for the surface fuel, noise, and emissions modeling enhancements. This will be conducted in close collaboration with the AEDT developers and key stakeholders and will focus on AEDT capabilities matched to the needs of different user classes. Sensitivity studies will also be conducted as needed. Specific planned tasking is described below.

### **Task 1: Undertake more detailed studies to extend AEDT capabilities to model surface noise and emissions impacts**

In the prior phase of the work, relevant literature sources and other modeling approaches have been identified and reviewed with respect to surface noise and emissions modeling (e.g., ACRP reports, P3-T3 emissions models, etc.). Based on these activities, a roadmap has been developed of how the researchers will use the enhanced surface fuel flow models to benefit noise and emissions modeling in AEDT. The current proposal is to map engine power settings for different taxi phases (stops, idle taxi, and accelerations) to noise and emissions effects. By considering the accuracy of resulting noise and emissions effects as a function of location on the airport surface, we can start to understand the potential utility of these proposed enhancements. We are initially using the case of A320 FDR data to illustrate how we can analyze taxi speed profiles to identify acceleration events on the airport surface. These in turn can be used to determine correlations between acceleration events and fuel flow and thrust spikes from the relevant parameters in the FDR data. In this Task, similar correlations will be found for other aircraft types contained in our FDR data archive which can then be used for airports where we do not have FDR data but do have ASDE-X data, from which we can identify acceleration events as a function of time and location. The resulting fuel flow and thrust profiles will be used as inputs to appropriate noise and emissions analyses for those airports. Sensitivity studies will also be conducted as appropriate.

The main subtasks will therefore be:

1. **Enhance noise modeling** by incorporating location-specific thrust levels during taxi (e.g., ramp area, taxiways, runway queues).
2. **Evaluate and refine baseline emissions indices** by considering modeling techniques that are based on analysis of FDR data, as has been considered for cruise emissions (e.g., DLR or P3-T3 methods). We will also consider ranges provided by different methods, and the discrepancies with the International Civil Aviation Organization (ICAO) Emissions Databank values. We have begun to analyze the A4A fuel burn data for this purpose and will continue to do so.
3. **Initial investigation and assessment of APU emissions** by considering prior Airport Cooperative Research Program (ACRP) studies (e.g., ACRP 02-25 and ACRP 02-03a). We will also look into the possibility and value of obtaining FDR data that includes APU parameters.

### **Task 2: Identify representative application scenarios and estimate the impact of improved surface movement modeling capability**

The main subtasks undertaken will be:

1. Identify a few practical scenarios that represent environmental analysis of typical airport settings.
2. Use AEDT baseline modeling and user defined inputs to predict noise, emission, and fuel burn for the scenarios identified.
3. Compare the predictions and evaluate the impact of the improved surface movement modeling capabilities from the ongoing phase.
4. Compare with field measurement data if such data are available.

Priorities for extensions will be established through continued engagement with FAA sponsors, AEDT developers, and appropriate other stakeholders.





### Task 3: Develop implementation plan to transition appropriate surface modeling enhancements into the operational AEDT product

The research team conducts regular analysis status and results review with FAA sponsors and AEDT developers. This will continue in the current tasking with the intent of identifying an implementation plan and schedule to transition specific surface modeling enhancements into appropriate versions of the operational AEDT product given their developmental maturity and programmatic priorities. Further engagement with AEDT developers in prior phases of the work identified the need for functionality tailored to different user classes, ranging from:

1. **Basic users** wanting the ability to select “pre-canned” options representative of typical operating conditions, e.g., based on ASPM-derived empirical distributions. We can also analyze the impact of infrastructure development (for example, runway construction) that can change the airport capacity and traffic flows on the surface and have a subsequent effect on fuel burn, noise, and emissions.
2. **Intermediate users** wanting the ability to modify behaviors based on appropriate modeled parameters, e.g., available in the existing AEDT delay and sequence model.
3. **Advanced users** wanting complete control over all aspects of aircraft and airport dynamics, e.g., based on ASDE-X data.

### References

- ACRP 02-25. (2012). Handbook for evaluating emissions and costs of APUs and alternative systems. Transportation Research Board
- ACRP 02-27. (2009). Enhanced modeling of aircraft taxiway noise, volume 1: Scoping. Transportation Research Board
- ACRP 02-27. (2013). Enhanced modeling of aircraft taxiway noise, volume 2: Aircraft taxi noise database and development process. Transportation Research Board
- ACRP 02-45. (2016). Methodology to improve EDMS/AEDT quantification of aircraft taxi/idle emissions. Transportation Research Board
- S. Badrinath, M. Li and H. Balakrishnan. “An Integrated Surface-Airspace Model of Airport Departures,” AIAA Journal of Guidance, Control, and Dynamics, Vol. 42, No. 5, pp. 1049-1063, 2018.
- S. Badrinath, H. Balakrishnan, E. Joback and T.G. Reynolds. “Impact of Uncertainty on the Control of Airport Surface Operations,” *Transportation Science*, Vol. 54, No. 4, 2020, <https://doi.org/10.1287/trsc.2019.0957>.
- S. Badrinath, J. Ma, H. Balakrishnan and D. Delahaye. “A Comparative Analysis of Departure Metering at Paris (CDG) and Charlotte (CLT) Airports,” USA/Europe Air Traffic Management R&D Seminar, June 2019.
- Chati, Y.S., and Balakrishnan, H., “Analysis of Aircraft Fuel Burn and Emissions in the Landing and Takeoff Cycle using Operational Data,” Intl. Conf. on Research in Air Transportation, Istanbul, 2014.
- E. Clemons, T.G. Reynolds, S. Badrinath, Y. Chati and H. Balakrishnan, “Enhancing Aircraft Fuel Burn Modeling on the Airport Surface”, AIAA Aviation Conference, Atlanta, June 2018.
- Doppelheuer, A. & Lecht, M. (1998). Influence of engine performance on emission characteristics. RTO AVT Symposium on Gas Turbine Engine Combustion, Emissions and Alternative Fuels, Lisbon.
- DOT-VNTSC-FAA-16-11, “Aviation Environmental Design Tool – Technical manual, Version 2b”, U.S Department of Transportation (FAA), 2016.
- International Civil Aviation Organization (ICAO). (2014). Aircraft Engine Emissions Databank. Online database
- H. Khadilkar and H. Balakrishnan, “Estimation of Aircraft Taxi Fuel Consumption using Flight Data Recorder Archives”, Transportation Research Part D: Transport and the Environment, 17(7), 2012.
- Martin, R.L., Oncina, C.A., & Zeeben, J.P. (1996). A simplified method for estimating aircraft engine emissions. Appendix C of Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis.
- I. Simaiakis and H. Balakrishnan. “A Queuing Model of the Airport Departure Process,” *Transportation Science*, 50(1), pp. 94-109, February 2016.