Project 045 Takeoff/Climb Analysis to Support AEDT APM Development

Georgia Institute of Technology

Project Lead Investigator

Prof. Dimitri Mavris
Professor Dimitri N. Mavris
Director
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Phone: (404) 894-1557
Fax: (404) 894-6596
Email: dimitri.mavris@ae.gatech.edu

Dr. Michelle R. Kirby, Co-PI
Chief, Civil Aviation Research Division
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Phone: (404) 385-2780
Fax: (404) 894-6596
Email: michelle.kirby@ae.gatech.edu

University Participants

Georgia Institute of Technology (GT)

- P.I.(s): Prof. Dimitri Mavris, Dr. Michelle R. Kirby (Co-PI)
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FAA funded amount is $250,000 for the period of performance of August 15, 2016 to August 14, 2017. The Georgia Institute of Technology has agreed to a total of $250,000 in matching funds. Subsequently, the FAA funded amount is $75,000 for the period of performance of August 15, 2017 to August 14, 2018. The Georgia Institute of Technology has agreed to a total of $75,000 in matching funds. This total includes salaries for the project director, research engineers, graduate research assistants and computing, financial and administrative support. The institute has also agreed to provide equipment funds as well as tuition remission for the students paid for by state funds.

Investigation Team

Prof. Dimitri Mavris, Dr. Michelle Kirby, Dr. Don Lim, Dr. Yongchang Li, Dr. Holger Pfaender, Dr. Matthew Levine, and Mr. Jim Brooks. Graduate Students: Ameya Behere, Zhenyu Gao, Yee Chan Jin, Junghyun Kim.

Project Overview

Accurate modeling of aircraft performance is a key factor in estimating aircraft noise, emissions and fuel burn. Within the Aviation Environmental Design Tool (AEDT), many assumptions are made for aircraft performance modeling with respect to aircraft weight and departure procedure coupled with the fact that, typically the aircraft departure is modeled assuming full rated takeoff power/thrust is used. As operations around airports continue to evolve, there is a need to examine those assumptions and to improve the modeling accuracy with flight data. In recent years, flight data has been used more and more to enhance models and bring model estimation even closer to reality. Research is needed to build on prior work with a view to develop a robust set of recommendations for improved estimation processes for takeoff weight, reduced thrust takeoffs, and departure profiles within AEDT.

Task 1- Development of New Profile for Improving Weight and Thrust Modeling in APM

Georgia Institute of Technology

Objective(s)

In the previous year's P45 effort, Georgia Tech identified the AEDT assumptions in question, the validity of the physics behind the APM assumptions, and suggested improvements and the issues in data availability or modeling fidelity associated with the suggested improvements. Based on the literature review and analysis on the real world flight data, the research team found that AEDT underestimates the takeoff weight, and AEDT uses full thrust for takeoff while airlines use reduced takeoff thrust when it is possible. In addition, most airlines use NADP1 and NADP2 procedure instead of STANDARD, ICAO A or ICAO B procedures which are defined in AEDT. To improve AEDT's current APM assumptions, new profiles were developed for the major commercial and general aviation jets in AEDT. The new profiles contain reduced thrust, alternative weight, flap and speed schedule information.

New profiles for several aircraft were developed in order to help AEDT model real world aircraft operations. Before the implementation of this profile, most AEDT aircraft could only perform takeoffs using maximum climb thrust. Further, the weights which were assigned to the different stage lengths were significantly lower than what was observed from flight data. One of the reasons behind this was the assumption of a 65% load factor. In present times, average load factors of more than 80% are often observed. Due to the combination of these two factors, real world flight trajectories could not be modeled in AEDT. An additional factor is that aircraft use NADP profiles for takeoff rather than STANDARD or ICAO profiles. Currently, NADP profiles are not modeled in AEDT. This is an important area of improvement and will be the focus of attention for this project mobbing forward.

By the creation of these new profiles, users now have more options to choose when running environmental analyses. The implementation of reduced thrust and alternate weights will help users better match real world trajectories. This improvement in accuracy may help with future policy decisions by better informing the users of the real-world environmental effects of aviation.

Research Approach

The development of the new profiles involved multiple steps which are explained in this section. The new profiles were created as several Excel tables meant for importing in the AEDT Databases using SQL scripts. There were two aspects of modification of the existing profiles to create the new profiles – thrust and weight. It was decided that the STANDARD profile set be used as the baseline, this is because not all aircraft have ICAO A or ICAO B procedures defines, however, STANDARD departure profile is always present. Based on the STANDARD profiles, seven additional profiles with reduced thrust and alternative weight were created for all stage lengths for the batch of 90 aircraft.

Selection of aircraft

This section explains how the batch of 90 aircraft was selected for additional profile generation. First, the list of all aircraft was exported from the AEDT Database Table "FLT_ANP_AIRPLANES". The table was then filtered to include major commercial and general aviation jets with noise category 3 or 4. This process reduced the list to 92 aircraft. Of these, 2 had to be excluded as they contained point-based departure profiles and hence could not be used for alternate profile generation. Thus, the finalized batch of 90 aircraft was created.

Creation of modified weights and additional thrust types

It was previously found that AEDT tends to underestimate the takeoff weights assigned to the different stage lengths. These weights are defined in the SQL table "FLT_ANP_AIRPLANES_PROFILES". After a series of discussions among the AEDT development team and the FAA liaisons, it was decided that the weights should be increased for all stage lengths except for the maximum stage length. This increase would be in the form of updating the weights for a specific stage length to the average weight of the current stage length and the next stage length. This calculation is illustrated in Figure 1. The final stage length was excluded from modification as it was understood that it is typical for the aircraft maximum takeoff weight to be assigned to the final stage length.

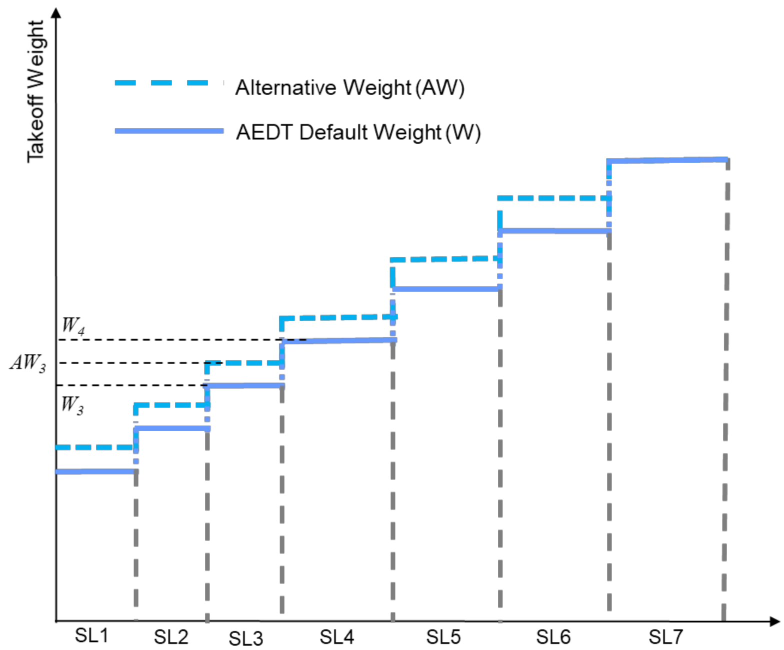


Figure 1. Calculation of alternate weights for profiles

The creation of additional thrust types was more involved. In AEDT, thrust is calculated with the help of thrust types such as "Takeoff" or "Climb". The thrust is calculated with the help of several thrust coefficients. Currently, AEDT uses the maximum available thrust for these two thrust modes. In order to implement reduced thrust departure procedures, new thrust types had to be defined and implemented in AEDT. Thrust types are defined in the SQL table "FLT_ANP_AIRPLANES_THRUST_JET". Takeoff thrust was implemented as either 5%, 10% or 15% reduction. Climb thrust reduction was implemented as a constant 10%, to be utilized only when the takeoff thrust reduction is 10% or more. Table 1 shows a typical thrust definition table for an aircraft. Note that not all aircraft have high temperature coefficients defined. It was decided that the high temperature coefficients not be derated as in a high temperature departure, it is unlikely that derated thrust will be used. This is illustrated in Figure 2. Note that although AEDT already had provisions for reduced climb and takeoff thrust, they were not implemented in AEDT itself, thus new derated thrust types had to be created.

Table 1. Description of new and existing AEDT thrust types

Existing AEDT Thrust Types	Description	New AEDT Thrust Types	Description	Based on
I	Idle	A	10% derated Max Climb (High Temp)	B
J	Idle (High Temp)	D	10% derated Max Climb	C
C	Max Climb	E	5 % derated Max Takeoff (High Temp)	S
B	Max Climb (High Temp)	F	5 % derated Max Takeoff	T
N	Max Continuous	W	10 % derated Max Takeoff (High Temp)	S
M	Max Continuous (High Temp)	X	10 % derated Max Takeoff	T
T	Max Takeoff	Y	15 % derated Max Takeoff (High Temp)	S
S	Max Takeoff (High Temp)	Z	15 % derated Max Takeoff	T
Q	Reduced Climb			
P	Reduced Climb (High Temp)			
H	Reduced Takeoff			
G	Reduced Takeoff (High Temp)			

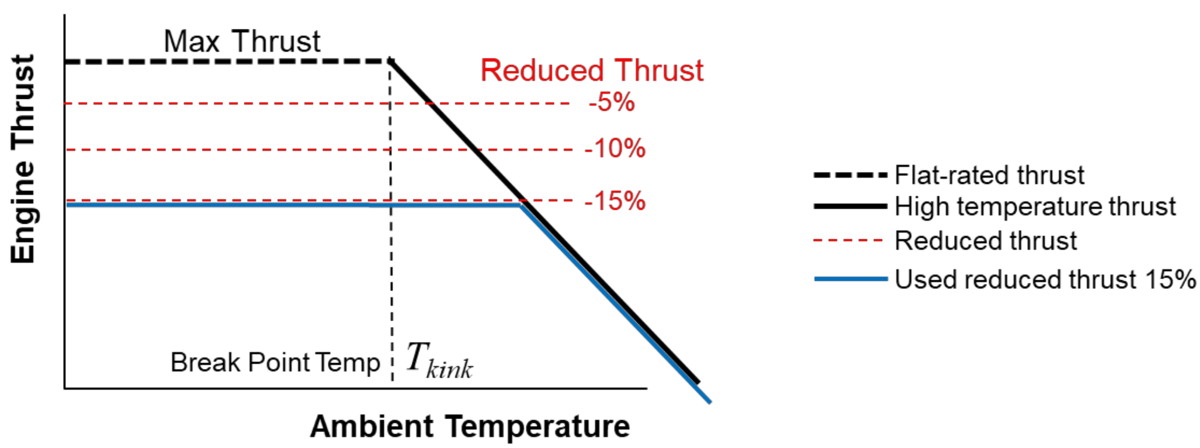


Figure 2. High temperature thrust calculations in AEDT

Creation of new profile and procedure tables
AEDT handles profiles through two separate SQL tables. The first is the “FLT_ANP_AIRPLANE_PROFILES” which contains information which is displayed in the AEDT GUI when a profile is to be selected. It contains the aircraft ID, operation type, profile name, stage length and weight information. For each of the batch of 90 aircraft, the new profiles were created for all stage lengths. Further, these new profiles were named as “MODIFIED_RT05”, “MODIFIED_RT10”, “MODIFIED_RT15”, “MODIFIED_AW_RT05”, “MODIFIED_AW_RT10”, and “MODIFIED_AW_RT15”. The weights were modified only for the profiles containing the “_AW” tag. Table 2 summarizes the type of changes made to each new profile set.

Table 2. Summary of new profile types

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)

The second table is the "FLT_ANP_AIRPLANE_PROCEDURES". This is the main table where all of the profile steps are defined. A typical AEDT procedural profile consists of a takeoff ground roll, initial climb, thrust cutback, acceleration and retraction of flaps and final climb to end of terminal area. The order and number of these steps vary from aircraft to aircraft but the general structure is the same. Each of these steps has a specific step type defined with it and based on this step type, AEDT uses extra information in the form of parameters. These parameters specify either climb rate, target speed or target altitude as appropriate.

The use of climb rate as one of the parameters posed a problem as it is strongly dependent on the aircraft weight. As we are also modeling additional weight profiles, it would not be accurate to use the baseline climb rates that were defined specifically for the existing AEDT weights. Fortunately, there is a simple solution to this as AEDT offers two types of accelerated climbs. The common type is to specify a climb rate and a target speed. AEDT will then calculate the required thrust for maintaining the climb and then allocate the remaining thrust to perform the horizontal speed acceleration. Alternatively, AEDT can also perform accelerated climbs using energy share percentage. In this, the procedure step specifies the percentage of energy which is to be allocated to climb and acceleration. AEDT will then calculate the climb rate using this information. A detailed explanation of this is provided in subsequent sections. Many AEDT aircraft use the first type of accelerated climb, a notable exception is the Boeing 787-800 which uses an energy share percent climb with a value of 55% and 50% for the final step. The climb rates for a given energy share percent are highly dependent on the instantaneous weight of the aircraft and the thrust level. It is difficult to estimate what this climb rate might be. However, when we look at this from the point of view of energy allocation, it turns out that the fraction of energy allotted to climb is roughly the same regardless of the aircraft weight and thrust level. Hence, this energy share approach proves to be very useful when creating the new profiles.

Defining the new procedural steps for the sets of 7 new profiles involved changing the accelerated climb step types, allotting the energy share percentage and assigning the appropriate thrust type. High temperature thrust coefficients never appear in these tables as they are not used explicitly. AEDT is designed to invoke the high temperature thrust coefficients as necessary. Further, the flap setting for each step was retained, no changes were made to the flap retraction schedule or to the flap setting used for takeoff.

Development and Validation of Energy Share

As mentioned in the previous section, the RoC of the STANDARD profile is not correct and cannot be used for the new profile any more when the takeoff weight and thrust change. This section will discuss how the new energy share (ES) based profiles are built to and validated for the RoC-based profiles. The new profiles are first built using the energy share method, and then tested and validated to make sure that they work properly and accurately. During this process, the energy share values are calculated analytically using potential energy and kinetic energy, given by the equation:

$$ES\,\% = \frac{\Delta KE}{\Delta KE + \Delta PE}$$

where the change in kinetic energy ΔKE is determined via aircraft speed and weight from performance calculating model, and the change in potential energy ΔPE is determined from the altitude and weight information. During the aircraft takeoff process, different energy share values are associated with different stage lengths. For example, an energy share value of 100% is used during ground roll in order to add kinetic energy; an energy share value of close to 0% happens during the constant speed takeoff when most of the excess power is used to add potential energy. In other climb stages, a typical energy share value varies from 40% to 70%. The energy share values for all 90 aircraft and all stage lengths were calculated and implemented in the new profiles.

After the initial calculations of the energy share values were finished, a validation analysis was conducted to test the validity of the ES-based profiles. The flowchart of the complete validation process is shown in Figure 3. The test was conducted for all stage lengths of 90 aircraft (409 cases total). As shown in Figure 3, first, the FLEET DB in SQL database is used to generate .xml files for all 90 aircraft, for RoC-based group and ES-based group, respectively. Then the AEDT tester, a tester that mimics the way aircraft are flown in AEDT, was run to generate performance and noise reports for all test cases. Then, a post-processing process was conducted to compare the flight trajectory and noise results between RoC- and ES-based profiles for each test pair to validate the new ES-based profiles.

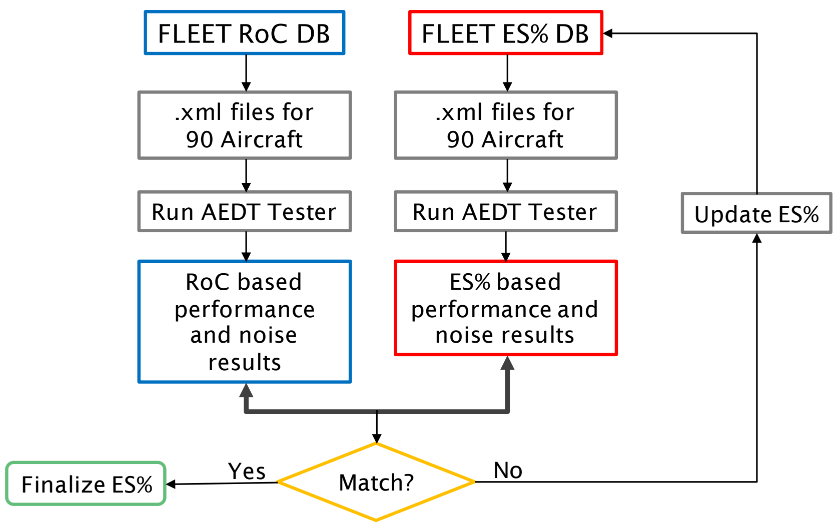


Figure 3. Energy Share DB Validation Process

Three different comparisons were considered in this process: flight trajectory, noise contour, and noise difference between ES- and RoC-based profiles. Examples of the three types of comparisons are shown in Figure 4-Figure 6. An excellent flight trajectory match is shown at the left of Figure 4. In this plot, for a given aircraft, flight trajectories of different stage lengths generated from the RoC and ES-based profiles are almost identical, with only minor differences. In a poor flight trajectory match shown at the right of Figure 4, large discrepancies exist between the two groups of flight trajectories. Similar to the flight trajectory comparison, the noise contour comparison provides another analytical way to validate the ES values for a profile. In an excellent noise contour match shown at the left of Figure 5, two groups of the noise contours show a high degree of agreement. A poor noise contour match shown at the right of Figure 5 indicates that the corresponding ES values are not accurate enough. The last comparison method utilizes the percentage differences in the magnitude of noise at all measurement points. An example of an excellent match is at the left of Figure 6 where the noise differences across all points are within the range of $\pm 0.06\%$. While in a poor noise difference match, the percentage difference at some points can go to as high as 6.5%. By examining the comparison plots for all 90 aircraft and all stage lengths, one can find out cases where the ES calculations are far from the target. For those ES values which don't provide a good agreement with the corresponding

RoC-based profile, such as the ones shown at the right of Figure 4-Figure 6, it is necessary to go back and modify the ES values until a good agreement between the RoC- and ES-based profiles is reached.

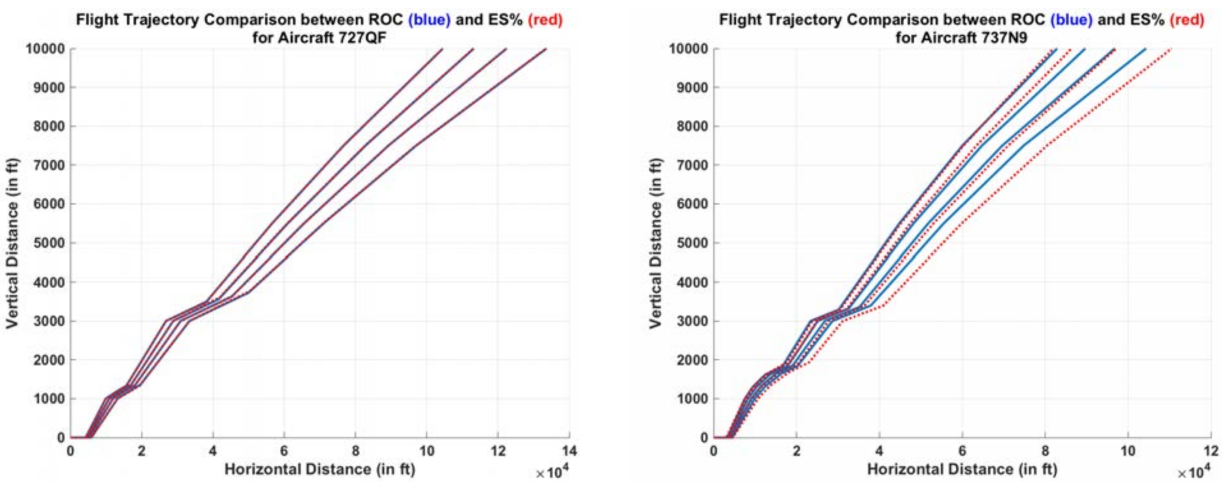


Figure 4. Example of Flight Trajectory Comparison: Excellent (Left) and Poor (Right) Matches

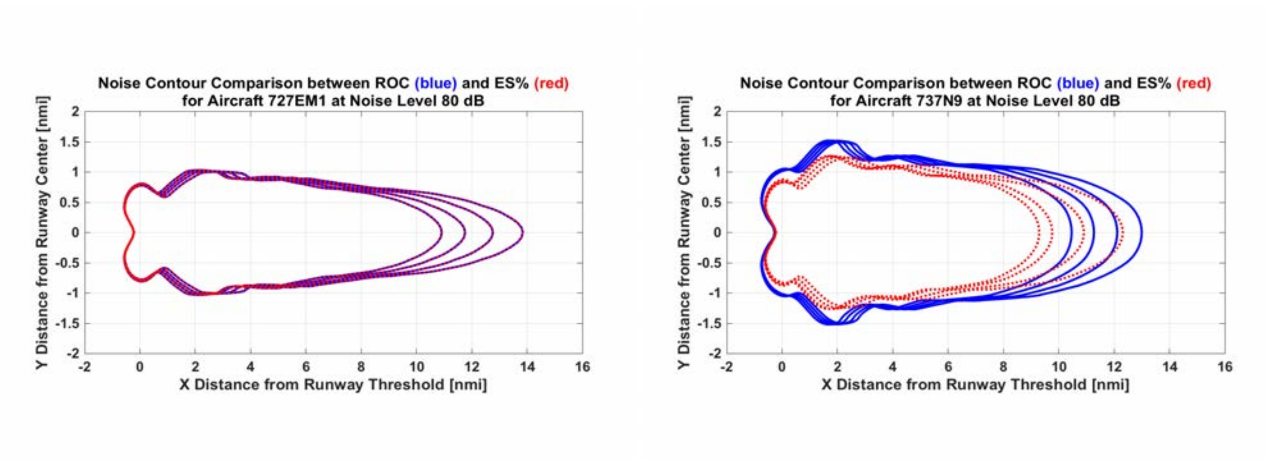


Figure 5. Example of Noise Contour Comparison: Excellent (Left) and Poor (Right) Matches

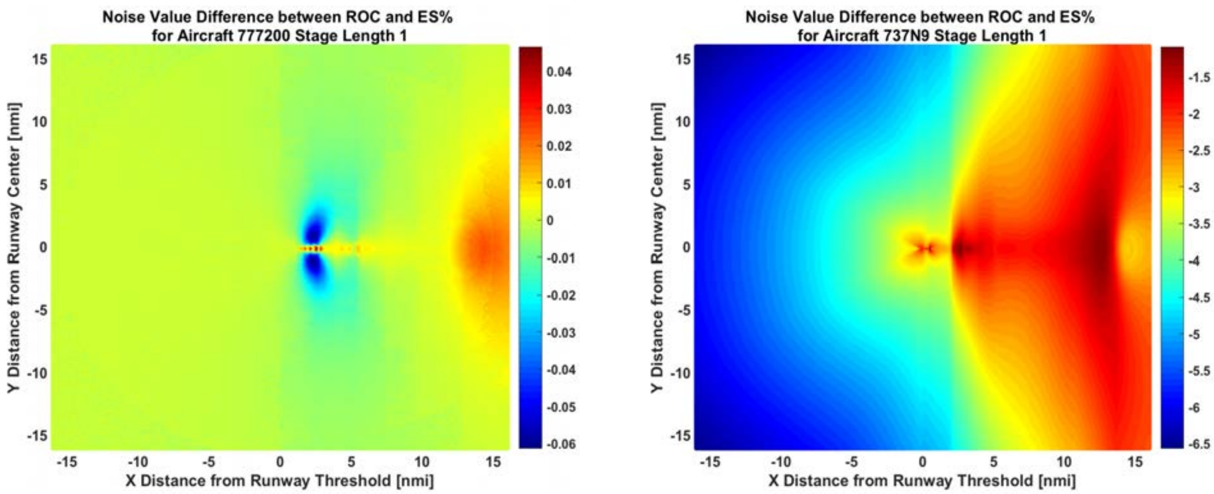


Figure 6. Example of Noise Difference Comparison: Excellent (Left) and Poor (Right) Matches

It was found out that between flight trajectory and noise plots, the flight trajectory comparison is a more rigorous criterion. That being said, if the flight trajectories between RoC- and ES-based profiles for a test case show excellent agreement, similar agreement can also be found in the relevant noise comparisons. However, an excellent agreement in the noise plots does not necessarily mean that the same agreement will also happen in the flight trajectory comparison. Based on this observation, the flight trajectory comparison results became the main reference in this validation process.

After the flight trajectory comparison was chosen as the main reference, a metric was developed to quantitatively assess the validity of an ES-based profile: the maximum trajectory difference in percentage (Max Diff %). At each trajectory segment, the altitudes of both the RoC and ES-based trajectories are obtained as y_{RoC} and y_{ES}, and the trajectory difference at the point is given by:

$$\text{Diff \%} = \frac{|y_{RoC} - y_{ES}|}{y_{RoC}} \times 100\%$$

The quantitative criterion for an excellent match is that, when the maximum of trajectory differences (Max Diff %) during the entire trajectory is less than 5%, the ES values for the corresponding case are deemed to be "good enough". When the Max Diff % for a case is greater than 5%, a process consisting of three step is taken to modify the ES values until satisfactory:

Step 1: Visually identify the takeoff segments in which the deviation in trajectories happens

Step 2: Identify the direction to modify ES values:

If the ES-based trajectory is below the RoC-based one: corresponding ES value is too large and should be reduced

If the ES-based trajectory is above the RoC-based one: corresponding ES value is too small and should be increased

Use the increment of modification to be plus or minus 5%, and reduce the increment if needed

If the ES value is not the reason behind a trajectory mismatch, look for other possible reasons

Step 3: Modify the ES values until the Max Diff % of the case is smaller than 5%.

The energy share development and validation process concluded when a trajectory Max Diff % of less than 5% is achieved for all the 409 STANDARD profiles. A histogram of the final Max Diff % results by aircraft and stage length can be found in Figure 7. Across the 409 STANDARD profiles, the set of final trajectory Max Diff % values has a mean of 1.40% and standard deviation of 1.04%, indicating that the final ES values are accurate enough. After the final ES values are finalized, they are used to replace the RoC-based profiles in future studies.

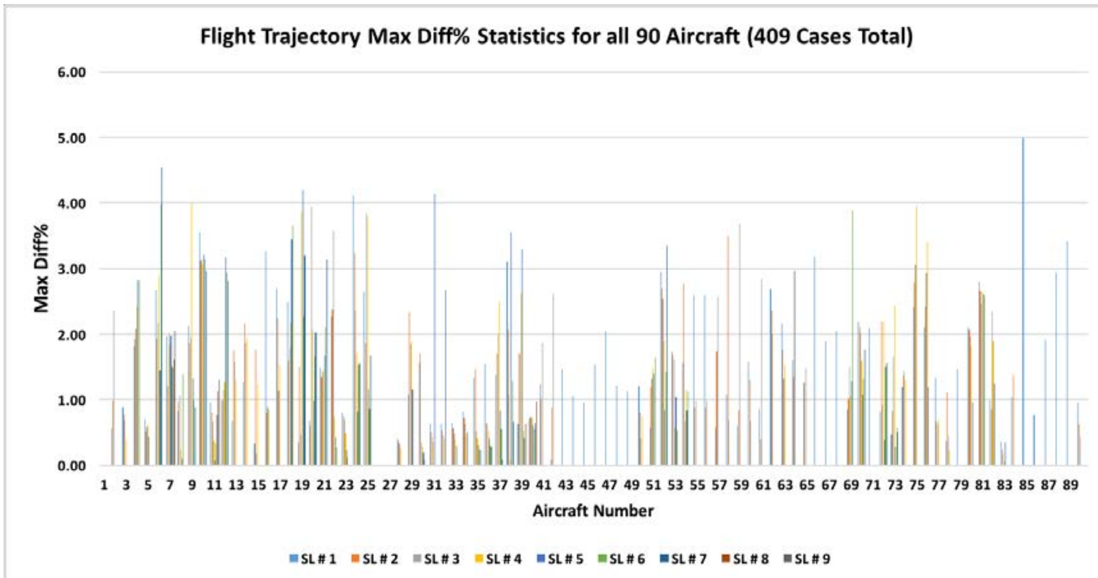


Figure 7. Final ES Validation Results: Statistics for the Max Diff %

Task 2- V&V Studies for Reduced Weight and Alternative Weight Profiles

Georgia Institute of Technology

Objective(s)

This task focused on V&V the newly developed profiles to verify if they are working properly for different aircraft at different stage length, airport, weather profiles, and conducted sensitivity analysis to compare the fuel burn, emission, and noise results of the new profiles to see how the reduced thrust and alternative weight impact the results. In addition, further analysis was performed to investigate the main drivers to the noise results.

Research Approach

V&V Study for Reduced Thrust Profiles

The reduced thrust and alternative weight profiles were developed to simulate real world operations practiced by airlines, and can more accurately model the takeoff operations. A comprehensive study is also conducted to analyze the performance, fuel burn, emissions and noise impacts of these new profiles. The study started with a full factorial experiment for selected airport and weather conditions within the ANP database, and the test matrix is listed below:

Test Matrix

- AEDT version: Sprint 106
- Aircraft: all 90 aircraft
- Airport: one airport, KIAH
- Runway: east-west for departure
- Weather Profile: sea level standard (temperature 59F, pressure 1013.25mb)

- Profiles: 1 STANDARD + 7 MODIFIED
- Stage Length: all stage lengths, ranging from 1-9 for different aircraft

The AEDT study was created by running a series of SQL scripts, and consisting a total number of 3,562 cases. The study was run with AEDT and the performance and noise reports generated were then extracted and analyzed through a large scale post-processing process. Through the study, the research team is interested in how the new profiles impact the performance, emissions and noise metrics:

- Performance: fuel burn
- Emissions: CO, NOx
- Noise: noise contour area, length, and width at different noise levels

When the experiment was finished, all the 3,562 cases were successfully run without any failure case. After that, all the performance and noise reports were further processed and analyzed by an integrated analysis code in MATLAB. The comparison results for the above metrics of interest across different profiles were summarized in two large tables, and visualized through box plots. In the following sections, performance, emissions and noise results will be summarized separately.

Performance and Emissions Results

As stated above, when comparing the aircraft takeoff performance and emissions across different profiles, the team is interested in three performance metrics: fuel burn, NOx emissions, and CO emissions. For each of the 90 aircraft, these metrics are calculated and compared across the 8 profiles for all the stage lengths. Table 3 shows an example of the performance metrics comparison across different profiles for aircraft 737-00 only. In this example table, the three metrics can be compared across new profiles against STANDARD profile, as well as different stage lengths.

With this table, several trends can be observed for a typical aircraft like the Boeing 737700. First, with more thrust reduction, all the three metrics display a monotonically increasing or decreasing pattern. Among the three of them, fuel burn and CO emission, in general, increase with more reduced thrust, compared to NOx emission which decreases with more reduced thrust. The increase in fuel burn is expected because the takeoff process is defined as the aircraft operation from the ground until the altitude of 10,000 ft AFE. With more reduced thrust, the aircraft has a shallower climbing slope, leading to a longer flight path and greater fuel consumption. This trend is also shown in Figure 8 with trajectory comparisons for the same aircraft with different profiles. In the meantime, with more reduced thrust, the CO emission also increases, but the differences are very slight compared to the fuel burn. The largest CO change in this case is 0.5%, which is one order of magnitude less than the fuel burn change. The NOx emission, however, decreases with more reduced thrust for aircraft 737700. This is because that when the thrust is reduced, the emission index of NOx is reduced which lead to the reduction in NOx. The second overall observation is that, the trends for different reduced thrust profiles are the same within each weight group (with or without 'AW'). The alternative weight group (AW) in general has larger positive changes in the three metrics compared to the Non-AW group. Lastly, the trends across different stage lengths are the same, with differences only in the magnitude of percentage changes.

Table 3. Example of the Performance Metrics Comparison

Profile	SL 1	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %	SL 4	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %
STANDARD		687.25	0	6463	0	10915	0		769.26	0	6506	0	12890	0
MODIFIED_RT05		687.65	0.06	6463	0	10792	-1.13		769.87	0.08	6506	0	12742	-1.15
MODIFIED_RT10		698.38	1.62	6469	0.09	10071	-7.73		784.83	2.02	6514	0.13	11922	-7.51
MODIFIED_RT15		698.8	1.68	6469	0.1	9929	-9.03		785.7	2.14	6515	0.14	11757	-8.79
MODIFIED_AW		697.7	1.52	6468	0.09	11165	2.29		798.63	3.82	6521	0.24	13593	5.45
MODIFIED_AW_RT05		697.94	1.56	6468	0.09	11035	1.1		799.25	3.9	6522	0.24	13435	4.23
MODIFIED_AW_RT10		709.29	3.21	6475	0.18	10303	-5.61		816.3	6.11	6531	0.38	12592	-2.31
MODIFIED_AW_RT15		709.75	3.27	6475	0.19	10158	-6.94		817.33	6.25	6532	0.4	12419	-3.65
Profile	SL 2	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %	SL 5	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %
STANDARD		707.3	0	6473	0	11397	0		826.95	0	6536	0	14276	0
MODIFIED_RT05		707.78	0.07	6474	0	11269	-1.12		827.83	0.11	6537	0.01	14112	-1.15
MODIFIED_RT10		719.78	1.76	6480	0.1	10528	-7.62		847.14	2.44	6547	0.17	13252	-7.17
MODIFIED_RT15		720.29	1.84	6481	0.11	10381	-8.91		848.36	2.59	6548	0.18	13071	-8.44
MODIFIED_AW		718.62	1.6	6479	0.09	11667	2.37		827.31	0.04	6537	0	14283	0.05
MODIFIED_AW_RT05		718.93	1.64	6480	0.1	11532	1.18		828.06	0.13	6537	0.01	14118	-1.11
MODIFIED_AW_RT10		731.65	3.44	6486	0.2	10781	-5.4		847.39	2.47	6547	0.17	13258	-7.13
MODIFIED_AW_RT15		732.21	3.52	6487	0.21	10630	-6.73		848.61	2.62	6548	0.18	13077	-8.4
Profile	SL 3	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %	SL 6	Fuel Burn	Difference %	CO	Difference %	NOx	Difference %
STANDARD		728.88	0	6485	0	11916	0		827.41	0	6537	0	14287	0
MODIFIED_RT05		729.32	0.06	6485	0	11780	-1.14		828.29	0.11	6537	0.01	14123	-1.15
MODIFIED_RT10		742.23	1.83	6492	0.11	11009	-7.61		847.63	2.44	6547	0.17	13263	-7.17
MODIFIED_RT15		742.85	1.92	6492	0.12	10855	-8.9		848.86	2.59	6548	0.18	13082	-8.43
MODIFIED_AW		752.17	3.2	6497	0.19	12473	4.67		827.54	0.02	6537	0	14289	0.01
MODIFIED_AW_RT05		752.59	3.25	6497	0.19	12329	3.47		828.29	0.11	6537	0.01	14123	-1.15
MODIFIED_AW_RT10		767.06	5.24	6505	0.31	11537	-3.18		847.63	2.44	6547	0.17	13263	-7.17
MODIFIED_AW_RT15		767.79	5.34	6506	0.32	11377	-4.52		848.86	2.59	6548	0.18	13082	-8.43

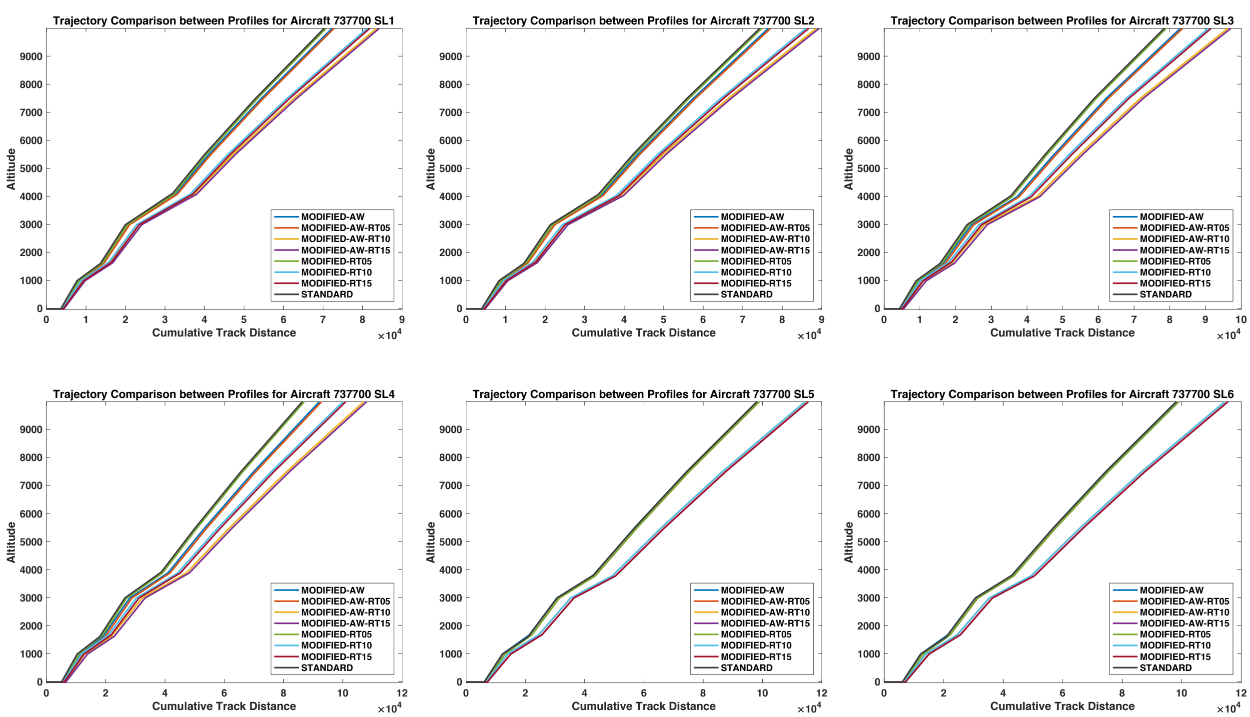
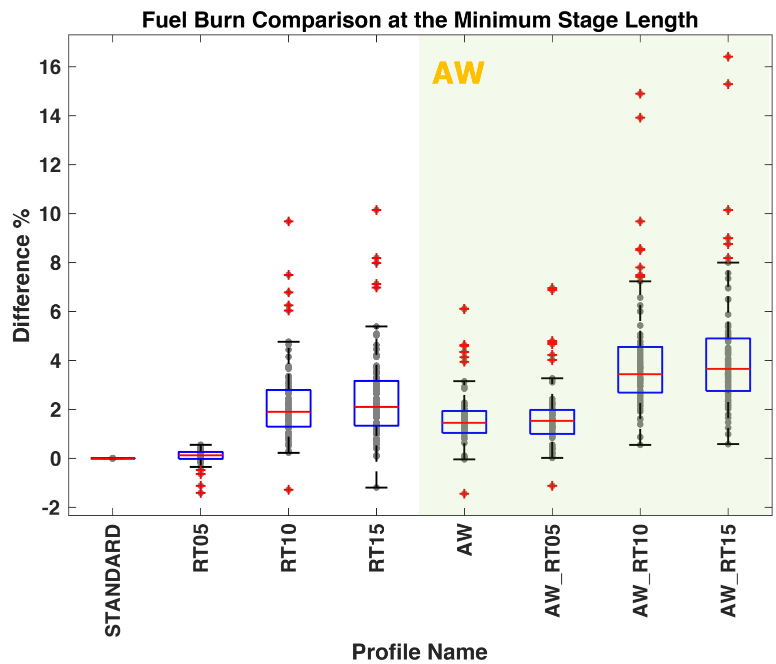


Figure 8. Trajectory Comparison for Different Profiles

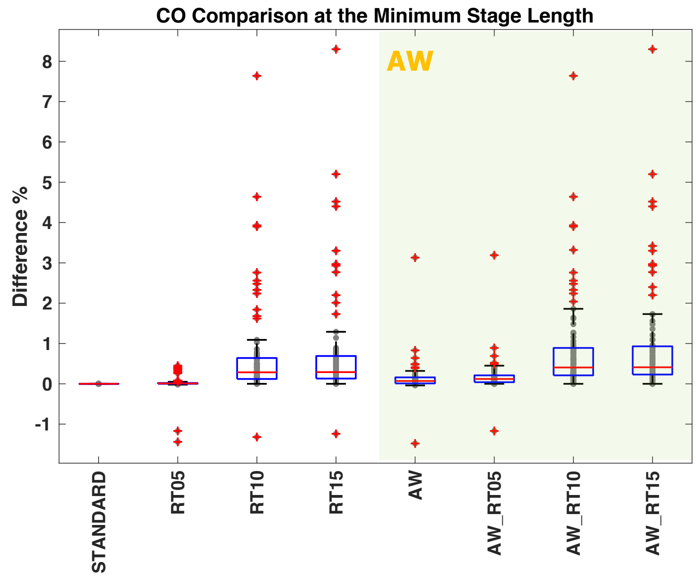
In addition to the comparison at aircraft level, the research team is also interested in investigating the pattern among the 8 profiles for all 90 aircraft at system level. Since different aircraft have different numbers of stage length ranging from 1 to 9, and considering the fact that some aircraft only have 1 stage length, only the minimum stage length is used in this comparison. The comparison results for fuel burn, NOx emission and CO emission are presented by box plots as shown in Figure 9 - Figure 11. Each box plot contains two different groups: with alternative weight (AW, in the right half), and without alternative weight (non-AW, in the left half). Within each group, results of the four different thrust levels (-0%, -5%, -10%, -15%) are displayed from left to right. Several descriptive statistics can be identified from the box plot, including the median (red horizontal line), first and third quartile (boundaries of the blue box), max and min (two ends of the whisker), and outliers (red dots). The mean values of the profiles are also shown below the box plot.



Median: 0 0.125 1.9100 2.105 1.460 1.540 3.435 3.665

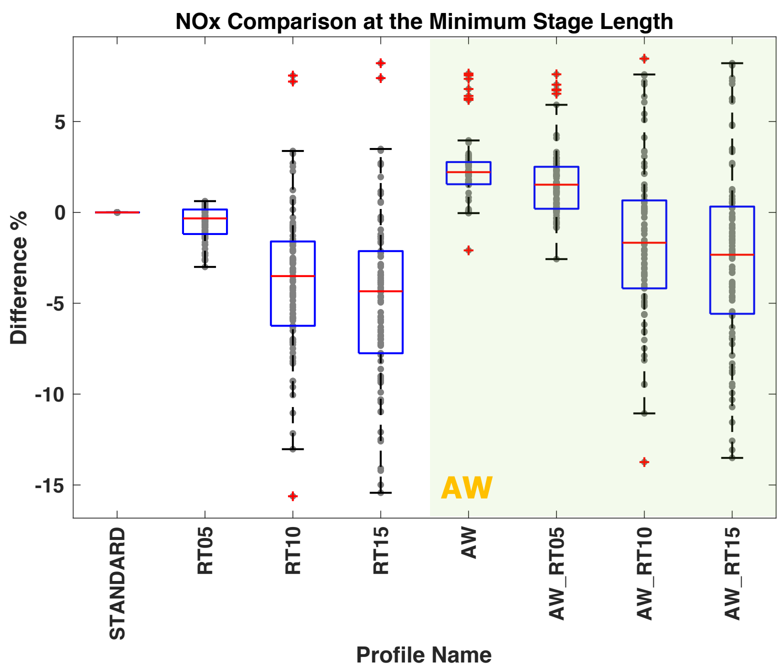
Figure 9. All 90 Aircraft Performance Comparison: Fuel Burn

Figure 9 shows the fuel burn comparison for the 8 profiles of all 90 aircraft. It can be observed that the overall trend is similar to the analysis of Boeing 737700, in which takeoff fuel burn generally increases with more reduced thrust. In the meantime, with the implementation of alternative weight (AW), each reduced thrust profile has a higher fuel burn value (approximately 1.5% higher) compared to its counterpart in the non-AW group. This general trend is exactly what was expected and can be used to further validate the effectiveness of the new reduced thrust and alternative weight profiles. Figure 10 shows the CO emission comparison for all 90 aircraft. Compared to the fuel burn results, now the CO emission results are in general less affected by the reduced thrust (the magnitude of the mean percentage changes are less than 1%), and have more outliers. Yet still, the results show that CO emission also increases with more reduced thrust, and is further increased by around 0.1% when alternative weight is added. Figure 11 shows the NOx emission comparison for all 90 aircraft. When compared to fuel burn and CO emission results, the NOx emission results have the fewest outliers and show a clear opposite trend: NOx emission generally decreases with more reduced thrust. One thing worth mentioning here is that for a number of aircraft, the NOx emission in fact increase with more reduced thrust, as shown by the left part of Figure 11. This is due to different characteristics of different aircraft and engines in which the increased fuel consumption is dominated the NOx calculation even though the EI of NOx is reduced.



Median: 0 0.010 0.285 0.290 0.070 0.120 0.405 0.410

Figure 10. All 90 Aircraft Performance Comparison: CO Emission



Median: 0 -0.330 -3.505 -4.340 2.215 1.525 -1.670 -2.330

Figure 11. All 90 Aircraft Performance Comparison: NOx Emission

Although individual differences can be significant among the 90 aircraft, the general trends of fuel burn, CO emission, and NOx emission changes for the new profiles are clear and interpretable. Below the general observations for the three metrics are summarized:

1. With more reduced thrust, the fuel burn increases
2. With more reduced thrust, the CO emission increases
3. With more reduced thrust, the NOx emission decreases
4. With the alternative weight, all of fuel burn, CO emission and NOx emission are increased by a certain level
5. Magnitude of change: NOx emission > Fuel burn > CO emission

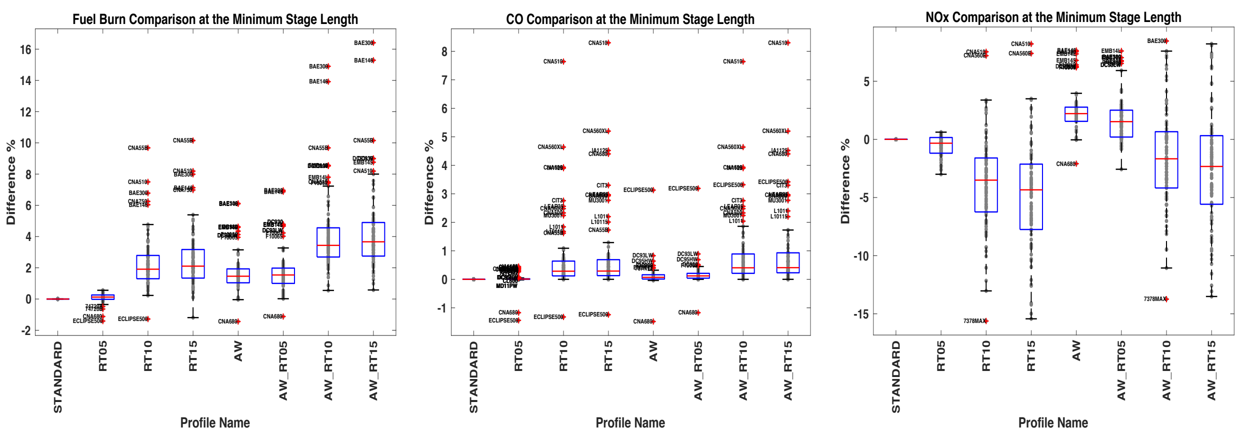


Figure 12. Outlier Identification for Performance Metrics Comparison

From the box plots shown in Figure 9 - Figure 11, there are outliers whose value are far from the median. It is necessary to identify all those outliers and see if further investigation or validation for some specific aircraft is needed. Figure 12 shows the identification of all the outliers directly from the box plots. Most of the outlier aircraft are repetitive in the three comparisons: CNA510, CNA560 series, CNA55B, BAE146, BAE300, ECLIPSE500, CNA680, DC930, DC93LW, L1011, L10115, F10062, F10065. Note that this short list of 13 aircraft contains no frequently-used aircraft in today's operation. Therefore, no further investigation is necessary to find out the reasons behind these outliers.

Nevertheless, when it comes to the NOx emission result, it was observed from the box plots and the outlier identification that the Boeing 737 Max 8 (737MAX8) aircraft is an outlier for the reduced thrust profiles. The difference compared to STANDARD profile was up to -15 % for the RT10 and AW_RT10 profiles. This large difference reduced slightly with increasing stage lengths but stood out consistently. To investigate this further, the performance and emissions data tables from AEDT were analyzed. It was observed that the percent difference in NOx was exactly the same as the percent difference in Fuel Burn, up to the "Terminal Climb" trajectory mode. To pinpoint the exact source of deviation, various plots were created to visualize the trajectory, cumulative NOx emissions, fuel flow rate, and segment fuel burn among many others. After detailed inspection, it was deemed necessary to replicate AEDT's NOx calculations independently. AEDT uses the Boeing Fuel Flow Method 2 for NOx calculations and the method is explained in detail in the Technical Manual. The investigation is done and it was found out that NOx EI for this aircraft was highly reduced for the profiles with reduced climb thrust which lead to big reduction in NOx results. This is an aircraft specific phenomenon which is not normal for other aircraft and engine.

Noise Results

Noise metrics are another major category to investigate with the results from the large scale experiment. A similar comparison was also conducted with the noise reports for all the 3,562 cases. The team identified 9 noise metrics of interest to calculate and analyze: 70 dB Noise Contour Area, 70 dB Noise Contour Length, 70 dB Noise Contour Width, 80 dB Noise Contour Area, 80 dB Noise Contour Length, 80 dB Noise Contour Width, 90 dB Noise Contour Area, 90 dB Noise Contour Length, and 90 dB Noise Contour Width. Figure 13 contains an example of the noise contour plots for aircraft 737700 stage length 1, with the definitions of the noise contour area, length, and width. For each of the 90 aircraft, the 9 noise metrics are then calculated and compared across the 8 profiles for all the stage lengths. Table 4 shows an example of the noise metrics comparison across different profiles, for aircraft 737700.

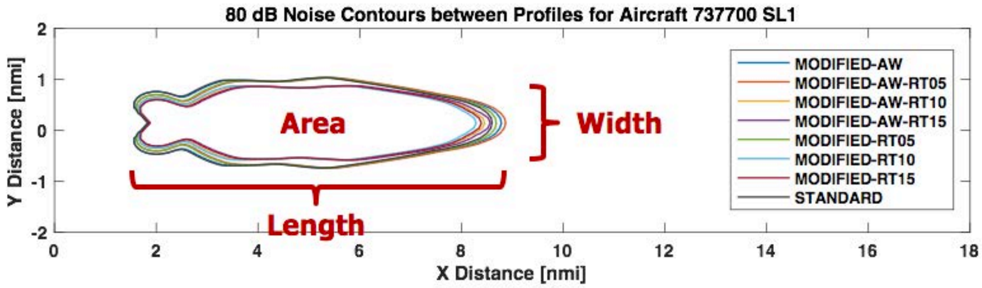


Figure 13. Example of the Noise Contour with Metrics Definition

Compared to the performance results, the noise results display more complex changing patterns. As can be seen from Table 4, among the changing patterns of contour area, length, and width at different noise levels, changes of contour area and width are consistent. When the thrust level is reduced from 0% to 15%, both the contour area and width monotonically decrease. It can also be observed that alternative weight (AW) profiles produce increased contour area by a certain amount compared to the non-AW profiles, but have almost no influence on the contour width. The changing pattern of contour length is relatively complicated and will be analyzed and discussed later.

Table 4. Example of the Noise Metrics Comparison

Profile	SL 1	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		44.841	0	12.928	0	3.9706	0	9.185	0	6.8526	0	1.7537	0	1.0903	0	2.4233	0	0.62981	0
MODIFIED_RT05		44.387	-1.01	12.92	-0.06	3.9654	-0.13	9.0282	-1.71	6.8867	0.51	1.7537	0	1.0397	-4.64	2.4751	2.14	0.57734	-8.33
MODIFIED_RT10		43.068	-3.95	14.144	9.41	3.5755	-9.95	7.3459	-20.02	6.438	-6.05	1.4569	-16.92	0.86341	-20.81	2.358	-2.69	0.50933	-19.13
MODIFIED_RT15		42.758	-4.66	14.17	9.61	3.5731	-10.01	7.3053	-20.46	6.5144	-4.94	1.4497	-17.33	0.8398	-22.98	2.4439	0.85	0.45745	-27.37
MODIFIED_AW		46.061	2.72	13.249	2.48	3.9759	0.13	9.3659	1.97	7.032	2.62	1.7577	0.23	1.1184	2.58	2.4849	2.54	0.62907	-0.12
MODIFIED_AW_RT05		45.532	1.54	13.242	2.43	3.9707	0	9.1926	0.08	7.0646	3.09	1.7557	0.11	1.0632	-2.49	2.5548	5.43	0.57191	-9.19
MODIFIED_AW_RT10		44.26	-1.3	14.519	12.31	3.5788	-9.87	7.5171	-18.16	6.6035	-3.64	1.4528	-17.16	0.88022	-19.27	2.4269	0.15	0.50226	-20.25
MODIFIED_AW_RT15		43.945	-2	14.549	12.54	3.5771	-9.91	7.4762	-18.6	6.6843	-2.46	1.4516	-17.23	0.85669	-21.43	2.516	3.83	0.45214	-28.21
Profile	SL 2	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		47.161	0	13.573	0	3.9522	0	9.5326	0	7.2086	0	1.7382	0	1.1369	0	2.556	0	0.61868	0
MODIFIED_RT05		46.647	-1.09	13.57	-0.02	3.9493	-0.07	9.3727	-1.68	7.2474	0.54	1.7382	0	1.0835	-4.7	2.6204	2.52	0.56719	-8.32
MODIFIED_RT10		45.434	-3.66	14.912	9.87	3.5603	-9.92	7.6732	-19.51	6.7919	-5.78	1.4435	-16.95	0.89768	-21.04	2.4923	-2.49	0.49945	-19.27
MODIFIED_RT15		45.114	-4.34	14.947	10.12	3.5578	-9.98	7.6317	-19.94	6.8751	-4.63	1.4346	-17.47	0.87451	-23.08	2.5872	1.22	0.44717	-27.72
MODIFIED_AW		48.493	2.82	13.924	2.59	3.9574	0.13	9.7775	2.57	7.4006	2.66	1.7422	0.23	1.1651	2.48	2.6202	2.51	0.61748	-0.19
MODIFIED_AW_RT05		47.936	1.64	13.922	2.57	3.9545	0.06	9.6067	0.78	7.4419	3.24	1.7418	0.21	1.1048	-2.82	2.6888	5.2	0.56122	-9.29
MODIFIED_AW_RT10		46.751	-0.87	15.33	12.94	3.5642	-9.82	7.8628	-17.52	6.9739	-3.26	1.4385	-17.24	0.91498	-19.52	2.5523	-0.14	0.49363	-20.21
MODIFIED_AW_RT15		46.428	-1.55	15.367	13.22	3.5603	-9.92	7.8177	-17.99	7.0593	-2.07	1.4352	-17.43	0.89107	-21.62	2.6571	3.96	0.44217	-28.53
Profile	SL 3	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		49.497	0	14.241	0	3.9397	0	10.065	0	7.6545	0	1.7242	0	1.1886	0	2.691	0	0.60703	0
MODIFIED_RT05		48.979	-1.05	14.237	-0.03	3.9371	-0.07	9.956	-1.08	7.6947	0.53	1.7232	-0.06	1.1296	-4.96	2.7727	3.04	0.55707	-8.23
MODIFIED_RT10		47.778	-3.47	15.685	10.14	3.5484	-9.93	8.1348	-19.18	7.2489	-5.3	1.4305	-17.03	0.93494	-21.34	2.6314	-2.21	0.48891	-19.46
MODIFIED_RT15		47.45	-4.14	15.726	10.43	3.5472	-9.96	8.0895	-19.63	7.3397	-4.11	1.418	-17.76	0.91211	-23.26	2.7361	1.68	0.43638	-28.11
MODIFIED_AW		52.217	6.5	14.97	5.12	3.9481	0.21	10.564	4.96	8.0608	5.31	1.7285	0.25	1.214	2.14	2.8486	5.86	0.59762	-1.55
MODIFIED_AW_RT05		51.615	4.28	14.974	5.15	3.9455	0.15	10.416	3.49	8.1097	5.95	1.7275	0.19	1.1747	-1.17	2.9309	8.91	0.54694	-9.9
MODIFIED_AW_RT10		50.538	2.1	16.559	16.28	3.5562	-9.73	8.5453	-15.1	7.6377	-0.22	1.421	-17.58	0.9752	-17.95	2.7846	3.48	0.47792	-21.27
MODIFIED_AW_RT15		50.198	1.42	16.608	16.62	3.5543	-9.78	8.4962	-15.59	7.743	1.16	1.4207	-17.6	0.94997	-20.08	2.9	7.77	0.4322	-28.8
Profile	SL 4	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		53.921	0	15.527	0	3.9016	0	10.947	0	8.4849	0	1.6846	0	1.2702	0	3.0066	0	0.58719	0
MODIFIED_RT05		53.364	-1.03	15.532	0.03	3.9016	0	10.807	-1.28	8.5428	0.68	1.6844	-0.01	1.2255	-3.52	3.1059	3.3	0.53441	-8.99
MODIFIED_RT10		52.23	-3.14	17.186	10.68	3.5116	-10	8.8558	-19.1	8.0481	-5.15	1.405	-16.6	1.0143	-20.15	2.9448	-2.06	0.4719	-19.63
MODIFIED_RT15		51.872	-3.8	17.248	11.08	3.5116	-10	8.7639	-19.94	8.1634	-3.79	1.3828	-17.92	0.99109	-21.97	3.0732	2.22	0.4358	-25.78
MODIFIED_AW		57.333	6.33	16.449	5.94	3.9105	0.23	11.585	5.83	9.0044	6.12	1.6896	0.3	1.3295	4.67	3.1948	6.26	0.57242	-2.52
MODIFIED_AW_RT05		56.729	5.21	16.466	6.05	3.9092	0.19	11.431	4.42	9.0734	6.94	1.6896	0.3	1.2807	0.83	3.2994	9.74	0.52278	-10.97
MODIFIED_AW_RT10		55.716	3.33	18.298	17.85	3.5198	-9.79	9.3783	-14.33	8.5596	0.88	1.3887	-17.57	1.063	-16.31	3.1364	4.32	0.47332	-19.39
MODIFIED_AW_RT15		55.343	2.64	18.373	18.33	3.5194	-9.8	9.2761	-15.26	8.6864	2.37	1.3833	-17.89	1.0378	-18.3	3.2785	9.04	0.43959	-25.14
Profile	SL 5	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		60.562	0	17.416	0	3.9169	0	12.071	0	9.5474	0	1.6426	0	1.3938	0	3.4152	0	0.57025	0
MODIFIED_RT05		59.893	-1.1	17.438	0.13	3.9181	0.03	11.928	-1.18	9.6273	0.84	1.6424	-0.01	1.3431	-3.64	3.5301	3.36	0.51849	-9.08
MODIFIED_RT10		59.076	-2.45	19.462	11.75	3.4719	-11.36	9.7856	-18.93	9.0959	-4.73	1.3741	-16.35	1.1121	-20.21	3.3439	-2.09	0.47674	-16.4
MODIFIED_RT15		58.691	-3.09	19.551	12.26	3.4728	-11.34	9.7228	-19.45	9.2379	-3.24	1.3507	-17.77	1.0874	-21.98	3.5034	2.58	0.44324	-22.27
MODIFIED_AW		60.611	0.08	17.418	0.01	3.9181	0.03	12.09	0.16	9.5474	0	1.6426	0	1.3948	0.07	3.4173	0.06	0.57043	0.03
MODIFIED_AW_RT05		59.92	-1.06	17.445	0.17	3.9181	0.03	11.931	-1.16	9.6273	0.84	1.6424	-0.01	1.3437	-3.59	3.533	3.45	0.51865	-9.05
MODIFIED_AW_RT10		59.102	-2.41	19.471	11.8	3.4719	-11.36	9.7891	-18.9	9.0959	-4.73	1.373	-16.41	1.1125	-20.18	3.3446	-2.07	0.47674	-16.4
MODIFIED_AW_RT15		58.719	-3.04	19.559	12.3	3.4728	-11.34	9.6855	-19.76	9.2469	-3.15	1.3499	-17.82	1.088	-21.94	3.505	2.63	0.44324	-22.27
Profile	SL 6	Area - 70 dB	Difference %	Length - 70 dB	Difference %	Width - 70 dB	Difference %	Area - 80 dB	Difference %	Length - 80 dB	Difference %	Width - 80 dB	Difference %	Area - 90 dB	Difference %	Length - 90 dB	Difference %	Width - 90 dB	Difference %
STANDARD		60.616	0	17.431	0	3.9181	0	12.078	0	9.5577	0	1.6426	0	1.3946	0	3.4177	0	0.57043	0
MODIFIED_RT05		59.946	-1.11	17.453	0.13	3.9181	0	11.938	-1.16	9.6384	0.84	1.6424	-0.01	1.3439	-3.64	3.533	3.37	0.51865	-9.08
MODIFIED_RT10		59.129	-2.45	19.479	11.75	3.4719	-11.39	9.7933	-18.92	9.102	-4.77	1.3729	-16.42	1.1127	-20.21	3.3474	-2.06	0.47677	-16.42
MODIFIED_RT15		58.746	-3.08	19.569	12.27	3.4728	-11.37	9.6882	-19.79	9.2469	-3.25	1.3499	-17.82	1.0881	-21.98	3.5071	2.62	0.44324	-22.3
MODIFIED_AW		60.638	0.04	17.425	-0.03	3.9181	0	12.091	0.11	9.5477	-0.1	1.6426	0	1.3951	0.04	3.4196	0.06	0.57043	0
MODIFIED_AW_RT05		59.946	-1.11	17.453	0.13	3.9181	0	11.938	-1.16	9.6384	0.84	1.6424	-0.01	1.3439	-3.64	3.533	3.37	0.51865	-9.08
MODIFIED_AW_RT10		59.129	-2.45	19.479	11.75	3.4719	-11.39	9.7933	-18.92	9.102	-4.77	1.3729	-16.42	1.1127	-20.21	3.3474	-2.06	0.47677	-16.42
MODIFIED_AW_RT15		58.746	-3.08	19.569	12.27	3.4728	-11.37	9.6882	-19.79	9.2469	-3.25	1.3499	-17.82	1.0881	-21.98	3.5071	2.62	0.44324	-22.3

Similar to the performance results, a comprehensive comparison using results for all 90 aircraft was also conducted. Still, only the minimum stage length was used to compare across different aircraft with different number of stage length. Figure 14 - Figure 16 contains the comparison results for all 90 aircraft for noise contour area, length, and width, respectively. Within each figure and noise contour metric, the three subplots show results for three different noise levels: 70 dB, 80 dB, and 90 dB. In each figure, one can compare between the 8 profiles for a certain noise level, or observe the differences across different noise levels by comparing the three subplots. Median of contour area, length and width for each noise level can be found in Table 5 - Table 7.

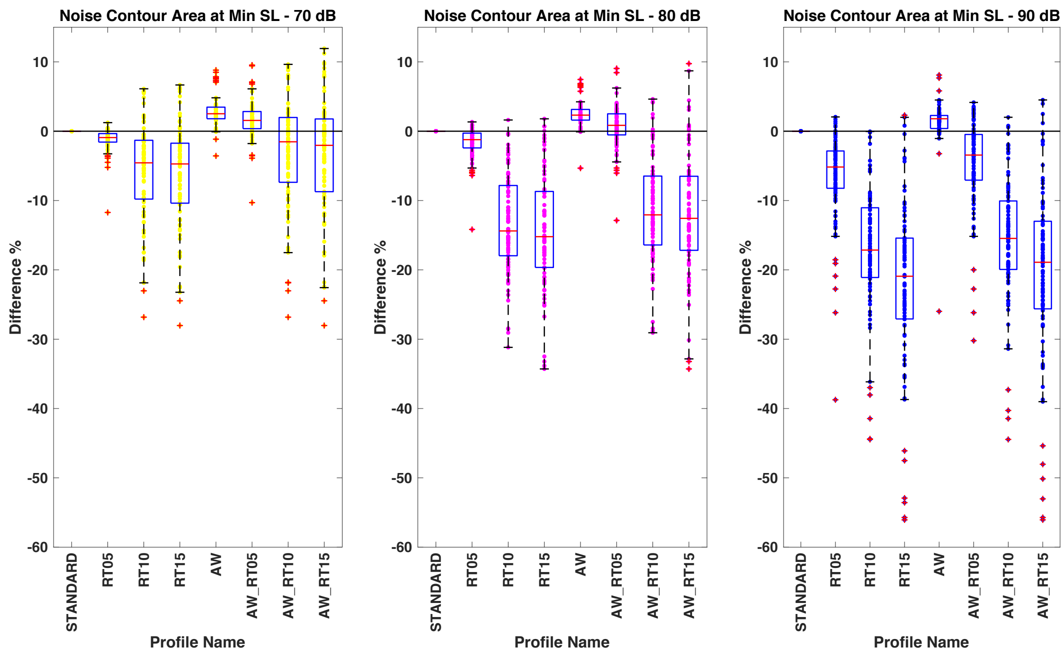


Figure 14. All 90 Aircraft Noise Comparison: Noise Contour Area

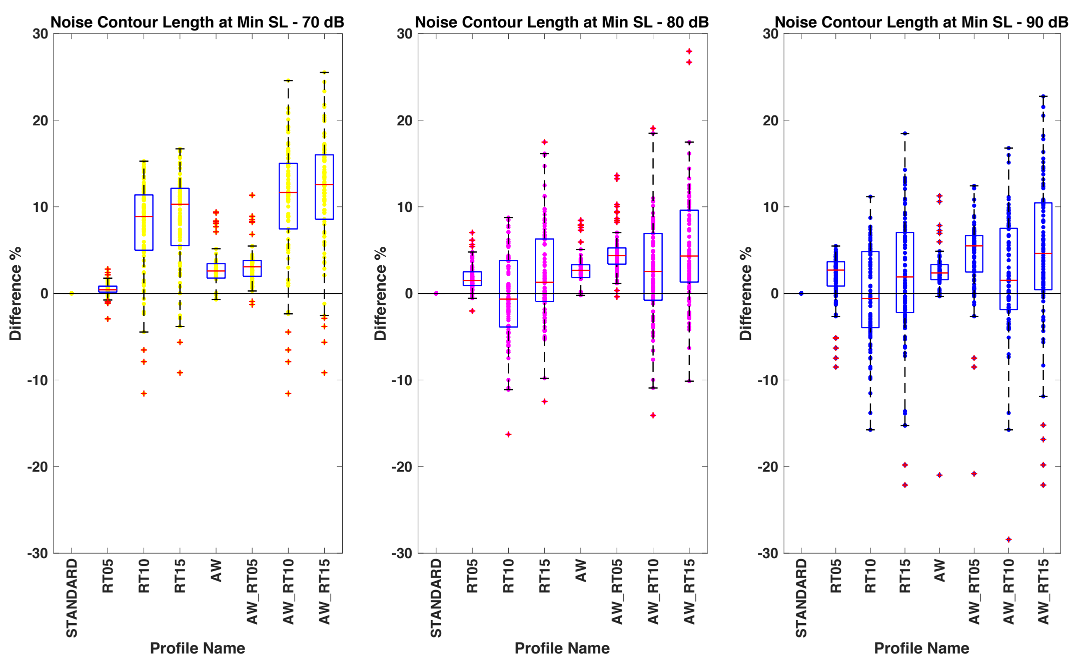


Figure 15. All 90 Aircraft Noise Comparison: Noise Contour Length

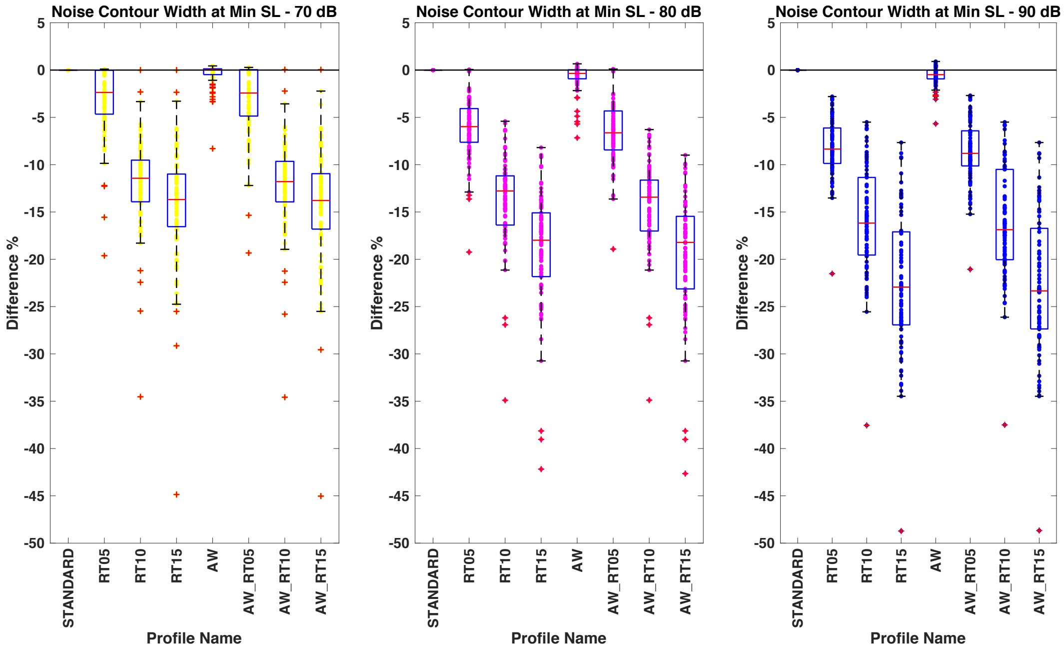


Figure 16. All 90 Aircraft Noise Comparison: Noise Contour Width

Table 5. Medians for Noise Contour Area Comparison for all 90 Aircraft

Profiles	STANDARD	MODIFIED RT05	MODIFIED RT10	MODIFIED RT15	MODIFIED AW	MODIFIED AW_RT05	MODIFIED AW_RT10	MODIFIED AW_RT15
70 dB	0.000	-0.915	-4.560	-4.720	2.520	1.555	-1.525	-2.040
80 dB	0.000	-1.215	-14.385	-15.210	2.320	0.845	-12.065	-12.570
90 dB	0.000	-5.165	-17.145	-20.920	1.800	-3.440	-15.465	-18.905

Table 6. Medians for Noise Contour Length Comparison for all 90 Aircraft

Profiles	STANDARD	MODIFIED RT05	MODIFIED RT10	MODIFIED RT15	MODIFIED AW	MODIFIED AW_RT05	MODIFIED AW_RT10	MODIFIED AW_RT15
70 dB	0.000	0.410	8.885	10.295	2.590	3.070	11.665	12.580
80 dB	0.000	1.490	-0.655	1.290	2.665	4.375	2.540	4.315
90 dB	0.000	2.695	-0.595	1.900	2.360	5.485	1.515	4.625

Table 7. Medians for Noise Contour Width Comparison for all 90 Aircraft

Profiles	STANDARD	MODIFIED RT05	MODIFIED RT10	MODIFIED RT15	MODIFIED AW	MODIFIED AW_RT05	MODIFIED AW_RT10	MODIFIED AW_RT15
70 dB	0.000	-2.365	-11.435	-13.685	0.040	-2.425	-11.790	-13.785
80 dB	0.000	-5.980	-12.775	-17.985	-0.355	-6.630	-13.435	-18.215
90 dB	0.000	-8.350	-16.175	-22.940	-0.485	-8.805	-16.870	-23.340

The integrated analysis for noise metrics for all 90 aircraft unveils general impacts of the new profiles on noise contour. Figure 14 and Table 5 show the noise contour area comparison among the 8 profiles at three different noise levels. Three general observations can be made from the contour area comparison. First, when the thrust level is further reduced, the noise contour area at all the three noise levels becomes smaller. This results shows that the reduced thrust takeoff operation can in fact abate the noise impact to the ground. Second, when comparing across the AW and non-AW groups (left and right four columns), the use of alternative weight increases the noise contour area by around 2.5%. Third, at a larger noise level, the noise contour area is reduced by a larger extent under the influence of reduced thrust takeoff. Figure 15 and Table 6 show the noise contour width comparison of this round. The changing pattern of the contour width is the most straightforward among the three: with more reduced thrust, the noise contour width decreases monotonically. It is less influenced by the alternative weight, and the percentage of reduction is larger at larger noise levels. Figure 16 and Table 7 show the noise contour length comparison between the 8 profiles. It can be observed that the changing pattern of the contour length is the most complicated one, as the changing trends are not consistent at three different noise levels. At the noise level of 70 dB, the contour length increases with more reduced thrust. Yet at 80 and 90 dB, the largest contour length happens when the reduced thrust level is -5%, and the trend is fluctuating as the reduced thrust level goes from 0% to -15%.

The difficulty of predicting the change of noise contour length is not a surprise, as the noise metrics are affected by a mix of several direct consequences brought out by a reduced thrust profile. On one hand, when the thrust level is reduced, the noise directly generated from the engine is expected to become smaller. On the other hand, with reduced thrust, the takeoff flight trajectory is also closer to the ground, as shown by Figure 8. A shallower trajectory amplifies the flight's noise impact to the ground. When both the plus (trajectory) and minus (engine) effects are added together, predicting the noise metrics impact requires the identification of the most dominant effects at different stages and noise levels. A quantitative study to uncover the reasons behind the complex changing pattern for noise metrics will be discussed later.

Although due to significant differences among the 90 aircraft and the complexity of noise metrics, the changing patterns of noise metrics are more complicated compared to the performance metrics, some general observations for noise metrics are summarized below:

1. With more reduced thrust, the noise contour area at different noise levels decreases
2. With more reduced thrust, the noise contour width at different noise levels decreases
3. With more reduced thrust, the change of noise contour length does not have a monotonic changing pattern, and displays different characteristics at different noise levels
4. With the alternative weight, the noise contour area and length are increased by a certain increment. Contour width is less influenced by the alternative weight
5. For noise contour area and width, the percentage change with reduced thrust is greater at higher noise levels.

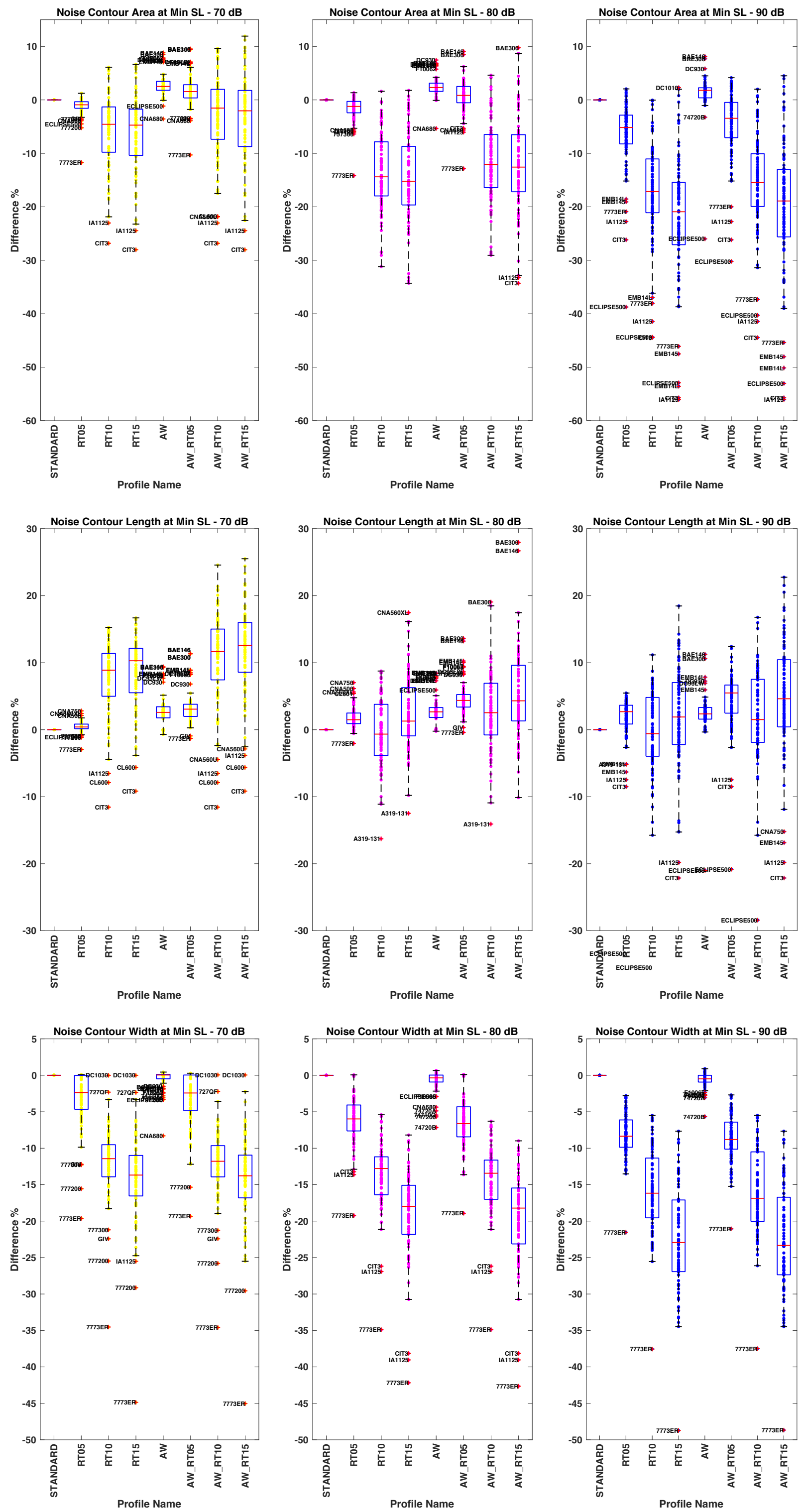


Figure 17. Outlier Identification for Noise Metrics Comparison

An outlier analysis was also conducted to identify and analyze outlier aircraft in the noise results. The outliers in Figure 14-Figure 16 are first identified and marked out in Figure 17. A complete list of outlier aircraft in noise results include: 717200, ECLIPSE500, IA1125, F10062, F10065, 74720B, 777200, 7773ER, 757PW, BAE146, BAE300, 727EM2, 727QF, CIT3, DC930, DC1030, DC93LW, 727QF, 767JT9, A300-622R, A319-131. From the list, it can be found out that most of the outlier aircraft are still aircraft that are old aircraft and not commonly operated in today's operations. Some representative aircraft, such as A319-131 and 777200, are outliers only in one of the metrics, or are not too far from the ends of the whisker. For those aircraft, there's no need to specifically investigate the reasons behind. However, for one aircraft, the Boeing 777-300ER (7773ER), it is a standing-out outlier in contour width comparison in all the three noise levels. Although the noise contour width changing trend for 7773ER is consistent with other aircraft, its contour width decreases much more than other aircraft (around 20% more compared to the median of the 90 aircraft). An investigation on the performance report of 7773ER was therefore conducted to further explain the reasons behind this outlier. After checking the performance data from various angles, no abnormal pattern has been found. A speculation of the reasons behind 7773ER being an outlier is that the 7773ER aircraft and engine data provided by the manufacturers may be relatively new compared to other aircraft. The more up-to-date data can cause better performance as of the environmental impacts.

Quantitative Root Cause Analysis on Noise Results

After the large scale AEDT study with all 90 aircraft and all stage lengths was conducted, the analysis results for key performance and noise metrics were presented in the previous sections. For the new reduced thrust profiles, while the changing patterns for the performance metrics are relatively straightforward and easy to be interpreted, the changing patterns for the noise metrics are more complex and require further in-depth analysis. In general, the observed changing patterns for the three noise metrics are:

- Noise Contour Area: monotonically decreases with more reduced thrust
- Noise Contour Width: monotonically decreases with more reduced thrust
- Noise Contour Length: does not have a monotonically changing trend with reduced thrust.

The reason why the changing patterns of the noise results are more difficult to explain is that, with a reduced thrust profile, the changes for all of contour area, length, and width are affected by two direct consequences caused by reduced thrust:

- Consequence 1 – Thrust Change: with reduced thrust, the magnitude of noise that directly comes from the engine is also reduced. This is a negative effect to the contour area, length, and width on the ground.
- Consequence 2 – Trajectory Change: with reduced thrust, the aircraft takeoff trajectory is closer to the ground. This is a positive effect to the contour area, length, and width on the ground.

Therefore, to better explain why for different reduced thrust profiles, the noise metrics change in the way we observed, an advanced statistical analysis is needed to identify the most influential factors to each noise metrics for different noise levels. When such influential factors are identified, the changing trends of the noise metrics should follow the directions given by the most influential factors. In the meantime, the study was done from a mode's perspective, in which the noise metrics contribution from four takeoff modes were distinguished. Overall, a takeoff process consists of four different modes according to the performance report:

Mode 1: Taxi

Mode 2: Takeoff Ground Roll

Mode 3: Takeoff Airborne

Mode 4: Terminal Climb

Because AEDT does not model Taxi noise, only Mode 2-4 are considered in this analysis. With all these information, the analysis is formulated as shown in Figure 18. In this whole analysis, we have 9 objectives to study, which are the 9 noise metrics: percentage of noise contour area, length, and width at 70, 80 and 90 dB levels, as shown at the left of Figure 18. In the meantime, there are 6 predictors of interest for each of the 9 metrics: percentage of thrust change and trajectory change for Mode 2-4, as shown in the middle of Figure 18. Then, each of the 9 noise metrics is a function of the 6 predictors, indicated by the matching at the right of Figure 18.

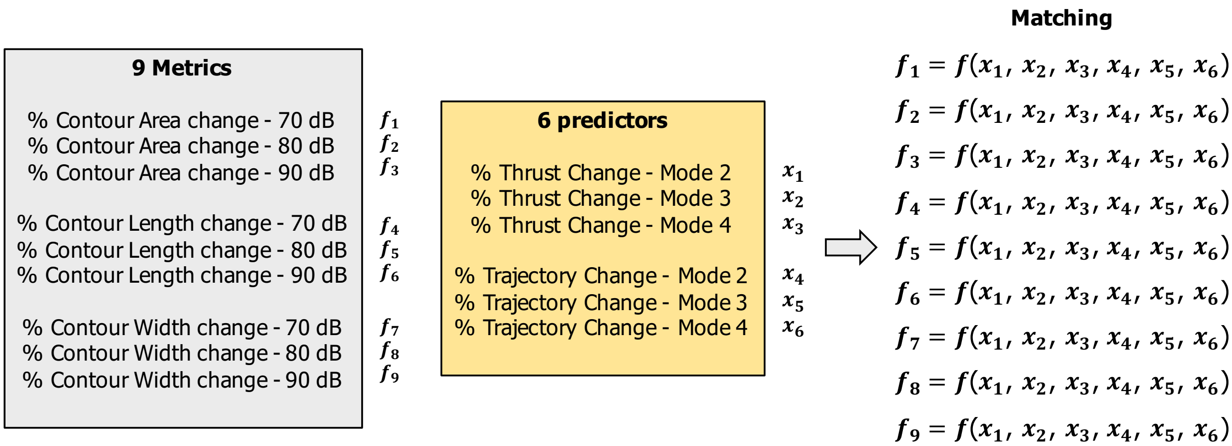


Figure 18. The Root Cause Statistical Analysis Set-up

After the analysis approach is formulated, information from the previous analyses must be re-organized for the statistical model selection process. The necessary information for the statistical analysis is calculated and organized into a table shown in Table 8. Due to the limited space, Table 8 only contains part of the complete table. With each row representing one case, the complete table has more rows and includes all the cases summarized above in Figure 14 - Figure 16 (the full factorial combination of all 90 aircraft, 8 profiles, and stage length 1). The table can be divided into two parts. The left part contains 9 columns that are highlighted in gray, and they correspond to the percentage changes of the 9 noise metrics. The right part contains 6 columns that are colored in yellow, and they correspond to the percentage changes of the 6 predictors. Among the 6 predictors, the definition of the percentage change in trajectory needs to be emphasized. Here, a 20% increase in trajectory means that compared to the old trajectory, the new one is 20% closer to the ground.

When the pre-analysis table is ready, statistical learning methods LASSO (**L**east **A**bsolute **S**hrinkage and **S**election **O**perator) and Elastic Net are used to identify the most influential predictors for each noise metric. Both the LASSO and Elastic Net are methods from the category of linear model selection and regularization. In a regression setting, a linear model can be written as

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon$$

where Y is the metric of interest, $X_1, X_2, \ldots, X_n$ are the predictors and $\beta_1, \beta_2, \ldots, \beta_n$ are the coefficients. The first statistical method LASSO is an important statistical learning method for model selection (or in our context, predictor selection). For a certain model with many predictors, the LASSO is a shrinkage method and is able to remove the redundant predictors, select the most influential ones and rank among them. Mathematically, the LASSO estimate minimizes

$$\sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{n}\beta_j x_{ij}\right)^2 + \lambda\sum_{j=1}^{n}|\beta_j|$$

where $\lambda\sum_{j=1}^{n}|\beta_j|$ is called the LASSO penalty, and is controlled by the value of λ. As λ increases, more shrinkage is employed and more coefficients go to zero. In this process, a predictor is more influential if its corresponding coefficient remains non-zero for larger λ values.

The second statistical learning method considered, the Elastic Net, is a modified version of LASSO. It makes a compromise between LASSO and Ridge Regression (also a shrinkage method but uses different penalty function) and has a better performance when some of the predictors are highly correlated. The Elastic Net minimizes

$$\frac{1}{2}\sum_{i=1}^{n}\left(y_i-\beta_0-\sum_{j=1}^{n}\beta_j x_{ij}\right)^2+\lambda\left[\frac{(1-\alpha)}{2}\sum_{j=1}^{n}|\beta_j|^2+\alpha\sum_{j=1}^{n}|\beta_j|\right]$$

where the α is adjusted to assign weights between LASSO and Ridge Regression. It becomes LASSO when $\alpha = 1$, and Ridge Regression when $\alpha = 0$.

Table 8. The Format of the Pre-Analysis Table for LASSO and Elastic Net Analysis

70dB - Area	70dB - Length	70dB - Width	80dB - Area	80dB - Length	80dB - Width	90dB - Area	90dB - Length	90dB - Width	Mode 2 Trajectory	Mode 3 Trajectory	Mode 4 Trajectory	Mode 2 thrust	Mode 3 thrust	Mode 4 thrust
3.1588	3.5779	-0.38062	3.4496	3.3673	-1.4328	2.3895	2.6647	0.50695	5.1732	4.7263	3.5992	-0.054155	-0.24377	-0.076558
2.7004	3.9506	-0.4183	1.4505	4.7635	-3.9085	-6.1374	7.1547	-7.1943	10.554	11.343	4.2905	-5.0424	-5.2343	-0.43638
-11.559	2.9816	-12.266	-14.786	1.1476	-14.673	-15.922	7.8097	-13.452	16.528	18.836	20.507	-10.031	-10.218	-10.067
-12.181	3.6276	-12.266	-15.84	3.405	-20.372	-25.009	10.659	-19.173	23.204	27.422	21.413	-15.019	-15.209	-10.427
-0.58546	0.30644	-0.086675	-0.95646	1.4073	-3.0314	-8.9272	3.695	-7.729	5.1111	6.3017	0.63563	-4.9883	-5.0041	-0.32154
-14.332	-0.62945	-11.765	-16.808	-2.2197	-14.627	-18.252	3.9812	-13.832	10.785	13.44	16.137	-9.9765	-10.001	-9.9602
-14.981	0.0082823	-11.803	-17.834	0.017758	-19.634	-27.116	7.0402	-19.547	17.127	21.593	16.995	-14.971	-15.005	-10.32
3.6025	3.6911	-0.51979	3.3033	3.6755	-0.55653	2.5352	3.3939	-0.55611	5.2168	1.8129	4.0106	-0.047033	-0.11842	0
0.86749	19.126	-13.533	-9.9929	4.9122	-15.436	-11.55	2.9899	-17.461	16.695	18.333	23.382	-10.034	-10.108	-9.999
-3.0394	14.488	-12.99	-13.012	1.0983	-14.865	-13.937	-0.56798	-16.947	10.901	16.14	18.332	-9.9945	-10.007	-10.002
3.2783	3.4274	-0.74668	3.4448	3.8466	-0.88568	2.269	3.7718	-0.6217	5.1802	1.8319	3.9557	-0.034958	-0.10239	-0.026346
0.72056	3.5382	-2.8172	1.4405	4.6171	-9.551	-0.63526	6.6955	-10.67	10.631	9.1557	5.2763	-5.3695	-5.083	-0.4391
-9.0718	15.562	-17.211	-28.81	-7.6472	-17.744	-19.938	-3.983	-20.372	16.688	17.681	22.479	-10.347	-10.078	-10.003
-10.938	16.297	-25.177	-30.135	-6.3247	-25.524	-22.712	0.26214	-29.209	23.459	27.708	24.306	-15.325	-15.074	-10.433
-2.5899	0.11576	-3.0379	-2.087	0.75822	-8.8158	-3.1836	2.9591	-9.8316	5.1775	6.8904	1.3146	-4.999	-4.9806	-0.42153
-12.338	11.375	-16.61	-31.18	-11.12	-17.105	-21.96	-7.4264	-19.656	10.933	15.187	17.613	-10.313	-9.9832	-9.9939
-14.121	12.064	-24.6	-32.491	-9.7976	-24.929	-24.749	-3.2907	-28.693	17.365	24.93	19.38	-15.29	-14.986	-10.424
3.882	3.8777	-0.56688	3.0447	3.6836	-0.594	2.2488	3.3633	-1.3042	5.2715	2.5435	4.1136	-0.052079	-0.16406	-0.009827
1.975	4.2067	-2.0959	0.55301	5.4034	-9.4305	-4.5392	8.7792	-12.905	10.705	10.244	5.3005	-5.0443	-5.1513	-0.42256
-1.8791	0.3128	-2.2399	-2.5294	1.6326	-8.8671	-6.9189	5.0703	-11.894	5.1576	7.2505	1.152	-4.9922	-4.9955	-0.42256
3.1679	3.2385	0.10002	2.7325	3.1781	-0.50176	2.4321	3.2597	0.51201	5.1321	4.7486	3.4864	-0.084598	-0.3229	-0.076634
3.1959	3.0142	0.22708	2.7158	3.0102	-0.91851	2.1085	3.2903	-0.84	5.0776	4.6896	3.3715	-0.070179	-0.2884	-0.04462
-2.2168	13.856	-15.184	-14.089	0.75329	-12.8	-17.962	-0.58589	-21.268	16.51	18.533	19.89	-10.046	-10.256	-10.04
-5.4398	10.242	-15.281	-16.449	-2.4034	-12.197	-19.914	-3.9102	-20.722	10.871	13.201	15.847	-9.9754	-10.002	-10.001
3.1024	2.9944	0.22024	2.3673	3.1537	0.092513	2.2086	2.6205	-0.61409	5.0524	4.6894	3.3888	-0.077489	-0.28487	-0.03635
-2.8949	13.551	-17.397	-16.397	-0.8288	-14.839	-21.072	-1.8803	-21.816	16.498	18.517	20.083	-10.049	-10.255	-10.033
-6.056	9.9935	-17.498	-18.432	-3.8805	-14.278	-22.883	-4.8858	-21.501	10.887	13.179	16.028	-9.9816	-9.9983	-9.9903
3.468	3.2007	0.1611	3.1476	3.2328	-0.22516	1.943	2.884	-1.6564	5.1773	4.7861	3.4667	-0.08285	-0.32121	-0.020789
-0.052058	14.914	-10.117	-8.9204	4.1601	-11.011	-15.122	0.086293	-14.666	16.624	18.891	20.201	-10.052	-10.285	-10.02
-3.4284	11.106	-10.19	-11.449	0.83137	-10.902	-17.177	-3.3018	-15.12	10.875	13.422	16.046	-9.9807	-9.9961	-9.9716
2.7207	2.483	0.13348	1.9695	2.618	0.22809	2.5773	2.542	-0.1175	4.2891	3.9362	2.8394	-0.054225	-0.22809	-0.17346
2.6186	2.6433	-0.50774	2.3709	2.8011	-0.79773	1.5439	2.4066	-1.1955	4.5846	2.8211	3.0451	-0.061232	-0.16494	0
0.71227	2.9563	-4.6692	-2.0578	4.072	-9.9668	-10.544	4.096	-13.23	9.9736	9.6245	4.4862	-5.0496	-5.1555	-0.47925
-2.453	12.611	-13.444	-21.14	-4.9183	-18.905	-23.359	2.0633	-24.643	15.962	17.382	19.264	-10.038	-10.146	-10.002
-3.6052	13.481	-14.919	-23.287	-2.6334	-25.167	-33.932	0.66624	-33.948	22.655	26.308	21.169	-15.026	-15.137	-10.482
-2.0587	0.2852	-4.8126	-4.0888	1.2905	-9.4623	-12.203	1.4786	-12.856	5.1496	6.5999	1.4086	-4.9924	-5	-0.47925
-5.2849	9.4533	-13.189	-23.016	-7.4888	-18.391	-24.966	-1.0401	-23.997	10.872	14.118	15.641	-9.9808	-10	-10.002
-6.4143	10.281	-14.943	-25.163	-5.3836	-24.749	-35.236	-1.9807	-33.284	17.266	22.76	17.473	-14.973	-15	-10.482
2.4809	2.5544	0	2.0605	2.3015	-0.30566	3.8375	1.9835	0.36672	3.4031	2.4471	2.685	-0.048703	-0.14621	0
2.6561	3.7881	-3.7756	2.8068	6.0833	-5.2622	-5.0095	2.716	-4.7644	8.7288	10.123	3.862	-5.0367	-5.1408	-0.42413
0.013834	8.359	-7.7738	-2.2358	6.8678	-10.115	-9.5325	4.4696	-8.9089	14.644	19.061	22.706	-10.025	-10.135	-10
0.6548	10.249	-11.331	0.58916	12.489	-14.403	-14.768	5.7367	-12.742	21.255	29.614	24.324	-15.013	-15.125	-10.424
0.22134	1.2179	-3.5174	0.79159	3.6712	-4.777	-6.6998	0.16574	-5.1166	5.146	8.083	1.1341	-4.988	-4.9993	-0.42413
-2.4998	5.5437	-7.5512	-4.254	4.2158	-9.6122	-11.356	2.0477	-9.1795	10.864	16.804	19.248	-9.9801	-9.9986	-10
-1.8261	7.3705	-11.1	-1.5499	9.7436	-14.352	-16.505	3.2934	-13.05	17.252	27.081	20.83	-14.968	-14.998	-10.424
3.7603	3.5638	-0.40333	3.5231	3.6228	-0.60221	2.6965	3.3507	-0.64339	5.5332	2.4889	4.0872	-0.026441	-0.097209	0
2.5901	3.8634	-3.7861	2.1291	4.5374	-6.578	0.87292	6.0142	-8.6037	10.932	9.5938	5.1805	-5.0238	-5.0896	-0.40496
1.3061	16.421	-12.884	-13.07	2.1311	-13.867	-18.268	-4.0877	-17.529	16.928	17.74	21.977	-10.015	-10.089	-9.9975
0.084028	16.896	-16.811	-14.232	3.4097	-20.234	-21.894	-0.44958	-26.194	23.628	27.202	23.43	-15.012	-15.081	-10.402
-1.0009	0.23093	-3.8445	-1.1828	0.75475	-5.1883	-1.4191	2.4239	-7.358	5.1085	8.6728	1.02	-4.9907	-4.9924	-0.37121
-2.5171	12.015	-11.739	-15.909	-1.6782	-12.56	-20.399	-7.5241	-16.543	10.783	16.726	16.899	-9.9881	-9.9917	-9.9722

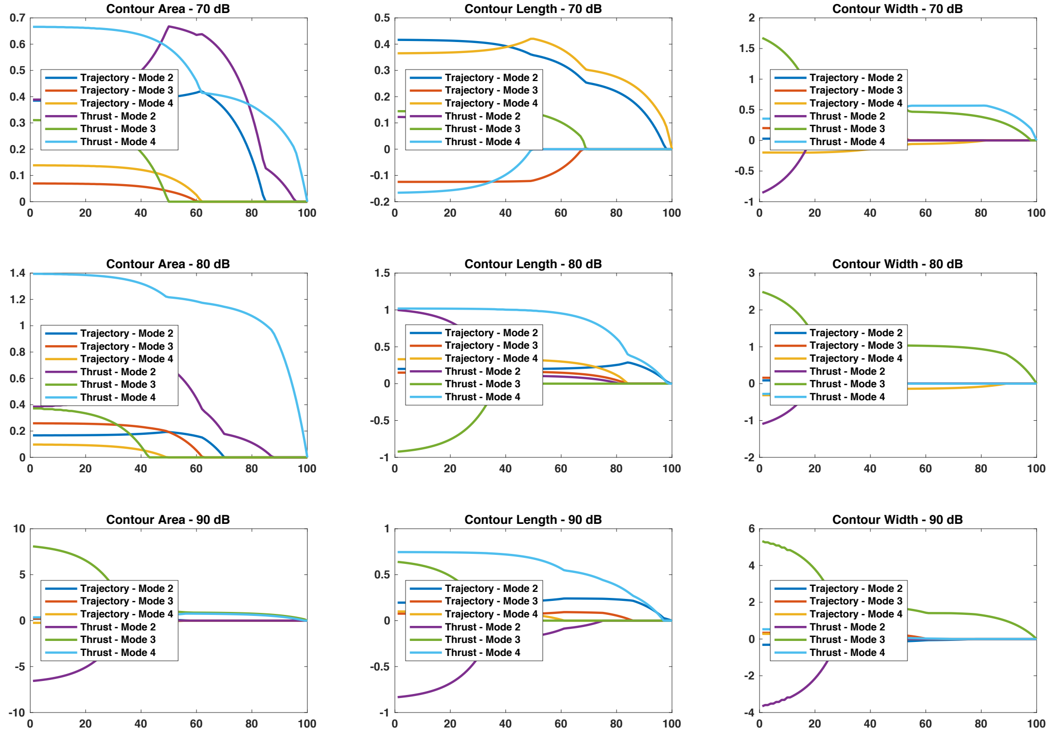


Figure 19. LASSO Results for the 9 Noise Metrics

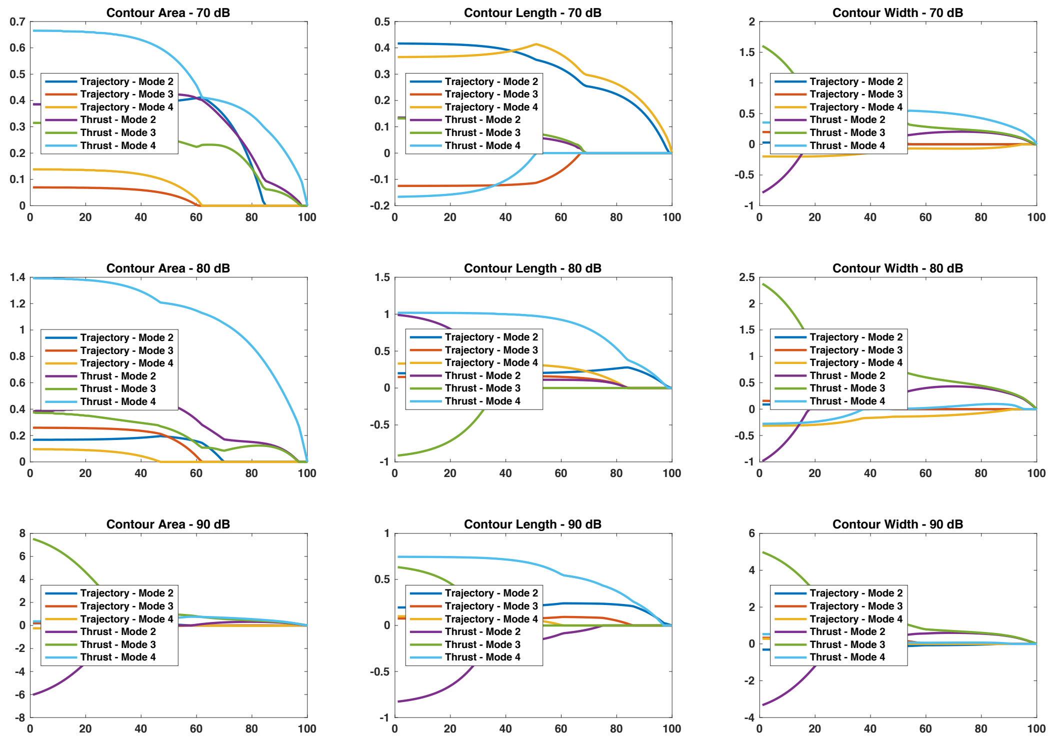


Figure 20. Elastic Nets Results for the 9 Noise Metrics

Both LASSO and Elastic Net were used in the analysis. It is worth mentioning here that the Elastic Net must be used carefully. Among the 6 predictors that we have, the correlations between them is not simple. On one hand, there are indeed correlations between the percentage reduced thrust and the percentage trajectory change. On the other hand, although the changing patterns are very similar within the groups of reduced thrust predictors and trajectory change predictors, it does not mean that the predictors within each group are also correlated – it is just a result of the setting. In the end, it was decided that LASSO and Elastic Net with a α value of 0.95 are both used in the analysis, and the results from the two methods are combined to make a judgment.

After the analysis is done, the graphical results are shown in Figure 19 and Figure 20. As can be seen from the Figures, when the penalty value (x-axis) increases, the later the corresponding coefficient goes to zero, the more important that predictor is. The graphical results in Figure 19-Figure 20 are also summarized in Table 9. In our study, due to its complexity and variations among different aircraft, the second 50% of the predictor ranking may not be precise. Therefore, only the results from the first 50% of the predictor ranking (first three most influential predictors) are extracted and studied.

Table 9. Statistical Learning with LASSO and Elastic Net – Results Summary

Contour Area - 70 dB			Contour Length - 70 dB			Contour Width - 70 dB		
Top Predictors	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**
1	Mode 4 Thrust	Mode 4 Thrust	1	Mode 4 Trajectory	Mode 4 Trajectory	1	Mode 4 Thrust	Mode 4 Thrust
2	Mode 2 Thrust	Mode 3 Thrust	2	Mode 2 Trajectory	Mode 2 Trajectory	2	Mode 3 Thrust	Mode 3 Thrust
3	Mode 2 Trajectory	Mode 2 Thrust	3	Mode 3 Thrust	Mode 3 Thrust	3	Mode 4 Trajectory	Mode 2 Thrust
Contour Area - 80 dB			**Contour Length - 80 dB**			**Contour Width - 80 dB**		
Top Predictors	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**
1	Mode 4 Thrust	Mode 4 Thrust	1	Mode 2 Trajectory	Mode 2 Trajectory	1	Mode 3 Thrust	Mode 3 Thrust
2	Mode 2 Thrust	Mode 3 Thrust	2	Mode 4 Thrust	Mode 4 Thrust	2	Mode 4 Trajectory	Mode 2 Thrust
3	Mode 2 Trajectory	Mode 2 Thrust	3	Mode 4 Trajectory	Mode 4 Trajectory	3		Mode 4 Thrust
Contour Area - 90 dB			**Contour Length - 90 dB**			**Contour Width - 90 dB**		
Top Predictors	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**	**Top Predictors**	**Lasso**	**Elastic Net**
1	Mode 3 Thrust	Mode 3 Thrust	1	Mode 2 Trajectory	Mode 2 Trajectory	1	Mode 3 Thrust	Mode 3 Thrust
2	Mode 4 Thrust	Mode 4 Thrust	2	Mode 4 Thrust	Mode 4 Thrust	2	Mode 2 Trajectory	Mode 2 Thrust
3		Mode 2 Thrust	3	Mode 3 Trajectory	Mode 3 Trajectory	3		Mode 2 Trajectory

It can be observed from Table 9 that, for most of the 9 noise metrics, the ranking of the top 3 predictors from LASSO and Elastic Net are in good agreement. For all the 9 noise metrics, the first most influential predictors from the two methods are the same. Most of the second most influential predictors from the two methods are also the same. For some LASSO results, there are only two influential predictors identified, because all the rest of the predictors are deemed redundant (or insignificant and relatively incomparable) by LASSO. When the Elastic Net results are further compared with the actual changing directions of the 9 noise metrics, a final result is given in Table 10. In this table, the changing directions of the top three predictors and the metrics are marked with different symbols: the green down arrow means decrease, the red up arrow means increase, and the yellow circle means fluctuation. As a reminder, Mode 2 is Takeoff Ground Roll, Mode 3 is Takeoff Airborne, and Mode 4 is Terminal Climb.

Table 10. Comparison between the Changing Directions of Noise Metrics and Their Top Predictors

Top 3 Predictors Ranking	70 dB Contour Area ▼	70 dB Contour Length ▲	70 dB Contour Width ▼	80 dB Contour Area ▼	80 dB Contour Length ⊙	80 dB Contour Width ▼	90 dB Contour Area ▼	90 dB Contour Length ⊙	90 dB Contour Width ▼
1st	Mode 4 Thrust ▼	Mode 4 Trajectory ▲	Mode 4 Thrust ▼	Mode 4 Thrust ▼	Mode 2 Trajectory ▲	Mode 3 Thrust ▼	Mode 3 Thrust ▼	Mode 2 Trajectory ▲	Mode 3 Thrust ▼
2nd	Mode 3 Thrust ▼	Mode 2 Trajectory ▲	Mode 3 Thrust ▼	Mode 3 Thrust ▼	Mode 4 Thrust ▼	Mode 2 Thrust ▼	Mode 4 Thrust ▼	Mode 4 Thrust ▼	Mode 2 Thrust ▼
3rd	Mode 2 Thrust ▼	Mode 3 Thrust ▼	Mode 2 Thrust ▼	Mode 2 Thrust ▼	Mode 4 Trajectory ▲	Mode 4 Thrust ▼	Mode 2 Thrust ▼	Mode 3 Trajectory ▲	Mode 2 Trajectory ▲

Some general conclusions can be made from the results in Table 10. First, the noise contour area and contour width metrics monotonically decrease with bigger thrust reduction, and this is because for all the 6 contour area and width metrics, their top 2 most significant predictors are the percentage changes in thrust (negative effect). Therefore, the changing directions of contour area and width follow the changing directions of thrust. The changing directions for noise contour length display two different patterns. At the noise level of 70 dB, it can be seen from the table that the top two predictors are the percentage changes in trajectory (positive effect). This explains why the contour length at 70 dB monotonically increases with more reduced thrust. At the noise level of 80 and 90 dB, now the contour length fluctuates with more reduced thrust. This can also be explained by the statistical learning results because the top 3 predictors for contour length at 80 and 90 dB consist of both the percentage change in thrust and in trajectory (a mix of positive and negative effects). To better predict the contour length changing direction, detailed analysis has to be done for individual aircraft. In the meantime, the above statistical learning results make sense from the mode's perspective. For example, when the noise level increases from 70 dB to 90 dB, the most influential predictors involve from the Mode 4 thrust or trajectory to ones from Mode 3 and Mode 2. This coincides with the real world situation: with a higher noise level, the noise contour becomes smaller and should be more influenced by the earlier modes during takeoff.

In conclusion, the above statistical learning analysis is a way to quantitatively explain the root causes behind the noise metrics change. When the change of a metric is complex and involves with different factors, these methods provides a path to distinguish the most influential factors, such that the overall trend can be predicted from the changing directions of a subset of predictors. The analysis explains the observed changing patterns of the noise metrics and concludes the study for the reduced thrust profiles.

Task 3- Improved Departure Procedure Modeling

Georgia Institute of Technology

Objective(s)

For most aircraft types in AEDT, the manufactures provided flight profiles for three departure procedures: STANDARD, ICAO-A, and ICAO-B. Under this research, the GT team conducted a literature review on departure procedures. The team also conducted interviews with airline pilots and flight engineers regarding the usage of departure procedures by the airlines. Based on the literature review, both ICAO-A and ICAO-B procedures are obsolete. ICAO PANS-OPS and FAA AC91-53 have adopted two noise abatement departure procedures (NADPs) in the 1990s. The PANS-OPS allows a maximum of two different takeoff procedure to be implemented by an airline: one to mitigate noise impact to the communities close to the airport and the other to mitigate the noise impact to the communities far from the airport. Literature review and the interviews confirmed that none of the airlines uses ICAO-A and ICAO-B procedures anymore. The ICAO-A and ICAO-B procedures were originally defined in ICAO PANS-OPS in 1993 and were replaced by NADP1 and NADP2 in 2004. Most airlines in the United States currently use NADP2. NADP1 is popular in Asia and Europe where communities tend to be closer to the airports.

In AEDT 3a, the new weight and thrust options were implemented to the existing STANDARD departure procedures. The AEE decided not to pursue the modeling of NADPs in AEDT 3a due to limited resources, including time constraint. The GT team has identified some challenges modeling NADP1 and NADP2 for the majority of the aircraft types in AEDT 3a timeframe. Therefore, the focus of the third year effort will be to address the ways to overcome the challenges. First of all, to be able to model NADPs in future AEDT versions, extensive NADP data should be collected for all major airlines and aircraft types. The GT team will continue to work with the FAA, airlines, and airports to obtain such data.

GT has conducted further literatures review on prior research to understand the work has been done in the area of improving departure procedure modeling. New profiles were developed under ACRP 02-55 project. GT reviewed the report of this project and see how to leverage NADP procedure with the work done under ACRP 55 project.

Research Approach

As part of process for improving the departure procedure modeling, the ACRP 02-55 project was reviewed. The ACRP 02-55 project is titled "Enhanced AEDT Modeling of Aircraft Arrival and Departure Profiles". The objective of the project is to help users of AEDT better model real world aircraft trajectories by providing them with more options. These options were created by observing real world radar data, and then matching that data with customized AEDT profiles. The result of this matching is that the resulting noise and emissions calculations will also be more accurate. In addition to the new proposed profiles, a Profile Customization Tool was also envisioned which can help users modify profiles to their liking without needing to know advanced programming skills of the details of AEDT database manipulation.

AEDT currently has several different methods to model aircraft operations. These are shown in Figure 21. Going from left to right, users have the option of performing higher fidelity analysis, at the expense of higher modeling effort and data requirements. As is evident from the figure, the ACRP 02-55 proposed methods are on the lower end of the fidelity spectrum and are meant to supplement the existing default profiles in AEDT.

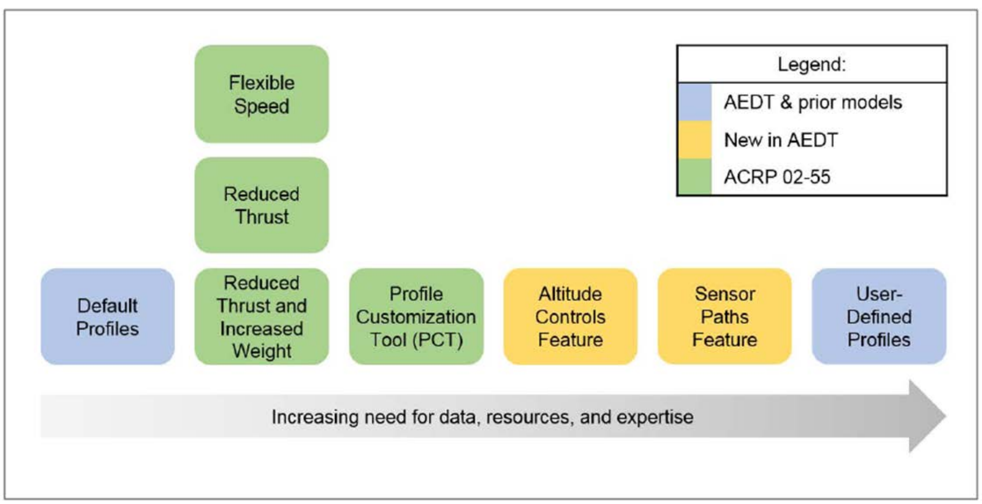


Figure 21. Available and proposed new options for operation modeling in AEDT

These new profiles for AEDT were created using extensive radar data from a large number of U.S. airports. Operation data for 29 U.S. airports over a period of 30 days were utilized. A total of 840 approach and 1,410 departure profiles were created. The general process of profile creation started with segregation of data based on aircraft type, category, runway, operation, stage length etc. Next, the radar tracks for these were visualized and a single candidate trajectory was created. This was then compared with the existing default modeling option in AEDT – the STANDARD profiles. Based on the amount of deviation of the AEDT option from the radar candidate profile, a prioritized list of aircraft and operations was created. The new profiles were then created for this prioritized set of aircraft. Figure 22 shows the flowchart for the modeling process.

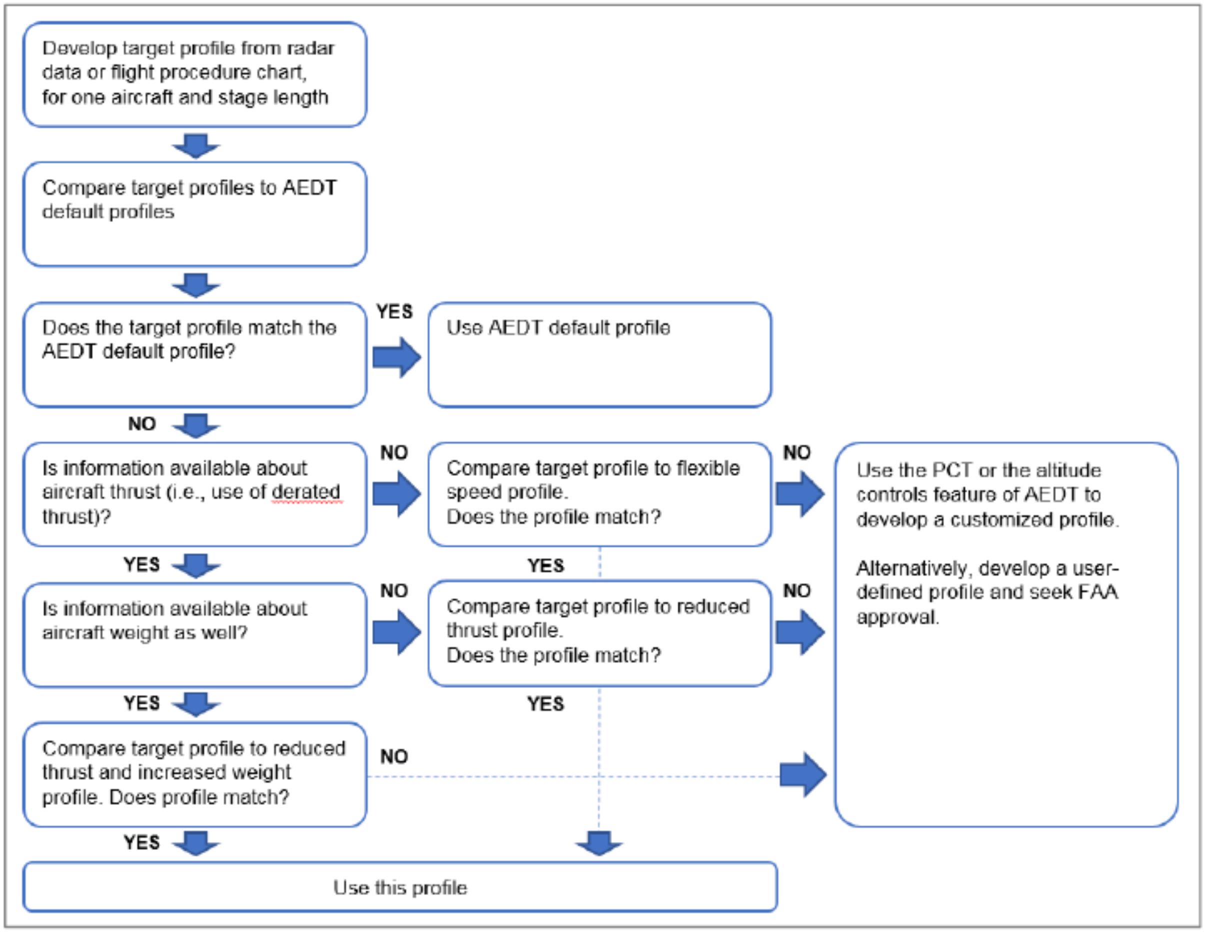


Figure 22. Profile Modeling Flow Chart (from ACRP 02-55 Guidance Document)

The approach profiles were created by adding “level off” segments to the single 3-degree glideslope constant descent which is common in many aircraft. While a few aircraft already make use of level segments, the altitude and duration of these segments could be varied to get new profiles. With these new and/or modified segments, the team able to achieve good match between the radar tracks and their profiles. Figure 23 shows a comparison of several alternate approach profiles.

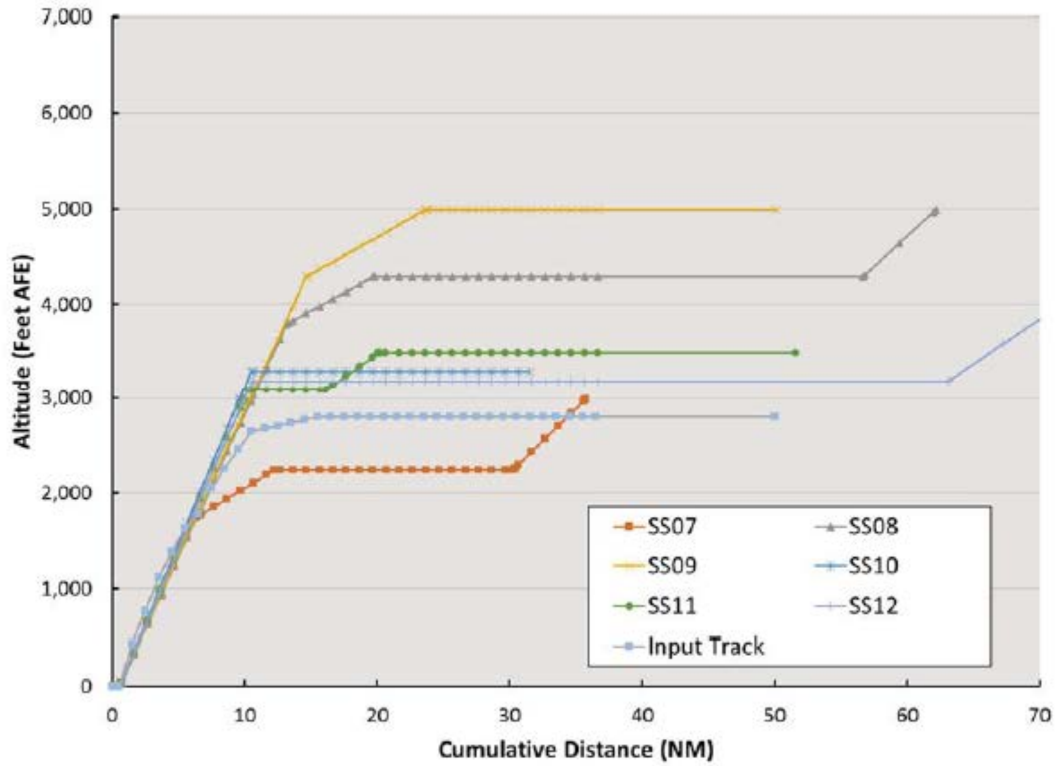


Figure 23. Trajectory comparison for several candidate alternate approach profiles

For departure profiles, it was seen that because real world operations used reduced thrust, there was a large difference between the target trajectory and what could be obtained in AEDT. To address this, three sets of profiles were proposed. The first set, called "Flexible Speed" profiles would remove the restriction on maximum speed of 250 KCAS below 10,000 ft. altitude. This would lead to any excess thrust being materialized into additional speed instead of higher climb rates; therefore, a closer match could be obtained. The second set utilized reduced thrust and reinstated the speed limit. Thrust reduction was varied as 0 to 44% in increments of 2% and the best match profile was chosen. The final set made the use of both reduced thrust and increased weight. The weight was varied between the BADA minimum and ANP maximum weight, in increments of 2% of the difference. It was observed that the average thrust reduction is about 25% and the average weight increase is between 0 to 12%. Figure 24 shows a comparison of several different candidate departure profiles.

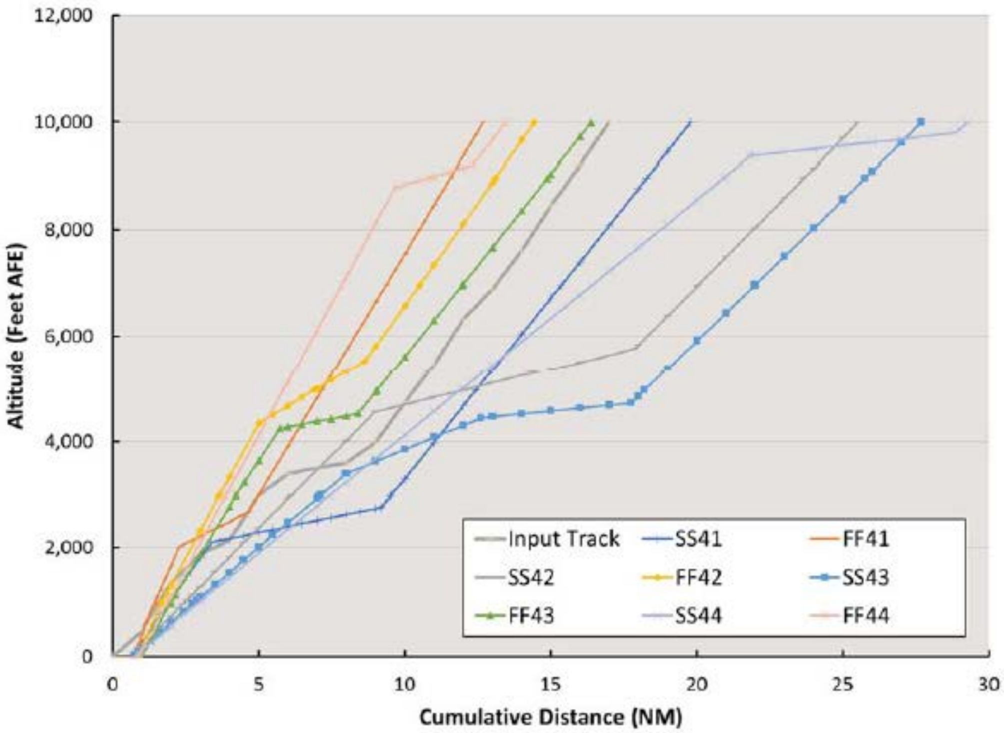


Figure 24. Trajectory comparison for several candidate alternate departure profiles

The methodology of the ACRP 02-55 project may have some applications in future modeling efforts of the ASCENT 45 project. Specifically, the trajectory comparison methods, grouping methods and radar trajectory candidate profile generation technique may all prove to be useful.

Milestone(s)

Milestone	Due Date	Estimated Date of Completion	Actual Completion Date	Status	Comments (Problems & Brief Resolution Plan)
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

- Developed new reduced thrust and alternative weight profiles for 90 major commercial and general aviation jets. Converted rate of climb in the procedure to energy share percentage for each stage length of the 90 aircraft.
- Validated the energy share value against the RoC based profiles.
- Conducted comprehensive tests and analysis on the new profiles to investigate the impact of the new profiles. In addition, carried out statistical analysis to study the main drivers on the noise results.

Publications

Matthew J Levine, Dongwook Lim, Yongchang Li, Michelle R Kirby, Dimitri, Mavris, Quantification of Error for Rapid Fleet-Level Noise Computation Model Assumptions, AVIATION conference, June 17-21, 2018.

Dongwook Lim, Matthew Levine, Vu Ngo, Michelle Kirby, and Dimitri Mavris, Improved Aircraft Departure Modeling for Environmental Impact Assessment, AVIATION conference, June 17-21, 2018.

Outreach Efforts

- Bi-weekly calls with the Project Managers.
- ASCENT annual meeting.
- FAA Noise workshop.
- FAA External tools calls.

Awards

None

Student Involvement

Ameya Behere, Zhenyu Gao, Yee Chan Jin, Junghyun (Andy) Kim– Graduate Research Assistant, Georgia Institute of Technology

Plans for Next Period

The primary focus for the next period will be:

- Improve each sensitivity assumption to AEDT
- Assessment of new assumptions at the airport level