FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Parametric Uncertainty Quantification of AEDT

Project 36

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Introduction

- Aviation Environmental Design Tool (AEDT) is the heart of the FAA's environmental tool suites for assessing fleet wide fuel burn, emissions, and noise impacts
- As AEDT sets the global standard for environmental impact analysis, it is under continuous improvements to implement the best modeling methods and data
- FAA is interested in quantifying uncertainties in AEDT output due to uncertainties in input parameters
- The main objectives of this research are to
  1. Perform Verification and Validation (V&V) for new methods and functionalities implemented to AEDT sprint releases
  2. Identify and quantify major contributors to output uncertainties
  3. Identify gaps in the tools' functionality and areas for further development

Practical Outcomes

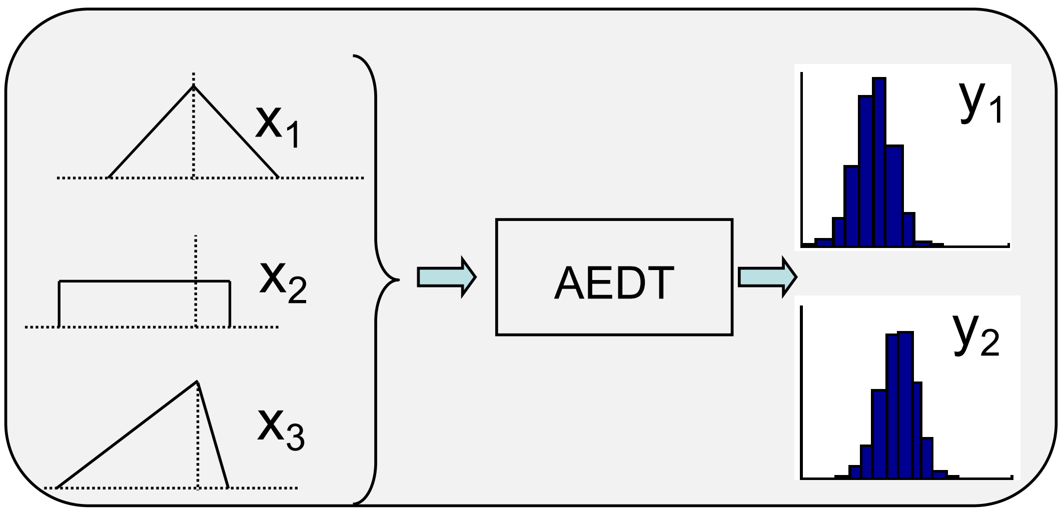
- Short term
  - Perform capability demonstrations and system testing
  - Perform V&V for new methods and functionalities implemented to AEDT sprint releases
  - Perform system level parametric uncertainty/sensitivity analysis
- Long term
  - Contribute to the external understanding of AEDT
  - Help users of AEDT understand sensitivities of output response to variation in input parameters/assumptions
  - Identify gaps in functionality
  - Identify high-priority areas for further research and development
  - Build confidence in AEDT's capability and fidelity (ability to represent reality)

Research Approach

- AEDT development team has been exercising the agile development process
- For each AEDT sprint, depending on the type of updates,
  - identify the key features and functionalities to conduct capability demonstration and system testing
  - identify the best available methods and data to conduct V&V
  - identify the key sources of uncertainties and the best approach to conduct parametric uncertainty quantification analysis

Inputs

1. Define a probability distribution for each factor (x_1, x_2, x_3)
2. Draw a random sample for each factor
3. Goto #2 and repeat



Outputs

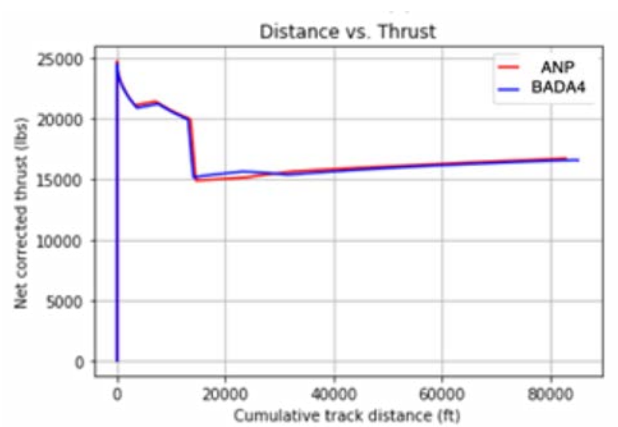
1. Model computes the outputs (y_1, y_2) for each random draw of factors
2. Results in probability distributions for each output that may be used to compute means, standard deviations, and confidence intervals

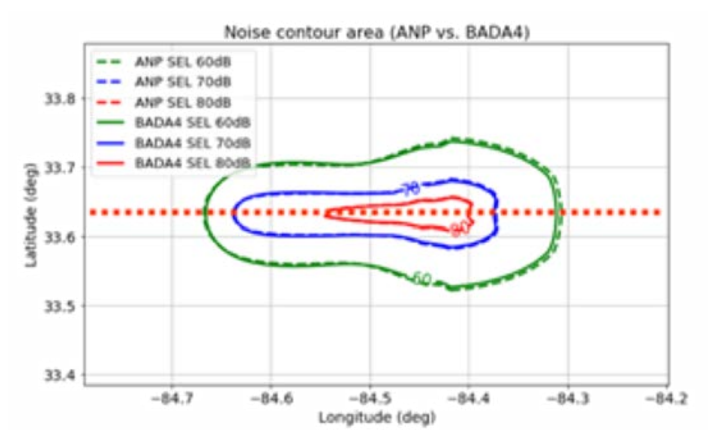
Major Updates in AEDT 3b

- Alternative weight and reduced thrust departure profiles

PROF_ID1	Weight	Takeoff Thrust Level	Climb Thrust Level
STANDARD	Standard Weight	0% Reduction	0% Reduction
MODIFIED_RT05	Standard Weight	5% Reduction	0% Reduction
MODIFIED_RT10	Standard Weight	10% Reduction	10% Reduction
MODIFIED_RT15	Standard Weight	15% Reduction	10% Reduction
MODIFIED_AW	Alternative Weight	0% Reduction	0% Reduction
MODIFIED_AW_RT05	Alternative Weight	5% Reduction	0% Reduction
MODIFIED_AW_RT10	Alternative Weight	10% Reduction	10% Reduction
MODIFIED_AW_RT15	Alternative Weight	15% Reduction	10% Reduction

- BADA4 aircraft performance model
  - High fidelity aircraft model (thrust, lift, drag)
  - Includes terminal area data (excluding ground roll)





Parametric Uncertainty Quantification

- For the newly implemented BADA4 performance model, a system-level parametric uncertainty analysis was performed to better understand the variation of outputs resulting from the variation of inputs

Step 1 — **Uncertainty Characterization**

- **Identify** inputs and outputs parameters
- **Mapping** of key BADA4 inputs to key environmental metrics based on literature review and expert knowledge
- **Specify the variability** of input parameters
- **Correlation analysis** of input parameters (when data is available)

Step 2 — **Sensitivity Analysis**

- **One-factor-at-a-time (OFAT) design of experiments**: change each input parameter one at a time while fixing other parameters at baseline values

Step 3 — **Uncertainty Propagation**

- **Screening Test**: to reduce the number of variables for surrogate models
- **Surrogate Modeling**: Artificial Neural Network (ANN)
- **Monte Carlo Simulation**
- **Copulas theory** is used to capture correlation between input parameters

Step 4 — **Global Sensitivity Analysis**

- Assess the impact of the input parameters on the outputs
- **Total sensitivity index (TSI)** can measure the relative impact of each of the input parameters

Basic Study Information

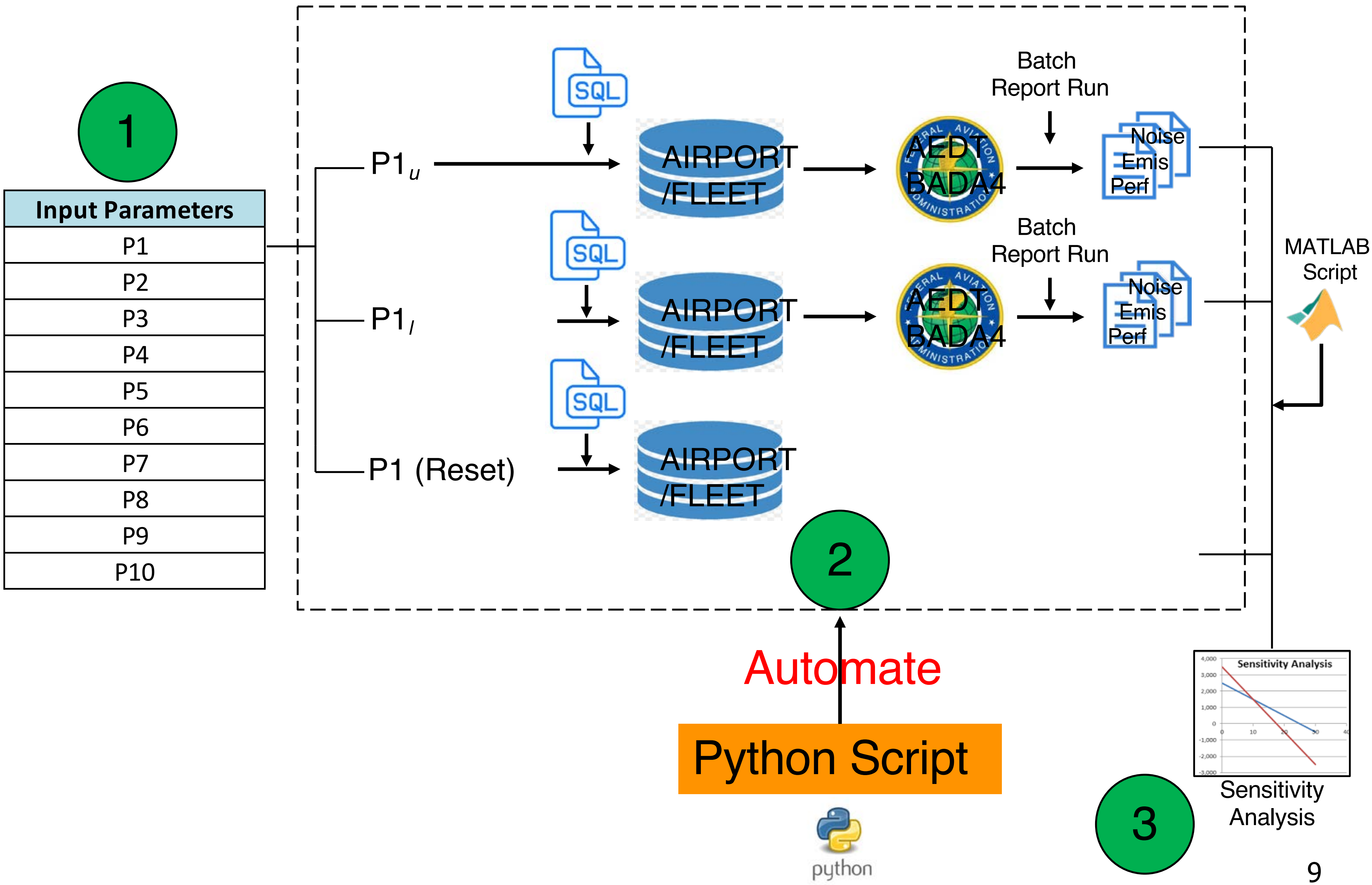
- Inputs:
  - Aircraft takeoff weight
  - Aircraft takeoff thrust
  - weather parameters
- Outputs:
  - Fuel burn: full flight and segments
  - NOx Emissions: full flight and segments
  - Noise: Contour Area, Length, and Width at 3 different noise levels
- AEDT Study:
  - Aircraft: B737800 and A320-200
  - Operations: departure and arrival
  - Airport: KATL
- Analysis:
  - Parameter Variation Range:
    - Weight: alternative weight
    - Thrust: reduced thrust
    - Weather parameters: varied based on historical range
  - Design of Experiment type: One-factor-at-a-time (OFAT)

Analysis of Physical Parameters

- Physical parameters were varied according to real-world range
- Historical weather data at KATL were used to define the upper and lower bounds in the uncertainty analysis
- Detailed parameters and ranges:

Parameter	Baseline Value	Upper Bound	Lower Bound
Temperature @ KATL	62	94	25
SL Pressure @ KATL	1018.02	1032	1004
ST Pressure @ KATL	980.61	993	968
Dew Point @ KATL	50.86	74	9
Relative Humidity@ KATL	67.65	100	20
Wind Speed @ KATL	7.03	24	0
Takeoff Weight	BL Weight	Alternative Weight	
Takeoff Thrust	100%	Three levels: -5%, -10%, -15%	

Automated Sensitivity Analysis Process on BADA4 Model



Sensitivity Analysis for B737-800 - Departure

Case No.	Parameter Name	Bounds	Fuel Burn	NOx Emission	75 dB: Area	75 dB: Length	75 dB: Width	80 dB: Area	80 dB: Length	80 dB: Width	85 dB: Area	85 dB: Length	85 dB: Width
1	TEMPERATURE (F)	94	6.3%	-21.2%	-17.2%	12.6%	-15.5%	-43.8%	-23.1%	-19.7%	-46.5%	-27.1%	-25.2%
2		25	-3.5%	10.3%	20.4%	-2.2%	25.0%	24.1%	5.1%	11.2%	7.9%	2.5%	5.9%
3	SLP_PR (mb)	1032	-0.2%	0.6%	-1.7%	-1.6%	0.0%	-1.6%	-1.5%	0.0%	-1.6%	-1.4%	0.0%
4		1004	0.2%	-0.6%	1.8%	1.6%	0.0%	1.6%	1.6%	-0.1%	1.6%	1.5%	-0.1%
5	ST_PR (mb)	993	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6		968	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	DEW_P (F)	74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8		9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9	REL_HUM (%)	100	0.0%	-5.5%	3.5%	0.2%	2.1%	1.7%	0.8%	0.6%	-1.0%	-0.5%	-0.3%
10		20	0.0%	8.7%	-9.5%	-2.1%	-5.8%	-19.7%	-10.4%	-7.6%	-25.5%	-16.1%	-10.3%
11	WND_SPD (Knots)	24	-1.2%	-1.5%	-4.0%	-5.6%	2.0%	-3.2%	-5.0%	2.2%	-3.5%	-5.9%	2.5%
12		0	0.5%	0.6%	1.7%	2.4%	-0.8%	1.4%	2.1%	-0.9%	1.5%	2.5%	-1.0%
13	ALT WEIGHT	-	1.7%	2.3%	2.6%	2.6%	-0.6%	2.5%	2.7%	-0.7%	2.3%	2.6%	-0.8%
14	REDUCED THRUST	-5%	0.0%	0.0%	-1.7%	0.3%	-3.4%	-2.0%	0.6%	-7.7%	-4.2%	1.4%	-9.6%
15	REDUCED THRUST	-10%	1.6%	2.2%	-5.2%	10.5%	-13.4%	-19.7%	-5.1%	-15.3%	-23.1%	-7.1%	-18.5%
16	REDUCED THRUST	-15%	1.7%	2.2%	-6.1%	11.2%	-14.0%	-21.0%	-4.1%	-19.7%	-25.2%	-4.7%	-25.4%

- For weather parameters, uncertainties in temperature, relative humidity, and wind speed can cause relatively large variations on the outputs
- Dew point and ST pressure does not have any impact on departure outputs
- SL pressure can have minor impact on the outputs
- Reduced thrust and alternative weight can also cause different values on the outputs

Sensitivity Analysis for B737-800 - Arrival

Case No.	Parameter Name	Bounds	Fuel Burn	NOx Emission	70 dB: Area	70 dB: Length	70 dB: Width	75 dB: Area	75 dB: Length	75 dB: Width	80 dB: Area	80 dB: Length	80 dB: Width
1	TEMPERATURE (F)	94	-0.6%	-25.1%	-35.6%	-16.0%	-22.6%	-28.7%	-8.0%	-25.0%	-34.0%	-18.2%	-19.0%
2		25	0.9%	11.9%	-6.5%	-4.2%	-1.3%	-7.8%	-3.2%	-6.6%	-14.5%	-6.8%	-8.1%
3	SLP_PR (mb)	1032	0.7%	1.6%	1.1%	0.5%	0.5%	0.9%	0.6%	0.6%	1.5%	0.8%	0.8%
4		1004	-0.7%	-1.6%	-1.2%	-0.5%	-0.5%	-0.9%	-0.6%	-0.6%	-1.5%	-0.7%	-0.8%
5	ST_PR (mb)	993	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6		968	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	DEW_P (F)	74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8		9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9	REL_HUM (%)	100	0.0%	-6.5%	-2.1%	-0.7%	-1.6%	-1.2%	-0.4%	-1.4%	0.1%	0.0%	0.2%
10		20	0.0%	10.3%	-27.2%	-12.9%	-16.6%	-23.4%	-7.0%	-20.4%	-32.3%	-17.2%	-18.2%
11	WND_SPD (Knots)	24	10.7%	15.5%	7.7%	2.2%	7.7%	10.9%	3.9%	9.6%	19.7%	9.2%	9.9%
12		0	-3.7%	-5.3%	-2.9%	-0.7%	-2.7%	-4.1%	-1.3%	-3.9%	-6.4%	-3.2%	-3.3%

- Temperature, SL pressure, and wind speed have observable impacts at the arrival fuel burn, emissions, and noise outputs
- Dew point and ST pressure does not have any impact on arrival outputs
- Relative humidity does not have impact on fuel burn, but has impact on NOx emission and noise
- Overall, uncertainties in temperature, relative humidity, and wind speed can cause relatively large variations on the outputs

Sensitivity Analysis for A320-200 - Departure

Case No.	Parameter Name	Bounds	Fuel Burn	NOx Emission	75 dB: Area	75 dB: Length	75 dB: Width	80 dB: Area	80 dB: Length	80 dB: Width	85 dB: Area	85 dB: Length	85 dB: Width
1	TEMPERATURE (F)	94	7.0%	-16.4%	-35.8%	-18.6%	-9.1%	-39.6%	-25.6%	-13.1%	-32.0%	-26.3%	-16.3%
2		25	-3.3%	-3.6%	15.0%	8.3%	6.3%	-5.1%	-4.3%	1.5%	-14.9%	-12.0%	-3.3%
3	SLP_PR (mb)	1032	-0.3%	0.1%	-1.6%	-1.3%	-0.4%	-1.8%	-1.4%	-0.4%	-2.1%	-1.7%	-0.3%
4		1004	0.3%	-0.1%	1.6%	1.4%	0.4%	1.8%	1.4%	0.3%	2.1%	1.8%	0.3%
5	ST_PR (mb)	993	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6		968	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	DEW_P (F)	74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8		9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9	REL_HUM (%)	100	0.0%	-5.5%	2.5%	1.5%	1.1%	1.1%	0.5%	0.5%	1.6%	1.3%	0.5%
10		20	0.0%	8.6%	-19.3%	-11.1%	-7.2%	-25.6%	-15.6%	-10.1%	-28.2%	-20.7%	-13.6%
11	WND_SPD (Knots)	24	-1.1%	-1.6%	-3.9%	-5.4%	1.7%	-4.6%	-6.8%	2.2%	-4.5%	-6.5%	2.8%
12		0	0.4%	0.7%	1.6%	2.4%	-0.7%	1.9%	2.8%	-0.9%	1.9%	2.5%	-1.1%
13	ALT WEIGHT	-	1.6%	2.2%	2.4%	2.6%	-0.6%	2.2%	2.7%	-0.7%	1.9%	3.0%	-0.7%
14	REDUCED THRUST	-5%	-0.1%	-0.1%	-0.9%	0.9%	-5.4%	-1.3%	1.7%	-6.0%	-1.8%	3.4%	-6.4%
15	REDUCED THRUST	-10%	2.2%	-2.2%	-14.8%	-2.8%	-10.7%	-14.4%	-2.2%	-11.6%	-14.6%	-6.2%	-12.5%
16	REDUCED THRUST	-15%	2.3%	-2.0%	-15.7%	-1.5%	-16.2%	-15.7%	0.2%	-17.8%	-16.7%	-2.1%	-19.2%

- For weather parameters, uncertainties in temperature, relative humidity, and wind speed can cause relatively large variations on the outputs
- Dew point and ST pressure does not have any impact on arrival outputs
- SL pressure can have minor impact on the outputs
- Reduced thrust and alternative weight can also cause different values on the outputs

Sensitivity Analysis for A320-200 - Arrival

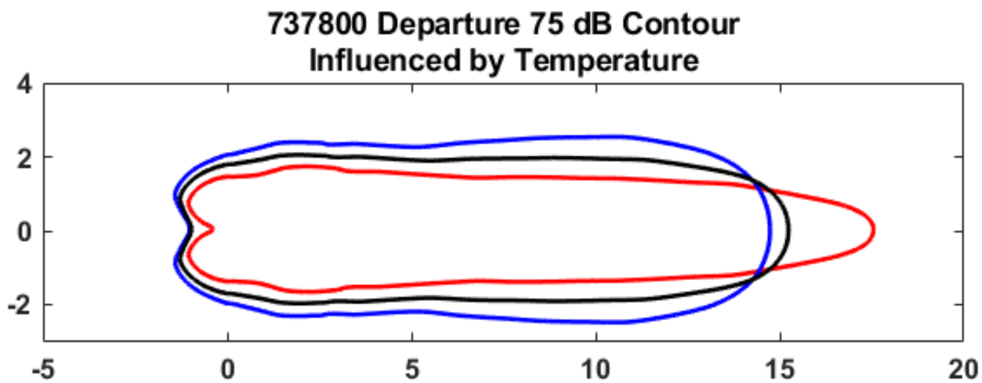
Case No.	Parameter Name	Bounds	Fuel Burn	NOx Emission	70 dB: Area	70 dB: Length	70 dB: Width	75 dB: Area	75 dB: Length	75 dB: Width	80 dB: Area	80 dB: Length	80 dB: Width
1	TEMPERATURE (F)	94	-0.7%	-19.3%	-32.1%	-16.2%	-17.2%	-28.3%	-13.0%	-19.3%	-28.7%	-12.2%	-17.1%
2		25	0.8%	12.1%	-2.9%	-1.7%	0.1%	-7.7%	-3.1%	-4.2%	-13.3%	-4.1%	-8.3%
3	SLP_PR (mb)	1032	0.7%	1.3%	1.5%	0.5%	0.7%	1.5%	0.8%	0.8%	1.5%	0.7%	0.9%
4		1004	-0.7%	-1.3%	-1.5%	-0.5%	-0.7%	-1.5%	-0.7%	-0.9%	-1.5%	-0.6%	-0.9%
5	ST_PR (mb)	993	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
6		968	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	DEW_P (F)	74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
8		9	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
9	REL_HUM (%)	100	0.0%	-6.8%	-0.6%	-0.2%	-0.4%	0.4%	0.2%	0.0%	1.9%	0.7%	1.2%
10		20	0.0%	10.7%	-25.5%	-13.0%	-12.8%	-25.2%	-10.9%	-16.6%	-30.8%	-13.0%	-18.7%
11	WND_SPD (Knots)	24	8.9%	15.8%	7.0%	1.7%	5.7%	10.2%	4.4%	7.5%	13.7%	4.3%	8.7%
12		0	-3.1%	-5.4%	-2.7%	-0.8%	-2.2%	-3.7%	-1.2%	-2.8%	-5.2%	-1.7%	-3.3%

- Temperature, SL pressure, and wind speed have observable impacts at the arrival fuel burn, emissions, and noise outputs
- Dew point and ST pressure does not have any impact on arrival outputs
- Relative humidity does not have impact on fuel burn, but has impact on NOx emission and noise
- Overall, uncertainties in temperature, relative humidity, and wind speed can cause relatively large variations on the outputs

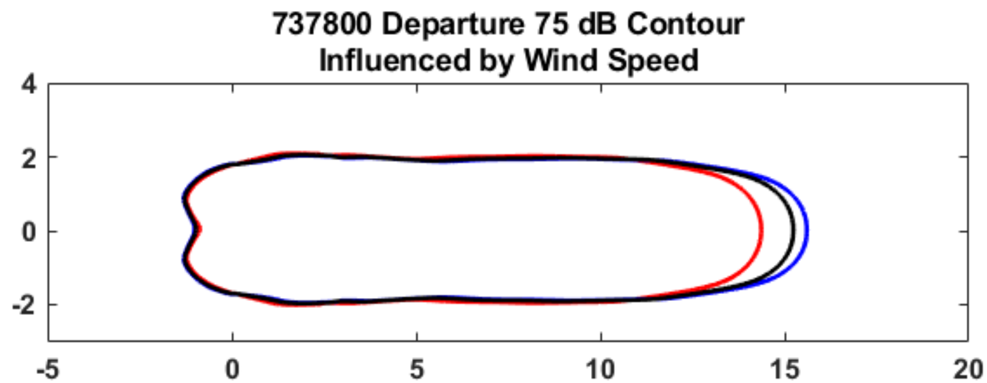
Noise Contour Differences
Caused by Uncertainties - Detailed Example

737-800 Departure Noise Contour at 75 dB

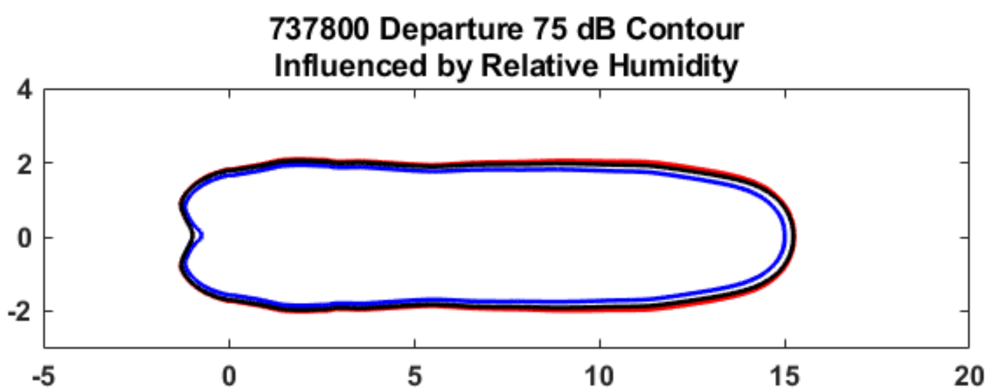
- High **- Baseline** **- Low**



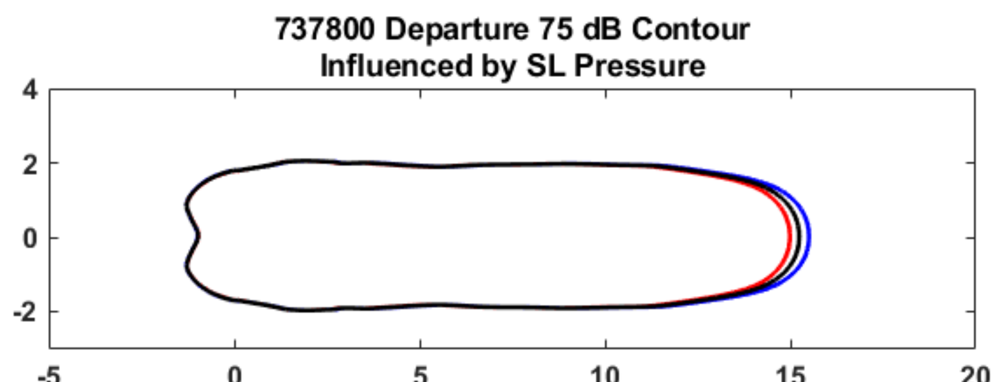
Parameter Name	Bounds	75 dB: Area	75 dB: Length	75 dB: Width
TEMPERATURE (F)	94	-17.2%	12.6%	-15.5%
	25	20.4%	-2.2%	25.0%



Parameter Name	Bounds	75 dB: Area	75 dB: Length	75 dB: Width
WND_SPD (Knots)	24	-4.0%	-5.6%	2.0%
	0	1.7%	2.4%	-0.8%



Parameter Name	Bounds	75 dB: Area	75 dB: Length	75 dB: Width
REL_HUM (%)	100	3.5%	0.2%	2.1%
	20	-9.5%	-2.1%	-5.8%



Parameter Name	Bounds	75 dB: Area	75 dB: Length	75 dB: Width
SLP_PR (mb)	1032	-1.7%	-1.6%	0.0%
	1004	1.8%	1.6%	0.0%

Summary/Next Steps

- GT team is working very closely with the AEDT development team to conduct independent V&V of the current and future AEDT versions
- GT has tested and verified that the AEDT's new capabilities are working properly
- GT has applied parametric uncertainty quantification method to AEDT 3b to conduct sensitivity analysis on BADA4 model
- GT will remain flexible and use the best available methods and data in order to ensure accuracy and functionalities of future AEDT versions
- Primary next steps:
  - Continue the parametric UQ on BADA4 model
  - User defined profile editor
  - AERMOD/AERMET updates
  - FOA4 implementation
  - Perform independent testing and uncertainty analysis for any newly released features and functionality

Interfaces and Communications

- External
  - Weekly telecons with the AEDT development team
  - On-line communication via Team Foundation Server (TFS)
- Within ASCENT
  - Bi-weekly telecon with the FAA management
  - P45 (Takeoff/Climb Analysis), P43 (NPD+C), P10
- Publication:
  - Jung-Hyun Kim, Seulki Kim, Kisun Song, Yongchang Li, Dimitri Mavris, Aircraft Mission Analysis Enhancement by using Data Science and Machine Learning Techniques, AVIATION 2019 conference, June , 2019
  - Zhenyu Gao, Ameya Behere, Yongchang Li, Dongwook Lim, Michelle Kirby, Dimitri N. Mavris, Quantitative Assessment of the New Departure Profiles with Improved Weight and Thrust Modeling, To be submitted to AIAA Journal of Aircraft
  - AEDT quarterly and annual reports
- Contributors
  - Georgia Tech Team: Prof. Dimitri Mavris (PI), Dr. Yongchang Li (Co-PI), Dr. Michelle R. Kirby, Dr. Mohammed Hassan
  - Graduate Students: Zhenyu Gao, Ameya Behere, Bogdan-Paul Dorca, Santusht Sairam
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