FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Surface Analysis to Support Aviation Environmental Design Tool (AEDT) Aircraft Performance Module Development

Project 46

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ASCENT
AVIATION SUSTAINABILITY CENTER

Motivation

- Need accurate surface fuel burn prediction to support range of stakeholder analysis needs

Airlines

- **Fuel efficiency studies**
- **Airport-specific procedure development**

Airports

- **Emissions/community impact studies**
- **Airport infrastructure improvement**

FAA

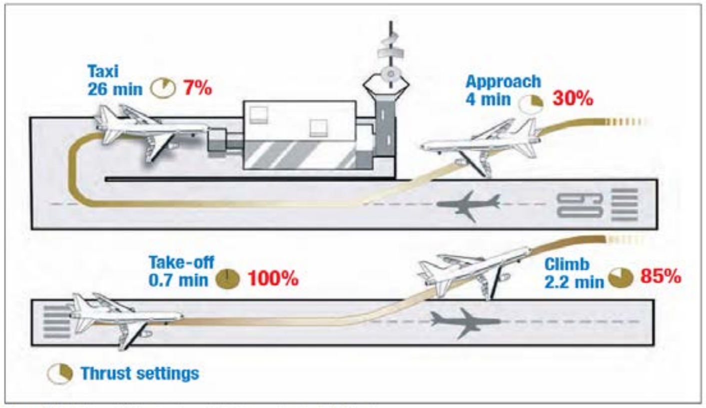
- **Network efficiency studies**
- **Environmental studies**
- **Safety / Regulations**

- Current versions of AEDT make several simplifying assumptions

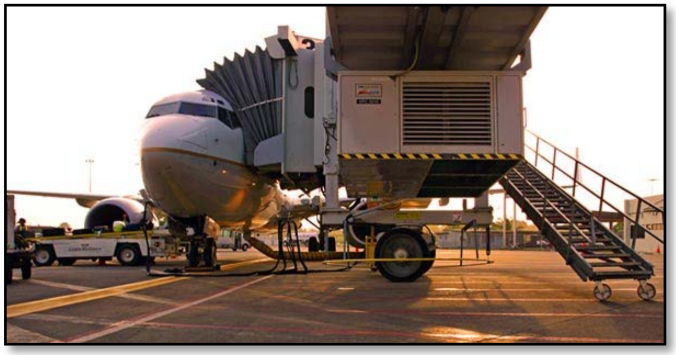
Airport Surface Fuel Burn Modeling Improvement Areas

1. Improved engine fuel flow estimates
   – ICAO databank certification data does not reflect fuel flows under operational conditions

2. Improved taxi time estimates
   – Simplified assumptions (e.g., LTO cycle) or outdated empirical distributions do not reflect range of taxi times under current operational conditions at relevant airports



3. Need estimates of fuel burn pre-taxi
   – Lack of estimates for fuel burnt at gate (APU) and during engine start-up



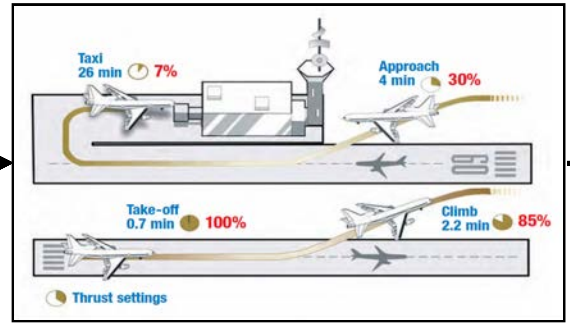
LTO = Landing & Take Off, APU = Auxiliary Power Unit

Airport Surface Fuel Burn Modeling Improvement Areas

- Previous AEDT versions did not have access to detailed thrust and fuel burn, leading to simplified assumptions

CURRENT MODELING

ICAO Emissions Databank Certification 7% Thrust Fuel Flows



LTO Cycle*, User-Specified or Out-dated Empirical Taxi Times

Current Surface Fuel Burn Models

*Assumes 19 min taxi-out, 7 min taxi-in

- Increased data availability provides enhancement opportunities

ENHANCED MODELING

Enhanced Taxi Fuel Flow Modeling (FDR data)

Enhanced Taxi Time Estimates (ASPM data)

Adding Pre-Taxi Fuel Estimates (FDR & ACRP reports)

(ASDE-X data)

Enhanced Surface Fuel Burn, Noise & Emissions Models

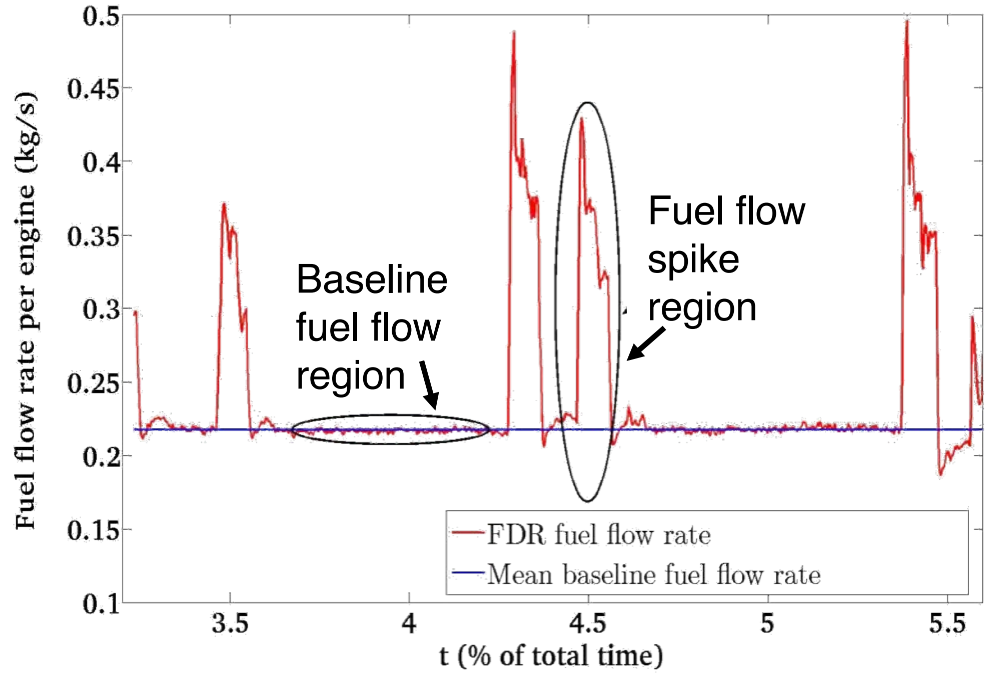
FDR = Flight Data Recorder, ASPM = Aviation System Performance Metrics, ACRP = Airport Cooperative Research Program

Schedule and Status

PHASE 1 Tasks (FY17-18)	
• Improvements in engine fuel flow estimates (1st order effects, initial set of a/c types)	[Complete]
• Improvements in taxi time estimates (aggregate distributions at different airports)	[Complete]
• Estimation of pre-taxi fuel burn (engine start-up and APU)	[Complete]
• Recommend AEDT enhancements & Coordination with AEDT developers	[Initial recommendations complete]
PHASE 2 Tasks (FY19-present)	
• Extend Phase 1 analysis to broader range of aircraft types from US domestic operations	[On-going]
• Extend Phase 1 findings on airport-specific differences that impact surface fuel burn	[On-going]
• Extend findings to taxi-in fuel burn	[On-going]
• Identify AEDT surface enhancements to support emissions and noise inventories	[On-going]

1. Improved Engine Fuel Flow Estimates

- FDR data used to characterize taxi fuel burn into two regions
  - Baseline fuel flow rate remains steady over time
  - Spikes in fuel flow neglected for 1st order analysis



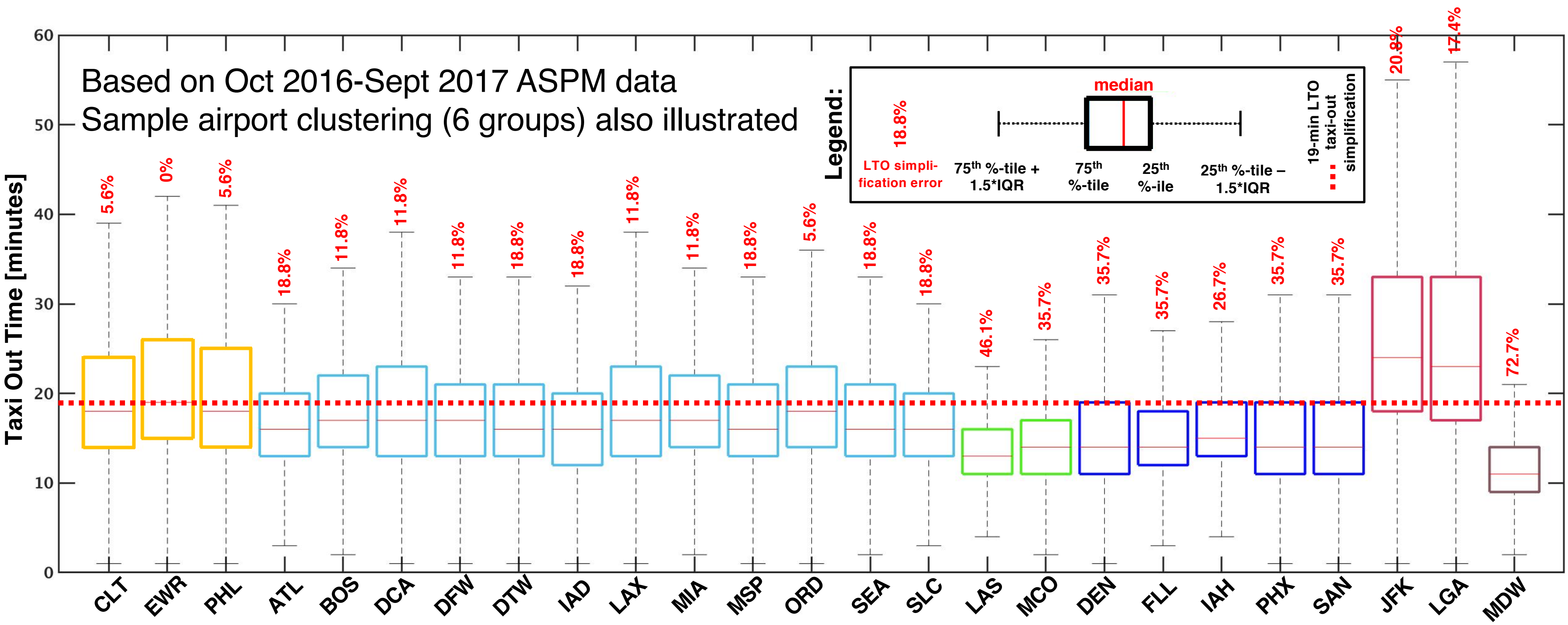
- Mean baseline fuel flow estimates developed for different aircraft types
  - Intended as improvement over AEDT equations (1.1 x ICAO Databank value of taxi fuel flow rate)

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

OLS = Ordinary Least Squares

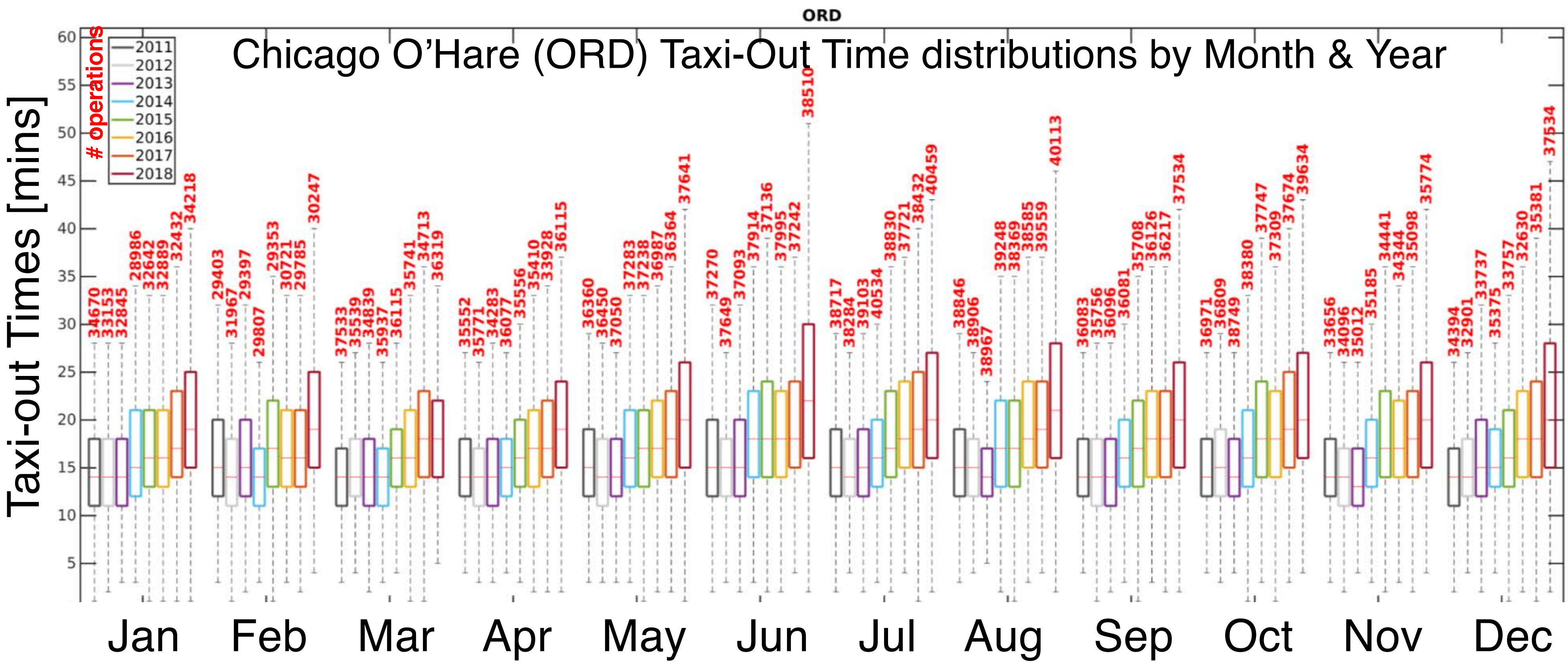
2. Improved Taxi Time Estimates

- Used up-to-date empirical data (ASPM) to develop operationally-realistic distributions of taxi-out and taxi-in times which capture effects of key operational factors
  - Runway configuration; Weather conditions, etc.
  - May need to update on regular basis to reflect changes in drivers



2. Improved Taxi Time Estimates

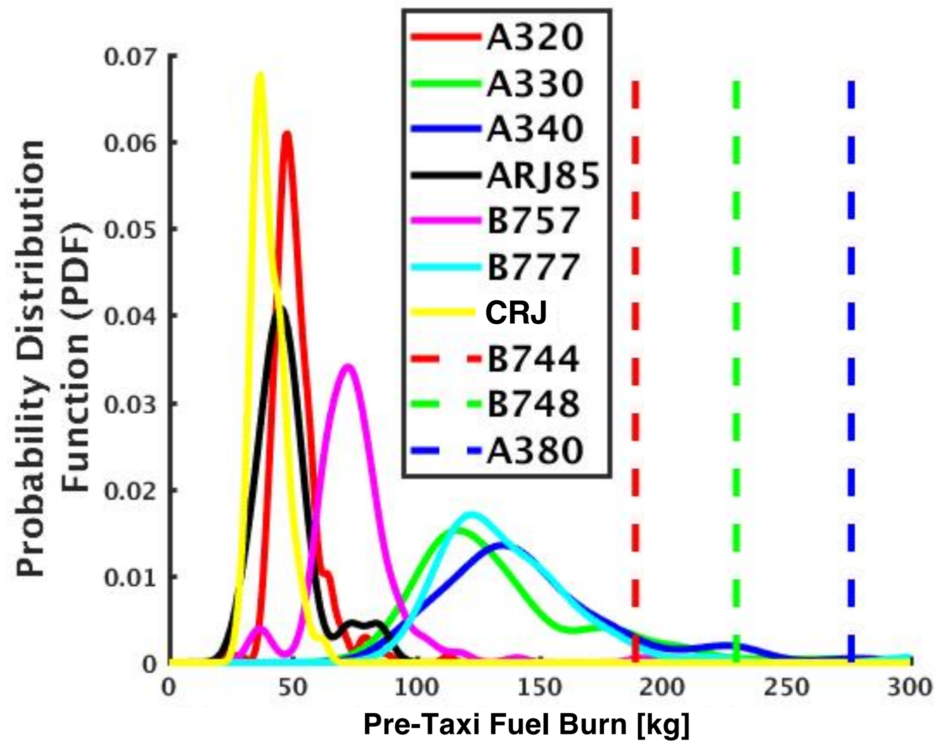
- Now developing taxi time distributions conditioned on different factors to support different types of AEDT analysis
  - Month/year analysis to assess effects of season, infrastructure, demand, etc.
  - Airport configuration to assess effects of runway usage, weather, etc.
  - Demand to assess effects of time of day, traffic level, etc.



3. Pre-taxi Fuel Burn Estimates

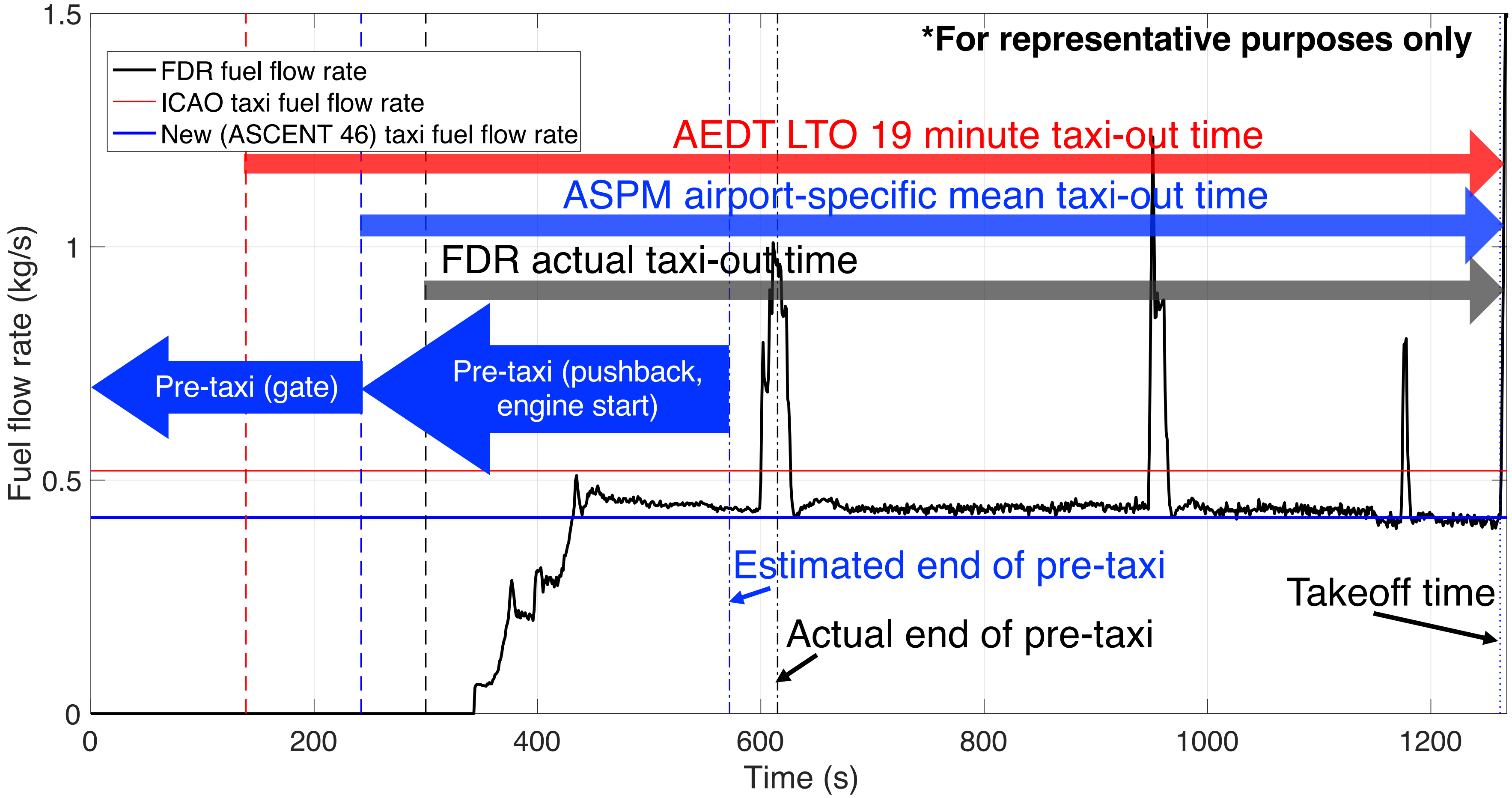
- Need to account for engine & APU fuel burn at gate, during push-back and engine start
  - Typically 10-40% of total taxi fuel

- Gate fuel burn
  - Pilot guidance on APU "on-time": 10-15 min at gate, longer if off-gate stand
  - Determined push-back & engine start times from FDR data
  - Multiplied by APU fuel burn estimates from ACRP 02-25



Fuel Burn Distributions – FDR data results (solid) and predicted (dashed)

Illustration of Fuel Burn Model Enhancements for a Sample Flight*



	FDR	AEDT Model	ASCENT 46 Enhanced Model		
			Pre-taxi	Taxi-out	Total
Engine fuel burn (kg)	**418.8**	605.9 (+45%)	97.5	345.2	**442.7 (+6%)**
APU fuel burn (kg)	N/A	---	46.5	0.0	46.5
Total taxi-out fuel burn (kg)	418.8 + APU**	605.9 + APU**			489.2

** APU contribution not available from FDR; not included for AEDT

Noise & Emissions Modeling Activities

- Literature review and identification of knowledge gaps
  - Initial references
    - ACRP 02-45 (emissions)
    - ACRP 02-27 (noise)
  - Additional literature survey on emissions modeling also conducted

- Considerations for **emissions modeling**
  - Duration matters for both inventory and dispersion models
    - Total taxi-time
    - Taxi speeds
  - Location matters for dispersion models
    - Taxi-routes
    - Queuing locations
  - Power settings and thrust levels
    - Stops and accelerations (NOT neglecting fuel flow spikes)
    - Idle taxi power

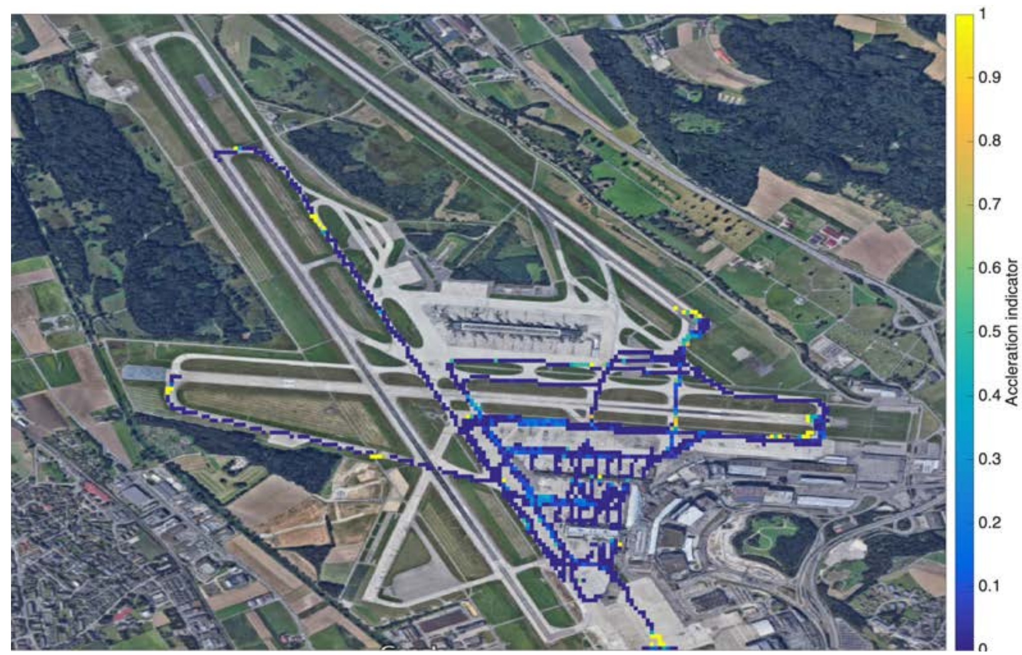
Noise & Emissions Modeling Activities [Continued]

- **Noise modeling** considerations based on recommendations of ACRP 02-27
  - "Aircraft Taxi Noise Database for Airport Noise Modeling", TRB 2013
  - **Need to study impact of breakaway thrust on airport noise**
    - Measurements indicate that noise at breakaway thrust is 3-7dB higher than noise at idle thrust conditions for large aircraft
    - Limited data on the frequency and duration of breakaway thrust
    - Can be modelled in INM7/AEDT if a detailed thrust profile is given
  - **Simplify tracks from terminal instead of individual gates**
  - Other recommendations of ACRP 02-27 not planned to be addressed: Creation of a new taxi Noise-Power-Distance (NPD) dataset; INM/AEDT spectral class might need corrections; need spectral directivity analysis for breakaway thrust; need synchronized measurement of noise and engine operating parameters

Proposed Focus Based on Literature Surveys

- Locations on the surface of increased (breakaway) thrust, which impacts both airport emissions and noise
  - Utilize FDR data to obtain speed, fuel flow and thrust correlations
  - Use correlations and observed speed profiles from ASDE-X data to model noise and emissions for broader set of US airports
  - Can also analyze single-engine taxi procedures and their impact

Heatmap of speed (knots)



Heatmap of acceleration indicator

Example FDR results for A320 aircraft at European airport (n=72)

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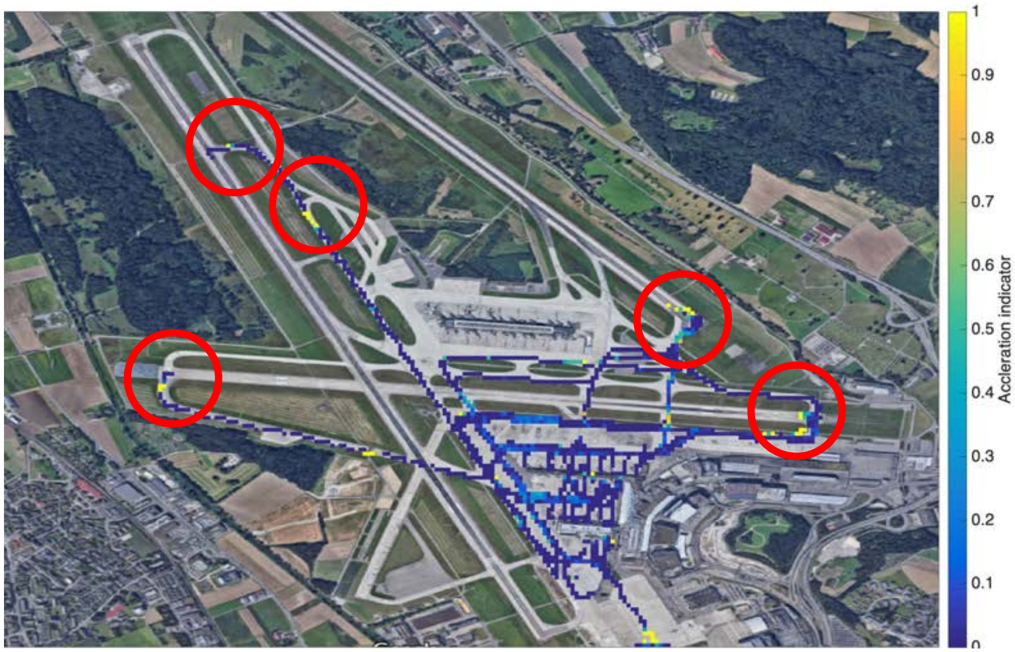
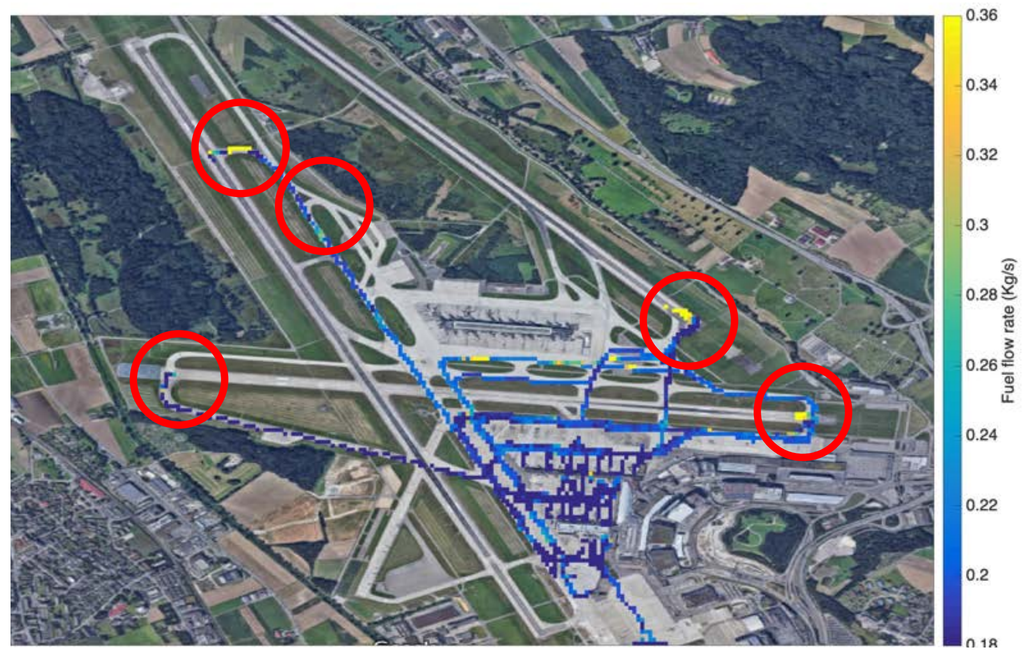


Heatmap of acceleration indicator



Heatmap of fuel flow rate (kg/s)

Example FDR results for A320 aircraft at European airport (n=72)

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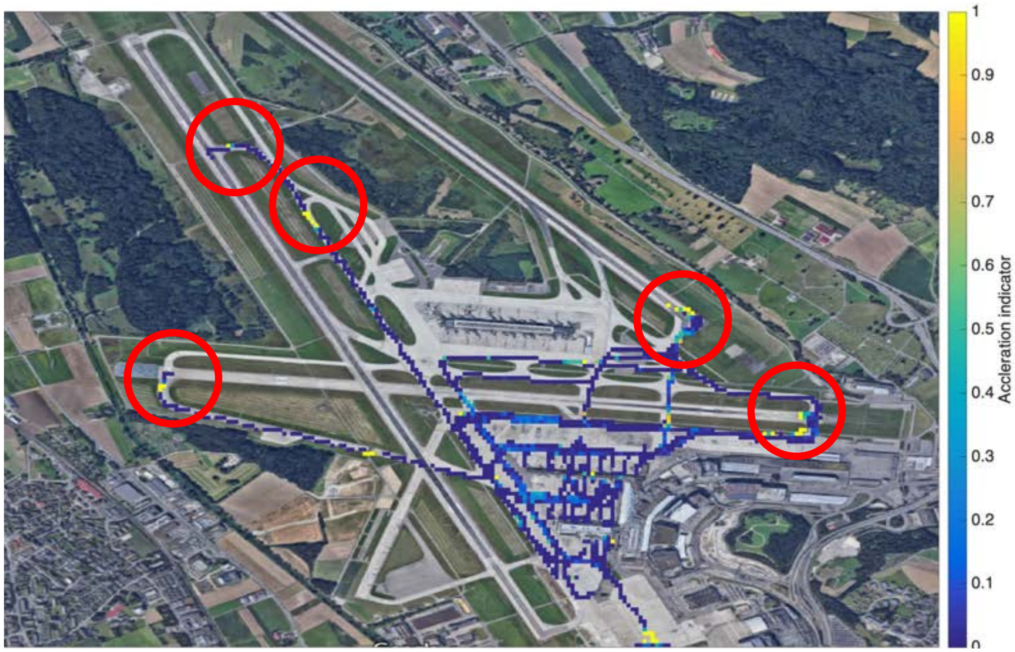

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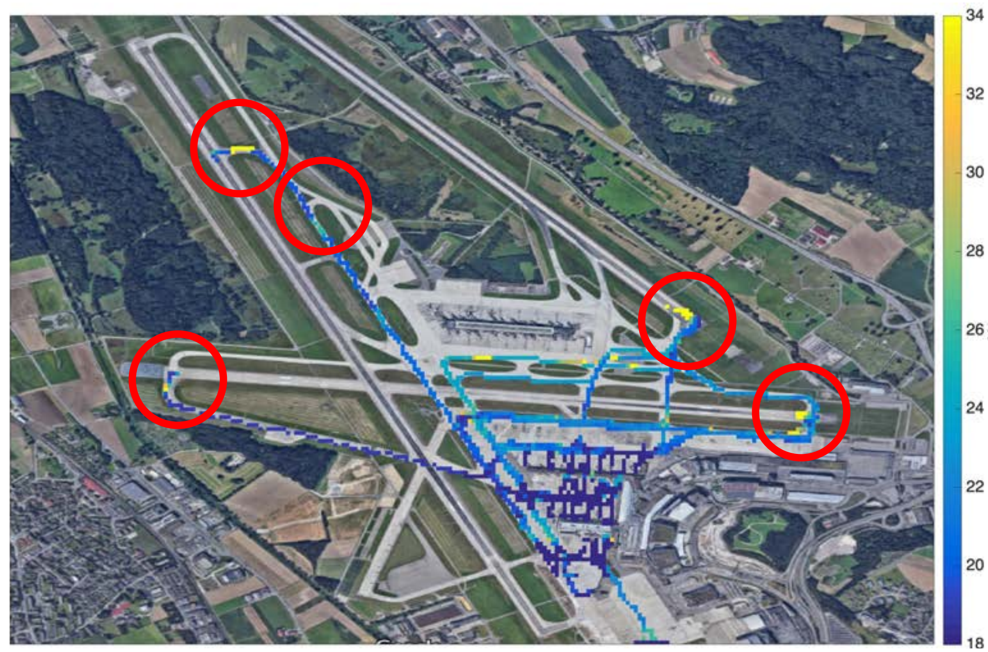

Heatmap of thrust level, N1 (%)

Example FDR results for A320 aircraft at European airport (n=72)

Summary

- Expanding enhancements to airport surface fuel burn modeling in the areas of baseline taxi fuel flow modeling, taxi time estimation and pre-taxi fuel burn that may be suitable for inclusion in future versions of industry models such as AEDT

- Undertaking initial studies to leverage fuel modeling improvements to enhance AEDT modeling of surface noise and emissions impacts

- Continuing to support AEDT development team in implementing future surface modeling enhancements

References

- ACRP 02-45, "Methodology to Improve EDMS/AEDT Quantification of Aircraft Taxi/Idle Emissions", Transportation Research Board, 2016.
- ACRP 02-27, "Aircraft Taxi Noise Database for Airport Noise Modeling", Transportation Research Board, 2013.
- ACRP 02-25, "Evaluating Alternatives For Aircraft Ground Power, Heating, and Air Conditioning", Transportation Research Board, 2011.
- 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.
- DOT-VNTSC-FAA-16-11, "Aviation Environmental Design Tool – Technical manual, Version 2b", U.S Department of Transportation (FAA), 2016.
- 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.
- 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.

Contributors

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- MIT Lincoln Laboratory: Emily Joback
- MIT Students: Sandeep Badrinath, Yashovardhan Chati (graduated; now at Apple)
- FAA: Bill He & Mohammed Majeed
- Volpe AEDT development team

Disclaimer

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Backup Slides

1. Improved Engine Fuel Flow Estimates

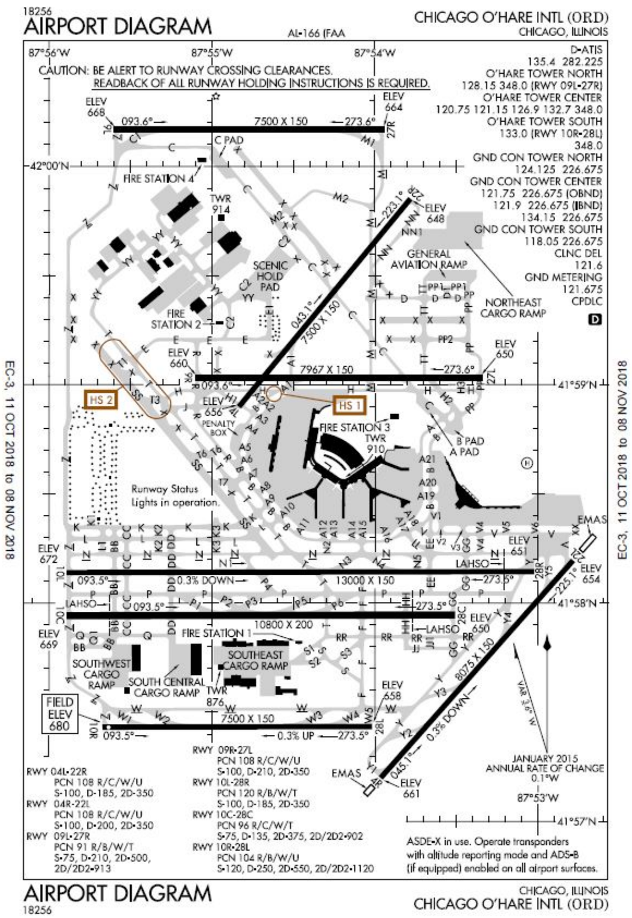
- OLS-based baseline fuel flow rate models found to decrease prediction errors on unseen test data during taxi-out

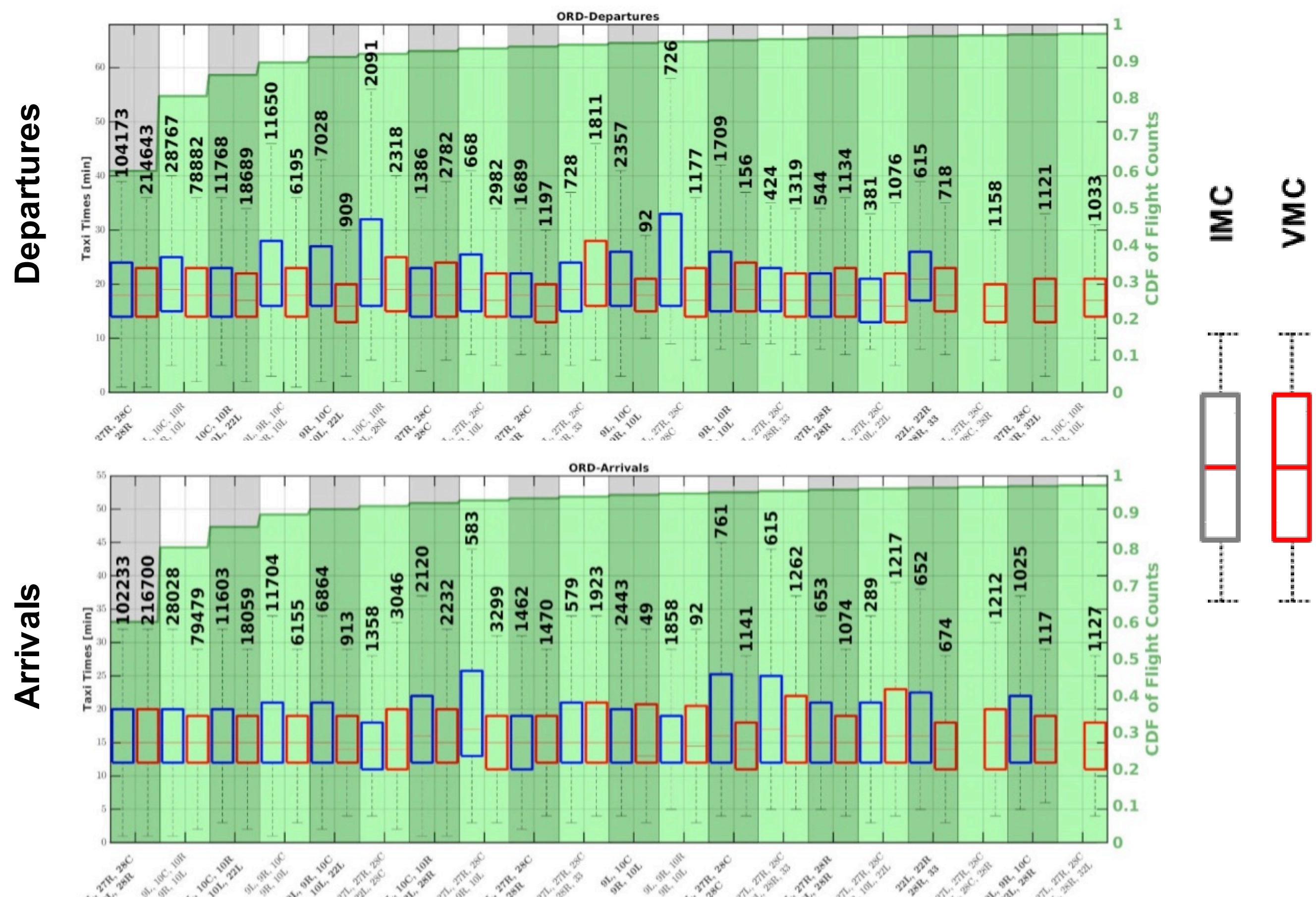
A/C Type	# Test Observations from FDR	Mean error (%)		Mean absolute error (%)	
		OLS Model	AEDT	OLS Model	AEDT
A320-214	34	1.0	36.3	13.3	39.4
A321-111	14	3.8	47.1	14.9	50.1
A330-343	37	-3.0	36.4	5.8	39.1
A340-313	12	-0.7	7.8	9.1	12.5
B777-300ER	25	-2.2	42.3	3.1	43.1
C Series100 (RJ)	30	0.1	17.7	5.5	19.3

- While fuel flow spikes during acceleration events are found to be a second-order contribution to fuel burn, they may be a more significant factor for noise and emissions

2. Improved Taxi Time Estimates

- Now developing taxi time distributions conditioned on different factors to support different types of AEDT analysis
  - Airport configuration to assess effects of runway usage, weather, etc.





2. Improved Taxi Time Estimates

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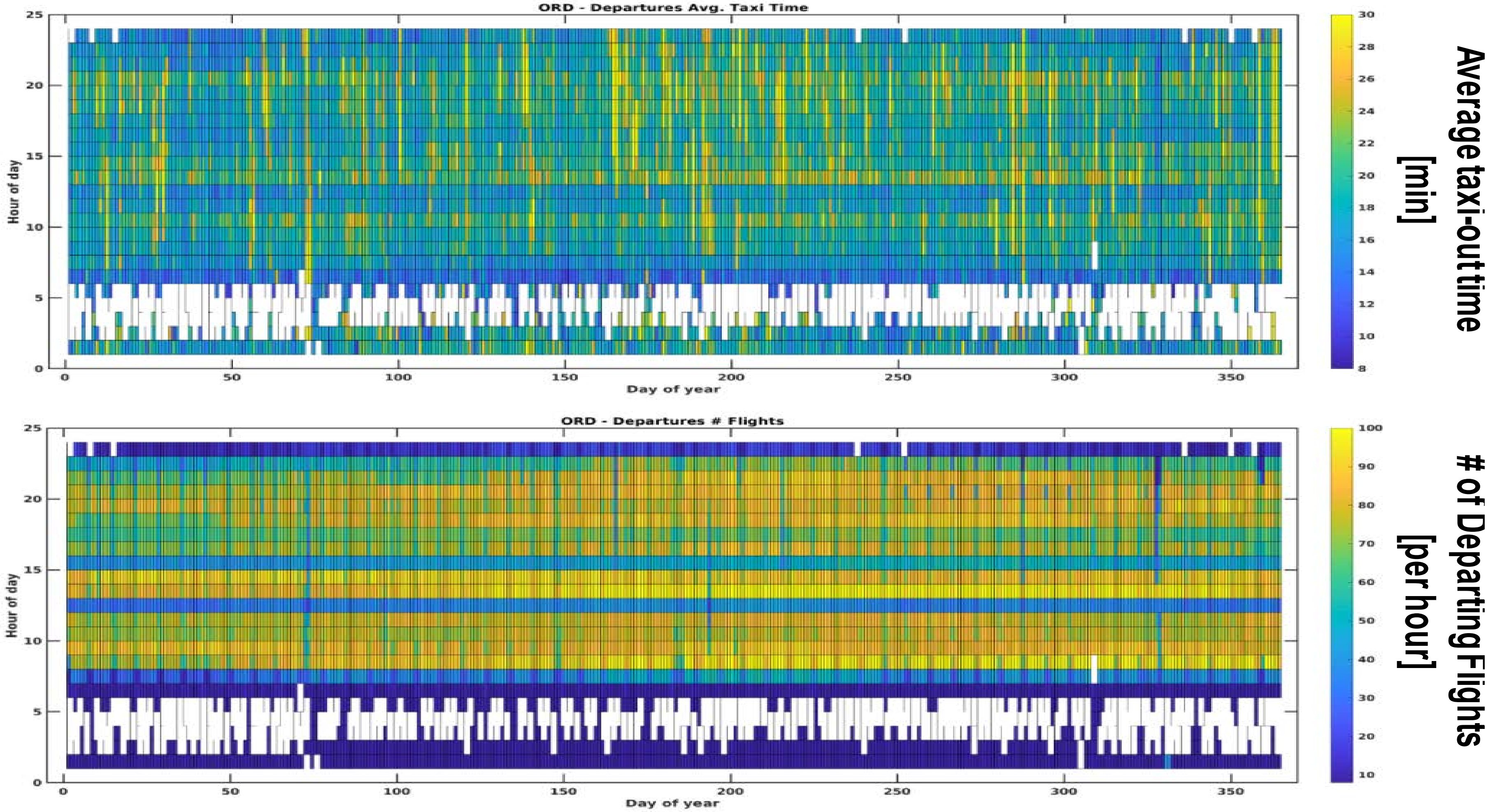
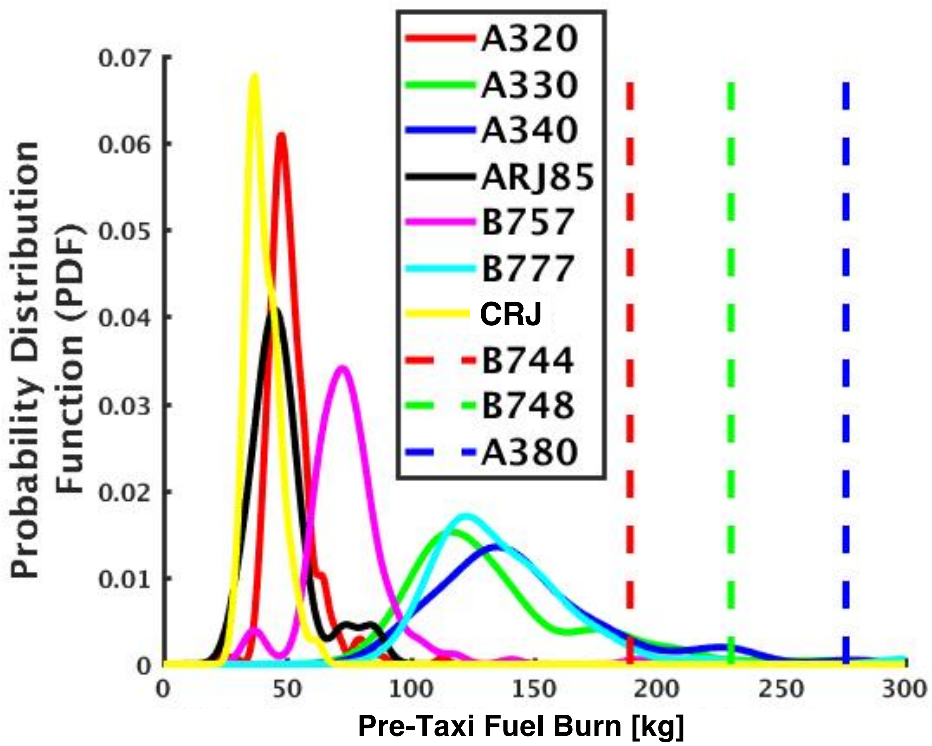
  - Demand to assess effects of time of day, traffic level, etc.

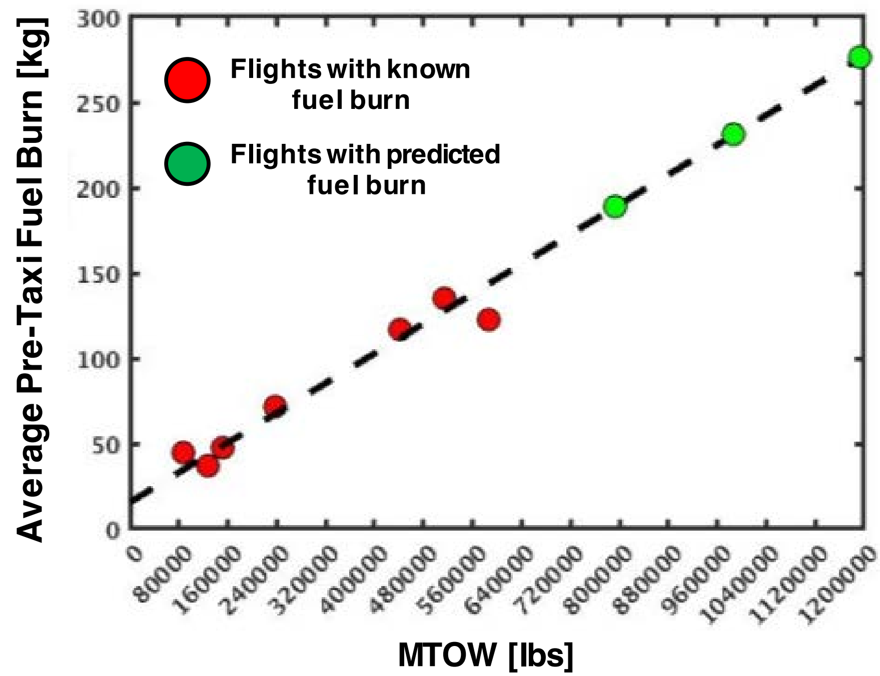


3. Pre-taxi Fuel Burn Estimates

- Correlation between total fuel burn and aircraft MTOW used to approximate heavier aircraft not found in the FDR dataset



Fuel Burn Distributions – FDR data results (solid) and predicted (dashed)



Regression to predict total fuel burn for aircraft types absent in dataset

MTOW = Maximum Takeoff Weight

Initial Literature Survey on Emissions Modeling

- Dopelheuer A., "Aircraft Emission Parameter Modelling," *Air and Space Europe*, Vol. 2, No. 3, 2000, pp. 34-37.
- Wasiuk, D.K., Lowenberg, M.H., and Shallcross, D.E., "An Aircraft Performance Model Implementation for the Estimation of Global and Regional Commercial Aviation Fuel Burn and Emissions," *Transportation Research Part D*, Vol. 35, 2015, pp. 142-159.
- Baughcum, S.L., Tritz, T.G., Henderson, S.C., and Pickett, D.C., "Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis," NASA Contractor Report 4700, 1996.
- Kim B. et al., "System for assessing Aviation's Global Emissions (SAGE) Version 1.5, Technical Manual," John A. Volpe National Transportation Systems Center, Massachusetts Institute of Technology, and Logistics Management Institute, Report No. DOT-VNTSC-FAA-05-14, 2005.
- International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank 2014.
- Dopelheuer A., and Lecht, M., "Influence of Engine Performance on Emission Characteristics," RTOAVT Symposium on Gas Turbine Engine Combustion, Emissions and Alternative Fuels, Lisbon, October 1998.
- Martin, R.L., Oncina, C.A., Zeeben, J.P., "A Simplified Method for Estimating Aircraft Engine Emissions," Appendix C of Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis by Baughcum, S.L. et al. 1996.
- Kyprianidis K.G., Nalianda, D., and Dahlquist, E., "A NOx Emissions Correlation for Modern RQL Combustors," *Energy Procedia*, Vol. 00, 2015.
- Deidewig, F., Dopelheuer, and Lecht., M., "Methods to Assess Aircraft Engine Emissions in Flight," Congress of the International Council of the Aeronautical Sciences, 1996.
- Schaefer, M., and Bartosch, S., "Overview on Fuel Flow Correlation Methods for the Calculation of NOx, CO, and HC Emissions and their Implementation into Aircraft Performance Software," DLR Report, 2013.
- M. Ahearn et al., "Aviation Environmental Design Tool (AEDT) Technical Manual, Version 2b, Service Pack 3," 2016.
- Kim, B., and Rachami, J., "Aircraft Emissions Modeling Under Low Power Conditions," Technical Report, Observatory for Sustainability in Aviation, 2008.