FAA CENTER OF EXCELLENCE FOR ALTERNATIVE JET FUELS & ENVIRONMENT

Takeoff/Climb Analysis to Support AEDT APM Development

Project 45

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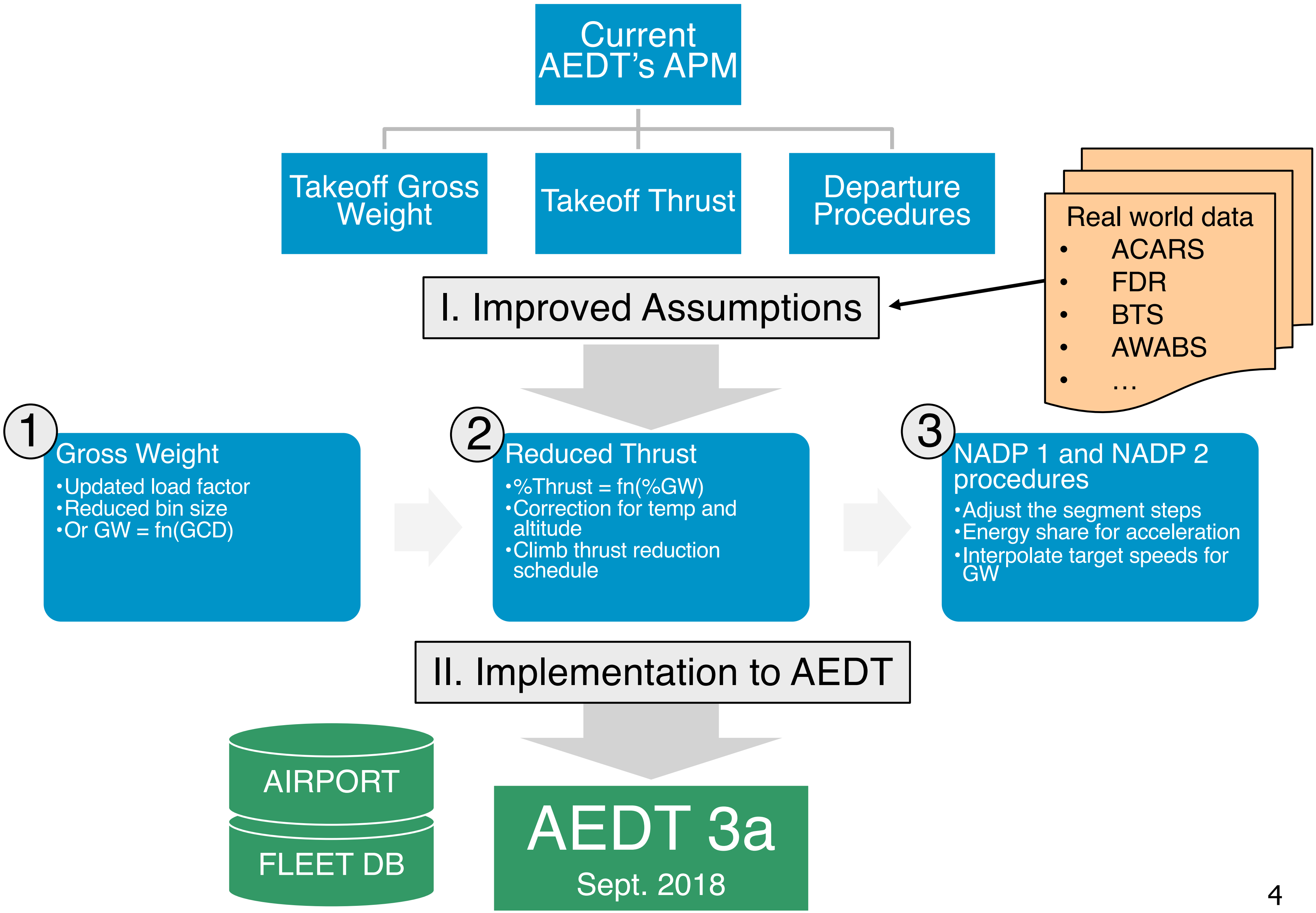
Introduction

- Accurate modeling of aircraft performance is a key factor in estimating aircraft noise, emissions and fuel burn
- Various assumptions are made for aircraft performance modeling (APM) within the AEDT with respect to:
  - Takeoff weight
  - Takeoff thrust
  - Departure procedure
- The main objectives of this research are to
  1. Identify prior relevant research methods and benchmark the current APM assumptions
  2. Conduct statistical analysis of real-world performance data
  3. Develop a state estimator
  4. Document recommendations for APM enhancements

Practical Outcomes

- Short term
  - Assessment of current modeling assumptions within the APM
  - Identification of modeling gaps to real world flight
  - Identification of necessary flight data to represent real world flight
  - Statistical analysis of real flight data
  - Sensitivity investigation of modeling assumptions, including fuel burn, NOx, and noise
- Long term
  - Recommendations for new algorithm to represent real world takeoff performance
  - Documentation of sensitivity analysis and implications of modifications to the procedures for the APM

Improving AEDT's Modeling Accuracy



Summary of the Findings and Recommendations

APM Assumptions	AEDT vs Reality (What's the problem?)	Importance (Does it matter?)	Changes to AEDT (how?)	Potential Data Source (by how much?)
Weight	• AEDT uses Stage Length (SL) bins • AEDT tends to underestimate GW by ~%5 for low SLs • AEDT may overestimate GW for high SLs	• **Medium** (-5 to +10%) difference in noise contour areas • NOx and FB (-5 to +10%)	• **Update the GW assumption for each bin** AND/OR • Reduce the bin size OR • Use a continuous function(s)	• IATA (GW) • BTS (Payload) • CAEP (LF) • SAPOE • AWABS • Users
Thrust	• AEDT uses 100% thrust • Airlines use reduced takeoff thrust when possible (~95% of the time) • Typically limited at 25% reduction • About 15% reduction on average, but can be as much as 40%	• **High** (Up to 40+%) difference in noise contour areas • NOx (-1%) • FB (+8%)	• **Change the thrust coefficients for takeoff and climb in the THRUST_JET table** • Change all Acceleration segments into Percent Acceleration segments in the PROCEDURES table	• IATA • Commercial runway analysis programs by FLYAPG.com • Project 35 → ACARS • Volpe → FDR • Physics based calculations • TTREAT • Users
Departure Procedures	• Most aircraft in AEDT have STANDARD, ICAO-A, and B Procedures • Airlines use NADP1 and 2 Procedures	• **Medium** (1~10%) difference in noise contour areas • NOx and FB (+5 to +19%)	• Rename the ICAO-A and B procedures to NADP1 and 2 • Adjust the segment steps • **Convert ROC to Energy Share percent** • Interpolate the VSTOP for different GW	• IATA • ICAO PANS-OPS • ICAO 2007 NADP Survey

New Profiles Implementation - Alternative Weight and Reduced Thrust

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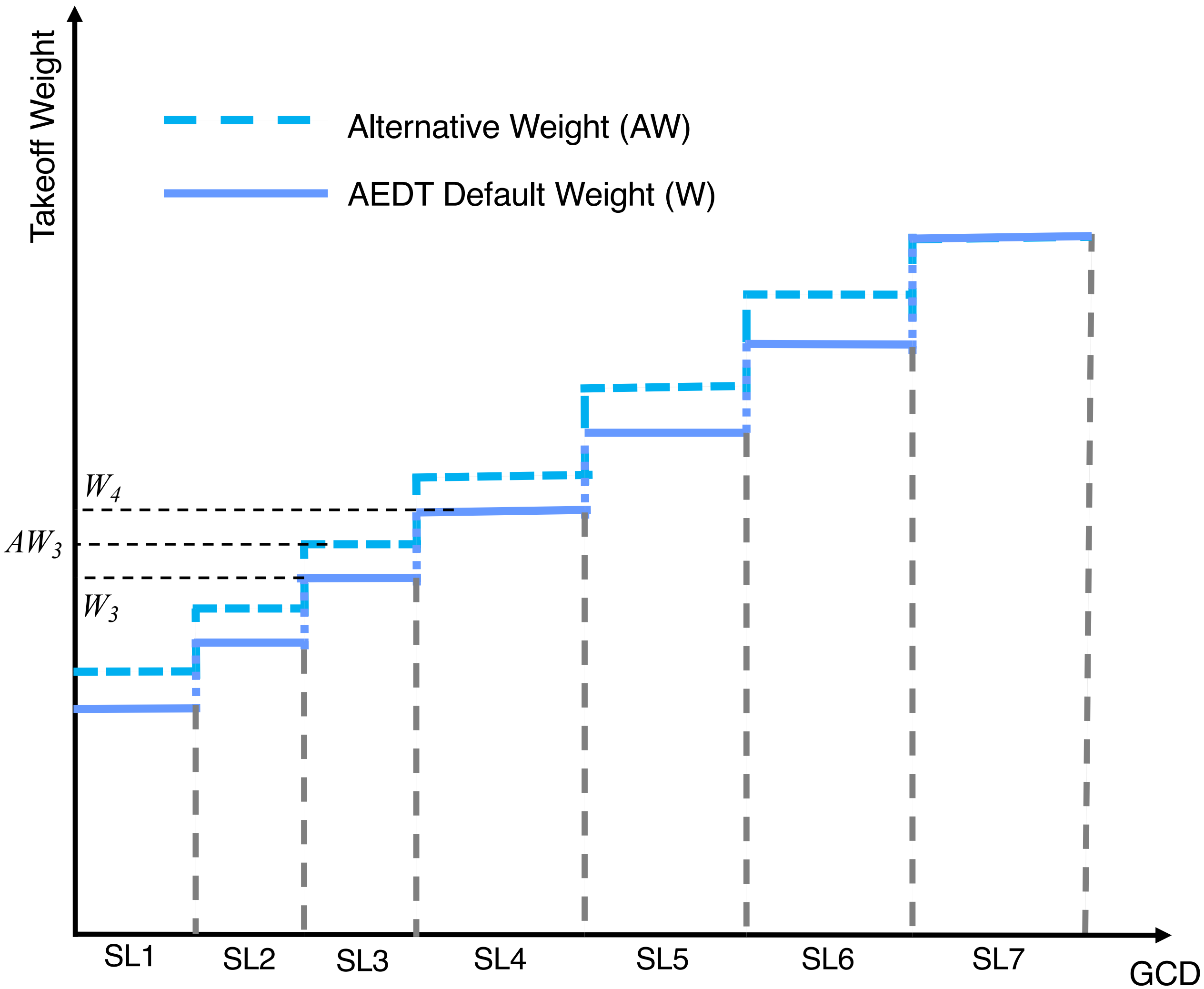
- Develop new profiles for 90 aircraft
  - 90 aircraft shortlisted by
    - ACFT_ID = "G" or "C"
    - NOISE_CAT = "3" or "4"
    - ENG_TYPE_CODE = "J"
  - Each aircraft to have 7 additional sets of profiles
- Populate FLEET DB
  - THRUST_JET table expanded from 417 entries to 941 entries
  - PROFILES table expanded from 1146 entries to 4289 entries
  - PROCEDURES table expanded from 6124 entries to 19760 entries

PROF_ID1	Weight	Takeoff Thrust Level	Climb Thrust Level	RoC/ES	Takeoff Thrust	Climb Thrust
STANDARD	Standard Weight	0% Reduction	0% Reduction	RoC	**T**	**C**
MODIFIED_RT05	Standard Weight	5% Reduction	0% Reduction	ES	**F** (new)	**C**
MODIFIED_RT10	Standard Weight	10% Reduction	10% Reduction	ES	**X** (new)	**D** (new)
MODIFIED_RT15	Standard Weight	15% Reduction	10% Reduction	ES	**Z** (new)	**D** (new)
MODIFIED_AW	Alternative Weight	0% Reduction	0% Reduction	ES	**T**	**C**
MODIFIED_AW_RT05	Alternative Weight	5% Reduction	0% Reduction	ES	**F** (new)	**C**
MODIFIED_AW_RT10	Alternative Weight	10% Reduction	10% Reduction	ES	**X** (new)	**D** (new)
MODIFIED_AW_RT15	Alternative Weight	15% Reduction	10% Reduction	ES	**Z** (new)	**D** (new)

Note: FAA AEE approval is required in order to use the modified profiles for regulatory applications. Users must submit a justification for the profile they select.

Takeoff Weight Implementation – Alternative Weight



- Maintain the current stage length (SL) bins
- The new weight of a stage length is the average of current SL weight and the weight of the immediate next SL

$$AW_i = \frac{W_i + W_{i+1}}{2}$$

- For the highest SL, use the original SL weight

$$AW_{max} = W_{max}$$

Takeoff Thrust Implementation – Reduced thrust for ANP

- The reduced takeoff thrust (C_{RT}) is implemented via a multiplication of the full thrust coefficients (C_{Full}) by the reduction percentage
- The reduced climb thrust is a function of the takeoff thrust reduction, for normal temperature:

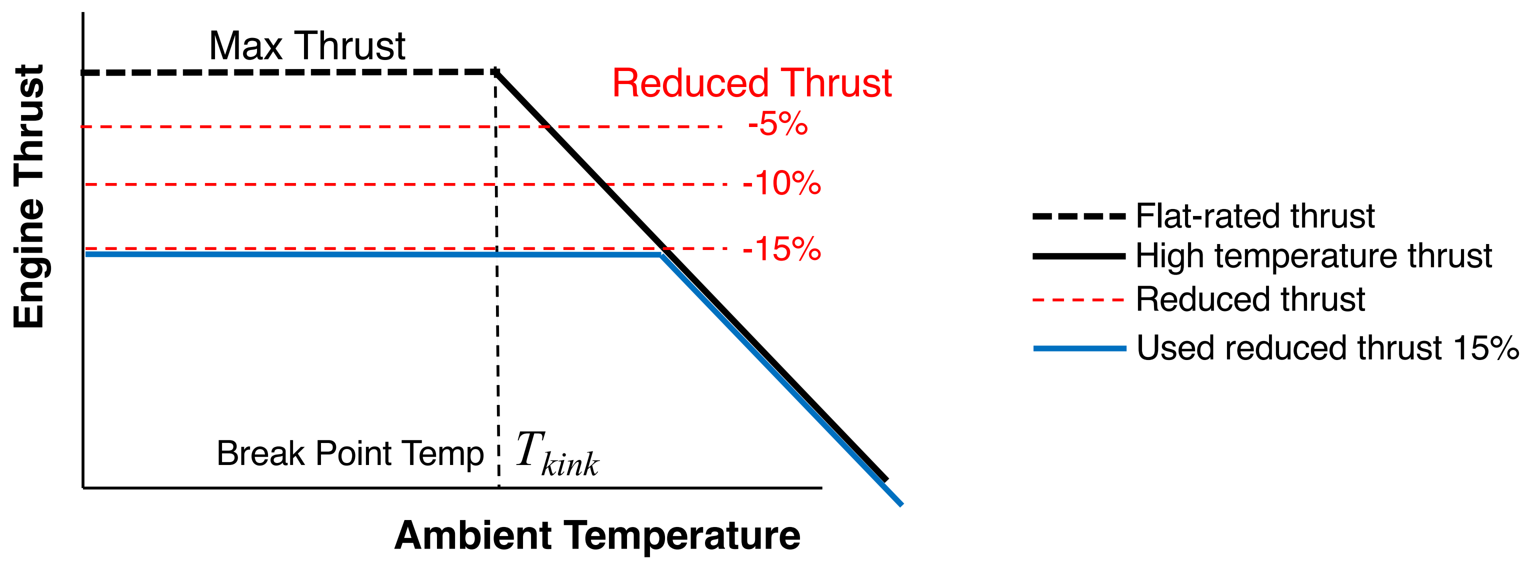
$$C_{RT} = k_{reduced} \cdot C_{Full}$$

Where:
C_{RT}: Reduced thrust coeff.
C_{Full}: Full thrust coeff.

$$k_{reduced} = \begin{cases} 1.00 & \textit{Full Thrust} \\ 0.95 & \textit{5\% reduced thrust} \\ 0.90 & \textit{10\% reduced thrust} \\ 0.85 & \textit{15\% reduced thrust} \end{cases}$$

Procedure thrust reduction	Takeoff Thrust Reduction	Climb Thrust Reduction
0% (standard)	0%	0%
5%	5%	0%
10%	10%	10%
15%	15%	10%

- However, the high temperature coefficients are not modified



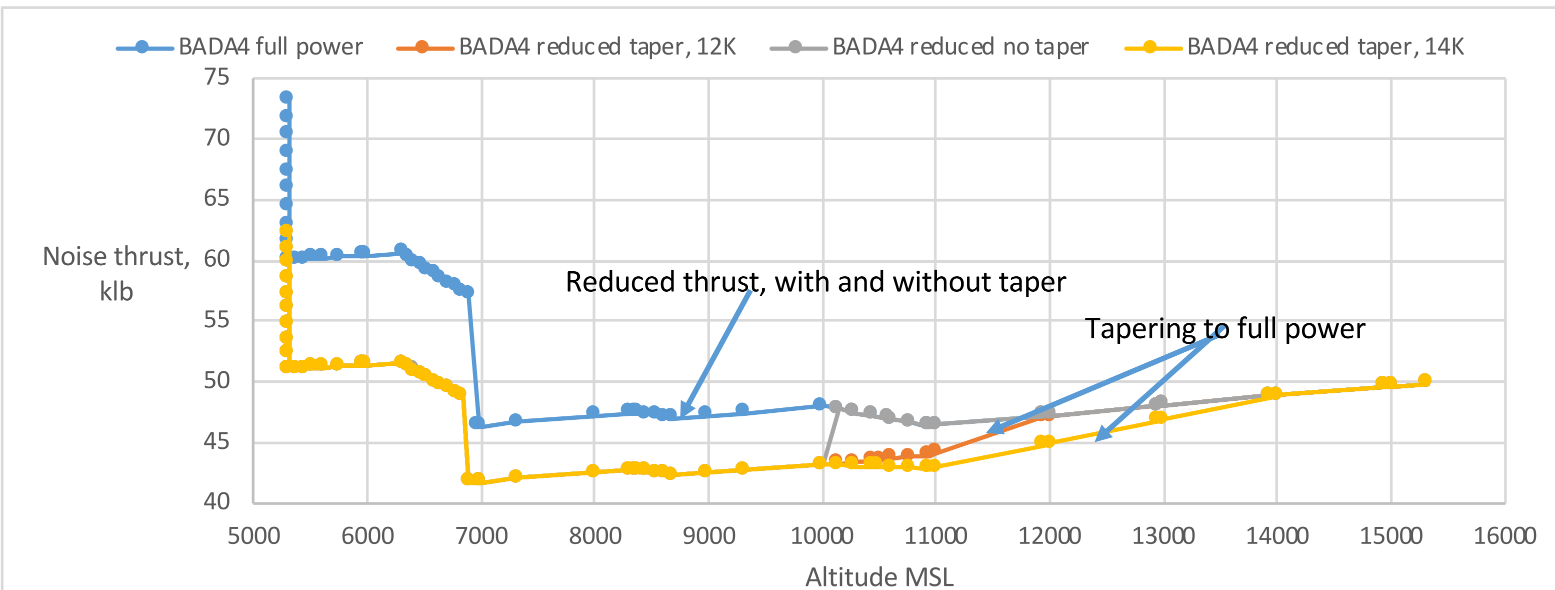
Takeoff Thrust Implementation – Reduced thrust for BADA4

- BADA 4 operations use the reduced thrust ANP departure procedure
- The flat area BADA4 thrust coefficient is scaled by the thrust reduction that corresponds to the procedure step's thrust type
- For high temperature, the thrust coefficient calculations implement the minimum thrust level method

$$C_{RT} = \begin{cases} k_{reduced} \cdot C_{Full,flat}\,, & T \leq T_{kink} \\ min(C_{Full,temp}, k_{reduced} \cdot C_{Full,flat})\,, & T > T_{kink} \end{cases}$$

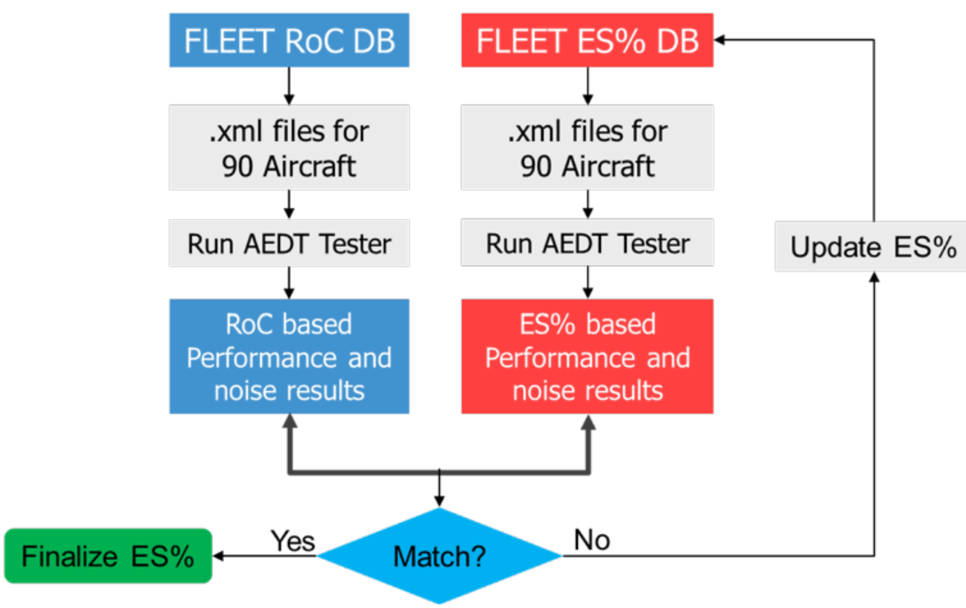
Where:
$C_{Full,flat}$: Full thrust at flat area
$C_{Full,temp}$: Full Thrust at high temp

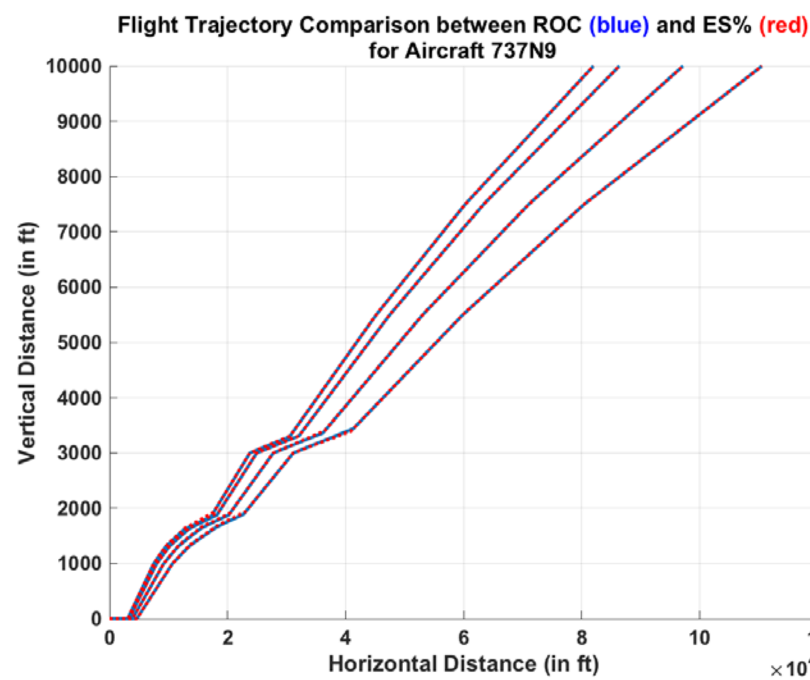
- Thrust taper was implemented for BADA4 reduced thrust profile



Takeoff Thrust Implementation - Procedure changes (Energy Share)

- With reduced thrust, the Rate of Climb (RoC) during acceleration steps of departure procedure is not correct
- The same energy share can be used for all the reduced thrust profiles of the particular aircraft
- Calculate energy share: $\frac{\Delta KE}{\Delta KE+\Delta PE}$
- Validate energy share:





Study 1: Testing All Combinations of Stage Lengths and New Profiles

- Test Matrix:

Aircraft	90	90 Aircraft
Operation	1	Departure
Procedure	8	STANDARD MODIFIED_RT05 MODIFIED_RT10 MODIFIED_RT15 MODIFIED_AW MODIFIED_AW_RT05 MODIFIED_AW_RT10 MODIFIED_AW_RT15
Runway	1	Shortest
Airport	1	Houston (KIAH)
Weather Data	1	ISA
Stage length	1 ~ 9	All

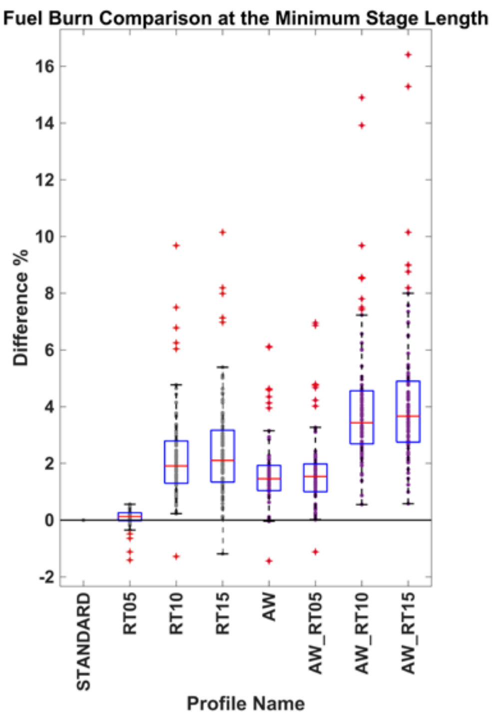
For each aircraft:
Departure:
1x1x1x1x(1~9)X8
Arrival: 1

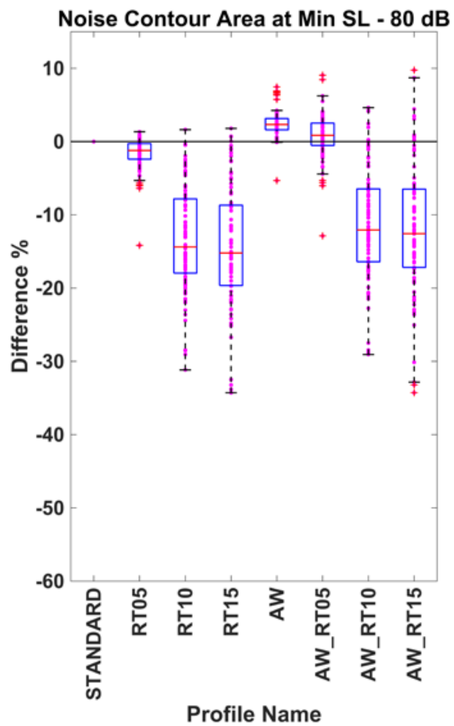
7124 cases for 90 aircraft

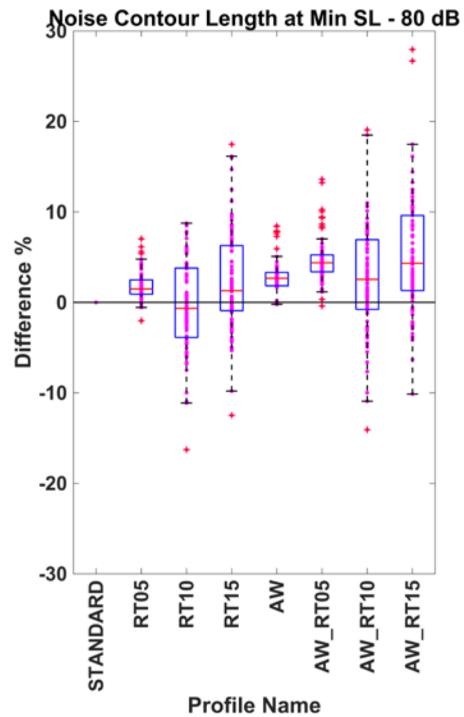
- Objective:
  - compare the fuel burn, emissions and noise results of the 8 profiles for all the stage lengths of each aircraft
- Overall, all cases ran successfully, there is no failure case

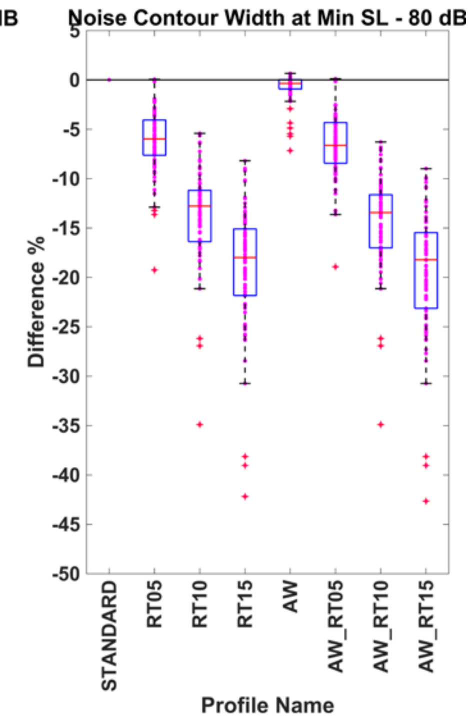
Test Results

- General trends for fuel burn and emissions:
  - With thrust reduction increases
    - Fuel burn, CO increases
    - NOx decreases
- General trends for noise contours:
  - With thrust reduction increases
    - Noise contour area and width decrease for all noise level
    - Noise contour length change is dependent on noise level









Study 2: Testing BADA4 and ANP Models with New Profiles

- Test Matrix:

Aircraft 90	Operation 2	Procedure 8
90 Aircraft	Departure Arrival	STANDARD MODIFIED_RT05 MODIFIED_RT10 MODIFIED_RT15 MODIFIED_AW MODIFIED_AW_RT05 MODIFIED_AW_RT10 MODIFIED_AW_RT15
Airport 3	**Runway 1**	
Atlanta (KATL) Houston (KIAH) Denver (KDEN)	Shortest	
Stage length 1	**Weather Data 2**	
Maximum	Normal Temp. High Temp.	

Departure:
3x1x1x1x2x8=48
Arrival:
3x1x1x2x1=6

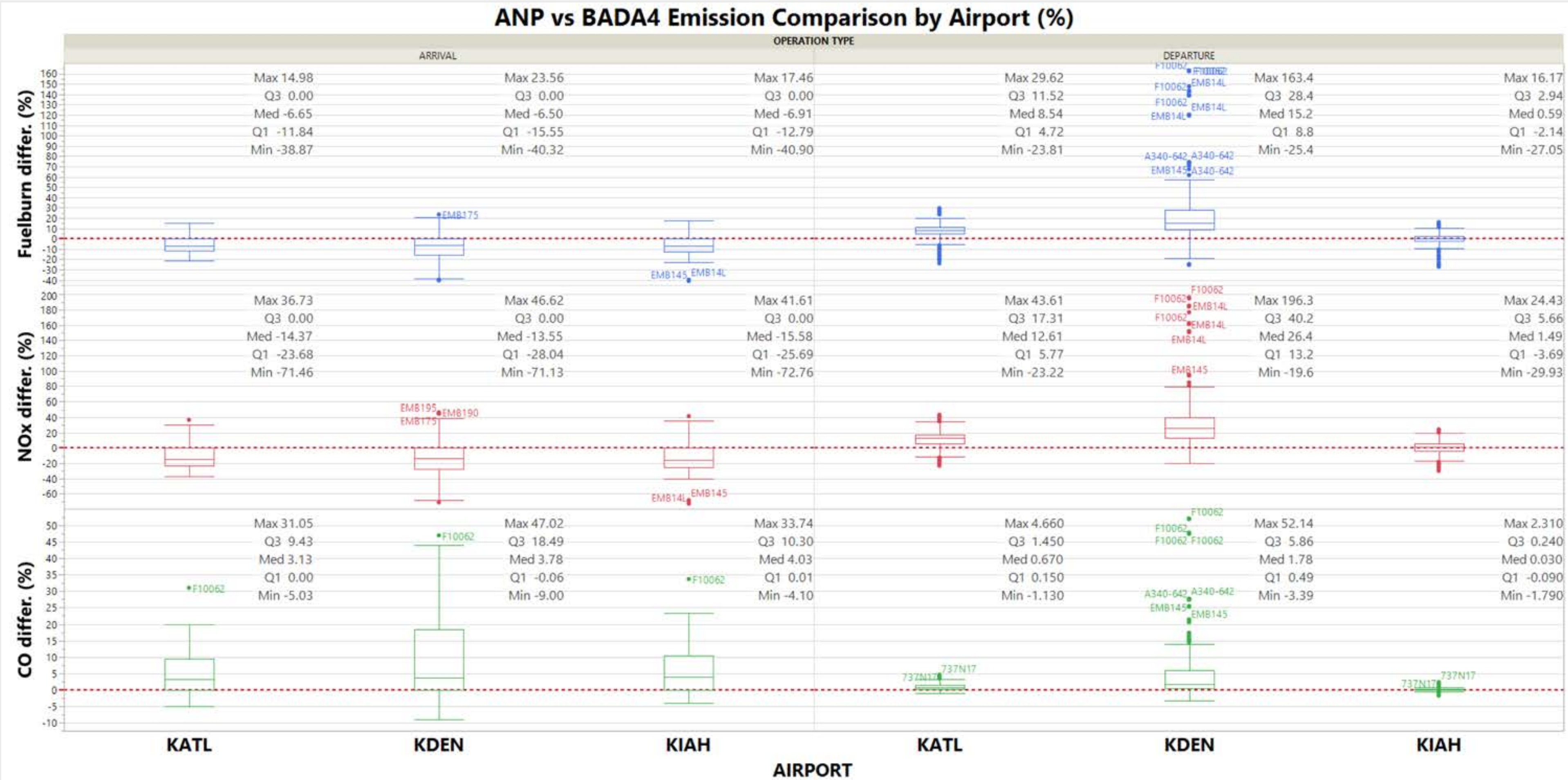
Total Case:
48+6=54

ANP & BADA4:
54x2=108
(4428 cases for 41 BAD4 aircraft and 2646 cases for ANP aircraft)

- Objective:
  - compare the fuel burn, emissions and noise results between BADA4 and ANP for all the 8 profiles of each aircraft

- 27 cases failed out of 4428 runs (0.6%)

Fuel Burn and Emissions Comparison by Airport



- Outliers were found to be from Embraer aircraft, MD82, 737N17, and A321-232; largely occurring for departure at KDEN

Summary

- Summary statement
  - Combination of better weight estimates, reduced thrust, and modeling of current Noise Abatement Departure Procedures (NADPs) will yield more realistic noise and emissions results
  - Developed and implemented new profiles with alternative weight and reduced thrust
  - Tested the new profiles, and compared ANP and BADA4 results with new profiles
  - Current procedures in AEDT do not match real world conditions for departure procedures
  - Results of this research will provide better understanding of the combined impacts of these factors

- Next steps
  - Improved takeoff weight modeling
  - Improved Takeoff Thrust Modeling
  - Add new flight procedures (NADPs) to better represent flights flown today

- Key challenges/barriers
  - Access to real flight data and other validation data
  - Iteration/automation of validation process

References

- AEDT APM algorithms and Fleet Database
- FAA AC 91-53A
- ICAO PANS OPS Chapter 3 Volume II
- ASCENT P35: Airline Flight Data Examination to Improve Flight Performance Modeling (2016)
- ASCENT P36: Parametric Uncertainty Quantification of AEDT 2b
- ACRP 02-41: Estimating Takeoff Thrust Settings for Airport Emissions Inventories (2014)
- ACRP 02-37: Integrated Noise Model Accuracy for General Aviation Aircraft (2014)
- BAH's Fuel Efficiency Project
- ACRP 02-12 Report 86
- ICAO 2007 NADP Survey
- Boeing 737 and 777 flight manuals
- GE and RR Reports on climb thrust

Contributors

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