Project 036 Parametric Uncertainty Assessment for Aviation Environmental Design Tool (AEDT)

Georgia Institute of Technology

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- FAA Award Number: 13-C-AJFE-GIT, Amendment 019, 29, and 30
- Period of Performance: January 1, 2017 – August 31, 2018
- Task(s):
    1. Development and Test of New Profiles with Reduced Thrust and Alternative Weight
    2. Validation and Verification of BADA4 Implementation
    3. Capability Demonstration and Validation of AEDT 2d and 2e Functionality

Project Funding Level

According to the original project plan, the funding from the FAA is $175,000 for 12 months. The Georgia Institute of Technology has agreed to a total of $175,000 in matching funds. The project was augmented for the period for 12/1/2016 to 3/31/2017 to add additional tasks. The augmented funding from the FAA is $80,000 for 4 months. The Georgia Institute of Technology has agreed to additional $80,000 in matching funds. The latest augmentation was for $300,000 for the period of performance of 4/1/2017 to 8/31/2018. The Georgia Institute of Technology has agreed to additional $300,000 in matching funds.

Investigation Team

Prof. Dimitri Mavris, Dr. Michelle Kirby, Dr. Dongwook Lim, Dr. Yongchang Li, Dr. Matthew Levine, Yee Chan Jin (Graduate student), Ameya Behere (Graduate student), Junghyun Kim (Graduate student), and Zhenyu Gao (Graduate student), with consultation/support by research staff Dr. Holger Pfaender.

Project Overview

The Federal Aviation Administration's Office of Environment and Energy (FAA/AEE) has developed a comprehensive suite of software tools that allow for a thorough assessment of the environmental effects of aviation, in particular the ability to assess the interdependencies between aviation-related noise and emissions, performance, and cost. At the heart of this tool suite is the high fidelity Aviation Environmental Design Tool (AEDT). AEDT is a software system that models aircraft performance in space and time to estimate fuel consumption, emissions, noise, and air quality consequences. This software has been developed by the FAA Office of Environment and Energy for public release. It is the next generation FAA environmental consequence tool. AEDT satisfies the need to consider the interdependencies between aircraft-related fuel consumption, emissions, and noise. AEDT 2 has been released in four phases. The first version, AEDT 2a, was released in March 2012 [1, 2]. The second version of AEDT 2b was released in May 2015 [3], the third version of AEDT 2c was released in September 2016, and the fourth version of AEDT 2d was released in September 2017. A new series AEDT 3a will be released in December 2018 which have major updates including Base of Aircraft Data 4 (BADA4) performance model for fuel consumption, emissions and noise, reduced thrust profiles, and implementation of ASCENT Project 45 findings.

This uncertainty quantification comprehensively assesses the accuracy, functionality, and capabilities of AEDT during the development process. The major purposes of this effort are to:

- Contribute to the external understanding of AEDT
- Build confidence in AEDT's capability and fidelity (ability to represent reality)
- Help users of AEDT to understand the sensitivities of output response to the variation of input parameters/assumptions
- Identify gaps in functionality
- Identify high-priority areas for further research and development

The uncertainty quantification consists of verification and validation, capability demonstrations, and parametric uncertainty/sensitivity analysis.

Task 1-Development and Test of New Profiles with Reduced Thrust and Alternative Weight

Georgia Institute of Technology

Objective(s)

Under ASCENT Project 45, new reduced thrust and alternative weight profiles were developed for major aircraft and implemented in AEDT 3a [4]. The new profiles allow the aircraft to takeoff at reduced thrust and alternative weight to better represent the real-world departure operations. There are three reduced takeoff thrust levels: 5%, 10% and 15% reduction on full takeoff thrust. In addition, the profiles with 10% and 15% takeoff thrust reduction also have a 10% climb thrust reduction. The alternative weight is a simple average of the current stage length weight and the weight of the immediate higher stage length. In the new profiles, the rate of climb for the acceleration step was converted to energy share percentage which can provide the same climb rate and be used for different reduced thrust levels.

The implementation of the reduced thrust and alternative weight profiles is a big change to AEDT, thus, uncertainty quantification analysis needs to be conducted to make sure these profiles were implemented correctly. In this task, the study focused on thoroughly testing the newly developed profiles to verify if they are working properly for different aircraft at different stage length, airport, weather profiles, and comparing the environmental impacts of the new profiles including fuel burn, emission and noise.

Research Approach

New departure profiles for AEDT were created for 90 aircraft. These profiles were based on the STANDARD procedural profiles. A total of 7 sets of profiles were created for each aircraft, 4 for the alternate weights and 4 for original AEDT weight. These 2 subgroups both contain profiles with full thrust takeoffs and reduced thrust takeoffs with 5%, 10% and 15% thrust reduction. The creation of these new profiles involved the use of SQL data tables. New thrust types were implemented for reduced thrust capabilities, this was done by applying the reduction percentage to the relevant thrust equation coefficients. High temperature thrust types were not modified. Alternate weight profiles were created by creating new profiles and assigning them the appropriate weight. The weight assigned to such profiles was taken to be the average of the current and the next stage length weight. The final stage length weight was not modified. Finally, the procedural profile steps were implemented for the new profiles by converting the accelerated climb steps to energy share percentage climb steps. The new thrust type codes were also assigned as appropriate. In total, across 90 aircraft, an additional 524 thrust settings and 3143 profiles were created involving an additional 13636 procedural steps.

To test the new profiles with reduced thrust and alternative, AEDT studies were created with the new profiles for different scenarios. Each metric results in AEDT was run with both ANP and BADA4, and the fuel burn, emissions and noise results will be compared between ANP and BADA4 for different scenarios.

ANP and BADA4 Case Study with New Profiles

The purpose of this study is to fully test the new profiles by comparing the fuel burn, NOx, CO, and noise between Aircraft Noise and Performance (ANP) model and BADA4 model using a fleet study consisting of 41 available BADA4 aircraft. This could then help understand the difference in the environmental impacts between ANP and BADA4 and identify the outliers for each of these parameters. The study consisted of a total of 2214 cases, which is the combinations of 41 aircraft, 2 operation types, 3 airports, 1 runway (shortest at the airport), 2 temperature profiles (modeling normal and hot day), 1 stage length (maximum stage length of the aircraft), and 8 profiles including the 7 new profiles for each aircraft, as shown in Figure 1. And in the name of profiles RT stands for reduced thrust and AW stands for alternative weight. The process of generating, running, extracting, and analyzing the large sum of cases can be seen in the depiction Figure 2.

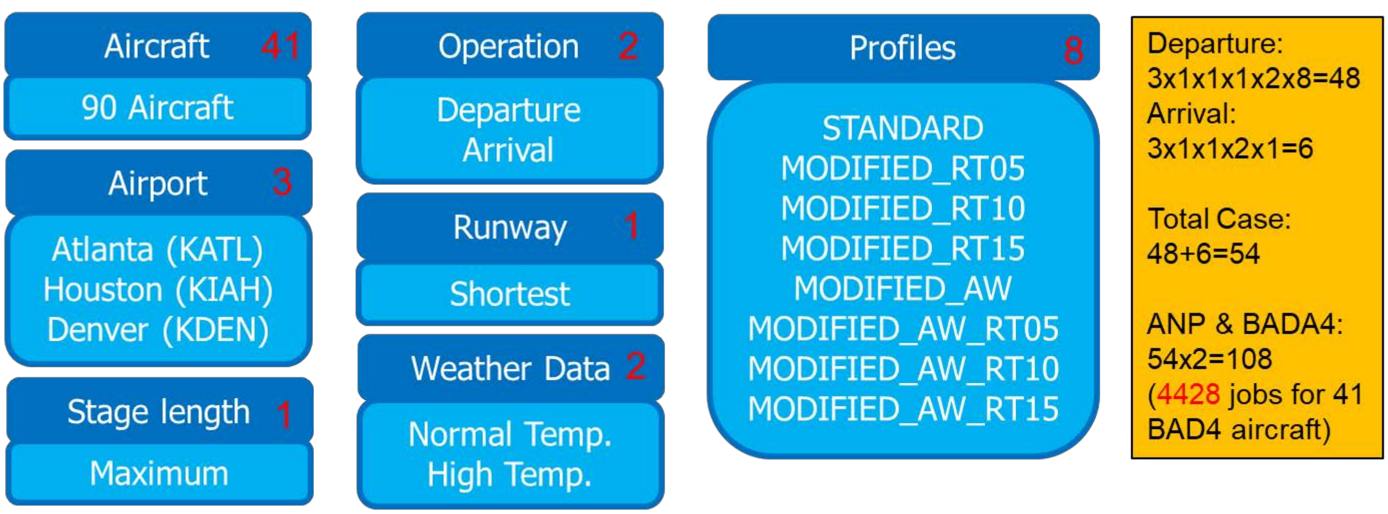

Figure 1. Combination of settings for the 41 BADA4 aircraft case study

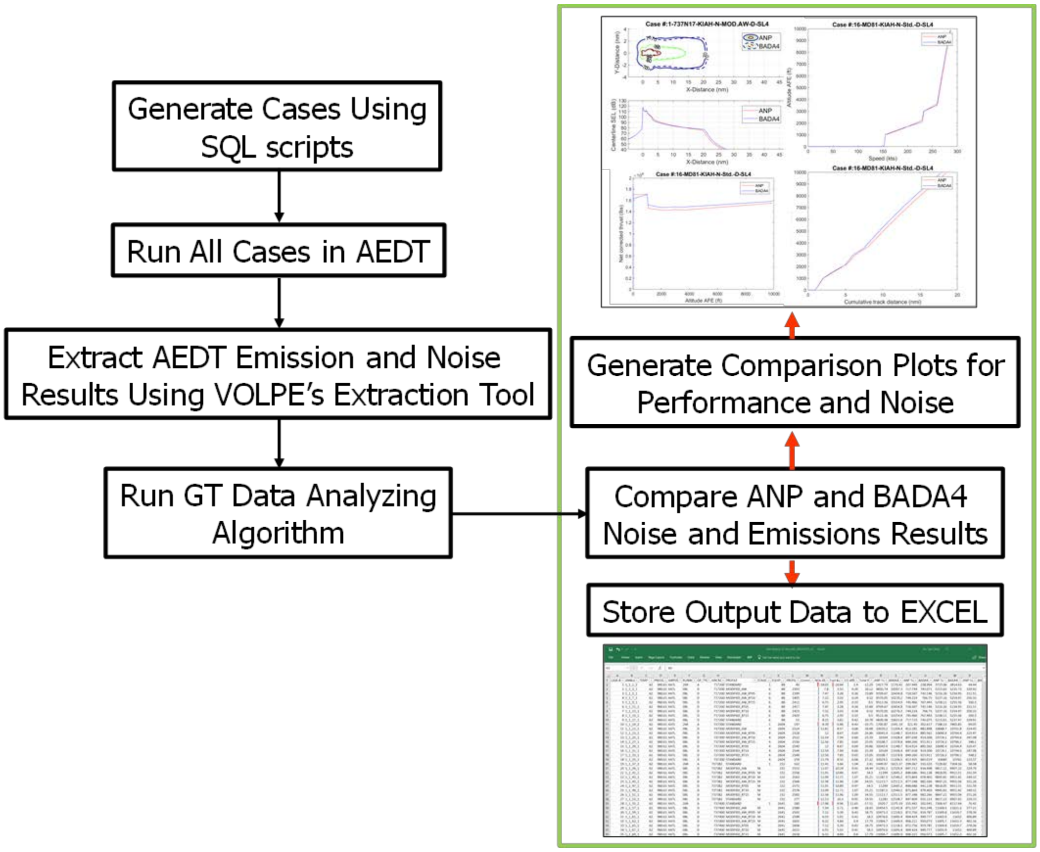

Figure 2. The processing cycle of the 41 BADA4 Case Study

The 2,214 cases were generated using a SQL script that automatically created the cases in AEDT by ANP and BADA4 (thus a total case study of 4,428 cases). Once the cases were generated and the study was run in AEDT. It was observed that 27 of 4428 jobs failed which is only 0.6% of total cases and they all happened at Denver airport. After the AEDT study was run, a batch mode tool developed by Volpe can be used to extract the performance, fuel burn, emissions and noise results. Then the fuel burn, emission and noise data were analyzed using a tool created by the Georgia Tech (GT) team. The tool could directly extract the necessary data from SQL or from relevant AEDT output files and generate a datasheet of input parameters, ANP versus BADA4 performance plots, noise contours, centerline plots, noise contour area differences, and emission comparisons. Essentially, the tool can generate all the relevant ANP and BADA4 comparison data, regardless of the case study size and complexity.

Figure 3 shows the fuel burn statistical comparison for departure and arrival operations of the 41 aircraft between ANP and BADA4. It can be seen that BADA4 departure fuel burn is greater by 12.6% on average than ANP. This is expected since BADA4 used the Mean Seal Level (MSL) based profile, that is, the 250 knot Calibrated Air Speed (CAS) at 10,000 ft above MSL rule is implemented in BADA, while ANP uses 250 knot CAS at 10,000 ft Above Field Elevation (AFE). This implementation results in differences in the performance, fuel burn, emissions and noise results between ANP and BADA4, especially for operations at airport with high altitude. This also leads to that BADA4 has much longer trajectories before reach 10,000 ft AFE, and thus produces more fuel. Since BADA4 follows the 250kt/10000ft MSL Federal Aviation Regulation (FAR) rule, its results are closer to the real aircraft operation and more accurate than ANP. It is also can be seen from Figure 3 that fuel burn produced by BADA4 is 7.6% less on average than ANP, which mainly is due to different approach modeling between ANP and BADA4. Readers can refer to the section Idle Descent where the difference in approach modeling was discussed and it was indicated that BADA4's results are more accurate.

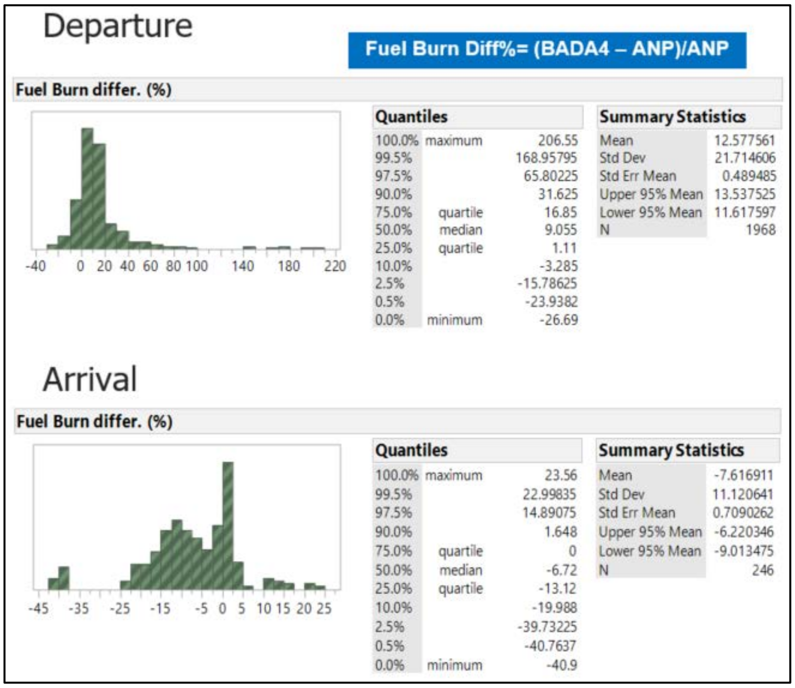

Figure 3. Fuel Burn Comparison between ANP and BADA4

Figure 4 to Figure 5 show the ANP versus BADA4 emission comparisons for NOx, fuel burn, and CO by airport and profile type for all profiles, with labels showing the outlier aircraft models. The airport specific plot has also been divided into departure and arrival procedures. The figures show a grouping of outliers for KDEN departure procedures, which is further explained in the outlier analysis section, and very little, to no outliers in the other two airports. Furthermore, the F10062 and several Embraer aircraft can be seen showing up as outliers throughout different profile types for all emission types; however, it was decided to rather draw concern on outliers that were either Airbus or Boeing aircraft since these are the more prevalent models. Consequently, the outlier plots show the A340-642 and B737-N17 as consistent outliers for departure operation throughout various profile types for all the emission types. The A340-642 was then selected for further investigation to narrow down the source of the large emission differences between ANP and BADA4.

In the airport-specific study for departure cases, the gap between the first and third quartile (except for KDEN) is extremely small around 2-10%. This means that for KIAH and KATL departure cases, the emission results comparison between APN and BADA4 are quite similar regardless of the aircraft type. Additionally, only a handful of aircraft showed up as outliers under these settings. This is not the case for departure cases at KDEN where the maximum differences in emission reach up to 200%. This is four to five times larger than the maximum emission differences from each of the corresponding airports. The difference in first to third quartile for KDEN departure is also around 20%, which is at least twice that of the other airports. Further looking into arrival procedures, there is a similar trend in CO results as KDEN shows a much larger quartile difference of 20% compared to that of the other two airports of 10%. Nevertheless, the arrival cases show relatively uniform emission result plots across the different airports compared to that of departure cases. It was found that many of the outliers occurred for departure cases at KDEN.

Looking at the emission results by profile type in general, the modified profiles (which are all departure procedures since arrival procedures do not have modified profiles) had mean emission values (for CO, fuel burn, and NOx) that were above zero. Fortunately, the quartile differences for CO and fuel burn were less than 10%; however, the quartile differences for NOx were relative high at 20% for all modified profiles. The outliers for all the modified profiles were found to be consistent throughout the profiles with F10062 and Embraer showing up with the largest emission differences between ANP and BADA4. For the standard profiles, which included arrival procedures, shows similar trends to that of the modified profiles. The profile-specific study shows how the outliers are not necessarily dependent on profile types (since they are equally spread out over all the profiles), but rather dependent on airport type and aircraft model.

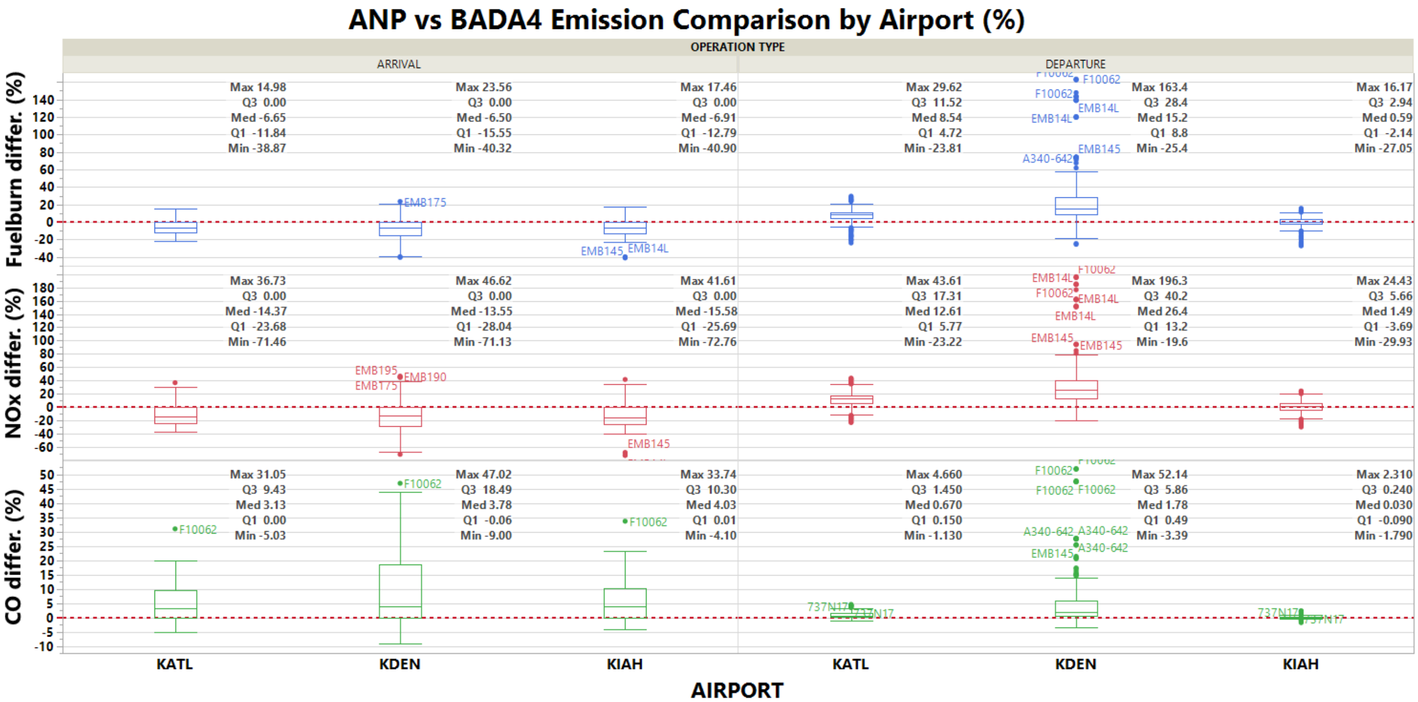

Figure 4. ANP vs. BADA4 Emission Comparison by Airport

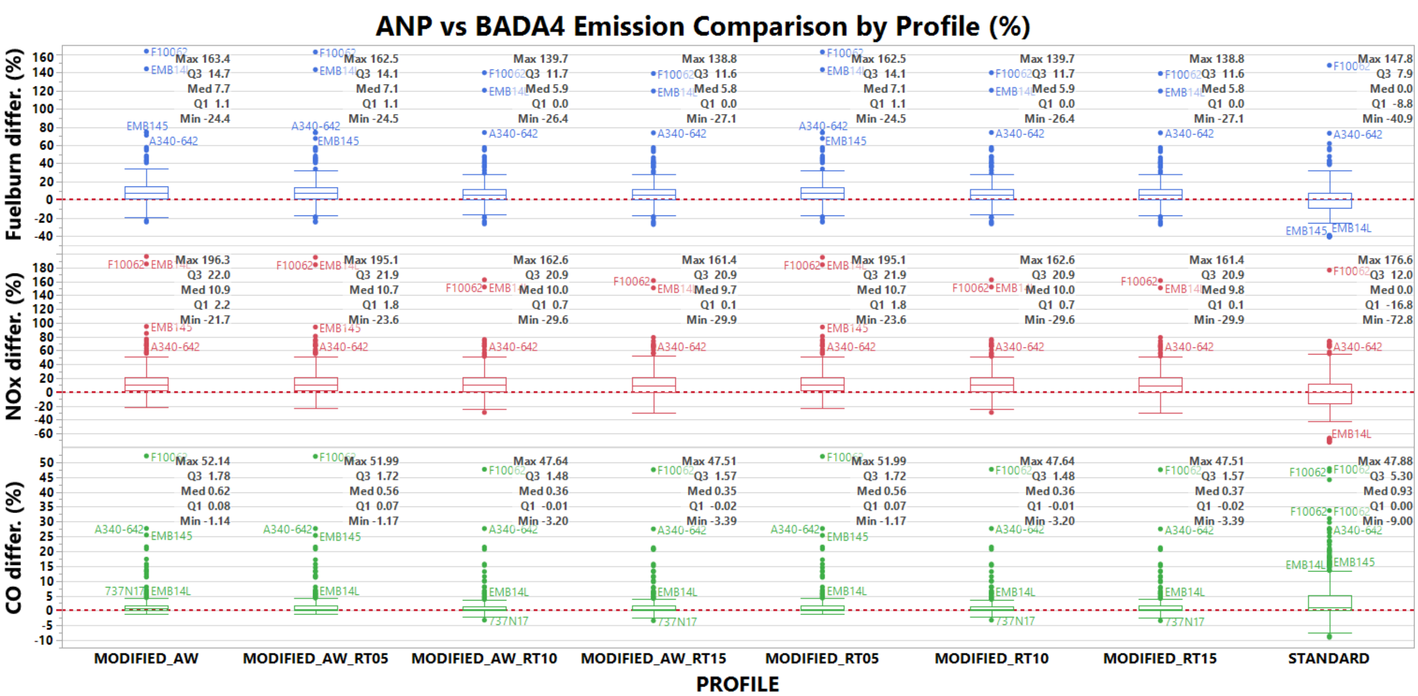

Figure 5. ANP vs. BADA4 Emission Comparison by Profile Type

Subsequently, Figure 6 to Figure 7 show the noise comparison between ANP and BADA4 by airport and profile type. The noise levels are categorized by SEL, from 70 dB to 90 dB with the airport specific plot also split into departure and arrival procedures. As mentioned in the emission outlier study, the majority of the outliers seem to occur around the KDEN airport, which will be further explained in the analysis section, but is primarily due to the airport's high elevation. Congruent to that of the emission study, the F10062 and several Embraer aircraft have been identified as outliers throughout the selected SEL range for all three airports. Furthermore, the MD82 had emerged as a consistent outlier in the noise study, but no further investigation was performed by GT as it was selected by the FAA for further data updates. Looking through the different profiles, besides the outliers already identified through the emission study, some new outliers were found to be A321-232 and the B747-20B which occurred during standard profiles. Since these aircraft are either Boeing or Airbus, they were selected for further study.

Similar to the emission study, the airport-specific plots show a very small quartile difference throughout all the airports but show a cluster of outliers at KDEN airport. And further looking at the profile-specific study, it shows how the MD82 and Embraer aircraft are strong outliers throughout all profile types with no other specific clusters easily noticeable throughout the profiles. It is, however, important to note that the standard profiles experience a larger difference in ANP and BADA4 noise levels from outliers than that of modified profiles with maximum differences occurring at over 170%. Hence, from the noise study it was found that the majority of the noise outliers occurred around KDEN for standard profiles.

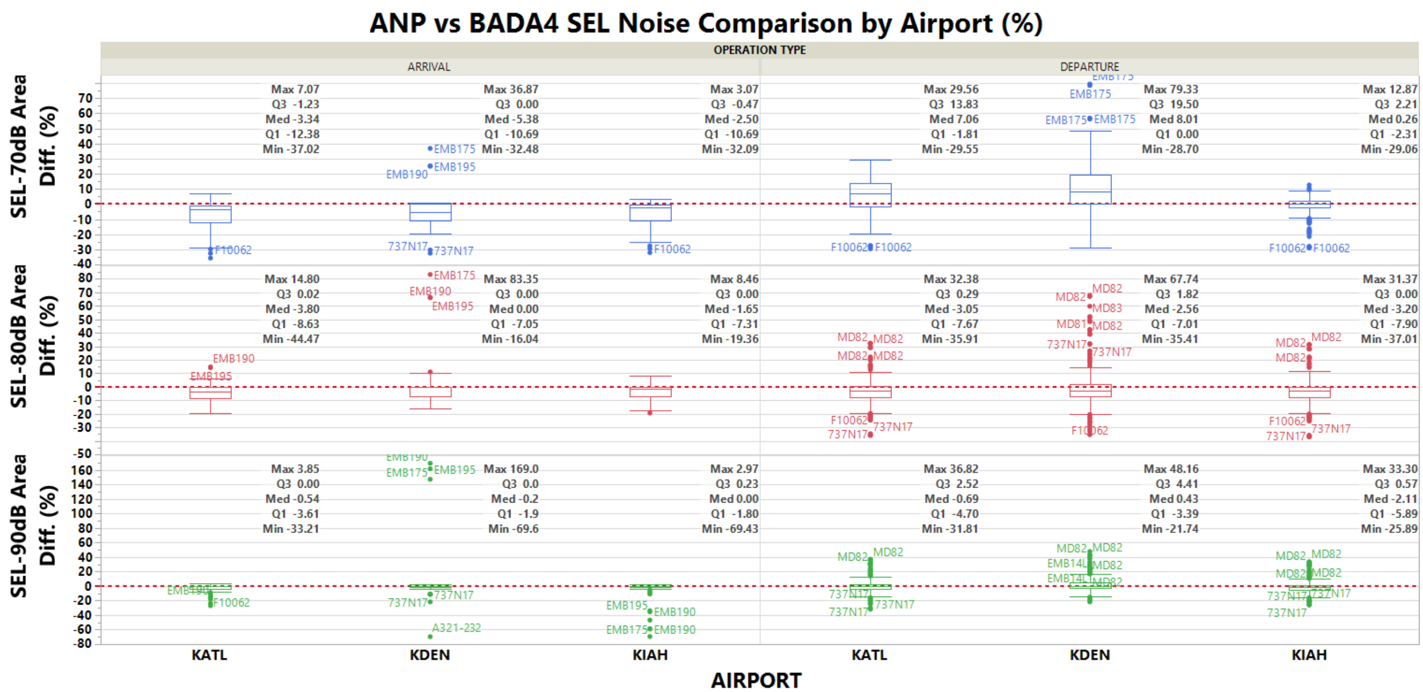

Figure 6. ANP vs. BADA4 SEL Noise Comparison by Airport

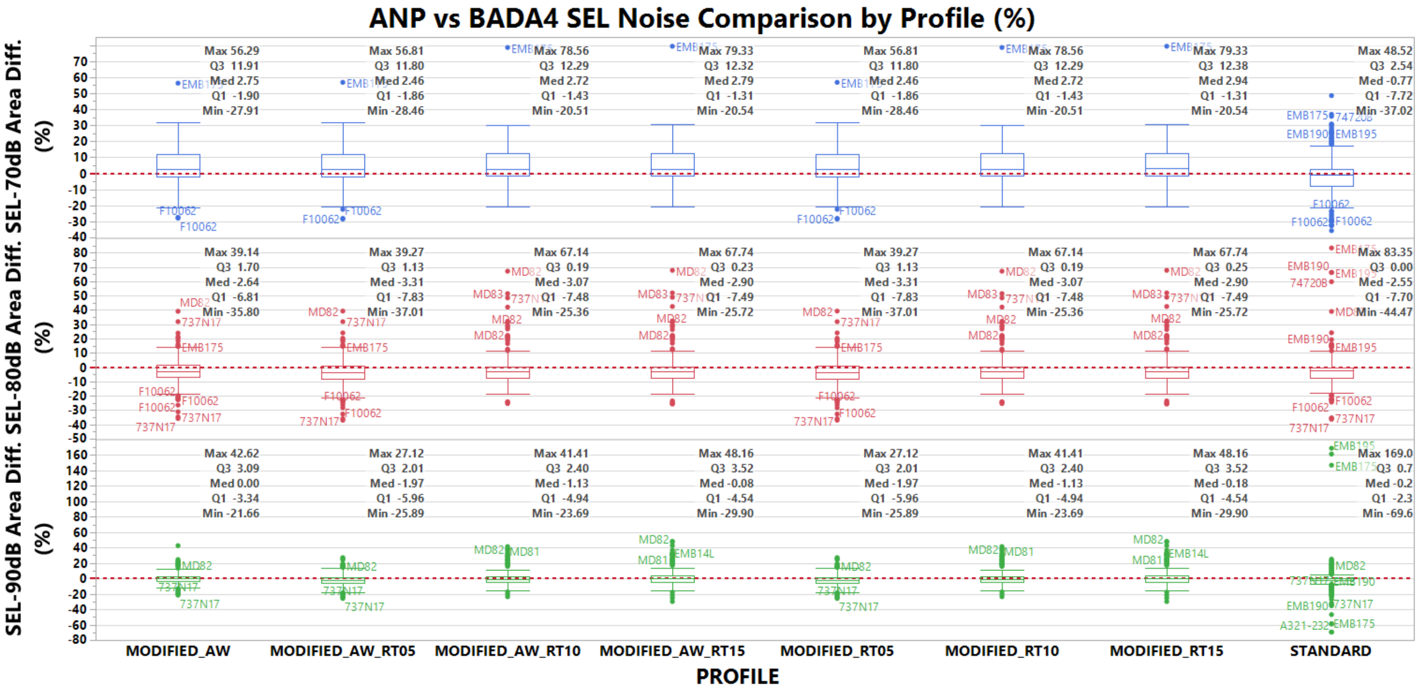

Figure 7. ANP vs. BADA4 SEL Noise Comparison by Profile Type

Outlier Analysis
In addition, the study shows that the outlier aircraft were MD82, F10062, A340-642, B737-N17, B747-20B, and several Embraer aircraft. Most of the outlier cases occurred at Denver International Airport (KDEN). The primary reason for much of the outliers being present in KDEN is due to the airport's high elevation (around 5,000 ft MSL) since BADA4 uses the 250 knot speed limit based on 10,000 ft MSL instead of 10,000 ft AFE which is used by ANP. Thus, the KDEN departure and arrival cases would have a relatively large difference in emission and noise results. An example of the trajectory differences for KDEN can be seen in Figure 8. The figure shows how the trajectories deviate away from each other around 5,000 ft AFE at KDEN, which is 10,000 ft MSL.

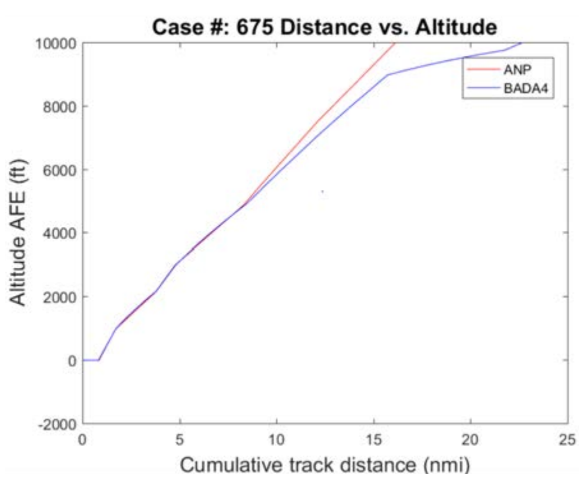

Figure 8. Differences in Trajectory between ANP and BADA4 for High-Elevation Airports

The figure shows that above 5,000 ft AFE, ANP maintains a constant climb rate while BADA4 will accelerate out and cover more distance. Consequently, this will lead to a higher fuel burn for BADA4 compared to that of ANP. For the KDEN outliers, the trajectory difference directly impacted the performance results. As an example, Figure 9 shows the net thrust, speed, and trajectory differences between ANP and BADA4 for the A340-642 during a standard departure at KDEN under average airport weather. At around 5,000 ft AFE, where ANP and BADA4 start to have different trajectories, the BADA4 shows a drastic increase in speed.

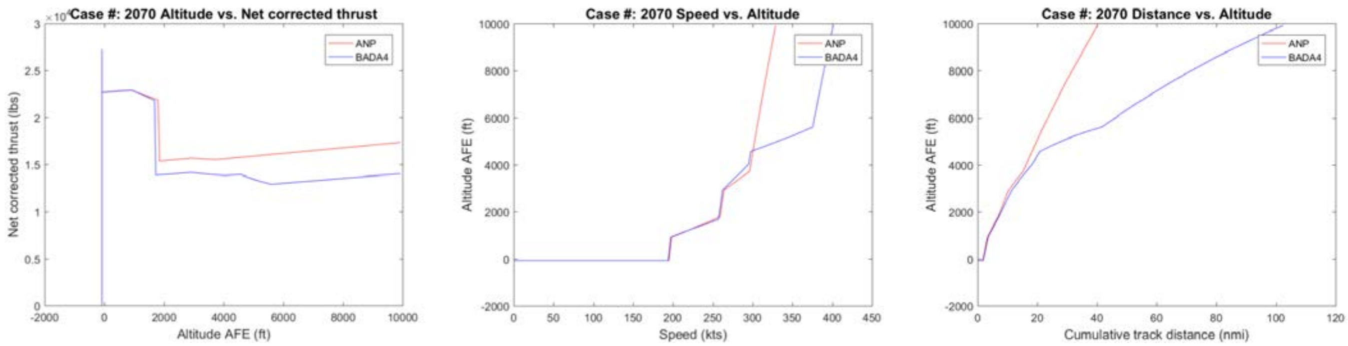

Figure 9. Net Corrected Thrust, Speed, and Trajectory Differences between ANP and BADA4 for the A340-642

Additionally, the subsequent noise contour plots and centerline plots are from the B737-N17 and the MD81 aircraft during departure at KIAH with 15% reduced thrust settings (the MD aircraft and B737-N17 are under further investigation). The contour plots show how the ANP runs generated a noise level of 70dB over a longer X-direction than that of BADA4. The centerline plot also shows the large differences in noise levels for ANP and BADA4, which is why these two aircraft were identified as outliers during the noise outlier study. Since this large noise difference for these aircraft occurred at KIAH (whose elevation is close to sea-level), it was an obvious choice for further investigations.

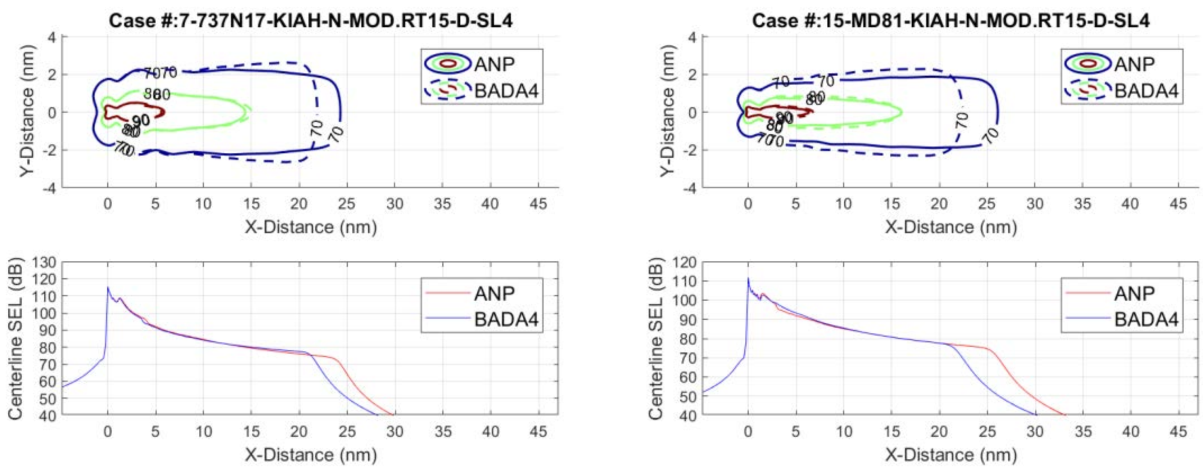

Figure 10. Noise Contour Plot and Centerline Plot of B737-N17 (left) and MD81 during 15% reduced thrust departure at KIAH

For outliers that appeared for airports besides KDEN, specifically the MD aircraft and the B737-N17, further investigation is underway to determine the source of the large differences in emission and noise (except the F10062 and Embraer; these were not pursued).

Task 2-Validation and Verification of BADA4 Implementation

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Objective(s)

The FAA has incorporated BADA4 as part of the AEDT Fleet DB. This task focuses on a fleet wide environmental V&V effort to assess the implications of BADA4 from the historical Fleet DB. GT will ensure that the BADA4 algorithm and associated data are properly incorporated into AEDT by performing investigation at flight segment, entire flight, and airport level tests. The BADA4 performance results will be compared to the results using ANP model for terminal area operations. The environmental impacts that are fuel burn, emission, and noise results, using BADA4 will be compared to the results from using ANP.

Research Approach

Performance and Environmental Impact Comparisons between ANP and BADA4

Base of Aircraft Data Family 3 (BADA3) method has been widely used for aircraft performance and fuel consumption modeling in AEDT. Although BADA3 works well in the cruise region, it is known that BADA3 is not optimized for terminal area operations. For this reason, AEDT uses BADA3 for aircraft performance modeling at altitude above 10,000 feet and uses Aircraft Noise and Performance (ANP) method for aircraft performance modeling at altitude below 10,000 feet. In order to address the drawbacks of BADA3 in the terminal area, the high fidelity Base of Aircraft Data Family 4 (BADA4) has been developed. The BADA4 model had only been used for sensor-path flights, which are based on trajectory-driven flight performance. Since the AEDT development team has added procedure-based flight performance using BADA 4, the research team investigated the BADA4 model with a procedure-based performance by comparing with ANP model.

As a system testing plan, the research team considered harmonizing a variety of scenarios with a testing matrix as shown in Figure 11 which consists of two aircraft, three airports, two operation types, two temperature profiles. In this example, the research team compared the performance results generated by BADA4 and ANP models for each case defined in the test matrix.

Figure 11. Testing matrix for BADA4 vs. ANP comparison

Since there were a lot of test cases, in order to avoid repeating work, the Python code was written to automate the generation and visualization of the detailed metric results. The general process includes the following steps: 1) Run AEDT; 2) Parse all results from SQL server; 3) Specify data-frames for both ANP and BADA4; 4) Plot performance comparison between ANP and BADA4 for each case; 5) Plot emission comparison between ANP and BADA4 for each case; 6) Modify the noise data-frame to calculate noise contour area; 7) Calculate ANP and BADA4 noise contour areas; and 8) Plot noise receptors. The algorithm overview is shown in the Figure 12. For a verification and validation purpose, the Python code was validated against AEDT results with respect to noise contour area. For instance, the difference in noise contour area between AEDT and the Python code were only approximately 0.01%.

Using the Python code, the research team was able to generate all comparison plots between ANP and BADA4 within approximately 6 seconds for one case comparison. After running all possible combinations from the testing matrix, the Python code was used to generate all metrics for all test cases. The results for all cases are summarized in the Table 1.

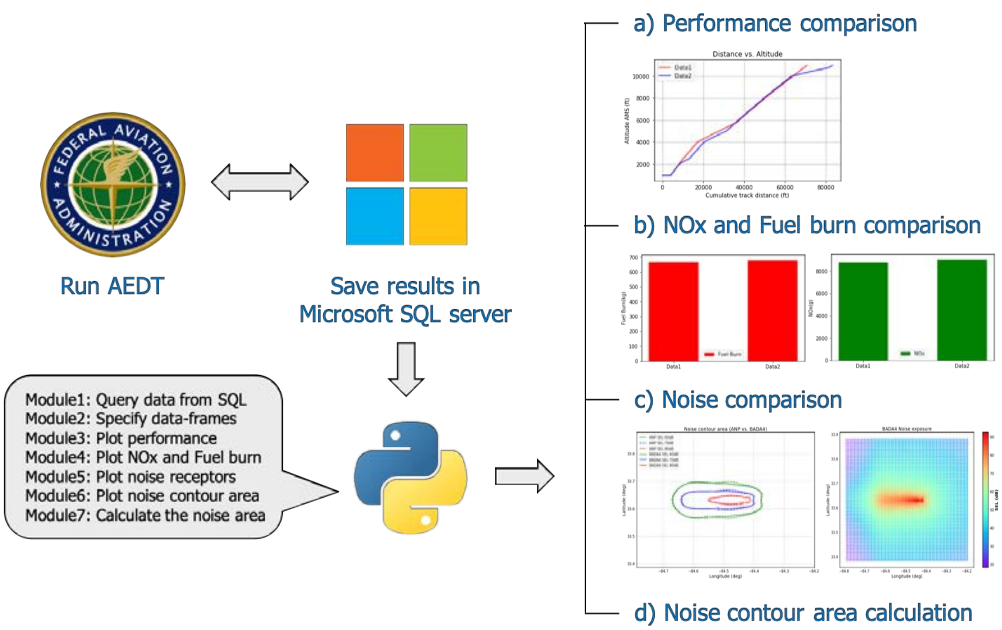

Figure 12. Overview of the Python code for AEDT post-processing

Table 1. Test results for all cases (BADA4 vs. ANP comparison)

Case #	Airport	Temperature	Weather data	Aircraft	Operation	NOx differ. (%)	Fuel Burn differ. (%)	BADA4 is working?
1	KATL	Normal	Airport average	B737-700	Departure	9.19	5.84	Yes
2	KATL	Normal	Airport average	EMB-190LR	Departure	7.25	3.98	Yes
3	KATL	Normal	Airport average	B737-700	Arrival	-16.27	-11.27	Yes
4	KATL	Normal	Airport average	EMB-190LR	Arrival	-2.64	-0.28	Yes
5	KSAN	Normal	Airport average	B737-700	Departure	0.78	1.72	Yes
6	KSAN	Normal	Airport average	EMB-190LR	Departure	-0.4	0.71	Yes
7	KSAN	Normal	Airport average	B737-700	Arrival	0	0	APM Fallback
8	KSAN	Normal	Airport average	EMB-190LR	Arrival	0	0	APM Fallback
9	KDEN	Normal	Airport average	B737-700	Departure	15.89	13.54	Yes
10	KDEN	Normal	Airport average	EMB-190LR	Departure	17.92	8.34	Yes
11	KDEN	Normal	Airport average	B737-700	Arrival	-19.83	-13.67	Yes
12	KDEN	Normal	Airport average	EMB-190LR	Arrival	22.27	12.18	Yes
13	KATL	Hot	Airport average	B737-700	Departure	13.35	8.62	Yes
14	KATL	Hot	Airport average	EMB-190LR	Departure	18.15	11.41	Yes
15	KATL	Hot	Airport average	B737-700	Arrival	-18.51	-11.84	Yes
16	KATL	Hot	Airport average	EMB-190LR	Arrival	8.92	4.63	Yes
17	KSAN	Hot	Airport average	B737-700	Departure	2.89	3.92	Yes
18	KSAN	Hot	Airport average	EMB-190LR	Departure	7.59	7.16	Yes
19	KSAN	Hot	Airport average	B737-700	Arrival	0	0	APM Fallback
20	KSAN	Hot	Airport average	EMB-190LR	Arrival	0	0	APM Fallback
21	KDEN	Hot	Airport average	B737-700	Departure	25.71	24.15	Yes
22	KDEN	Hot	Airport average	EMB-190LR	Departure	42.49	36.86	Yes
23	KDEN	Hot	Airport average	B737-800	Arrival	-22.6	-14.52	Yes
24	KDEN	Hot	Airport average	EMB-190LR	Arrival	51.51	23.91	Yes

As can be seen in the Table 1, some of cases had a small difference between ANP and BADA4 with respect to fuel burn and emission. Figure 13 and Figure 14 also show the performance and noise comparison for such cases with small difference between ANP and BADA4 at San-Diego airport. Although ANP and BADA4 were almost identical for most of the test cases, it was found that some of the cases produced a big difference in emission and fuel burn results. The research team conducted an airport elevation test for ANP and BADA4 performance comparison using the same aircraft, operation, temperature, and weather. As a result, it was observed that there is a big difference between ANP and BADA4 performance at high elevation airport as shown in the Figure 15. The research team investigated the reason that leads to the huge difference at high elevation airport; and concluded that the difference was due to MSL/AFE based procedure used by BADA4 and ANP BADA4 model respectively. To be more specific, at low elevation airport such as San-Diego, the performance profiles between ANP and BADA4 are very close; however, at high elevation airport such as Denver (field elevation 5,434ft), the performance results produced by ANP and BADA4 are very different. This is because BADA4 model calculates the performance based on Mean Sea-Level; whereas, ANP model is based on Above Field Elevation. Since the Denver airport has 5,434ft elevation, the performance calculation would be quite different between them. As discussed earlier, since BADA4 follows the 250kt/10000ft MSL FAR rule, its results are closer to the real aircraft operation and more accurate than ANP. In addition, the research team also investigated the other outlier cases such as the B737-700 arrival case with normal temperature at KATL airport. The results show that both fuel burn and emissions produced by ANP and BADA4 were different which is again due to the fact that they use different profile resulting different trajectory and thrust results. The results are shown in Figure 16.

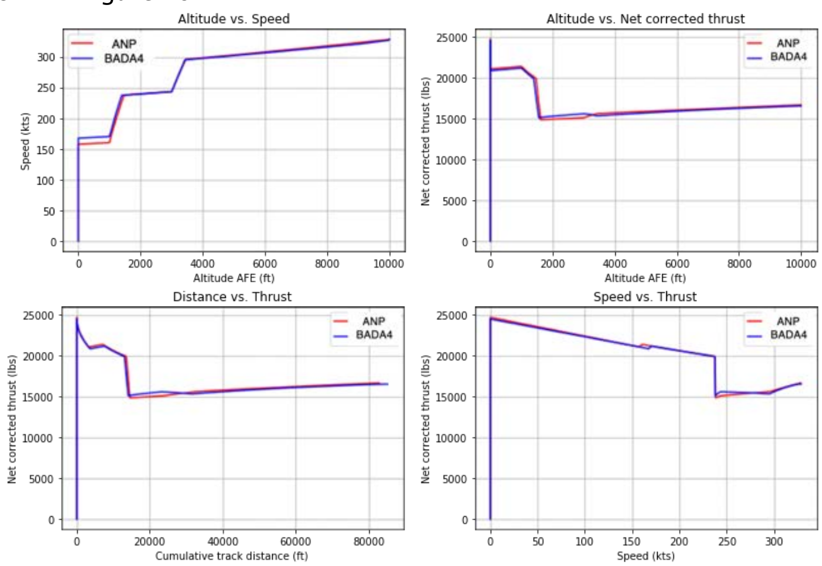

Figure 13. Performance comparison between ANP and BADA4

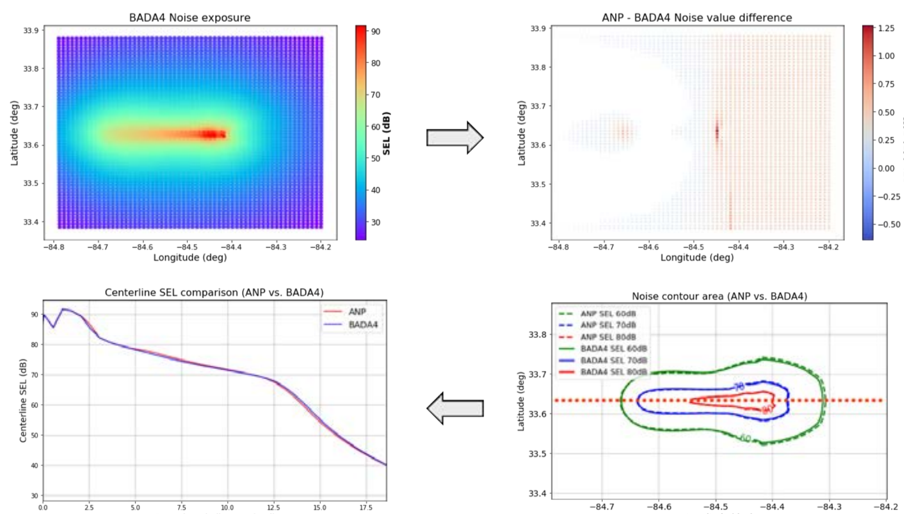

Figure 14. Noise contour and Centerline SEL comparison between ANP and BADA4

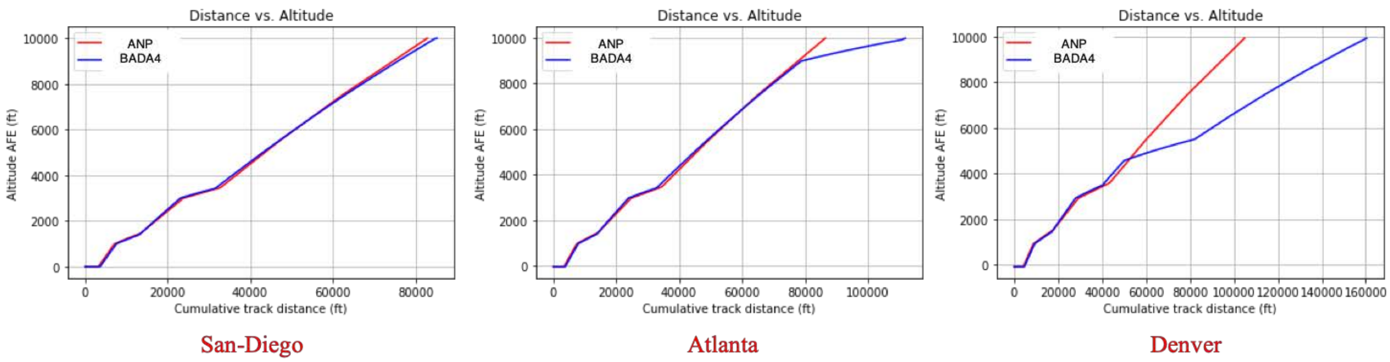

Figure 15. ANP vs. BADA4 comparison by airport with different elevations

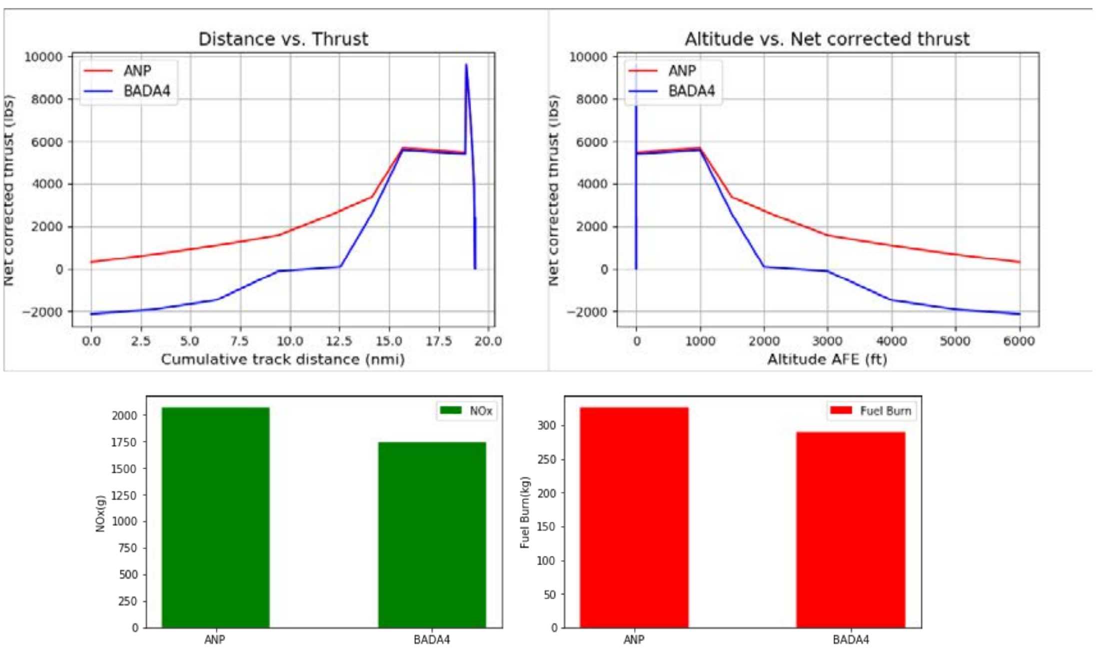

Figure 16. ANP vs. BADA4 comparison for the outlier arrival case at ATL

Task 3- Capability Demonstration and Validation of AEDT 2d and 2e Functionality

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Objective(s)

For AEDT 2d and 2e, the scope of the UQ effort identifying the key changes to the AEDT versions from the previous releases was formulated. Depending on the type of updates incorporated, it would be necessary to identify the key sources of uncertainties and the best approach to conduct V&V and parametric uncertainty analysis. Depending on the analysis scope of the V&V, Parametric UQ can be optional. The outcome of this task is the definition of analysis scope, required tools, required data, V&V method, Parametric UQ method, and a list of input parameters to vary and their uncertainty bounds. Due to the dynamic nature of the agile AEDT development process, it is important that the research team remains flexible in the choice of the V&V approach and the work scope. The best available methods and data will be used in order to ensure accuracy and functionalities of future AEDT versions based on the discussion with the FAA/AEE.

A V&V and capability demonstration was conducted of the newly released AEDT versions. The analysis in this task can take a couple of different approaches depending on the type of updates and data availability. In the past UQ efforts, one of the most important methods of ensuring confidence in the tool capability was to conduct a use case(s) using both legacy tools and the new AEDT release and compare the results. This method would be the most appropriate way whenever a legacy tool has the same or similar functionalities and a validated use case has been modeled in that legacy tool. When the new functionality of AEDT does not exist in the legacy tools, the V&V exercise should use direct comparisons to the results generated by the mathematical algorithms behind the newly added functionality and/or real world data whichever available.

Research Approach

In order to provide the best possible environmental impacts modeling capabilities, the FAA/AEE continues to develop AEDT by improving existing modeling methods and data and adding new functionalities. The AEDT development team led by Volpe has been exercising the agile development process, as shown in Figure 17, where minor updates are released in a new Sprint version every three weeks. Major updates and/or new functionalities are incorporated as new service packs or feature packs in about a three months cycles as shown in Figure 17. An AEDT development cycle includes rigorous testing of all levels of software functionality from the individual modules to the overall system. However, the FAA/AEE seeks a robust uncertainty quantification effort in addition to this test program.

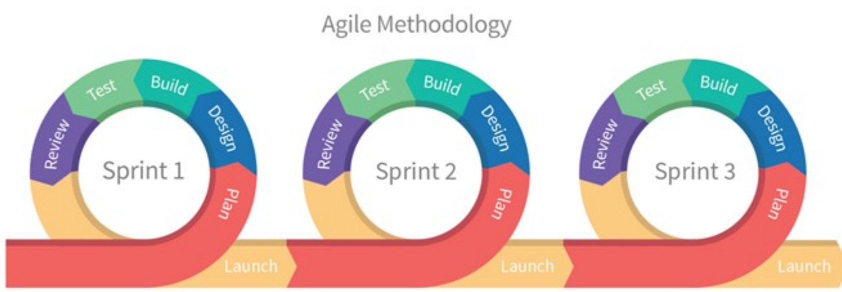


Figure 17. The Agile Methodology [Source: http://www.screenmedia.co.uk]

Table 2: AEDT Development and Public Release Schedule

Dates	Milestones
Sep. 2017	AEDT 2d Release
Dec. 2018	AEDT 3a Release

For each of the AEDT version and service pack releases, GT reviewed the AEDT requirement documents and AEDT release notes to identify the key features and functionalities that need to be tested. During the period of December 2017 to October 2018, two public version of AEDT were released – including AEDT 2d SP1, and AEDT 2e, as listed in Table **2**.

The main features/capabilities that were added to AEDT during the period include the following:

- BADA4 Features
    - BADA4 implementation of procedural departures and arrivals
    - Encryption of BADA 4 data
    - BADA4 with reduced thrust and alternative weight departure procedures
    - BADA4 implementation for sensor-path

- Climb thrust taper
- Emissions Analysis Features
  - Enhanced nvPM methods for CAEP nvPM Standard
  - Roadway network designer in AEDT GUI
  - Emission concentration display for non-closing contours
- Noise Analysis Features
  - Dynamic grid for non-dB metrics
  - Bulk creation of operations
  - Detailed noise results report
- Other Features
  - Non-closing contours
  - Fixed terminal area wind directions

The V&V and capability demonstration of the new features listed above are either completed or in progress. Starting from December 2017, all the new AEDT sprint releases including Sprints from 95 to 111 have been tested. Seventeen sprint releases of AEDT focusing on new features and capabilities added have also been tested. Some of the new features/capabilities were minor updates to the GUI, bug fixes or data updates. Major updates included BADA4 implementation of procedural departures and arrivals, BADA4 with reduced thrust and alternative weight departure procedures, enhanced nvPM, Idle descent, climb thrust tamper, NOx calculation.

In order to understand the background of new AEDT features, the relevant documents were reviewed including the software requirement documents, Database Design Documents (DDD), AEDT sprint release notes, updated technical manual [5, 6], user manual [7, 8], and research papers/reports [9-12]. Basic testing of all the new AEDT versions to confirm its functionality have been performed. While some of the tests are in progress, the next subsections discuss the current progress and findings in more details.

Investigation of Idle Descent

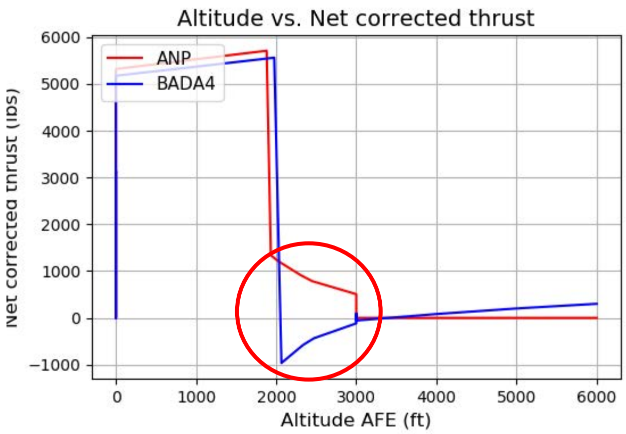
The purpose of this investigation is to determine the cause of large net thrust differences in ANP and BADA4 during approach procedures. AEDT may utilize different descent types during the approach procedure. Table 3 shows the different types of descent as well as their corresponding thrust equations for ANP.

Table 3. ANP Thrust Equations for Different Types of Descent

Step Type	Given	Calculate	Thrust Equation	Note
Descend	Initial and final speed and altitude Descent angle	thrust and horizontal distance	$\left(\frac{F_n}{\delta}\right)_2 = \frac{\left(\frac{W}{\delta_2}\right)\cdot\left(R_f - \frac{\sin\gamma}{1.03}\right)}{N}$	Neglect deceleration effects
Descend-decel	Initial and final speed and altitude Descent angle	thrust and horizontal distance	$\frac{F_n}{\delta} = \frac{W}{N\cdot\delta}\left(R\cdot\cos\gamma - \sin\gamma + \frac{a}{g}\right)$	SAE-AIR-1845 equation A15 with an additional acceleration term
Descend-idle	Initial and final speed and altitude Descent angle	horizontal distance Idle thrust is a rated thrust specification	$\frac{F_n}{\delta} = E + F\cdot v + G_A\cdot h + G_B\cdot h^2 + H\cdot T_C$	Preserves the acceleration value implied by its inputs

One of the reasons for net thrust differences to occur between ANP and BADA4 is because some ANP approach cases use step types that do not take deceleration into account (this is the case when “descend” is utilized for ANP) while BADA4 does take deceleration into account. Therefore, BADA4 would result in a more accurate representation of the approach procedure compared to that of ANP.

Besides the cases with deceleration affecting the net thrust differences between ANP and BADA4, large net thrust differences primarily occurred during the idle-descent segments of approach.



Step Number	Step Type	Altitude AFE (ft)
1	Idle Thrust Descend	6000
2	Idle Thrust Level	3000
3	Idle Thrust Level	3000
4	Idle Thrust Descend	3000
5	Idle Thrust Descend	2471
6	Idle Thrust Descend	2336
7	Idle Thrust Descend	2066
8	Descend	1976
9	Descend	50
10	Land	
11	Landing Decelerate	
12	Landing Decelerate	

Figure 18. Image Showing Region of Largest Net Thrust Difference Between ANP and BADA4 is During Idle-descent

Figure 18 shows the standard approach procedure for A340-642 at KATL under average airport weather conditions. Between 2,000 ft AFE and 3,000 ft AFE, the net thrust difference between ANP and BADA4 is largest as shown on the left image. The corresponding region is shown to be where the aircraft is flying under “idle thrust descend” conditions (shown on right). Further investigations into how ANP and BADA4 calculated net thrust during idle descent was conducted. It was found that both ANP utilized regression coefficients that depended on engine power states given by Equation (1).

$$\frac{F_n}{\delta} = E + Fv + G_A h + G_B h^2 + HT_c \tag{1}$$

Where

$\frac{F_n}{\delta}$ is corrected net thrust per engine (lbf)
v is the equivalent/calibrated airspeed (kt)
h is the pressure altitude MSL (ft)
T_c is the temperature at altitude (^{o}C)
E, F, G_A, G_B, H are the regression coefficients that depend on the engine power states and temperature state

Furthermore, the BADA4 idle thrust is calculated using a thrust coefficient.

$$Th = \delta W_{mref} C_T \tag{2}$$

$$C_T = ti_1\delta^{-1} + ti_2 + ti_3\delta + ti_4\delta^2 + (ti_5\delta^{-1} + ti_6 + ti_7\delta + ti_8\delta^2) \cdot M + (ti_9\delta^{-1} + ti_{10} + ti_{11}\delta + ti_{12}\delta^2) \cdot M^2 \tag{3}$$

Where

δ is the pressure ratio
m_{ref} is the reference mass (kg)
W_{mref} is the weight force at m_{ref} (N)
C_T is the thrust coefficient
M is the Mach number
ti_1 to ti_{12} are the idle rating thrust coefficients

The ANP and BADA4 idle thrusts were plotted against a variation of Mach number and altitude to visualize the thrust curves of both models, as shown in Figure 19. It was found that the ANP thrust curve closely resembled a typical thrust curve; however, the BADA4 thrust curves showed erratic behavior.

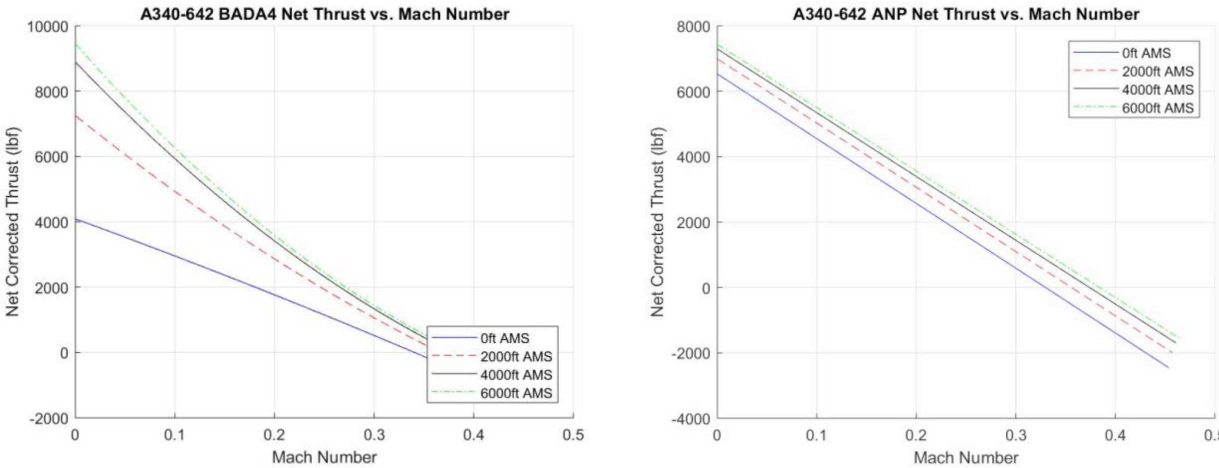


Figure 19. Image of ANP and BADA4 Thrust Curves for a Variety of Altitudes

The ANP thrust curve shows a gradual shift to the right as the altitude is increased with a reduction in net thrust as the Mach number is increased. The ANP thrust curve also shows the linear relationship between net thrust and Mach number, unlike BADA4. The BADA4 model shows a congruent behavior to that of ANP when increasing altitude and Mach number. However, it clearly shows that the net thrust, and Mach number do not necessarily behave linearly with each other.

Despite the large difference in thrust curves, ANP and BADA4 do not show a proportional difference for noise and emissions results. The following tables and figures show the noise contour, centerline plots, and emission results for the particular case above mentioned.

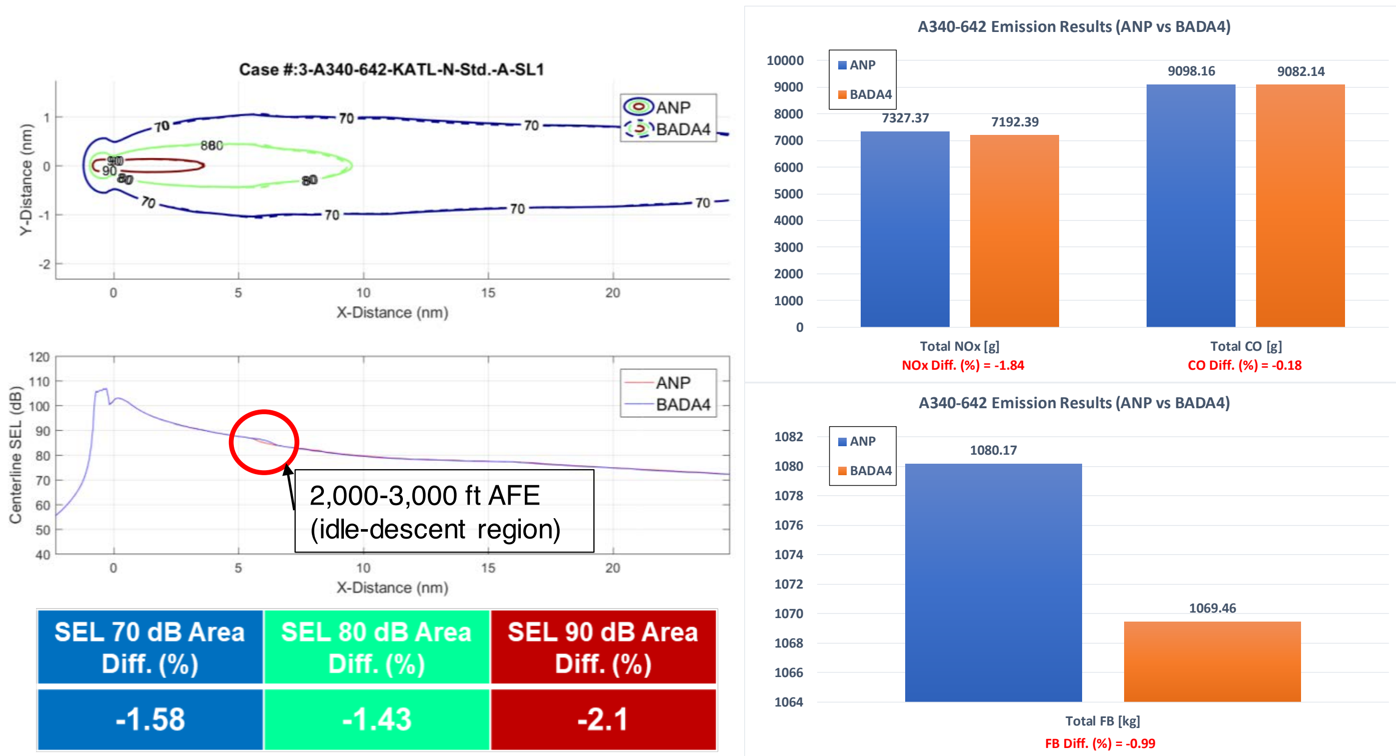


Figure 20. Images of Noise Contours, Centerline Plots, and Emission Results for the A340-642 during KATL Approach

Figure 20 shows that despite the large differences in net thrust during idle-descent segments, the difference is not propagated to noise and emission results. The largest noise contour area difference is only around 2% with the slight difference in centerline plot depicting the idle-descent segment (circled in red). The largest emission difference is from NOx emission, which comes to around -1.84%. This concludes the investigation with the notion that ANP and BADA4 idle thrust curves may have relatively different thrust curves. But the utilization of the thrust curves in the correct regions of Mach number and altitude have allowed the models to reflect similar noise and emission results between ANP and BADA4.

NOx Calculation

Through the idle-descent investigation, it was discovered that the NOx differences between ANP and BADA4 were relatively large compared to other emission results. Additionally, from the routine analysis at conducted to test all combinations of stage lengths and profiles using KIAH airport, it was found that there are several outliers for NOx calculations as shown in Figure 21. As can be seen in the figure, the Boeing 737 Max 8 aircraft was a prominent outlier for the reduced thrust cases. This aircraft was selected for further investigation into NOx calculations.

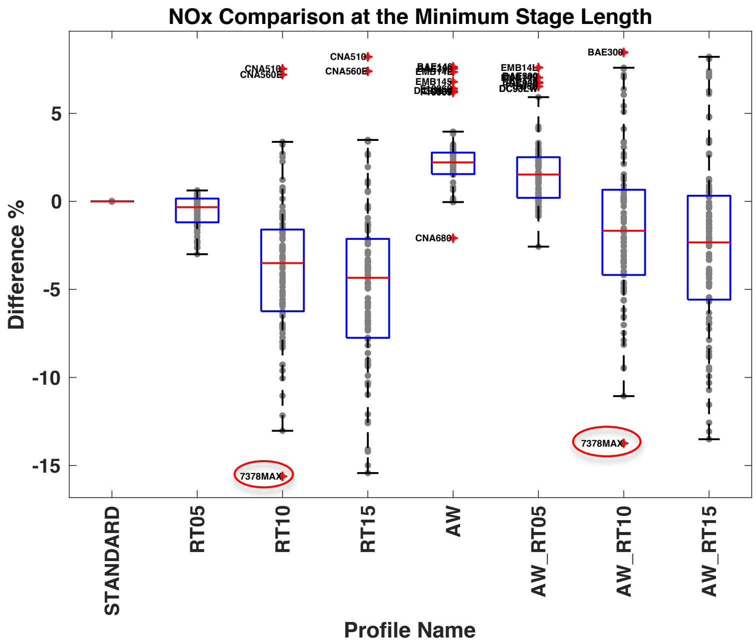


Figure 21. Outlier analysis for NOx calculations

A preliminary analysis revealed that the trend of reduction in NOx emissions is dependent only on whether reduced thrust was implemented. However, this reduction of NOx itself is not consistent with the change in fuel burn. As can be seen in Figure 22, for reduced thrust profiles, the fuel consumption increases by about 4 to 8% however, the NOx emissions decrease by about 12 to 15%. This anomaly is observed across all stage lengths and does not seem to be affected by the added weight profiles. Further, the amount of thrust reduction itself does not seem to affect the trend, rather it is driven by whether thrust reduction was applied or not. This preliminary analysis motivates the need to compare reduced thrust profiles to the others on a more detailed level.

7378MAX	Fuel/NOx Difference 5%													
Profile	**SL 1**		**SL2**		**SL 3**		**SL 4**		**SL 5**		**SL 6**		**SL 7**	
Fuel/NOx	Fuel	NOx	Fuel	NOx	Fuel	NOx	Fuel	NOx	Fuel	NOx	Fuel	NOx	Fuel	NOx
STANDARD	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MODIFIED_RT05	0.34	0.55	0.37	0.58	0.37	0.61	0.42	0.67	0.51	0.8	0.54	0.84	0.61	0.91
MODIFIED_RT10	4.15	-15.6	4.46	-15.4	4.78	-15	5.56	-14.6	6.68	-13.8	7.02	-13.6	7.76	-13
MODIFIED_RT15	4.63	-15	4.98	-14.7	5.35	-14.3	6.21	-13.7	7.48	-12.7	7.86	-12.4	8.69	-11.7
MODIFIED_AW	1.65	2.27	1.8	2.43	3.48	4.66	4.37	5.68	1.15	1.48	2.46	3.11	0	0.02
MODIFIED_AW_RT05	2	2.81	2.17	3.01	3.9	5.31	4.85	6.42	1.69	2.29	3.05	3.97	0.61	0.91
MODIFIED_AW_RT10	6.01	-13.7	6.51	-13.3	8.84	-11.1	10.8	-9.66	8.1	-12.5	10.1	-10.8	7.76	-13
MODIFIED_AW_RT15	6.51	-13.1	7.05	-12.6	9.45	-10.2	11.5	-8.65	8.91	-11.4	10.9	-9.54	8.69	-11.7

Figure 22. Comparison of NOx emissions and fuel burn across stage lengths

For detailed analysis, the performance and emissions tables from AEDT were analyzed. These tables break down the entire operation into segments (about 30, in this case). A typical performance table is shown in Figure 23. The segments for the RT05, RT10 and RT15 profiles were compared to the corresponding segments of the STANDARD profiles. In particular the percent change of segment fuel burn was compared to the percent change of segment NOx emission. It was observed that these match exactly, all the way up to segment 21, which approximately corresponded to about 1500 ft altitude. Beyond this segment, there was a high deviation in these two percentages. Further, this deviation was only observed for RT10 and RT15 profiles; the RT profile segment percent comparisons continued to be in agreement until the top of climb. These two observations seem to point towards the reduction in climb thrust as being the root cause of the problem.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	RESULT_ID	AIR_OP_ID	SEGMENT_	TRACK_LE	CUM_TRA	THRUST_C	SPEED_CH	FUELFLOW	FUELBURN	DURATION	LENGTH	OP_MODE	TRAJ_MOI	MACH_NU	TIME
2	15379	451	0	0	0	0	0	0.095	247.57	21:43.0	0	100000	0	0	00:00.0
3	15380	451	1	25	0	-42.2758	12.46514	1.307171	7.149963	00:02.7	25	1	1	0.009886	00:00.0
4	15381	451	2	75	25	-42.2758	12.46514	1.306757	7.147696	00:02.7	75	1	1	0.01212	00:02.7
5	15382	451	3	262.6527	100	-708.449	22.54556	1.293085	12.79269	00:04.9	262.6527	1	1	0.019663	00:05.5
6	15383	451	4	426.2204	362.6527	-708.449	22.54556	1.267669	12.54126	00:04.9	426.2204	1	1	0.035052	00:10.4
7	15384	451	5	589.788	788.873	-708.449	22.54556	1.247002	12.33679	00:04.9	589.788	1	1	0.057749	00:15.4
8	15385	451	6	753.3557	1378.661	-708.449	22.54556	1.230582	12.17435	00:04.9	753.3557	1	1	0.087754	00:20.3
9	15386	451	7	916.9234	2132.017	-708.449	22.54556	1.217911	12.04899	00:04.9	916.9234	1	1	0.125067	00:25.3
10	15387	451	8	1080.491	3048.94	-708.449	22.54556	1.208489	11.95577	00:04.9	1080.491	1	1	0.169688	00:30.2
11	15388	451	9	1244.059	4129.431	-708.449	22.54556	1.201816	11.88976	00:04.9	1244.059	1	1	0.221617	00:35.1
12	15389	451	10	384.2789	5373.49	4.264154	0.159766	1.197739	3.469769	00:01.4	388.4053	1	2	0.249537	00:40.1
13	15390	451	11	458.6554	5757.769	5.084603	0.190506	1.195485	4.129589	00:01.7	463.5806	1	2	0.249819	00:41.5
14	15391	451	12	545.4281	6216.424	6.039678	0.22629	1.192804	4.894276	00:02.1	551.285	1	2	0.250155	00:43.3
15	15392	451	13	687.9832	6761.853	7.607614	0.285036	1.189516	6.147866	00:02.6	695.3708	1	2	0.250567	00:45.3
16	15393	451	14	923.5089	7449.836	10.19349	0.381922	1.185229	8.20788	00:03.5	933.4257	1	2	0.251107	00:47.9
17	15394	451	15	1369.768	8373.345	15.08036	0.56502	1.179146	12.0805	00:05.1	1384.477	1	2	0.251876	00:51.4
18	15395	451	16	2435.832	9743.113	26.70368	1.000514	1.169095	21.20932	00:09.1	2461.989	1	2	0.253154	00:56.5
19	15396	451	17	1711.343	12178.95	-299.566	11.98027	1.156926	14.11255	00:06.1	1713.483	1	2	0.261669	01:05.6
20	15397	451	18	1818.378	13890.29	-299.566	11.98027	1.145401	13.97196	00:06.1	1820.652	1	2	0.27755	01:11.7
21	15398	451	19	2734.614	15708.67	-432.069	17.52626	1.130631	19.34117	00:08.6	2738.3	1	2	0.29692	01:17.8
22	15399	451	20	2954.181	18443.28	-432.069	17.52626	1.112569	19.03219	00:08.6	2958.163	1	2	0.320208	01:26.3
23	15400	451	21	1000	21397.46	-2504.3	0.373956	1.027496	5.753085	00:02.8	1004.985	1	3	0.332616	01:34.9

Figure 23: Sample AEDT metric result performance table, partially shown

Additionally, several plots were made to visualize these differences. Through several iteration of plots, it was concluded that time based plots seemed to be the best suited for these visualizations. Most notably, the segment level data allowed the calculation of the emissions index (EI) that AEDT was using to calculate the NOx emissions. Such a plot is shown in Figure 24. It is clearly seen that there is a large difference between the emissions indices for the RT10 and RT15 profiles when compared to the STANDARD or RT05 profile.

It was eventually deemed necessary to try to replicate the NOx calculations as done by AEDT. AEDT utilizes the Boeing Fuel Flow Method 2 (BFFM2) for calculating the NOx emission and a further investigation was conducted to verify that AEDT was correctly implementing the BFFM2 in its NOx calculations. In order to do so, an independent tool was created that could replicate the NOx results generated by AEDT. The tool would follow the steps of the BFFM2 while utilizing parameters generated in AEDT (i.e. temperature, pressure, Mach number, etc.).

After several iterations of the independent BFFM2 tool, the results from the tool matched with AEDT to an error of about 0.1 %. It was concluded that AEDT has a correct implementation of the method, albeit with a few ambiguities and an inconsequential deviation from the BFFM2 recommendations. These are explained in detail towards the end of this section.

The design of the independent tool helped better understand AEDT's implementation which was not always evident from the Technical Manual. With this new knowledge, the presence of the Boeing 737 Max 8 aircraft as an outlier in Figure 21 could finally be explained. As we know from Figure 24, the EI difference results from a change in the climb thrust. We know this because RT10 and RT05 profiles implement a derated climb thrust, whereas STANDARD and RT05 profiles use full climb thrust. In order to relate this 10% reduction in climb thrust to the ~30% reduction in NOx EI, a segment level comparison was performed. The comparisons were made for the final segment in the performance table and key metrics at different steps of the BFFM2 were compared. A summary of the comparisons is provided in Table 4. This table along with Figure 25 explains the large change in NOx EI that results from the reduction in climb thrust.

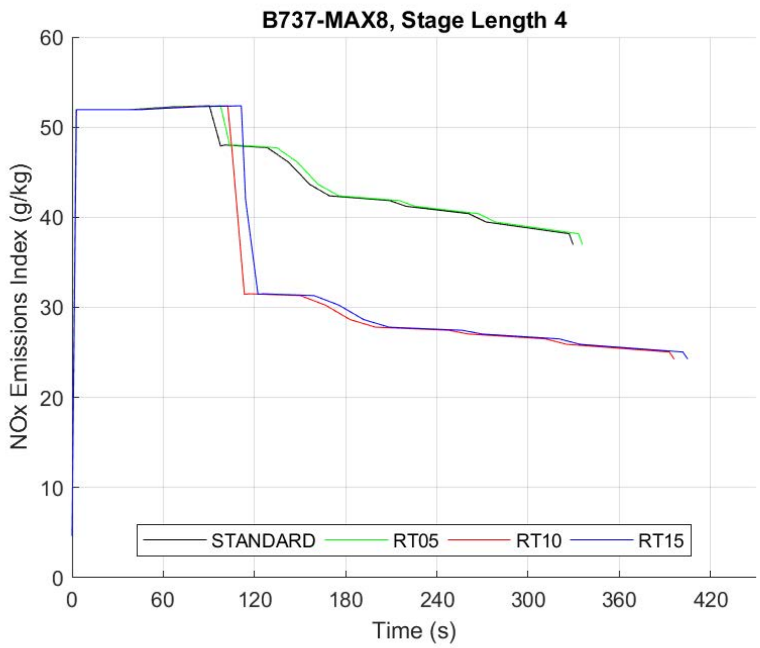


Figure 24. Emissions Indices comparison

Table 4. Key comparisons of BFFM2 steps, final segment, B737Max8, RT05 v/s RT10

Final segment performance metrics	Full Climb Thrust	Derated Climb Thrust	Difference (%)
Thrust	17561 lbs	15829 lbs	-9.86 %
Non-Reference Fuel Flow	0.800 kg/s	0.720 kg/s	-10.00 %
Reference Fuel Flow	0.9247	0.8322	-10.00 %
Log Reference NOx EI	1.5707	1.3877	-11.65 %
Reference NOx EI	37.22 g/kg	24.42 g/kg	-34.39 %
Non-Reference NOx EI	36.97 g/kg	24.26 g/kg	-34.27 %

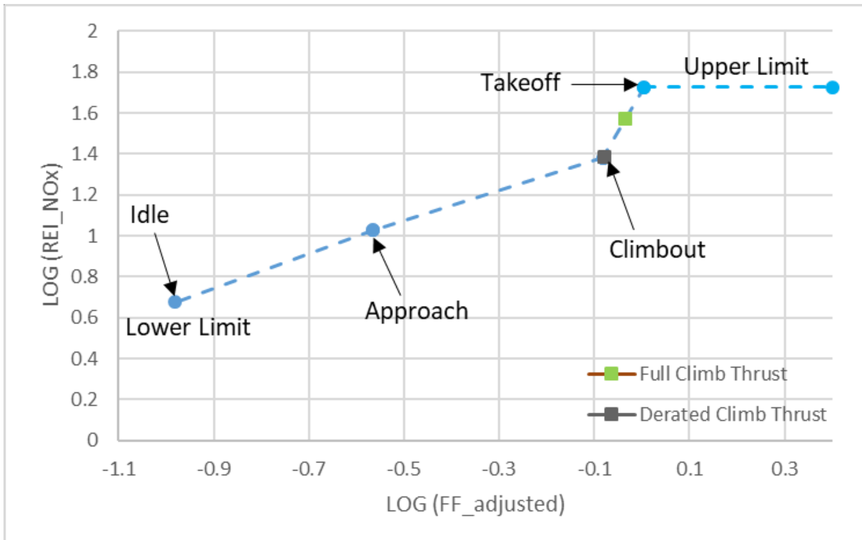


Figure 25. Reference NOx EI calculation, B737Max8

First, the thrust values are compared and is found to be around 10% as is expected. Note that the reduction is not exactly 10% as the aircraft flying these two profiles have different trajectories. The thrust, which depends on both speed and altitude is therefore not reduced by exactly 10%. Next, fuel flow values are compared. Non-reference values are the values provided by the AEDT performance calculations. Reference values are obtained from these using conversion formulas, these are explained in detail in the subsequent paragraphs. The BFFM2 method uses reference values to calculate the EIs. Both the fuel flows are also different by 10%. Next, from the Reference Emissions Index is found as shown in Figure 25. This figure gives us the logarithm (base 10) of the Reference EI. Finally, when this value is converted to the actual value, and the Reference EI to the non-Reference EI, the large difference of ~34% appears. By doing this step by step analysis, the exact step of the difference was isolated.

From the observation of the reference NOx EI values, it is seen that the change from the Takeoff point to the Climbout point is rather steep (noting that the axes are not of the same scale). Further, these differences are on a logarithmic scale, and the difference is amplified when the anti-log is taken. Thus, was concluded that the Boeing 737 Max 8 being an outlier for the reduced climb thrust profiles is a result of aircraft's reference Emissions Indices and not due to an incorrect implementation of the Boeing Fuel Flow Method 2 in AEDT.

The subsequent steps outline the BFFM2:
- Step 1: Using the four ICAO reference fuel flows provided in SQL (specific for each engine), multiply them by a modal-specific adjustment factor to account for installation effects. These modes reflect the four types of engine power settings.

Table 5:.Adjustment Factors for Installation Effects

Mode	Power Setting (%)	Adjustment Factor
Takeoff	100	1.010
Climbout	85	1.013
Approach	30	1.020
Idle	7	1.100

- Step 2: Using the adjusted fuel flows from step 1 and the reference emission index (REI) values from the FLEET database (there is one REI value for each mode and emission parameter), develop a log-log relationship between the REI and fuel flow values. An example of this point-to-point relationship is found in Figure 26.

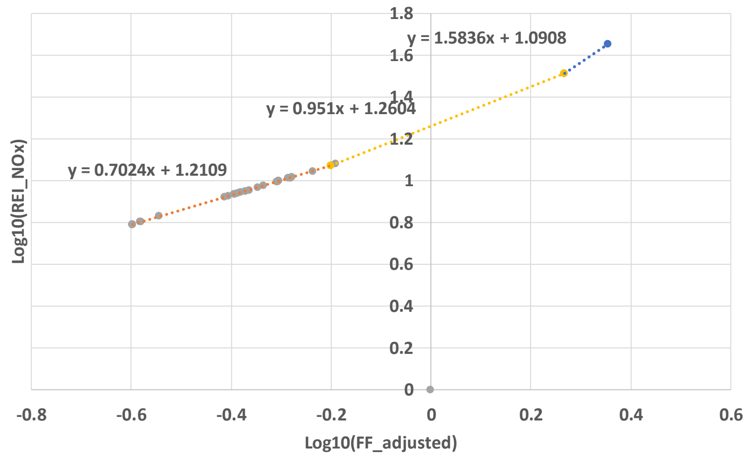


Figure 26. Example of a Log-Log Relationship between the REI Values and the Adjusted Fuel Flows

- Step 3: Obtain the non-reference fuel flow values calculated from AEDT case runs. These results can be found in the SQL database under dbo.RSLT_EMISSIONS_RESULTS after a case has been run.

- Step 4: Convert non-reference fuel flow from step 3 to reference conditions, to take into account the influence of fuel flow for different altitudes, using the following equation.

$$RWf = \frac{Wf}{\delta}\theta^{3.8}e^{0.2M^2} \tag{4}$$

Where
RWf is the fuel flow at reference conditions (kg/s)
Wf is the fuel flow at non-reference conditions (kg/s)
δ is the pressure ratio
θ is the temperature ratio
M is the Mach number

- Step 5: Using the reference fuel flow from step 4, find the corresponding REI values using the log-log plot from step 2. The corresponding REI values may not be outside the scope of the provided REI range (from idle REI to takeoff REI).

- Step 6: Convert the reference REI values to non-reference conditions using the following equation.

$$NO_xEI = NO_xREIe^H\left[\frac{\delta^{1.02}}{\theta^{3.3}}\right]^{0.5} \tag{5}$$

$$H = -19\left[\frac{0.62197058\phi P_v}{P-\phi P_v} - (6.34 * 10^{-3})\right] \tag{6}$$

Where
NO_xEI at non-reference conditions (g/kg)
NO_xREI at reference conditions (g/kg)
H is the humidity coefficient
ϕ is the relative humidity
P is the ambient pressure (psi)
P_v is the saturation vapor pressure (psi)
δ is the pressure ratio
θ is the temperature ratio
M is the Mach number

- Step 7: Lastly, multiply the obtained NO_xEI values from step 6 by the corresponding fuel burn (generated by AEDT) to get the NOx emission results for each segment. Combining all the segments would provide the total NOx emission.

Using the outlined BFFM2 process, a tool was created to replicate the NOx results obtained from AEDT, which was designed from the knowledge obtained from the AEDT manual and the AEDT source code. A tool that could successfully replicate the NOx results from AEDT could help verify that AEDT was implementing the BFFM2 correctly in calculating NOx emissions, as shown in Figure 27. Albeit some minor setbacks along the way, where the AEDT manual failed to explicitly define certain terms in its BFFM2 process and had to be resolved through analyzing the AEDT source code, the replication tool was completed. The image below shows the NOx results generated by AEDT compared to the NOx results obtained from the replication tool. The 0.01 difference found in the BADA4 results between AEDT and the tool is from the difference in significant figures during calculations.

	AEDT Gen. Nox Values	Replicated Nox BFFM2
ANP	7327.37	7327.37
BADA4	7192.39	7192.38
Diff. (%)	-1.84	-1.84

Figure 27. NOx Result Comparisons between the AEDT Generated Results and the Replication Tool Results

After successfully replicating the NOx results from AEDT, some ambiguous terms defined in the AEDT manual for the BFFM2 process were clarified. For example, the temperature ratios and pressure ratios used in AEDT's BFFM2 process were not defined as ratios under static conditions, which is the condition required for the BFFM2 process. To avoid future confusion, these terms were reported and will be updated in the manual for the upcoming AEDT 3a release.

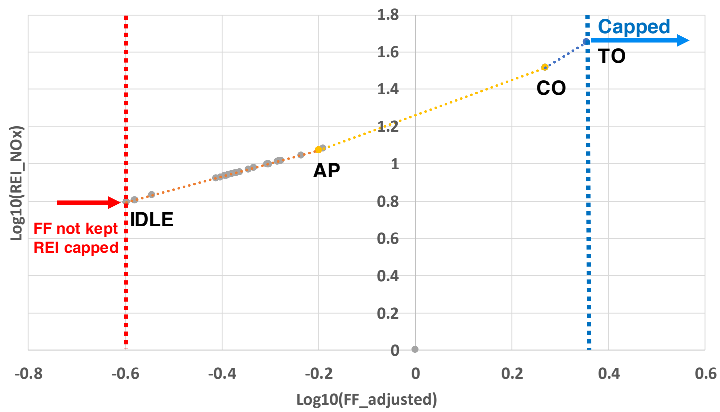


Figure 28. AEDT's bounds for the Log-Log relationship between REI and Fuel Flow

Other concerns were raised when it was discovered that the AEDT BFFM2 replaced reference fuel flow values that were found to be below the idle reference fuel flow value (depicted in Figure 28). It would set the reference fuel flow values equal to the idle reference fuel flow value while the emission index values would also be capped to the emission index value of idle. This could lead to loss of information and accuracy during approach and idle flight conditions. Further investigations are underway to resolve these events. For fuel flow values exceeding that of takeoff, the emission index would be capped to the emission index value of takeoff with the fuel flow values retained.

Thrust Taper

The purpose of this study is to evaluate the new capability of thrust taper, which was introduced in AEDT 3a, for BADA4 operations. The capability could only be utilized for cases with reduced thrust departure settings. This option would allow the engine to gradually change the thrust (starting from 10,000 ft Above Mean Sea Level (AMS)) from the reduced thrust setting to the full-power BADA4 climb setting at a user-defined taper upper limit (default set to 12,000 ft AMS). Hence, the rate at which the aircraft would transition from the reduced thrust setting to the full-power setting during departure could be varied.

The thrust during the reduced thrust to full-power transition is given as

$$k_{taper} = \begin{cases} 0, & h < H_1 \\ \frac{h-H_1}{H_2-H_1}, & H_1 \le h \le H_2 \\ 1, & h > H_2 \end{cases} \tag{7}$$

$$F_{flat,taper} = [k_{reduced} + (1 - k_{reduced}) \cdot k_{taper}] \cdot F_{flat} \tag{8}$$

Where

k_{taper} is the taper coefficient
h is the current altitude (AMS)
H_1 is the transition starting altitude (10,000 ft AMS)
H_2 is the upper taper limit altitude (user-defined)
$F_{flat,taper}$ is the thrust during transition
$k_{reduced}$ is the reduced thrust coefficient
F_{flat} is the thrust at full power

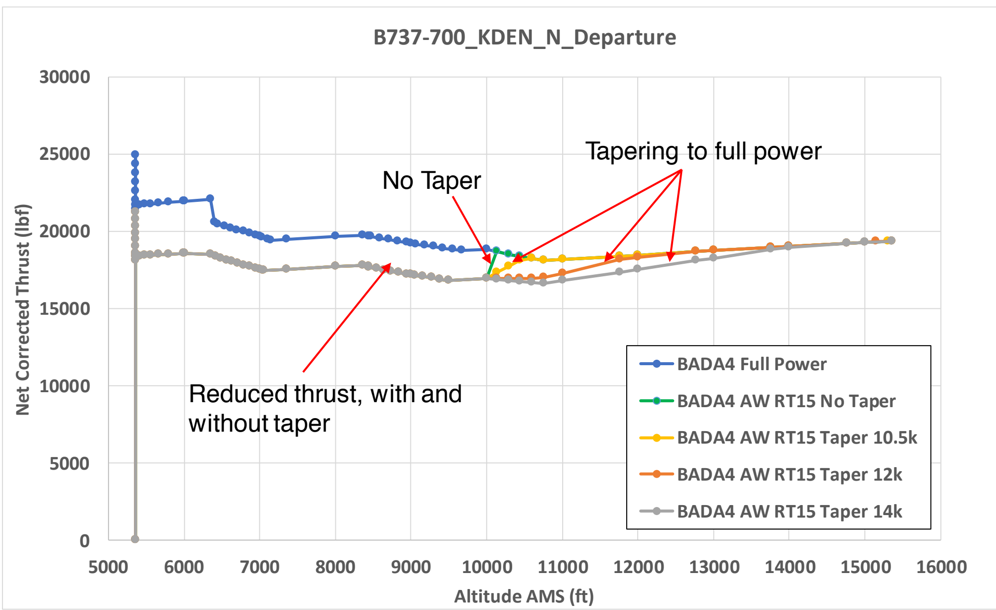


Figure 29. Reduced Thrust to Full-power Transitions for Different Thrust Taper Settings

This shows that the slope of the transition curve is primarily dependent on the full-power thrust curve since the taper coefficient increases linearly from 0 to 1 as h goes from H_1 to H_2 and the reduced thrust coefficient is a constant value (dependent on level of reduced thrust).

The thrust taper capability was tested on the B737-700 for departure at Denver International Airport (KDEN). Figure 29 shows how an upper taper limit setting of 14,000 ft AMS allows the engine to transition from reduced thrust to full-power at a slower rate than a upper taper limit setting of 10,500 ft AMS. Since the upper taper limit would define the final altitude at which the thrust must reach full-power, this outcome is expected. With no thrust taper setting, the thrust would simply jump from reduced thrust to full-power at 10,000 ft AMS.

Track control

AEDT has two different types of flight performance: 1) Procedure-Driven and 2) Trajectory-Driven flight. In the trajectory-driven flight, there are two types of flight performance: 1) Sensor path and 2) Track control flight. The track control flight consists of altitude and speed control. In particular, the track control flight is useful when the profiles do not represent actual routes. The diagram of flight performance modeling options in AEDT is shown in the Figure 30.

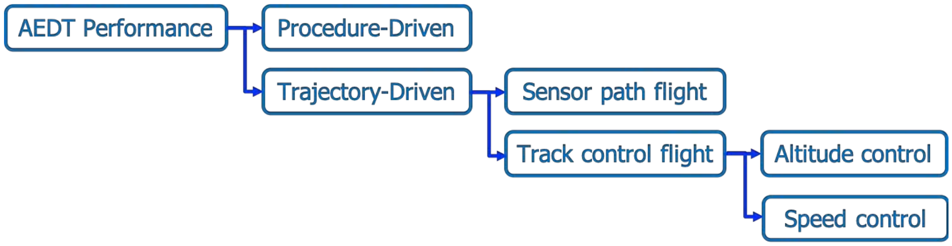


Figure 30. AEDT Flight Performance Diagram

A track control flight defines what aircraft's altitude must be as it passes over a particular track point. In AEDT, it provides three types of altitude/speed restrictions. For example, there are three different types of altitude control as shown in the Figure as below. First, "At" restricts the aircraft from being more than 300 ft from the target altitude when passing over the track point. Second, "At or Above" restricts the aircraft from being more than 300 ft below the target speed when passing over the track point. Third, "At or Below" restricts the aircraft from being more than 300 ft above the target speed when passing over the track point. This is described in the Figure 31.

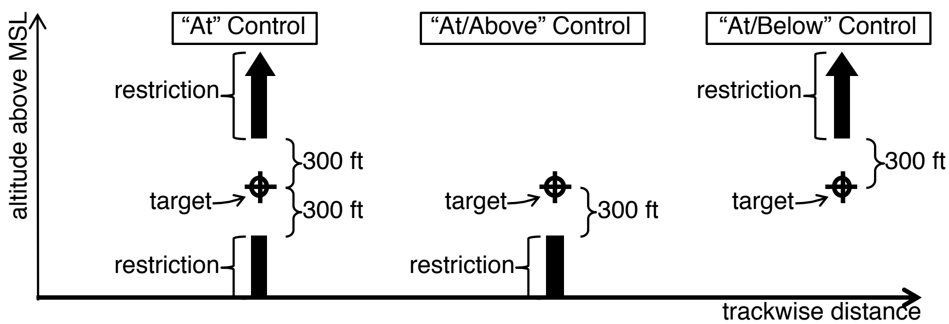
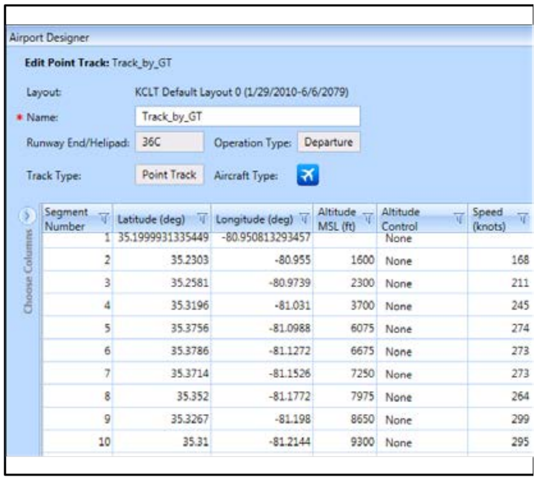


Figure 31. Options for altitude control in AEDT

The objective of this section is to demonstrate the functionality of track control flight.
In order to test a functionality of altitude/speed control, the research team created a new point track with real flight data from FlightAware, which is a global aviation software and data service platform. In FlightAware, they offer free flight tracking data information of world-wide commercial Air Transportation Network (ATN). Its comprehensive dataset contains time, speed, altitude, latitude, longitude, direction, rate of climb, etc. with accompanying information such as origin, destination, airline, flight number, operating aircraft. The case study used for this test is shown in the Figure 32.

Real Flight Data



AEDT Airport Designer – Point Track

Figure 32. Compiling flight data information and modeling point track with the information

To test all the combinations with ANP, BADA4, Altitude control, and Speed control, the research team created a test matrix as shown in the Table 5.

Table 5. Test matrix for track control flight in AEDT

Case #	Performance Model	Altitude Control	Speed Control
1	ANP	on	off
2	ANP	off	on
3	ANP	on	on
4	BADA4	on	off
5	BADA4	off	on
6	BADA4	on	on

When the altitude control was only turned on at the particular point with both ANP and BADA4 cases, it was observed that the track control functionality worked well as shown in the Figure 33 and Figure 34. (Note that only one point was controlled)

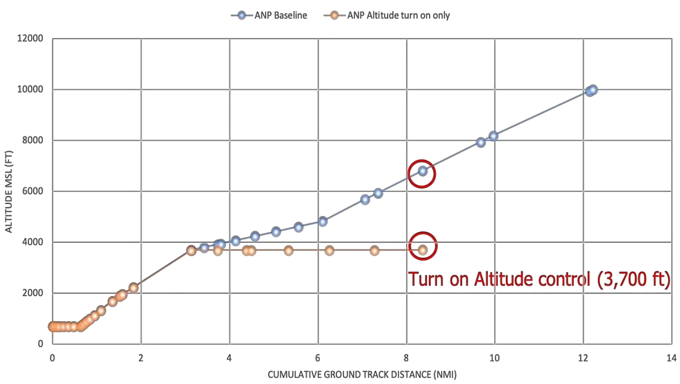


Figure 33. Altitude control only for ANP case

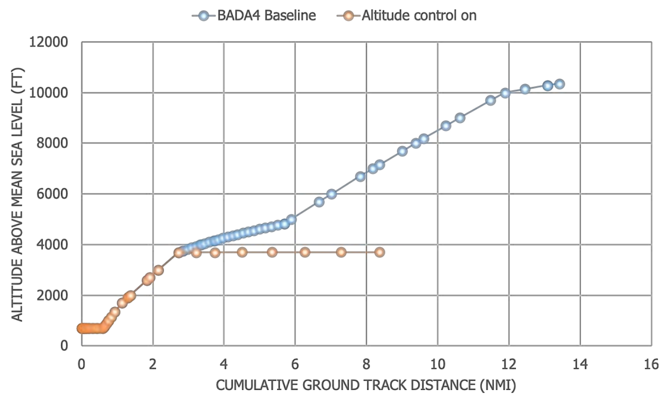


Figure 34. Altitude control only for BADA4 case

When the speed control was only turned on at the particular point with both ANP and BADA4 cases, it was observed that the track control functionality did not work. This was because the speed control should be implemented with the altitude control simultaneously regardless of the performance model in AEDT. For this reason, the research team conducted the test case with both speed and altitude control. They were turned on with Match option at the particular point in order to test the functionality for both ANP and BADA4. The test results are shown in the Figure 35 and Figure 36.

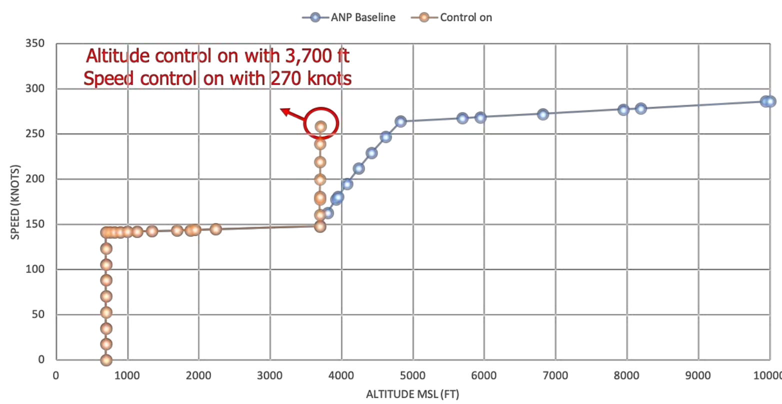


Figure 35. Speed and altitude control for ANP case

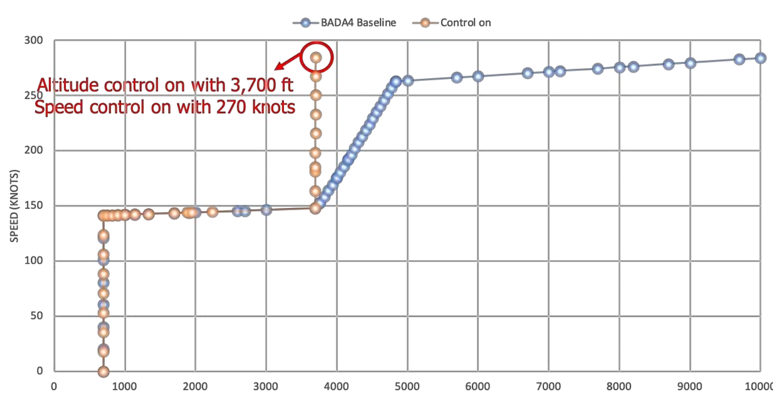


Figure 36. Speed and altitude control for BADA4 case

In summary, it was concluded that:

1) An altitude control for both ANP and BADA4 can be used without a speed control for track control flight in AEDT.
2) A speed control should be managed with an altitude control simultaneously for both ANP and BADA4.
3) Controls of both altitude and speed at the same time work for both ANP and BADA4.

According to the technical manual, there are a few control input requirements when users want to use track control flight in AEDT. The requirements are shown in the Table 6.

Table 6. Control input requirements in AEDT

Case	AEDT3a Technical manual (August 2018)
1	Controls specifying altitudes below 500 ft AFE are ignored by AEDT.
2	Controls on the first point in a departure track are ignored by AEDT.
3	Controls on the last two points in an approach track are ignored by AEDT.
4	An aircraft must have procedural standard profiles to be used with a track that includes altitude controls.
5	Overflight tracks containing altitude controls must have a minimum of two altitude controls above 500 ft AFE.
6	Approach tracks cannot have sequentially ascending altitude control targets.
7	Departure tracks cannot have sequentially descending altitude control targets.
8	BADA4 analysis of flight on controlled tracks requires observed controls of both altitude and speed.

The research team tested all the control input requirements in order to demonstrate the track control flight functionalities in AEDT. As a result, it was found that all the requirements are true except for case 3 and 5. For example, the research team tested the case shown in the Figure 37 and found that controls specifying altitudes below 500ft AFE should be an error in AEDT. For example, if the altitude control was turned at 852ft AFE, it worked well. However, if the altitude control was turned on at 250ft AFE, it was unable to process flight because the altitude control must exist above 500ft AFE.

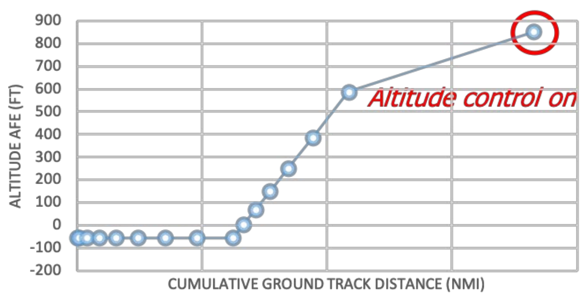
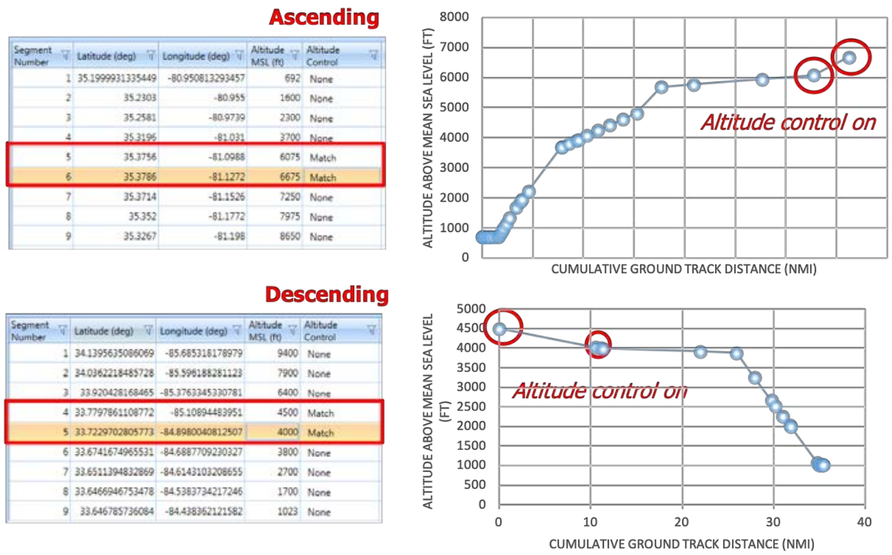


Figure 37. Control Input Requirement 1 - Test



Ascending

Segment Number	Latitude (deg)	Longitude (deg)	Altitude MSL (ft)	Altitude Control
1	35.1999931335449	-80.950813293457	692	None
2	35.2303	-80.955	1600	None
3	35.2581	-80.9739	2300	None
4	35.3196	-81.031	3700	None
5	35.3756	-81.0988	6075	Match
6	35.3786	-81.1272	6675	Match
7	35.3714	-81.1526	7250	None
8	35.352	-81.1772	7975	None
9	35.3267	-81.198	8650	None

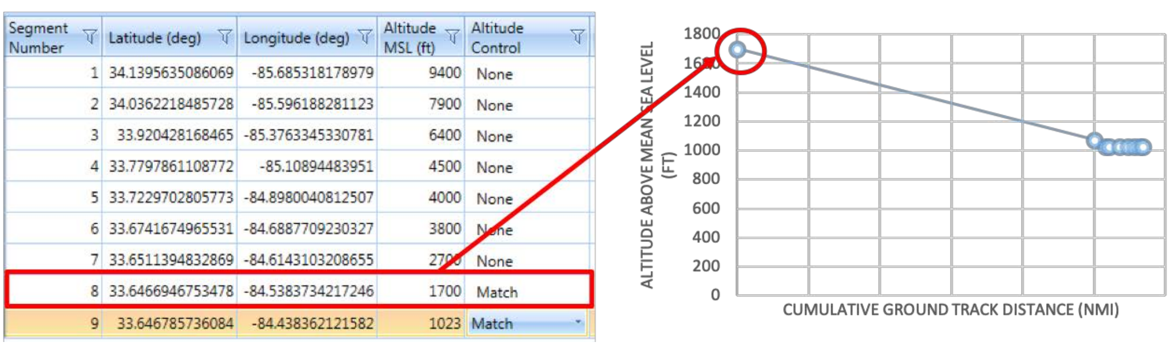
Descending

Segment Number	Latitude (deg)	Longitude (deg)	Altitude MSL (ft)	Altitude Control
1	34.1395635086069	-85.685318178979	9400	None
2	34.0362218485728	-85.596188281123	7900	None
3	33.920428168465	-85.3763345330781	6400	None
4	33.7797861108772	-85.10894483951	4500	Match
5	33.7229702805773	-84.8980040812507	4000	Match
6	33.6741674965531	-84.6887709230327	3800	None
7	33.6511394832869	-84.6143103208655	2700	None
8	33.6466946753478	-84.5383734217246	1700	None
9	33.646785736084	-84.438362121582	1023	None

Figure 38. Control input requirement 6 and 7 - Test

In a similar way, in order to test the control input requirement 6, the research team defined the sequentially ascending for a departure operation and descending for an approach operation altitude control targets. As a result, it was observed that approach tracks cannot have sequentially ascending altitude control targets. Furthermore, departure tracks cannot have sequentially descending altitude control targets. The results are shown in the Figure 38.

In order to test the control requirement 3, the research team specified two altitude control points at the last two points in an arrival track. Based on the technical manual, the controls on the last two points in an approach track should be ignored. However, it was observed that controls on the last point in an approach track are ignored but controls on the point before ground are not ignored as shown in the Figure 39.



Segment Number	Latitude (deg)	Longitude (deg)	Altitude MSL (ft)	Altitude Control
1	34.1395635086069	-85.685318178979	9400	None
2	34.0362218485728	-85.596188281123	7900	None
3	33.920428168465	-85.3763345330781	6400	None
4	33.7797861108772	-85.10894483951	4500	None
5	33.7229702805773	-84.8980040812507	4000	None
6	33.6741674965531	-84.6887709230327	3800	None
7	33.6511394832869	-84.6143103208655	2700	None
8	33.6466946753478	-84.5383734217246	1700	Match
9	33.646785736084	-84.438362121582	1023	Match

Figure 39. Control input requirement 3 - Test

Milestone(s)

Milestone	Due Date	Estimated Date of Completion	Actual Completion Date	Status	Comments (Problems & Brief Resolution Plan)
A36 Kickoff Meeting	5/3/2016	5/3/2016	5/3/2016	Completed	
Quarterly Report (Aug)	7/31/2016	7/31/2016	7/31/2016	Completed	

ASCENT Meeting	9/27-28/2016	9/27-28/2016	9/27-28/2016	Completed	
Quarterly Report (Nov)	10/31/2016	10/31/2016	10/31/2016	Completed	
Annual Report	1/18/2017	1/18/2017	1/13/2017	Completed	
Quarterly Report (Jan)	1/31/2017	1/31/2017	1/27/2017	Completed	
Quarterly Report (March)	3/31/2017	3/31/2017	3/31/2017	Completed	
ASCENT Meeting	4/18/2017	4/18/2017	4/18/2017	Completed	
Quarterly Report (June)	6/30/2017	6/30/2017	6/30/2017	Completed	
ASCENT Meeting	9/26/2017	9/26/2017	9/26/2017	Completed	
Quarterly Report (Oct)	10/30/2017	10/30/2017	10/30/2017	Completed	
Annual Report	11/30/2017	11/30/2017	11/30/2017	Completed	
Quarterly Report (Jan)	1/31/2018	1/31/2018	1/31/2018	Completed	
Quarterly Report (March)	3/31/2018	3/31/2018	3/31/2018	Completed	
ASCENT Meeting	4/3 - 4/2018	4/3 - 4/2018	4/3 - 4/2018	Completed	
Quarterly Report (June)	6/30/2018	6/30/2018	6/30/2018	Completed	
ASCENT Meeting	10/9 - 10/2018	10/9 - 10/2018	10/9 - 10/2018	Completed	
Quarterly Report (Oct)	10/30/2018	10/30/2018	10/30/2018	Completed	
Annual Report	11/30/2018	11/30/2018	11/30/2018	In Progress	

Major Accomplishments

Starting from December 2017, all the new AEDT sprint releases including Sprints from 95 to 111 have been tested. Seventeen Sprints of AEDT have been tested focusing on new features and capabilities added. Some of the new features/capabilities were minor updates to the GUI, bug fixes, or data updates. Major updates included enhanced nvPM, VALE reporting with MOVES, runup operation of military aircraft, open contour, vector track, track dispersion, contour combination, dynamic grid, detailed noise and bulk operation creation. In order to understand the background of new AEDT features, all the relevant documents were reviewed including the software requirement documents, Database Design Document, AEDT sprint release notes, updated technical manual, user manual, and research papers/reports. Basic testing of all the new AEDT versions and service packs was completed to confirm its functionality and a number of minor and major bugs and reported them to the FAA and the development team via bi-weekly ASCENT project telecons and weekly AEDT development-leads calls. Through the on-line system named Team Foundation Server (TFS), identified issues and follow-up actions taken by the developers were documented and shared. The TFS also allows for reporting any potential areas of improvements in AEDT algorithms and user-friendliness.

Finally, additional tests were conducted to investigate the environmental impact of new profiles with reduced thrust and alternative weight. Comprehensive analysis were carried out to compare the fuel burn, emissions and noise results produce by ANP and BADA4 for different scenarios with new profiles. It was concluded BADA4 has better performance modeling capability and can generate environmental results closer to real world data. Further studies were designed and performed to test new features, and findings and recommendations were reported.

Publications

Yongchang Li, Dongwook Lim, Michelle Kirby, Dimitri Mavris, George Noel, Uncertainty Quantification Analysis of the Aviation Environmental Design Tool in Emission Inventory and Air Quality Modeling, AVIATION 2018 conference, June 17 – 21, 2018.

Dongwook Lim, Yongchang Li, Matthew J Levine, Michelle R Kirby, Dimitri, Mavris, Parametric Uncertainty Quantification of Aviation Environmental Design Tool, AVIATION 2018 conference, June 17 – 21, 2018.

Jung-Hyun Kim, Kisun Song and Seulki Kim, Yongchang Li, Dimitri Mavris, Aircraft Mission Analysis Enhancement by using Data Science and Machine Learning Techniques, Submitted to AVIATION 2019 conference

Outreach Efforts

None

Awards

None

Student Involvement

Yee Chan Jin is a first year Master student who started in fall 2018. Mr. Jin has conducted a literature review on UQ methods, and performed tests for newly release AEDT features. Mr. Jin is being trained on related tools such as INM, AEDT Tester, AEDT2c and AEDT 2d.

Ameya Behere is a third year PhD student who started in fall 2016. Mr. Behere has conducted a literature review on UQ methods, and performed tests for newly release AEDT features. Mr. Behere is being trained on related tools such as INM, AEDT Tester, AEDT2c and AEDT 2d.

Junghyun (Andy) Kim is a third year Master student who started in fall 2015. Mr. Kim has conducted a literature review on UQ methods, and performed tests for newly release AEDT features. Mr. Kim is being trained on related tools such as INM, AEDT Tester, AEDT2c and AEDT 2d.

Zhenyu Gao is a third year Ph.D student who started in fall 2016. Mr. Gao has conducted a literature review on UQ methods, and performed tests for newly release AEDT features. Mr. Gao is being trained on related tools such as INM, AEDT Tester, AEDT2c and AEDT 2d.

Plans for Next Period

GT will continue uncertainty quantification tasks for new AEDT 2e AEDT 3a is planned to be released in December 2018. GT will perform the validation and verification tasks for the preliminary versions of AEDT 3a to identify any issues that need to be addressed by the development team.

Task 1. Proper Definition of AEDT Input Parameter Uncertainty

The first step in the UQ effort is to properly define the problem. For each of the AEDT service pack releases, GT will define the scope of the UQ effort identifying the key changes to the AEDT versions from the previous releases. Depending on the type of updates incorporated, it would be required to identify the key sources of uncertainties and properly define the uncertainties for the input parameters if it is necessary.

Task 2. Verification and Validation plus Capability Demonstrations

GT will continue to conduct V&V and capability demonstrations of the newly released AEDT versions. The V&V analysis can take a couple of different approaches depending on the type of updates and data availability. In the past UQ efforts, one of the most important methods of ensuring confidence in the tool capability was to conduct a use case(s) using both legacy tools and the new AEDT release and compare the results. This method would be the most appropriate way whenever a legacy tool has the same or similar functionalities and a validated use case has been modeled in that legacy tool. When the new functionality of AEDT does not exist in the legacy tools, the V&V exercise should use direct comparisons to the results generated by the mathematical algorithms behind the newly added functionality and/or real world data whichever available.

Task 3. Identification of Important Output to Input Relationships (Optional)
This optional task may not be performed for every AEDT service pack releases. Instead, this task will be performed when a major feature is added to the AEDT, and if potential sources of uncertainties remain through the analysis of previous two tasks. The outcome of this task will be the identification of the key input drivers across multiple vehicle types to multiple AEDT metric outputs. This can provide a comprehensive insight to the uncertainty associated with AEDT outputs and the joint-distribution of Fleet DB coefficients. Various uncertainty quantification techniques will be used depending on the metric of interest. This may include, but not limited to the following techniques: Analysis of Variance (ANOVA), Multivariate Analysis of Variance (MANOVA), Monte Carlo Simulation, Copula Techniques, or Global Sensitivity Analysis. The specific techniques will be proposed by GT and reviewed by the FAA for concurrence.[i]

Task 4. Guidelines for Future Tool Research
In this task, each of the prior tasks will culminate into a summary document of the data assumptions, techniques utilized, the resulting observations and findings to help guide the FAA to further research the areas of AEDT development to improve its supporting data structure and algorithms. In addition, the document will build confidence in AEDT's capability and fidelity and help users to understand the sensitivities of output response to the variation of input parameters/assumptions.

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