Project 045 Takeoff/Climb Analysis to Support AEDT APM Development

Georgia Institute of Technology

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Project Funding Level

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: Vu Ngo and Ameya Behere.

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: Literature Review and AEDT APM Evaluation

Georgia Institute of Technology

Objective(s)

Review the body of existing literature on estimating the takeoff and climb out performance of aircraft using flight data including several ACRP projects 02-41, 02-37, and 02-55 and also ASCENT Project 35 and the AEDT APM.

Research Approach

Using the existing body of work and Georgia Tech's detailed aircraft and engine modeling knowledge, the AEDT APM algorithms will be systematically evaluated to identify areas of improvement in current modeling methods. For all relevant APM assumptions, the team will identify the assumption in question, the validity of the physics behind the APM assumption, suggested improvements, and any issues in data availability or modeling fidelity associated with the suggested improvements. This analysis of APM assumptions will be critical in identifying tuning methods and calibrating AEDT performance to measured flight data.

The objective of ACRP 02-41 was to produce guidance to include the effects of reduced takeoff thrust in the emissions inventory calculations and to develop a Takeoff Thrust-Setting Estimator Tool (TTREAT) based on statistical analyses of extensive takeoff thrust data supplied by airlines. TTREAT was validated based on US Airways data and concluded that the majority of commercial aircraft use approximately a 15% reduced thrust takeoff. This conclusion is similar to the results of ASCENT Project 35.

The objectives of ACRP 02-37 was to assess the accuracy of general aviation aircraft SEL noise modeling within INM as compared to measured values. The research team focused on examining performance profiles to help identify causes of error and focused on departures using LJ35, GLF4, and EA50 aircraft, where the error was identified as discrepancies between measure and modeled levels of SEL and also altitude. The observations made were that INM modeling for almost all aircraft types computes departure SEL values higher than the measured levels. Also, the INM departure altitudes for the aircraft are higher than actually occurs. It is likely most error in the INM modeling is caused by significant differences between the standard noise and performance profiles (management of thrust, flaps, speed, climb rates and associated noise-power-distance curves) and actual average practice. The general cause for these discrepancies was the use of maximum thrust departures as standard INM input. Two solutions were proposed to correct the takeoff thrust to provide more realistic results and were based on an assumed temperature method (ATM), where ATM is a process where an aircraft Flight Management System (FMS) is asked to compute the thrust required to safely depart the aircraft from a given runway while demanding a decreased level of engine performance. The two solutions are:

- ATM1:
    - Requires determining the specific thrust levels from manufacturer or operator surveys then creating custom profiles to match these inputs
    - Requires updated Thrust Jet data in order to make reduced thrust departure profiles available as standard INM input.
    - Not a preferred option
- ATM2:
    - First uses the INM's internal computation process to determine the aircraft departure profile at an assumed elevated temperature. The resulting departure data are then converted into a static "profile points" style profile which is then input into the INM and run at the normal or average airfield temperature
    - No radar data, measured sound levels, pilot or manufacturer information is needed

- Preferred Option

Each method was applied to a set of aircraft and the noise exposure quantified to show a correction of approximately 2.5 dB for a small set of flights within INM, however the recommendations are applicable to AEDT. ATM2 was recommended as the preferred correction approach since ATM1 required manufacturer's input, but is limited to aircraft types that have hi-temperature coefficients. Similar to ACRP 02-41, reduced thrust takeoff was suggested as an improvement in noise exposure to real world flight and would also affect the trajectory of the departure.

The objective of ACRP 02-55 are to develop: (1) standard model aircraft approach and departure profiles that are not currently in AEDT, (2) methods to model customized aircraft approach and departure profiles using AEDT, and (3) technical guidance for selecting appropriate aircraft approach and departure AEDT profiles, including customized profiles, for specific user situations. At present, the results of this study are not public and will be reviewed once available. However, the objective of modeling departure procedures that are not within AEDT led the GT research team to identify typical departure procedures utilized in real world operations.

FAA AC 91-53A and ICAO PANS OPS Chapter 3 Volume II both contain the minimum safe standards for departure procedures. Both contain the same minimums which are:

1) No thrust cutbacks below 800' AFE, and
2) The level of the thrust cutback will not be less than the Airplane Flight Manual (AFM) thrust required to maintain the minimum engine-out climb gradient.

Both documents recommend that all carriers adopt no more than two procedures for each aircraft type; one for noise abatement of communities close to the airport and one for noise abatement of communities far from the airport. Within FAA AC 91-53A, these are defined as the Close-In and the Distant Procedure, which are similar to ICAO Pans Ops NADP1 and NADP 2 defined in CAEP/7 Working Paper 25. Through discussions with Jim Brooks, NAPD1 and NAPD2 most closely resemble real work departure procedures employed by pilots with a suggested variability in the cutback altitude utilized by different airlines of 800', 1000', and 1500' AFE.

The objective of ASCENT Project 35 was to develop a functional relationship between stage/trip length and takeoff weight that can improve the existing guidance provided for weight estimation; and subsequently to determine the percentage of departures that use reduced thrust and the level of reduced thrust that is used for the departure. The project focused on analyzing major US carrier flight data of four engine/airframe combinations, specifically:

- B757-200/PW2037
- B737-800/CFM56-7B26
- B767-400ER/CF680C2/B8F
- B767-300ER/CF680C2/B6F
-

A series of statistical regressions were conducted to determine the most appropriate functional form to estimate takeoff weight. An example of the results for the B737-800 is depicted in Figure 1 along with the assumption for takeoff weight (TOW) within the AEDT Fleet dB. As evident, the assumed TOW within AEDT is an underestimation of real world operations.

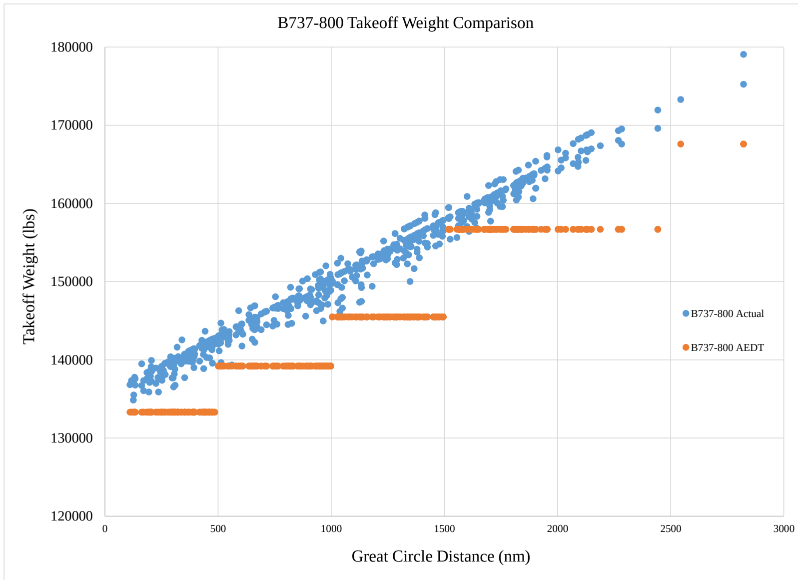

Figure 1. Takeoff Weight Variation with Great Circle Distance

Within AEDT, the manufacturers provide a series of performance and noise coefficients to define their aircraft as guided by BADA and SAE-AIR-1845. SAE-AIR-1845 is the Aircraft Noise and Performance (ANP) database which covers from takeoff and climb performance up to 10,000'. As part of the ANP data, the manufactures provide takeoff weights based on the guidelines in Figure 2 as defined by the AEDT 2b Technical Manual. The two key observations are that a load factor of 65% is assumed and that the TOW within a Stage Length band is constant in lieu of a continual increase with GCD. Based on the results of ASCENT Project 35, real world TOW are higher than the assumptions utilized in AEDT. The main driver for the TOW discrepancies may be the load factor assumption.

Parameter	Planning Rule
Representative Trip Length	Min Range + 0.70*(Max Range – Min Range)
Load Factor	65% Total Payload.
Fuel Load	Fuel Required for Representative Trip Length + ATA Domestic up to 3,000 nmi and International Reserves for trip length > 3,000 nmi. As an example, typical domestics reserves include 5% contingency fuel, 200 nmi alternate landing with 30 minutes of holding.
Cargo	No additional cargo over and above the assumed payload percentage.

Stage number	Trip length (nmi)	Representative Range (nmi)	Weight
1	0-500	350	lb
2	500-1,000	850	lb
3	1,000-1,500	1,350	lb
4	1,500-2,500	2,200	lb
5	2,500-3,500	3,200	lb
6	3,500-4,500	4,200	lb
7	4,500-5,500	5,200	lb
8	5,500-6,500	6,200	lb
9	6,500-7,500	7,200	lb
10	7,500-8,500	8,200	lb
11	>8,500		lb
M	Maximum range at MTOW		lb

Figure 2. ANP Guidance for Takeoff

The load factor assumption of 65% may be a bit low in comparison to historical data. According to the Bureau of Transportation Statistic (BTS), the average load factor, which includes passengers and belly freight, for all carriers and all airports has steadily increased since 2002[1] as depicted in Figure 3. While this data is an aggregate value, BTS does have load factor data at the aircraft level and also for specific air carriers, but is also slightly different than the load factor definition within AEDT. The project 35 results and the BTS data suggest that a further investigation to the load factor assumption should be conducted. Per the FAA Project Manager, Booz Allen Hamilton (BAH) is currently conducting an investigation to this assumption. When the results are publically available, the GT research team will review and incorporate the results for the aircraft not included in the Project 35 TOW results.

[1] "Load Factor", http://www.transtats.bts.gov/Data_Elements.aspx?Data=5, accessed Dec 20, 2016

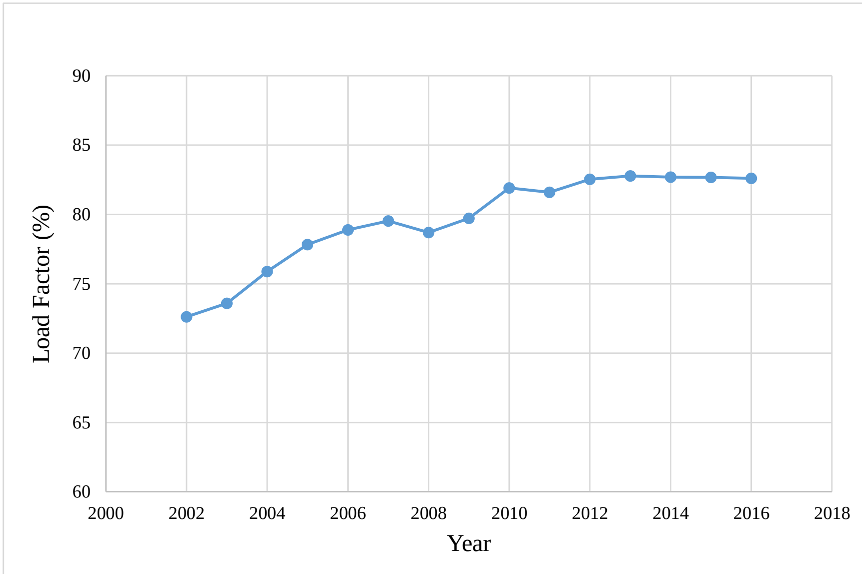

Figure 3. BTS Historical Load Factor

In addition to the load factor assumptions associated with the ANP database, the manufacturers are asked, as part of the standard aircraft noise and performance data submittal form, to provide three departure procedures that are used within AEDT. The guidance of the procedures is defined in the AEDT 2b Technical Manual as defined in Figure 4. In many cases, the “Default” procedure is the same as the ICAO B procedure within the AEDT Fleet dB. For each of these procedures, the manufacturer will fill out the performance of their aircraft based on the form depicted in Figure 5.

Default Procedure[xxxvi] **Modified BBN/AAAI Procedure**	**ICAO A**	**ICAO B**
Takeoff at MaxToPower (full power) and Climb to 1,000 feet AFE	Takeoff MaxToPower (full power)	Takeoff at MaxToPower (full power)
Pitch over and cutback to climb power. Accelerate to zero flaps retracting flaps on schedule (clean configuration)[xxxvii]	Climb at constant speed to 1,500 feet AFE	Climb to 1,000 feet AFE and pitch-over to accelerate at full power to clean configuration
Climb at constant speed to 3,000 feet AFE	Reduce thrust to Climb Power	At Clean Configuration, cutback top climb power
	Climb at constant speed to 3,000 ft AFE	Climb at constant speed to 3,000 ft
Upon achieving 3,000 feet AFE, accelerate to 250 knots[xxxvii]	Accelerate while retracting flaps to Zero (clean configuration)	Upon achieving 3,000 feet AFE, accelerate to 250 kts
	Continue accelerating to 250 knots	
Upon achieving 250 knots, climb to 10,000 feet AFE	Upon achieving 250 knots, climb to 10,000 feet	Upon achieving 250 knots, climb to 10,000 feet

Figure 4. ANP Guidance for Takeoff Departure Procedures Guidance

Stage Number		Procedure Type (Procedural or Points)		Procedure Name		
Segment Type[xxxviii]	Thrust Type[xxxix] (T/C)	Flap Configuration Identifier	Endpoint Altitude (ft AFE)	Rate-of-Climb (ft/min)	Endpoint Speed (KCAS)	Start Thrust[xl] (lb)
Takeoff						lb
Climb			ft			lb
Climb			ft			lb
Accelerate				fpm	kt	lb
Accelerate				fpm	kt	lb
Climb			ft			lb
Climb			ft			lb
Accelerate				fpm	kt	lb
Accelerate				fpm	kt	lb
Climb			10,000			lb

Figure 5. Takeoff Departure Procedures Profile Form

Based on the literature review conducted in Task 1, three elements were identified as the primary drivers for improvement of the APM departure profiles and environmental performance modeling and included the following that will be addressed in the remainder of this project:

- Reduced thrust takeoff of approximately 15%
- Proper takeoff weights as a function of GCD, and
- Proper departure procedure modeling of NADP 1 and 2 versus the existing AEDT STANDARD, ICAO A and ICAO B procedures
-

The standard procedures typically used in AEDT (and previously in INM) for inventory studies correspond to the sequence of segments first described in SAE-AIR-1845[2]. The ICAO-A and ICAO-B procedures are referenced as "ICAO Noise Abatement Take-off Procedure A and/or Procedure B" in ECAC.CEAC Doc29[3], and an ICAO report[4] from 1982 is cited. This nomenclature is abandoned in the CAEP/7 WP/25 Circular on NADP Noise and Emissions Effects and replaced with NADP1 and NADP2, partially because slight variants on previously defined noise abatement departure procedures were introduced. Georgia Tech investigated the similarities and differences between the ICAO-A and ICAO-B procedures currently in AEDT versus the procedures defined in this working paper. ICAO-A and NADP1 procedures were essentially identical, primarily characterized by delaying acceleration/flap retraction segments until the aircraft clears 3000-ft air-field equivalent altitude. ICAO-B and NADP2 procedures were both characterized by completing acceleration/flap retraction segments before the aircraft attains 3000-ft air-field equivalent altitude with one key difference. ICAO-B procedures perform thrust cutback after the acceleration/flap retraction segments are complete, whereas NADP2 procedures perform thrust cutback before initiating acceleration/flap retraction. In his discussions with Delta pilots, Jim Brooks confirmed that the NADP2 procedure is more consistent with the manner the pilots actually fly the procedures.

Task #2: Statistical Analysis of Flight Data

Georgia Institute of Technology

Objective(s)

Literature review and AEDT APM evaluation conducted in Task 1 will identify the key drivers of variations in takeoff weight and takeoff thrust in real-world day-to-day operations, including energy share profiles or hands on pilot approaches to

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[2] "Procedure for the Calculation of Airplane Noise in the Vicinity of Airports", SAE-AIR-1845, prepared by SAE Committee A-21, March 1986.

[3] ECAC.CEAC Doc 29, Report on Standard Method of Computing Noise Contours Around Civil Airports, Vol. 2, 3rd ed., Technical Guide, Dec. 2005.

[4] ICAO, 1982. Procedures for Air Navigation Services-aircraft operations: Volume 1, Flight Procedures, Part V — Noise abatement procedures, pages 5-4 to 5-7. Doc 8168-OPS/611, Volume 1, Amendment 2, 1983.

departures to understand the variability in the takeoff procedures that exists in reality. A quantification of the departure of the APM assumptions to real world operations will be conducted for the key drivers identified in Task 1.

Research Approach – Partial Derivative Process

The partial derivative approach focused on the investigation of the impact on terminal area performance due to the changes in assumption for takeoff gross weight, thrust and procedure for standard day sea level condition. The step by step of this process are shown in Figure 6. The approach begins with evaluation of the baseline AEDT STANDARD procedures in terms of noise contour, fuel burn and NOx. After obtaining the baseline results, weight and thrust was varied to gain knowledge about the effect on noise contour, fuel burn and NOx. Next, the vehicle procedure was changed from standard procedure to NADP procedures. The same process was repeated for changes in weight and thrust for the new procedure. The study was performed for three aircraft B737-800, B767-300ER, and B777-200ER for all stage lengths. The overall results for all three vehicles are in the appendix, however for the sake of discussion only B737-800 will be discuss in the main body.

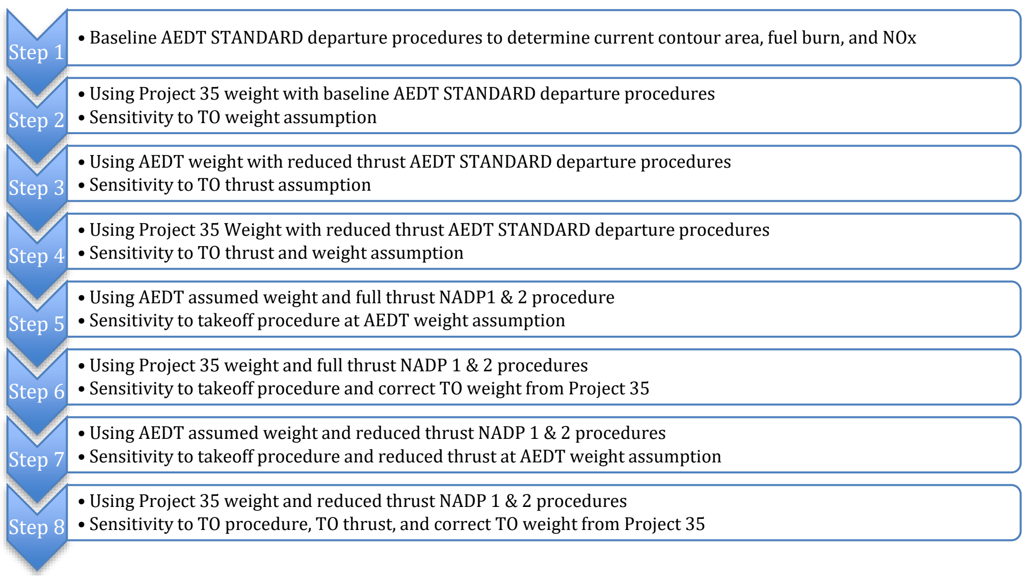

Figure 6: Partial Derivative Approach

Step 1

The first step is to evaluate of the AEDT STANDARD procedures at full takeoff thrust with max climb thrust for all vehicles at sea level condition, for all stage lengths. The AEDT STANDARD procedures parameters are found in AEDT ANP FLEET database. The general STANDARD procedure parameters for B737-800 are defined in Table 1. The plot of the departure profile for STANDARD procedure is also depicted, which can be broken down into segments.

Table 1: STANDARD Procedure

Segment	STANDARD
1	• Takeoff • Flaps 5 • 100% takeoff thrust
2	• Constant speed climb to 1,000 ft
3	• Acceleration step • Specify **ROC_1, $Vstop_1$**
4	• Acceleration step • Specify **ROC_2, $Vstop_2$** • Flaps 1
5	• Constant speed climb • Clean configuration.
6	• Constant speed climb to 3,000 ft • Reduce thrust to MCLT
7	• Acceleration step to 250 knots • Specify **ROC_3**, Vstop = 250 kts
8	• Constant speed climb to 5,500 ft
9	• Constant speed climb to 7,500 ft
10	• Constant speed climb to 10,000 ft

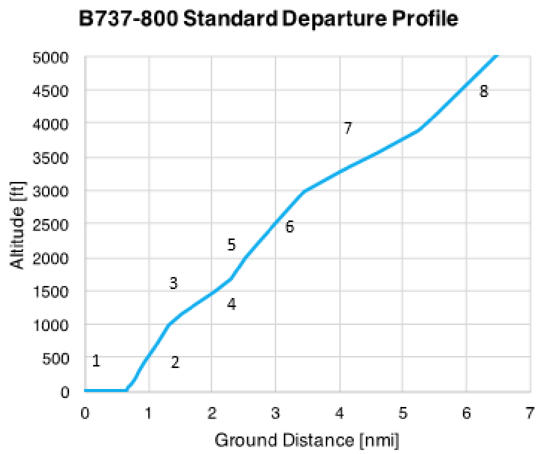

Figure 7: B737-800 STANDARD Procedures

The altitude versus ground distance is a sample of the STANDARD departure procedure as shown in Figure 7, where each of the segment steps are define in the Table 1. An example of stage length 3 STANDARD departure procedure parameters are shown in Figure 8 to Figure 14. Segment 1 is the ground roll and it requires that the takeoff flaps and thrust are specified. The takeoff flaps were set to Flaps 5 and full thrust was used for takeoff as shown in Figure 8. These are defined as STEP_TYPE T (for takeoff), FLAP_ID T_05 (flaps 05) and THR_TYPE T (max takeoff thrust).

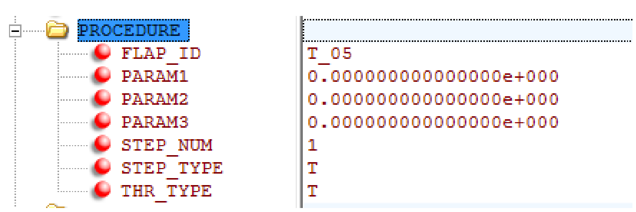

Figure 8: Segment 1 Parameters for Standard Procedure

Segment 2 is constant speed climb to cutback altitude, defined as the aircraft climbing at a constant airspeed until a specific altitude is met. PARAM1 is defined as 1000 ft which is the altitude at the end of the climb. The STEP_TYPE is C, which indicates a constant speed climb, as shown in Figure 9.

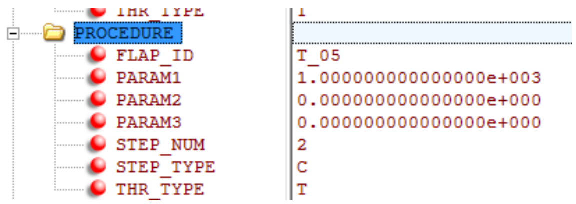

Figure 9: Segment 2 Parameters for STANDARD Procedure

Segment 3 is the first acceleration step, defined as the aircraft climbing and accelerating at a specified rate of climb until the specified airspeed is reached. Figure 10 shows the inputs for each of the relevant parameters. In the prior segment, PARAM1 was the altitude at the end of the climb. However, for the acceleration step (STEP_TYPE A), PARAM1 is the rate of climb in ft/min. PARAM2 is the final velocity (knots), which is the specified airspeed that the vehicle needs to reach at the end of the segment. The rate of climb was set to 1885.7 ft/min and the final velocity was set to 181.7 knots. This final speed corresponds to the flaps retraction schedule.

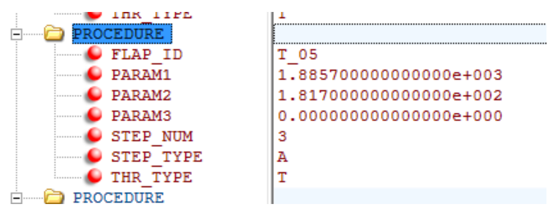

Figure 10: Segment 3 Parameters for STANDARD Procedure

The flap retraction from T_05 to T_01 happens instantaneously between segment 3 and segment 4. Segment 4 is also an acceleration segment where the rate of climb was set to 2112 ft/min and the end velocity is set to 204.8 knots as shown in Figure 11. At the end of segment 4 and before segment 5, the flap are retracted T_01 to T_00 which is the clean configuration.

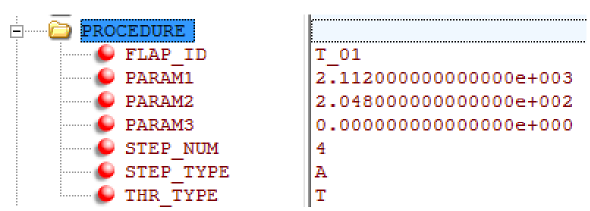

Figure 11: Segment 4 Parameters for STANDARD Procedure

Segment 5 is the constant speed climb where PARAM1 is set to 2040 ft, as shown in Figure 12. Note, this steps is not specified for NADPs procedures.

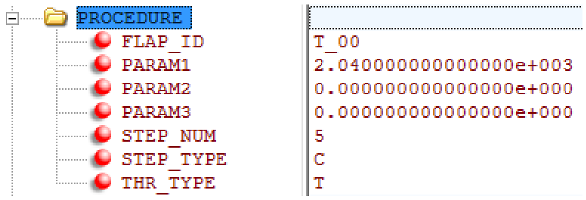

Figure 12: Segment 5 Parameters for STANDARD Procedure

Segment 6 is the constant speed climb, for the STANDARD procedure, cutback occurs at this step. PARAM1 is set to 3000ft and thrust type is set to C (climb thrust), as shown in Figure 13.

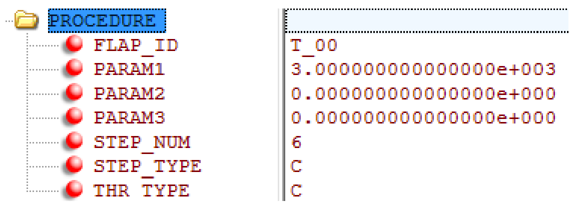

Figure 13: Segment 6 Parameters for STANDARD Procedure

Segment 7 is the final acceleration segment, where the final airspeed PARAM2 is always 250knots for all cases. The thrust type is set to C and PARAM1 is 1891.3 ft/min, as shown in Figure 14.

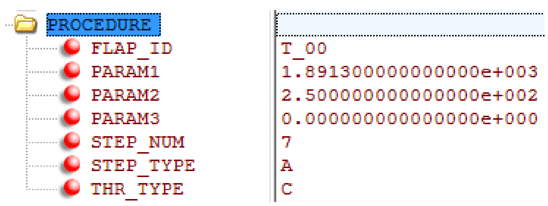

Figure 14: Segment 7 Parameters for STANDARD Procedure

Segments 8, 9, and 10 are the final constant climb segments, where the final altitudes are always 5500, 7500, and 10000 ft for all stage lengths. With these final segments, the entire STANDARD procedure is completely defined. After all the parameters for each segment have been identified for the STANDARD procedure, the aircraft was analyzed for noise, fuel burn, and NOx and tabulate in Table 2 and Table 3 at all stage lengths. This analysis served as the basis of comparisons for assessing the change of takeoff assumptions.

Table 2: Noise Contour Results for B737-800 STANDARD Procedure

Stage Length	70 dB SEL Contour Length [nmi]	70 dB SEL Contour Width [nmi]	70 dB SEL Contour Area [nmi^2]	80 dB SEL Contour Length [nmi]	80 dB SEL Contour Width [nmi]	80 dB SEL Contour Area [nmi^2]	90 dB SEL Contour Length [nmi]	90 dB SEL Contour Width [nmi]	90 dB SEL Contour Area [nmi^2]
1	14.369	4.491	54.156	7.662	2.205	12.159	2.536	0.842	1.474
2	15.160	4.452	57.084	8.104	2.172	12.694	2.655	0.826	1.519
3	16.035	4.414	60.314	8.599	2.152	13.278	2.785	0.807	1.568
4	17.650	4.346	66.305	9.506	2.109	14.345	3.015	0.777	1.660
5	19.327	4.285	72.522	10.445	2.071	15.452	3.273	0.750	1.760

Table 3: Fuel Burn and NOx Results for B737-800 STANDARD Procedures

Stage Length	NOX below 3,000 ft [g]	NOX 3,000 ft to 10,000 ft [g]	Fuel Burn below 3,000 ft [kg]	Fuel Burn 3,000 ft to 10,000 ft [kg]
1	6045.62	6232.65	226.35	264.25
2	6348.99	6570.48	237.54	278.59
3	6680.82	6942.53	249.77	294.38
4	7275.74	7654.39	271.60	324.59
5	7870.57	8394.50	293.37	356.01

Step 2

The second step of the partial derivative approach was to test the impact of the takeoff weight. Within AEDT, weight is defined into stage length bins. The aircraft take-off weight assumption was based on AEDT FLEET database and Project 35[5] results, except for the B777-200ER. Since B777-200ER was not analyzed in Project 35, no operational weights were available. Thus, the alternative weights were calculated based on the maximum payload weight and an operating weight from the Boeing Airport planning document for this aircraft. A 75% payload factor was assumed and it resulted in a constant change in weight being added to the aircraft. Fuel weight was not adjusted. The weight assumption for all three aircrafts which were used for the study are listed in Table 4. For the STANDARD procedure defined in step 1, the vehicle weight was changed from AEDT to the Project 35 weights. The weight change for B737-800 stage length 1 is shown in Figure 15 as an example.

Table 4: AEDT and Project 35 Weight for All Three Aircraft

	B737-800		**B767-300ER**		**B777-200ER**	
Stage Length	AEDT Weights [lbs]	P-35 Weights [lbs]	AEDT Weights [lbs]	P-35 Weights [lbs]	AEDT Weights [lbs]	ALT Weights [lbs]
1	133300	137725	265000	278500	429900	441900
2	139200	147590	275500	295600	442400	454400
3	145500	157165	286400	312120	456100	468100
4	156700	167620	305700	328575	483100	495100
5	167600	174203	330000	353100	516400	528400
6			355900	377615	551700	563700
7			367700	402135	589400	601400
8					629500	641500
9					656000	656000

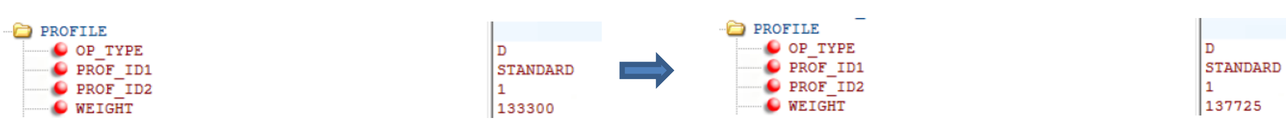

Figure 15: Aircraft Weight Modification in for STANDARD Procedure

For B737-800, as the weight increases from AEDT to Project 35 weight, the contour length and area increased as compared to the baseline for all SEL levels. However, the contour width decreased for all SEL levels is shown in Figure 17. For 70, 80, and 90 dB, increasing the weight resulted in a longer contour, which might be due to the heavier vehicle having a shallower trajectory. This difference in trajectory is shown in Figure 16. Table 5 through Table 7 show the calculated noise metric for baseline and changes in weight for all stage length, the results show an increased in contour length of about 4% to 10% for all SEL levels. There are slight changes in the contour width about less than 1% for SEL 70 and 80 dB. For SEL 90 dB the changes in contour width about 1% to 3%. Overall contour area increases anywhere from 3% to 11% for all SEL levels. Also, increasing the weight increased NOx and fuel burn for all stage lengths is shows in Table 8 and Table 9.

[5] Georgia Institute of Technology, 2016. Airline Flight Data Examination to Improve Flight Performance Modeling-Final Report Project 35.

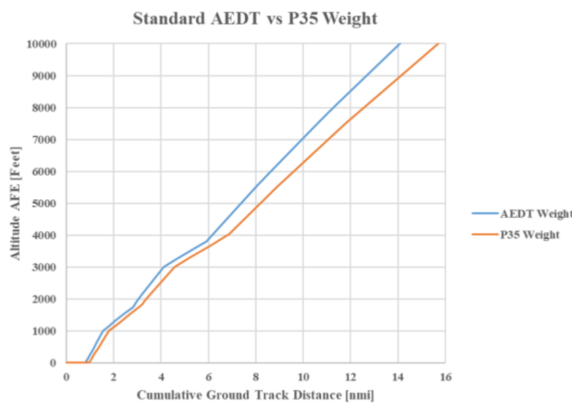

Figure 16: STANDARD AEDT vs. Project 35 Weight for Stage Length 3

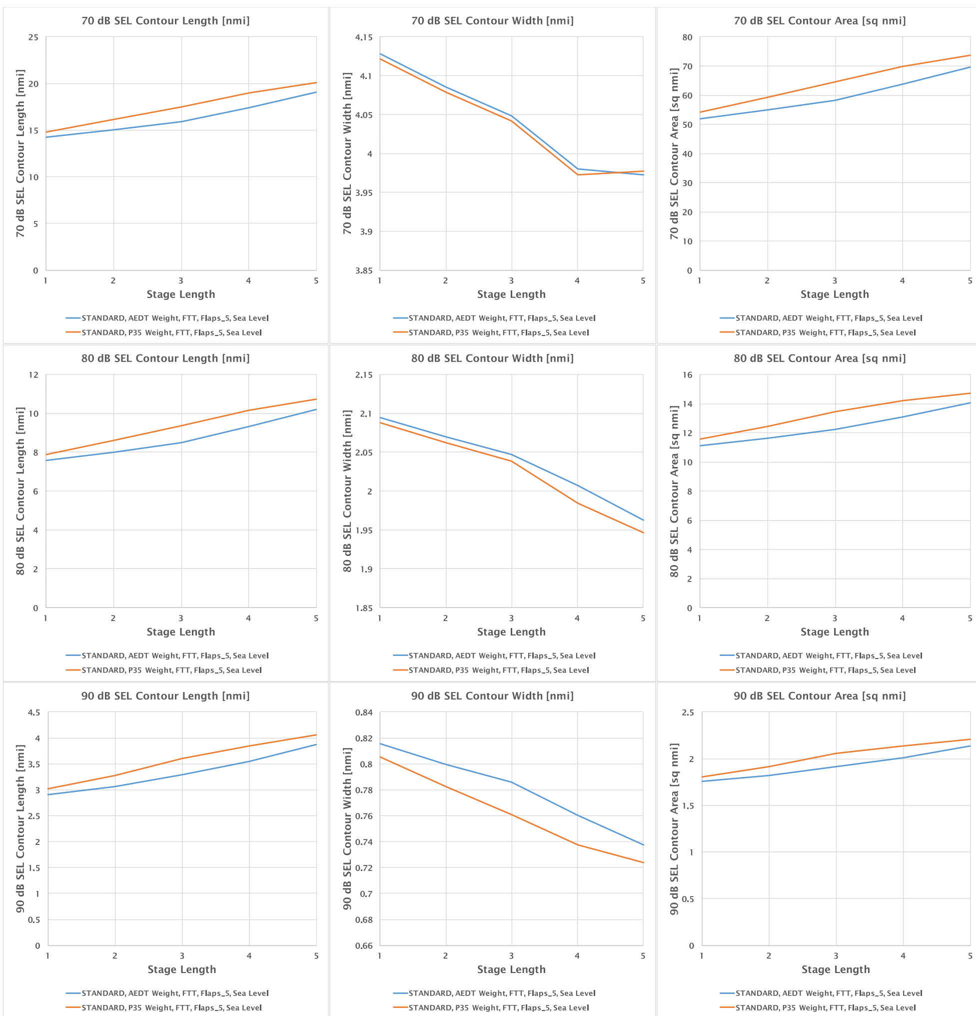

Figure 17: Weight Sensitivity Noise Results

Table 5: Weight Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	14.228	14.792	4%	4.128	4.122	0%	52.013	54.232	4%
2	14.998	16.113	7%	4.085	4.078	0%	54.833	59.194	8%
3	15.888	17.511	10%	4.049	4.041	0%	58.125	64.463	11%
4	17.421	19.020	9%	3.980	3.973	0%	63.722	69.895	10%
5	19.050	20.065	5%	3.973	3.978	0%	69.663	73.546	6%

Table 6: Weight Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.867	4%	2.095	2.088	0%	11.117	11.553	4%
2	7.985	8.587	8%	2.070	2.062	0%	11.601	12.437	7%
3	8.492	9.370	10%	2.047	2.038	0%	12.219	13.422	10%
4	9.313	10.163	9%	2.007	1.984	-1%	13.100	14.190	8%
5	10.196	10.733	5%	1.962	1.947	-1%	14.046	14.710	5%

Table 7: Weight Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	2.909	3.017	4%	0.816	0.805	-1%	1.753	1.803	3%
2	3.068	3.282	7%	0.800	0.783	-2%	1.818	1.916	5%
3	3.285	3.606	10%	0.786	0.761	-3%	1.912	2.057	8%
4	3.550	3.848	8%	0.760	0.737	-3%	2.013	2.133	6%
5	3.874	4.058	5%	0.738	0.724	-2%	2.136	2.209	3%

Table 8: Weight Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	STANDARD P35 FTT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	STANDARD P35 FTT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377491	6702.423261	4%	5479.081	5706.625	4%
2	6761.582634	7266.754357	7%	5787.113	6234.956	8%
3	7168.941787	7909.36733	10%	6125.350	6772.846	11%
4	7957.103434	8685.91611	9%	6551.746	7153.272	9%
5	8582.797272	9022.80602	5%	7221.653	7614.054	5%

Table 9: Weight Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	STANDARD P35 FTT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	STANDARD P35 FTT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	244.735	4%	232.659	242.325	4%
2	246.776	265.611	8%	245.762	264.790	8%
3	261.668	289.248	11%	260.150	287.665	11%
4	291.929	319.360	9%	278.414	304.008	9%
5	315.017	331.549	5%	306.898	323.592	5%

Step 3

For this experiment, the takeoff and climb thrust were changed to analyze the effect of thrust on the noise contours. The experiment was run using the STANDARD procedure at sea level condition with AEDT weight. The takeoff thrust was reduced by 15% and climb thrust was reduced by 10%. The derated thrust values for takeoff and climb thrust are based on Project 35. Data from more than a thousand flights gathered for Boeing aircraft showed that the aircraft were taking off with an average between 10% and 15.5% below their maximum takeoff thrust. Therefore, aircraft do not takeoff at maximum takeoff thrust as currently modeled in AEDT. For this study, a 15% reduction of maximum takeoff thrust was utilized. Currently, the climb thrust is set to maximum climb thrust in AEDT. However, based on recommendations by General Electric and Roll Royce, if the nominal takeoff thrust is 90% or higher of the maximum takeoff thrust, maximum climb thrust should be used.[6 7] For this study, a 15% reduction of max takeoff thrust value was selected, therefore a derated climb thrust of 10% reduction of max climb thrust was selected for the study. Maximum and derated takeoff and climb thrust values are listed in Table 10. The COEFF_E values were changed in the study to simulate a 15% takeoff thrust reduction and 10% reduction in climb thrust, as shown in Figure 18.

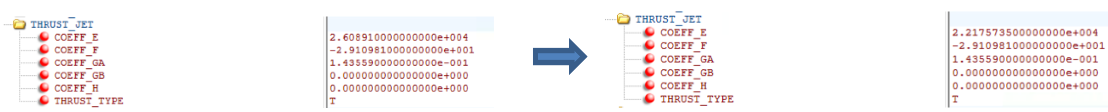

Figure 18: COEFF_E Modification for STANDARD Procedure for Reduced Thrust

Table 10: Full and Reduce Thrust Values for All Three Vehicles

	B737-800		**B767-300ER**		**B777-200ER**	
Thrust Type	Full Thrust	Reduced Thrust	Full Thrust	Reduced Thrust	Full Thrust	Reduced Thrust
Takeoff, T	26089.1	22175.735	56370	47914.5	93672.6	79621.71
Climb, C	22403.5	20163.15	45480	40932	67093.7	60384.33

The flaps were set to the lowest possible takeoff flaps setting as shown in Table 11. For the B737-800, the flaps were set to Flaps 01. Currently, AEDT models all of the flap settings except for Flaps 01, which is the required takeoff flap setting for B737-800. AEDT requires flap coefficients COEFF_C_D and COEFF_B to be defined in order to enable the vehicle to takeoff at that flap setting. Aircraft trajectories were determined using high fidelity validation data (HFVD) for a B737-800 takeoff with full thrust using Flaps 01 at the following required reference conditions as defined in SAE-AIR-1845:[8]

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[6] Donaldson, R., Fischer, D., Gough, J., & Rysz, M. (2007). Economic Impact of Derated Climb on Large Commercial Engines.Proceedings of the Performance and Flight Operations Engineering Conference.
[7] James, W., & O'Dell, P. (2005). Derated Climb Performance In Large Civil Aircraft.Proceedings of the Performance and Flight Operations Engineering Conference.
[8] FAA, 2016. Aviation Environmental Design Tool (AEDT) Version 2c User Guide

1) Wind: 4m/s (8 knots) headwind constant with height above ground
2) Runway Elevation: mean sea level
3) Runway gradient: None
4) Air temperature: 15C (59F)
5) Takeoff gross weight: 85% of maximum takeoff gross weight
6) Landing gross weight: 90% of maximum landing gross weight
7) Number of engines supply thrust along any segment of flight path: 2

Note that SAE-AIR-1845 does not specify thrust conditions for full or reduced engine power, which will likely impact the length of the ground roll.

Table 11: Takeoff Flaps Setting for All Three Vehicles[9]

	B737-800		**B767-300ER**		**B777-200ER**	
Flaps	Full Thrust	Reduced Thrust	Full Thrust	Reduced Thrust	Full Thrust	Reduced Thrust
Takeoff Flap	Flap 05	Flap 01	Flap 15	Flap 05	Flap 5	Flap 5

COEFF_B and COEFF_C_D were back calculated using HFVD data. Using SAE-AIR-1845, an "equivalent ground roll" can be calculated by using equation (1):

$$s_g = s_{gear\_up} - \left(\frac{h_{gear\_up}}{|\tan(\gamma)|}\right) \quad (1)$$

where,
γ : Flight path angle at the point where landing gear is retracted
s_{gear_up} : Ground distance
h_{gear_up} : Altitude at the point where landing gear is retracted

Using the calculated ground, COEFF_B was solved as [8]

$$s_g = \frac{B_f \theta \left(\frac{W}{\delta}\right)^2}{N\left(\frac{F_n}{\delta}\right)} \quad (2)$$

where,
s_g: Ground-roll distance
B_f: Ground-roll coefficient, which depends on the flaps setting
θ: Temperature ratio at the airport elevation
δ: Pressure ratio at the airport
$\left(\frac{F_n}{\delta}\right)_2$: Corrected net thrust per engine (lbf) at the end of the takeoff step

The ground roll equation can be simplified by matching the reference conditions specified in SAE-AIR-1845 and assuming the temperature and pressure ratios are equal to 1, resulting in Equation (3).

$$s_g = \frac{B_f W^2}{N(F_n)_2} \quad (3)$$

Rearranging Equation (3)to solve for COEFF_B results in Equation (4).

$$B_f = \frac{s_g N * (F_n)_2}{W^2} \quad (4)$$

[9] ICAO, 2007. Review of Noise Abatement Procedure Research & Development and Implentation Results, pages 9 to 10.

Using Equation (5) for calculating initial climb calibrated airspeed, COEFF_C_D can be back calculated.

$$v_2 = C_f * \sqrt{W} \tag{5}$$

where,
v_2: Initial climb calibrated airspeed
C_f: Takeoff speed coefficient that depends on flap settings
W: Departure profile weight; weight is assumed to remain constant for the entire departure profile

Rearranging Equation (5) in-term of COEFF_C_D results in:

$$C_f = \frac{v_2}{\sqrt{W}} \tag{6}$$

To validate the methodology, the COEFF_B and COEFF_C_D values were calculated for Flaps 05, which is contained in the Fleet DB. The calculated COEFF_B and COEFF_C_D are very similar to the values in AEDT FLEET DB for Flaps 05 as listed in Table 12, therefore this method can be used for calculating COEFF_B and COEFF_C_D for Flaps 1. Using this procedure Flaps 1 coefficient for full and reduce thrust was calculated, the results are listed in Table 13.

Table 12: Flap 05 COEFF_B and COEFF_C_D Calculated Values for Full Thrust

Coefficient	AEDT	Calculated	Percentage Difference
s_g [FT]	N/A	5182.874	N/A
COEFF_B [ft/lb]	0.009633	0.009758	1.30%
COEFF_C_D	0.435043	0.397091	-8.72%

Table 13: Flap 01 COEFF_B and COEFF_C_D Calculated Values for Full and Reduced Thrust

Coefficient	Using Full Thrust Takeoff	Using Reduced Thrust Takeoff
s_g [FT]	7273.1	7360.8
COEFF_B [ft/lb]	0.01359	0.01158
COEFF_C_D	0.41242	0.41424

The reduction of takeoff and climb thrust lead to a longer ground roll and add shallower climb as depicted in Figure 19. As a result, the noise contour lengths increased and the contour width and area decreased for all stage length as shown in Figure 20. Notice that for SEL 70 dB contour length trend does not increase at higher stage lengths, because the departure segment end altitude ends at 10000 ft resulted in the noise contour getting cutoff. The trends are similar for the B767-300ER and B777-200ER.

The tabulated noise results are provided in Table 14 to Table 16. An average decrease of 14% in contour width for SEL 70 dB was observed for all stage lengths. For SEL 80 and 90 dB, an increased in contour length of 3% for SEL 80 dB and between 16% and 23% for SEL 90 dB, because SEL 80 and 90 dB are more sensitive to thrust. There is a significant decrease in the overall noise contour width and area for SEL 80 and 90, for all stage length. NOx and fuel burn below 3,000 feet show an increase over the baseline full thrust takeoff due to the shallower climb out as listed in Table 17 and Table 18. Between 3000 ft and 10000ft there is significant less NOx production, but slight increase in fuel burn.

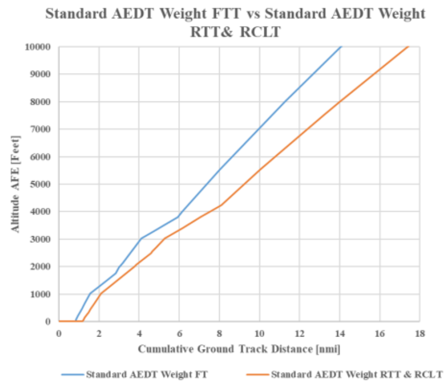

Figure 19: STANDARD Procedure for AEDT Weight Full vs Reduced Takeoff Thrust Trajectory for Stage Length 3

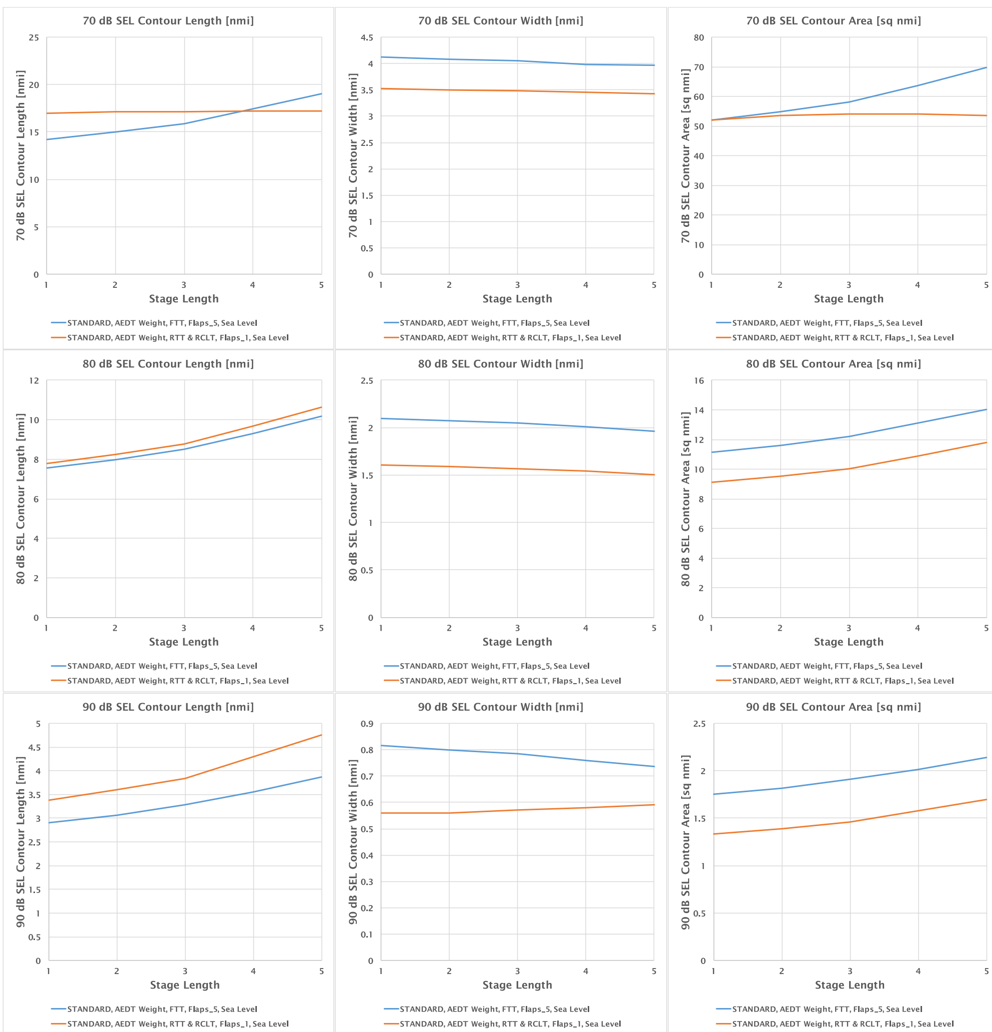

Figure 20: Thrust Sensitivity Noise Results

Table 14: Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	16.970	19%	4.128	3.520	-15%	52.013	52.050	0%
2	14.998	17.160	14%	4.085	3.490	-15%	54.833	53.620	-2%
3	15.888	17.170	8%	4.049	3.480	-14%	58.125	53.940	-7%
4	17.421	17.200	-1%	3.980	3.450	-13%	63.722	53.960	-15%
5	19.050	17.220	-10%	3.973	3.420	-14%	69.663	53.580	-23%

Table 15: Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.790	3%	2.095	1.610	-23%	11.117	9.110	-18%
2	7.985	8.250	3%	2.070	1.590	-23%	11.601	9.540	-18%
3	8.492	8.760	3%	2.047	1.570	-23%	12.219	10.020	-18%
4	9.313	9.690	4%	2.007	1.540	-23%	13.100	10.900	-17%
5	10.196	10.640	4%	1.962	1.500	-24%	14.046	11.790	-16%

Table 16: Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	3.380	16%	0.816	0.560	-31%	1.753	1.330	-24%
2	3.068	3.600	17%	0.800	0.560	-30%	1.818	1.390	-24%
3	3.285	3.840	17%	0.786	0.570	-27%	1.912	1.460	-24%
4	3.550	4.290	21%	0.760	0.580	-24%	2.013	1.580	-22%
5	3.874	4.760	23%	0.738	0.590	-20%	2.136	1.700	-20%

Table 17: Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	STANDARD AEDT RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	STANDARD AEDT RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377491	7350.469767	14%	5479.081	4937.643	-10%
2	6761.582634	7765.169042	15%	5787.113	5296.844	-8%
3	7168.941787	8226.378587	15%	6125.350	5628.586	-8%
4	7957.103434	9320.46483	17%	6551.746	6010.076	-8%
5	8582.797272	10163.54645	18%	7221.653	6687.051	-7%

Table 18: Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	STANDARD AEDT RTT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	STANDARD AEDT RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	322.661	37%	232.659	235.320	1%
2	246.776	340.738	38%	245.762	252.313	3%
3	261.668	360.817	38%	260.150	268.160	3%
4	291.929	409.512	40%	278.414	286.410	3%
5	315.017	446.284	42%	306.898	318.744	4%

Step 4

Using the STANDARD procedure define in step 1, the aircrafts weight were changed from AEDT weights to Project 35 weights and the takeoff and climb thrust were reduced as in Step 3, which resulted in a much shallower climb out trajectory as depicted in Figure 21. The takeoff flaps were set to the lowest possible flap setting permissible for takeoff. For B737-800, increasing the weight and reducing the thrust resulted in an increase in the contour length and a decrease in the contour width for all SEL dB level as shown in Figure 22. However, the contour area increased for SEL 70 dB, but decreased for SEL 80 and 90dB as shown in Figure 22. An increase in contour length is due to the shallower climb as depicted in Figure 21.

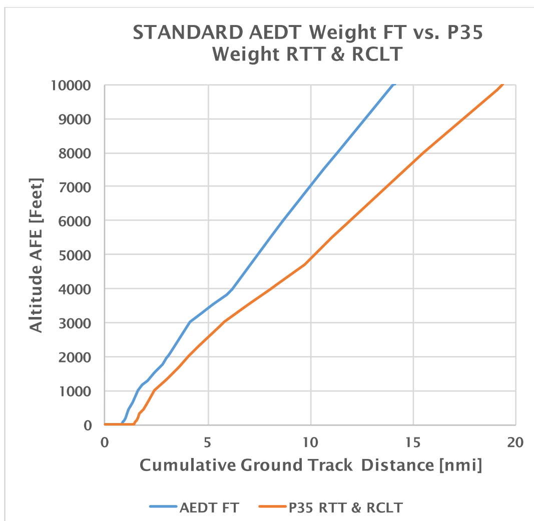

Figure 21: STANDARD AEDT Weight FT vs. Project 35 Weight RTT & RCLT for Stage Length 3

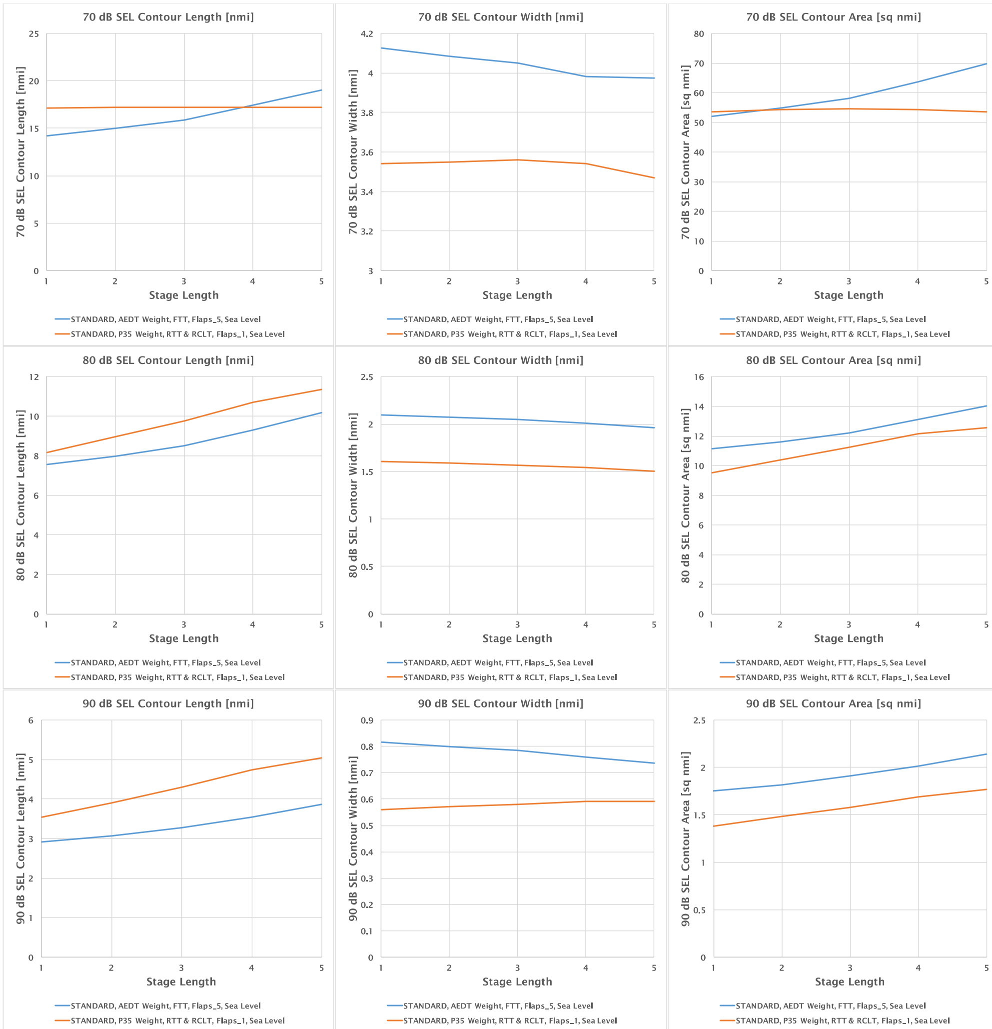

Figure 22: Weight and Thrust Sensitivity Noise Results

The calculated contour noise metrics are listed in Table 19 to Table 21. Note that there is a significant increase in contour length for SEL for SEL 70 dB of 21% at lower stage lengths. However, the contour does not increase further after stage length 1, because the noise contour was cut off due to the end altitude for the departure procedure end at 10000 ft. There are significant changes for SEL 70 dB contour width of 11% to 14% decrease overall. SEL 80 and 90 dB have an increased contour length and decreased in contour width and area. There is a significant increase in NOx and fuel burn below 3000 ft as listed in Table 22 and Table 23, due to the shallower climb due to heavier weight resulted in longer period of times for the aircraft to reach 3000 ft.

Table 19: Weight and Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	17.160	21%	4.128	3.540	-14%	52.013	53.660	3%
2	14.998	17.180	15%	4.085	3.550	-13%	54.833	54.410	-1%
3	15.888	17.200	8%	4.049	3.560	-12%	58.125	54.600	-6%
4	17.421	17.220	-1%	3.980	3.540	-11%	63.722	54.300	-15%
5	19.050	17.230	-10%	3.973	3.470	-13%	69.663	53.660	-23%

Table 20: Weight and Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	8.150	8%	2.095	1.610	-23%	11.117	9.530	-14%
2	7.985	8.950	12%	2.070	1.590	-23%	11.601	10.370	-11%
3	8.492	9.760	15%	2.047	1.570	-23%	12.219	11.240	-8%
4	9.313	10.720	15%	2.007	1.540	-23%	13.100	12.140	-7%
5	10.196	11.370	12%	1.962	1.500	-24%	14.046	12.560	-11%

Table 21: Weight and Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	STANDARD P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	STANDARD P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	STANDARD P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	3.540	22%	0.816	0.560	-31%	1.753	1.380	-21%
2	3.068	3.910	27%	0.800	0.570	-29%	1.818	1.480	-19%
3	3.285	4.300	31%	0.786	0.580	-26%	1.912	1.580	-17%
4	3.550	4.740	34%	0.760	0.590	-22%	2.013	1.690	-16%
5	3.874	5.040	30%	0.738	0.590	-20%	2.136	1.770	-17%

Table 22: Weight and Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	STANDARD P35 RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	STANDARD P35 RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.378	7713.759	20%	5479.081	5112.940	-7%
2	6761.583	8483.530	25%	5787.113	5690.379	-2%
3	7168.942	9267.492	29%	6125.350	6194.513	1%
4	7957.103	9391.562	18%	6551.746	7541.325	15%
5	8582.797	10823.022	26%	7221.653	7030.133	-3%

Table 23: Weight and Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	STANDARD P35 RTT & RCLT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	STANDARD P35 RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	338.517	44%	232.659	243.720	5%
2	246.776	372.050	51%	245.762	271.024	10%
3	261.668	406.190	55%	260.150	295.071	13%
4	291.929	408.801	40%	278.414	359.150	29%
5	315.017	475.102	51%	306.898	335.093	9%

Step 5

Currently, AEDT only models STANDARD procedures, but typically, pilots fly using a noise abatement departure procedure (NADP). FAA AC 91-53A and ICAO PANS OPS Chapter 3 Volume II both contain the minimum safe standards for departure procedures. Both documents recommend that all carriers adopt no more than two procedures for each aircraft type; one for noise abatement of communities close to the airport (NADP1) and one for noise abatement of communities far from the airport (NADP-2) as depicted in Figure 23. These procedures are not modeled within AEDT. Therefore, the NADP procedures were modeled based on HFVD. All three aircraft take-off procedures were modeled at STANDARD day sea level conditions. The differences between the existing procedures in AEDT and the new procedures are thrust, cutback altitudes, and the flap retraction schedule. The AEDT STANDARD procedure for the three aircraft was changed to NADP 1 & 2 procedure. The procedure defined in Figure 23 is different from Table 1, because the HFVD procedures use energy share percentage instead of specifying rates of climb. Since the energy share percentage value does not change for the three aircraft, as shown in Figure 24, the rates of climb do not need to be estimated.

NADP-1	STANDARD (ICAO-A)	STANDARD (ICAO-B)	NADP-2
Takeoff thrust, lowest flap setting	Takeoff thrust, Lowest flap setting	Takeoff thrust, Lowest flap setting	Takeoff thrust, Lowest flap setting
Climb at V2+15 KIAS to 800 ft AGL	Climb at V2+15 KIAS to 1500 ft AGL	Climb at V2+15 KIAS to 800 ft AGL	Climb at V2+15 KIAS to 800 ft AGL
Cutback to MCLT	Cutback to MCLT	Accelerate and retract flaps	Cutback to MCLT
		At zero flap cutback to MCLT	Accelerate and retract flaps
Constant speed climb to 3,000 ft AGL	Constant speed climb to 3,000 ft AGL	Constant speed climb to 3,000 ft AGL	Constant speed climb to 3,000 ft AGL
Accelerate to 250 KIAS while retracting flaps	Accelerate to 250 KIAS while retracting flaps	Accelerate to 250 KIAS	Accelerate to 250 KIAS
Climb at constant speed to 10,000ft AGL	Climb at constant speed to 10,000ft AGL	Climb at constant speed to 10,000ft AGL	Climb at constant speed to 10,000ft AGL
End profile at 10,000ft	End profile at 10,000ft	End profile at 10,000ft	End profile at 10,000ft

Not modeled in AEDT

Modeled in AEDT

Not modeled in AEDT

Figure 23: STANDARD and NADPs Procedures

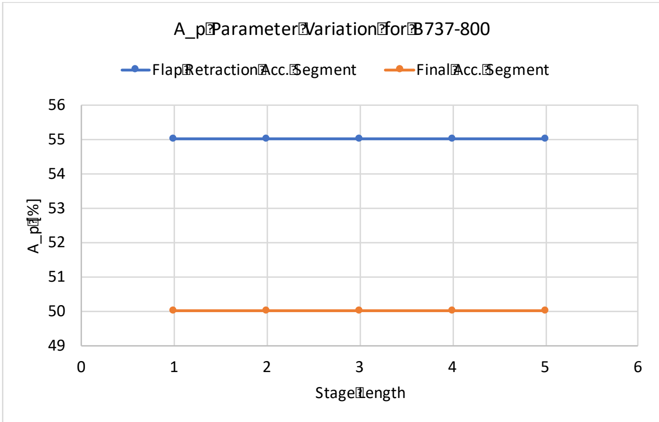

Figure 24: Energy Share Percentage

Energy share percentages of 55% before and 50% after flap retraction are used for the acceleration segment. Table 24 is a sample of NADP-1 procedure parameters defined for the B737-800 at stage length 1. The Flap_ID is the flap setting which in this case is Flaps 5 for B737-800 for takeoff. PARAM1 is the rate of climb for acceleration segment and altitude for constant speed climb segment. The type of segment is denoted in STEP_TYPE, where C is constant speed climb, while A and P are the acceleration climb steps. STEP_TYPE P is for defining energy share percentage for PARAM1 and for STEP_TYPE A, the PARAM1 is the rate of climb (ft/min). PARAM2 is the final velocity in knots.

Table 24: NADP-1 Procedure Parameters

Segment	Flap_ID	PARAM1	PARAM2	PARAM3	STEP_TYPE	THR_TYPE
1	T_05	0	0	0	T	T
2	T_05	1000	0	0	C	T
3	T_05	3000	0	0	C	C
4	T_05	55	175.3	0	P	C
5	T_01	55	209	0	P	C
6	T_00	50	250	0	P	C
7	T_00	5500	0	0	C	C
8	T_00	7500	0	0	C	C
9	T_00	10000	0	0	C	C

Since energy share percentage does not change, the only parameter that varies with stage length is the velocity at the end of the acceleration segment. The velocity at the end of acceleration segment can be acquired from HFVD. However, the end velocity using HFVD is very similar to STANDARD full thrust final velocity parameters. An experiment was performed to check the sensitivity of the noise contours and trajectories when using STANDARD procedure VSTOP parameters for reduced thrust takeoff for NADPs. It was found that the trajectories and contours are nearly identical when using velocities from the STANDARD procedure for NADP-1 and NADP-2.

Step 5 focused on analyzing the changes in noise contour, fuel burn and NOx due to changes in departure procedure for all three vehicles. The vehicle weights were set to AEDT weights, flaps were set to Flap 05, with full takeoff thrust and maximum climb thrust. The noise contour results for B737-800 NADP-1 are shown in Figure 26 and the calculate noise metric are in Table 25 to Table 27. Contour length is slightly longer for SEL 70 and 80 dB, but significantly shorter for SEL 90 dB. Contour width is wider at SEL 70dB, but smaller for SEL 90 dB. The contour width is insensitive to the changes in procedure for SEL 80 dB. Contour area for SEL 70 and 80 dB is larger, but smaller for SEL 90dB. Table 28 and Table 29 shows a 8% to 10% decreased in the fuel burn and NOx below 3000ft, but increase of 15% to 19% in fuel burn and NOx between 3000 ft to 10000 ft. This might be due to NADP-1 procedure cutback to climb thrust earlier than STANDARD procedure as shows in Figure 23.

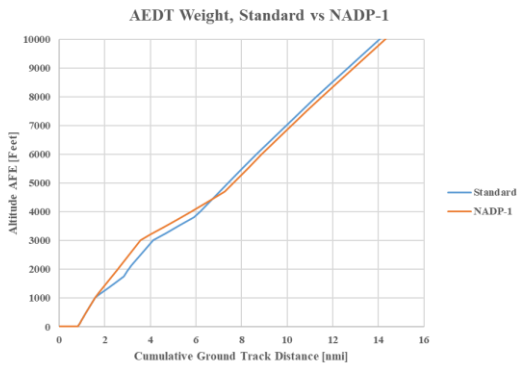

Figure 25: AEDT Weight STANDARD vs NADP-1 Procedure for Full Thrust

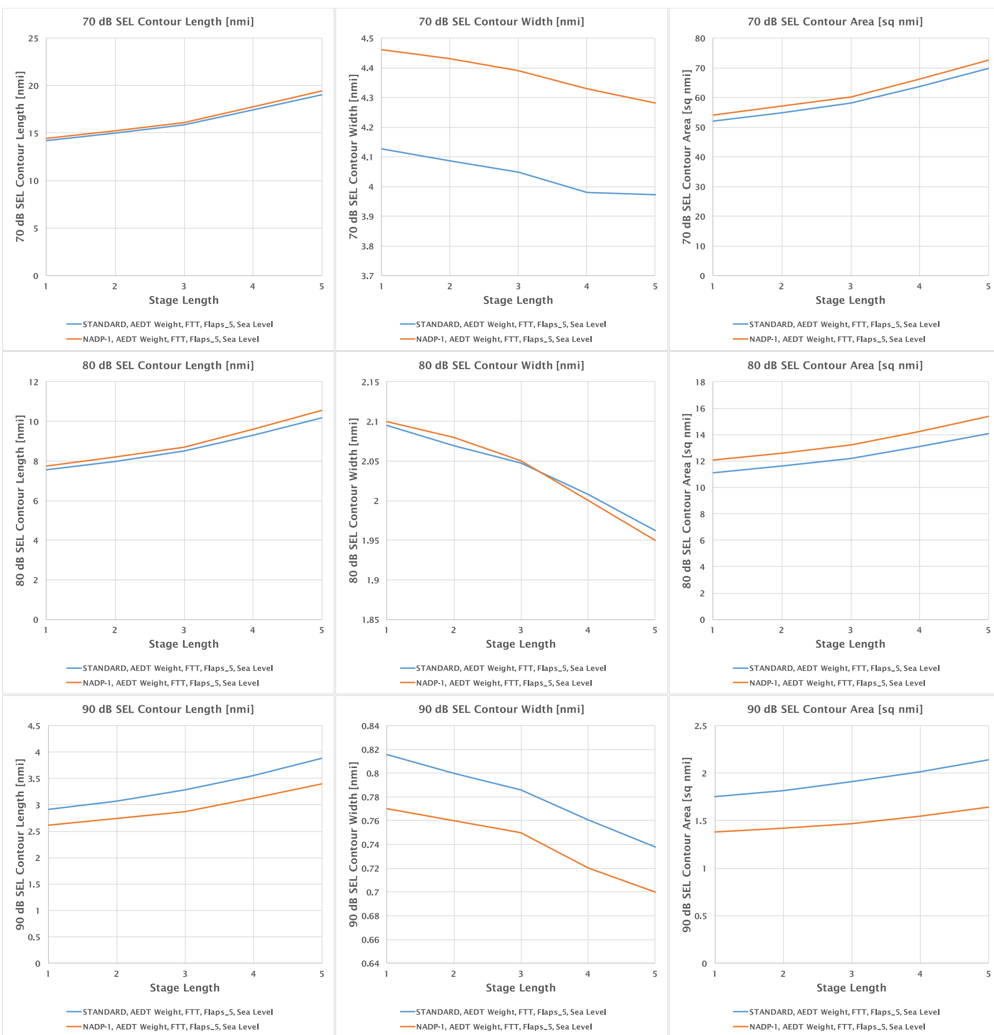

Figure 26: Procedure Sensitivity Noise Results

Table 25: Procedure Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	14.228	14.450	2%	4.128	4.460	8%	52.013	54.030	4%
2	14.998	15.250	2%	4.085	4.430	8%	54.833	56.980	4%
3	15.888	16.120	1%	4.049	4.390	8%	58.125	60.230	4%
4	17.421	17.750	2%	3.980	4.330	9%	63.722	66.240	4%
5	19.050	19.440	2%	3.973	4.280	8%	69.663	72.480	4%

Table 26: Procedure Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.750	3%	2.095	2.100	0%	11.117	12.050	8%
2	7.985	8.190	3%	2.070	2.080	1%	11.601	12.600	9%
3	8.492	8.690	2%	2.047	2.050	0%	12.219	13.190	8%
4	9.313	9.600	3%	2.007	2.000	0%	13.100	14.260	9%
5	10.196	10.550	3%	1.962	1.950	-1%	14.046	15.360	9%

Table 27: Procedure Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.610	-10%	0.816	0.770	-6%	1.753	1.380	-21%
2	3.068	2.740	-11%	0.800	0.760	-5%	1.818	1.420	-22%
3	3.285	2.870	-13%	0.786	0.750	-5%	1.912	1.470	-23%
4	3.550	3.120	-12%	0.760	0.720	-5%	2.013	1.550	-23%
5	3.874	3.390	-12%	0.738	0.700	-5%	2.136	1.640	-23%

Table 28: Procedure Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-1 AEDT FTT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-1 AEDT FTT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	5916.647	-8%	5479.081	6287.650	15%
2	6761.583	6199.107	-8%	5787.113	6648.208	15%
3	7168.942	6506.675	-9%	6125.350	7045.431	15%
4	7957.103	7068.306	-11%	6551.746	7786.112	19%
5	8582.797	7633.095	-11%	7221.653	8554.715	18%

Table 29: Procedure Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-1 AEDT FTT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-1 AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	224.634	-4%	232.659	266.550	15%
2	246.776	235.092	-5%	245.762	281.840	15%
3	261.668	246.470	-6%	260.150	298.685	15%
4	291.929	267.222	-8%	278.414	330.100	19%
5	315.017	288.059	-9%	306.898	362.705	18%

NADP2 noise results are shows in Figure 28 and calculated noise metric are found in Table 30 and Table 32. There is little to no changes in noise contour length and area for NADP-2 SEL 70 dB compare to STANDARD procedure for all stage length. There is a significant in contour width at earlier stage length, but the different between NADP-2 and STANDARD contour width decreases at higher stage length as shows in Table 30. For SEL 80 dB an increased in about 5% on the overall contour length for all stage length. Table 31 shows a decrease of 12% for contour width and 4% to 6% for contour area. There is a significant decrease for contour length, width and area for SEL 90 dB as shows in Table 32.

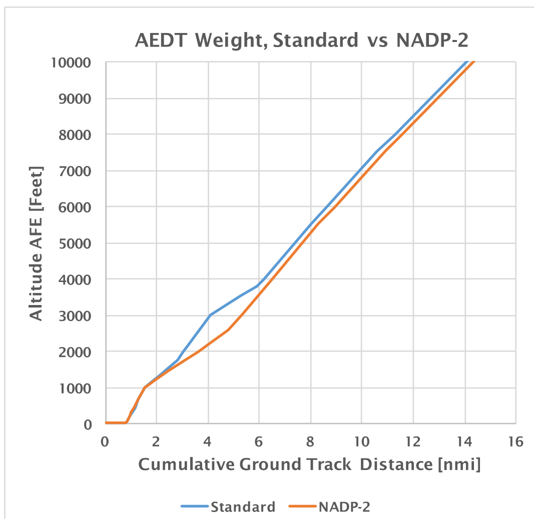

Figure 27: AEDT Weight STANDARD vs NADP-2 Procedure for Full Thrust

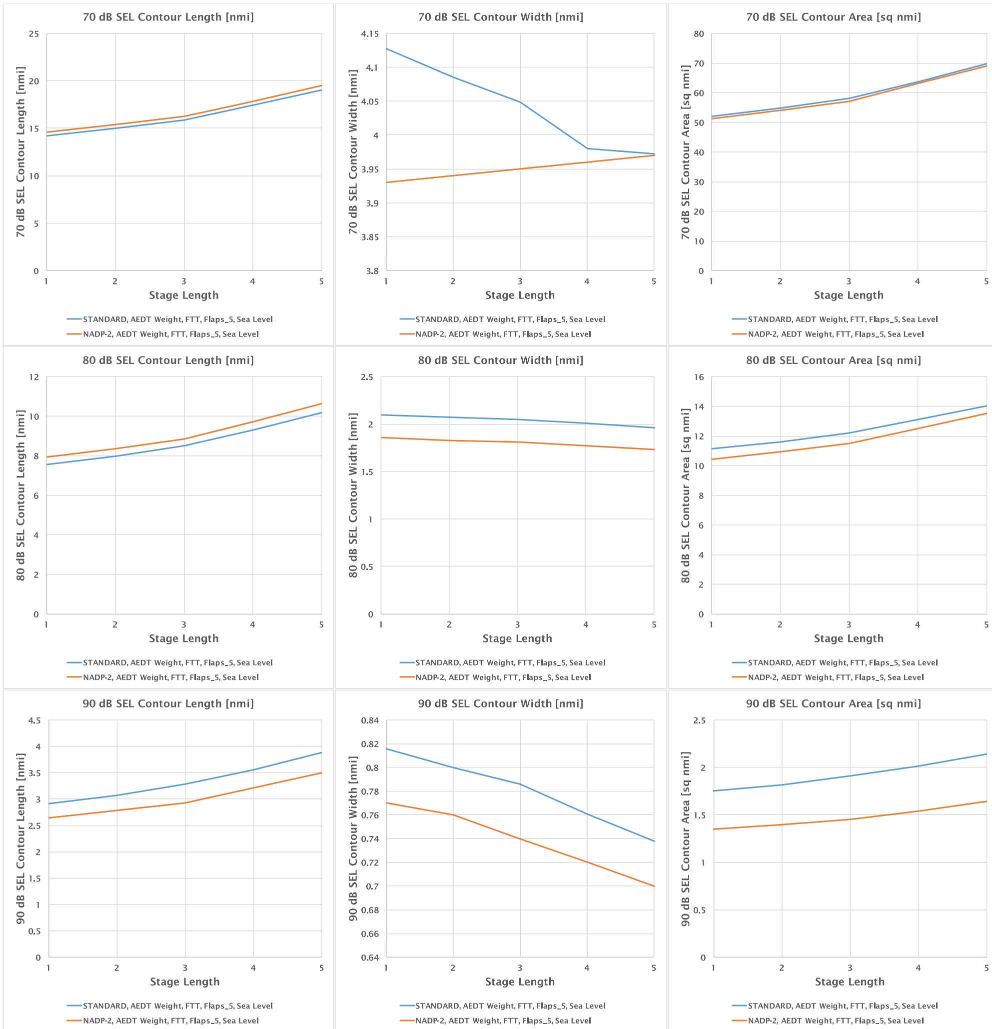

Figure 28: Procedure Sensitivity Noise Results

Table 30: Procedure Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	14.228	14.580	2%	4.128	3.930	-5%	52.013	51.160	-2%
2	14.998	15.360	2%	4.085	3.940	-4%	54.833	54.030	-1%
3	15.888	16.230	2%	4.049	3.950	-2%	58.125	57.190	-2%
4	17.421	17.830	2%	3.980	3.960	-1%	63.722	63.050	-1%
5	19.050	19.490	2%	3.973	3.970	0%	69.663	69.070	-1%

Table 31: Procedure Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.920	5%	2.095	1.860	-11%	11.117	10.430	-6%
2	7.985	8.360	5%	2.070	1.830	-12%	11.601	10.940	-6%
3	8.492	8.850	4%	2.047	1.810	-12%	12.219	11.490	-6%
4	9.313	9.740	5%	2.007	1.770	-12%	13.100	12.500	-5%
5	10.196	10.640	4%	1.962	1.730	-12%	14.046	13.500	-4%

Table 32: Procedure Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT FTT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.640	-9%	0.816	0.770	-6%	1.753	1.350	-23%
2	3.068	2.780	-9%	0.800	0.760	-5%	1.818	1.400	-23%
3	3.285	2.930	-11%	0.786	0.740	-6%	1.912	1.450	-24%
4	3.550	3.210	-10%	0.760	0.720	-5%	2.013	1.540	-23%
5	3.874	3.490	-10%	0.738	0.700	-5%	2.136	1.640	-23%

There is a significant increase in fuel burn and NOx below 3000 ft, but decrease between 3000 ft and 10000 ft as listed in Table 33 and Table 34.The effect on Fuel burn and NOx is opposite for NADP-2 when compared to NADP-1 procedure. Fuel burn and NOx are higher under 3000ft, but lower above 3000ft when comparing Table 33 and Table 34 to Table 28 and Table 29.

Table 33: Procedure Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-2 AEDT FTT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-2 AEDT FTT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	7063.876	10%	5479.081	4499.245	-18%
2	6761.583	7424.524	10%	5787.113	4769.526	-18%
3	7168.942	7817.392	9%	6125.350	5067.943	-17%
4	7957.103	8535.235	7%	6551.746	5625.374	-14%
5	8582.797	9253.635	8%	7221.653	6203.979	-14%

Table 34: Procedure Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-2 AEDT FTT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-2 AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	272.460	16%	232.659	191.523	-18%
2	246.776	286.276	16%	245.762	203.030	-17%
3	261.668	301.317	15%	260.150	215.736	-17%
4	291.929	328.773	13%	278.414	239.469	-14%
5	315.017	356.342	13%	306.898	264.105	-14%

Step 6

Similar to step 2, the aircraft weights were changed from AEDT to Project 35 weight for B737-800 and B767-300ER and ALT weight for B777-200ER. The procedure was also changed from STANDARD to the NADP procedures. All the other parameters were kept constant. Changing procedures and weights for B737-800 increased contour length and area for SEL 70 and 80 dB, but decreased for SEL 90 dB as shown in Figure 30. The increase in contour length is due to the shallower trajectory as shown in Figure 29. Contour width is wider for SEL 70 dB, but smaller for SEL 80 and 90 dB as shows in Figure 30. Table 35 and Table 37 shows calculate noise metric for SEL 70, 80,and 90 dB. The results showed there are significant changes to all the noise parameter for all SEL levels, except SEL 80 dB contour width. There little to no changes in contour width for SEL 80 dB. Changing departure procedure and weight, results in significant increase in the overall fuel burn and NOx between 3000 to 10000 ft. However, there is little to no changes for fuel burn and NOx below 3000 ft as shows in Table 38 and Table 39.

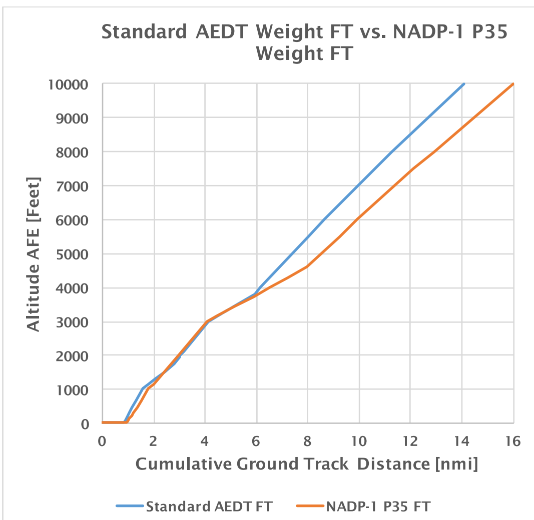

Figure 29: STANDARD AEDT Weight FT vs NADP-1 P35 Weight for Full Thrust

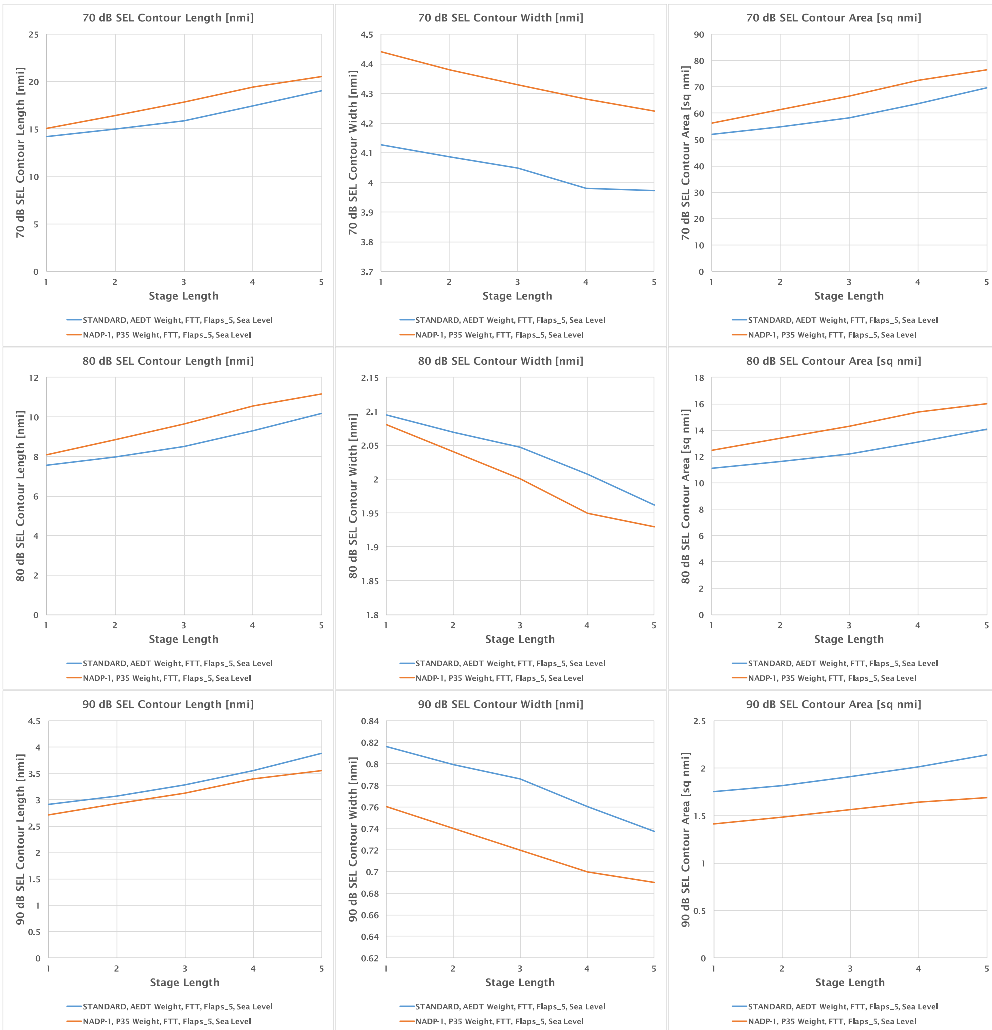

Figure 30: Procedure and Weight Sensitivity Noise Results

Table 35: Procedure and Weight Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	14.228	15.050	6%	4.128	4.440	8%	52.013	56.240	8%
2	14.998	16.420	9%	4.085	4.380	7%	54.833	61.340	12%
3	15.888	17.820	12%	4.049	4.330	7%	58.125	66.500	14%
4	17.421	19.440	12%	3.980	4.280	8%	63.722	72.480	14%
5	19.050	20.520	8%	3.973	4.240	7%	69.663	76.430	10%

Table 36: Procedure and Weight Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	7.559	8.080	7%	2.095	2.080	-1%	11.117	12.460	12%
2	7.985	8.850	11%	2.070	2.040	-1%	11.601	13.390	15%
3	8.492	9.640	14%	2.047	2.000	-2%	12.219	14.300	17%
4	9.313	10.550	13%	2.007	1.950	-3%	13.100	15.360	17%
5	10.196	11.150	9%	1.962	1.930	-2%	14.046	16.030	14%

Table 37: Procedure and Weight Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.710	-7%	0.816	0.760	-7%	1.753	1.410	-20%
2	3.068	2.920	-5%	0.800	0.740	-7%	1.818	1.480	-19%
3	3.285	3.130	-5%	0.786	0.720	-8%	1.912	1.560	-18%
4	3.550	3.390	-5%	0.760	0.700	-8%	2.013	1.640	-19%
5	3.874	3.560	-8%	0.738	0.690	-6%	2.136	1.690	-21%

Table 38: Procedure and Weight Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-1 P35 FTT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-1 P35 FTT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	6126.425	-5%	5479.081	6558.536	20%
2	6761.583	6609.235	-2%	5787.113	7180.958	24%
3	7168.942	7090.749	-1%	6125.350	7819.066	28%
4	7957.103	7633.095	-4%	6551.746	8554.715	31%
5	8582.797	7987.334	-7%	7221.653	9042.302	25%

Table 39: Procedure and Weight Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-1 P35 FTT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-1 AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	232.394	-1%	232.659	278.036	20%
2	246.776	250.258	1%	245.762	304.433	24%
3	261.668	268.044	2%	260.150	331.497	27%
4	291.929	288.059	-1%	278.414	362.705	30%
5	315.017	301.131	-4%	306.898	383.390	25%

For NADP-2 procedure, increasing in weight resulted shallower climb and longer ground roll as depicted in Figure 31, resulting in longer contour length for SEL 70 and 80 dB, but decrease for SEL 90 dB as showed in Figure 32. For SEL 70 dB, there is significant different in contour width at lower stage length. However at higher stage lengths, there is little to no changes in contour width as shows in Figure 32 and Table 40. There is a significant decrease in contour width for SEL 80 and 90 dB as shows in Table 41 and Table 42. There is an increase in contour area for SEL 70 dB, little to no changes in contour area for SEL 80 dB, and decrease in contour area for SEL 90 dB. Changing procedure and aircraft weight increased the fuel burn and NOx below 3000 ft, but decreased between 3000 ft and 10000 ft as shows in Table 43 and Table 44.

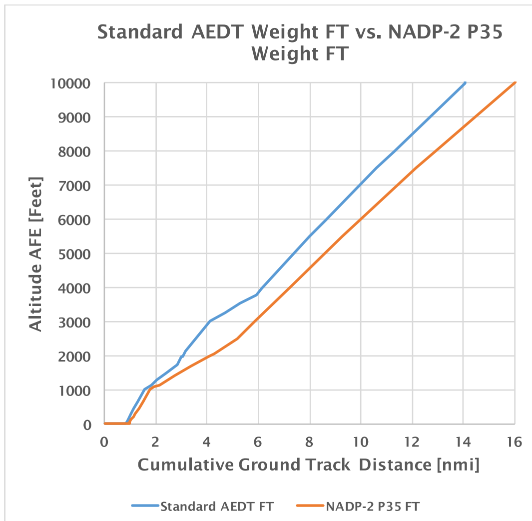

Figure 31: STANDARD AEDT Weight FT vs NADP-2 P35 Weight for Full Thrust

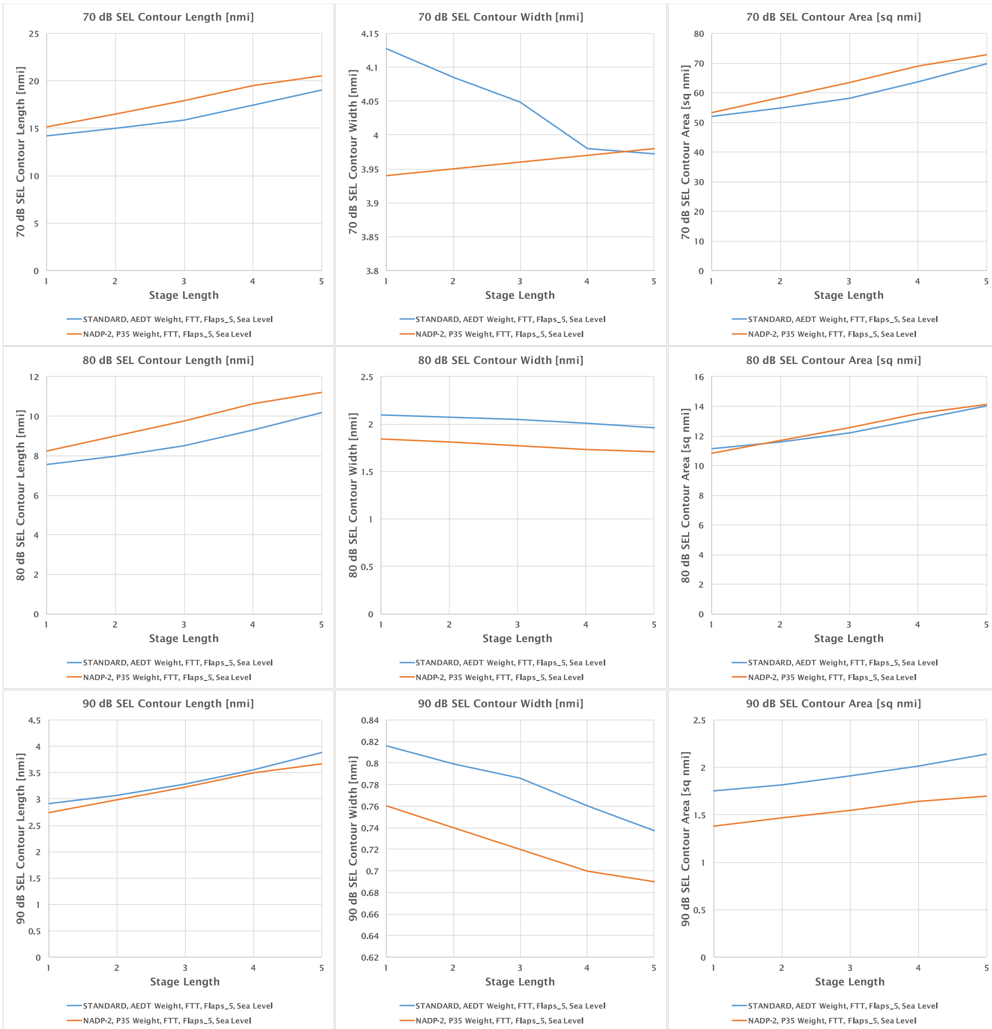

Figure 32: Procedure and Weight Sensitivity Noise Results

Table 40: Procedure and Weight Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	14.228	15.160	7%	4.128	3.940	-5%	52.013	53.310	2%
2	14.998	16.520	10%	4.085	3.950	-3%	54.833	58.260	6%
3	15.888	17.900	13%	4.049	3.960	-2%	58.125	63.300	9%
4	17.421	19.490	12%	3.980	3.970	0%	63.722	69.070	8%
5	19.050	20.540	8%	3.973	3.980	0%	69.663	72.880	5%

Table 41: Procedure and Weight Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	7.559	8.250	9%	2.095	1.840	-12%	11.117	10.820	-3%
2	7.985	9.010	13%	2.070	1.810	-13%	11.601	11.680	1%
3	8.492	9.770	15%	2.047	1.770	-14%	12.219	12.540	3%
4	9.313	10.640	14%	2.007	1.730	-14%	13.100	13.500	3%
5	10.196	11.210	10%	1.962	1.710	-13%	14.046	14.110	0%

Table 42: Procedure and Weight Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 P35 FTT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 P35 FTT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 P35 FTT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.740	-6%	0.816	0.760	-7%	1.753	1.380	-21%
2	3.068	2.980	-3%	0.800	0.740	-7%	1.818	1.470	-19%
3	3.285	3.220	-2%	0.786	0.720	-8%	1.912	1.550	-19%
4	3.550	3.490	-2%	0.760	0.700	-8%	2.013	1.640	-19%
5	3.874	3.670	-5%	0.738	0.690	-6%	2.136	1.700	-20%

Table 43: Procedure and Weight Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-2 P35 FTT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-2 P35 FTT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	7333.63	14%	5479.081	4701.141	-14%
2	6761.583	7949.366	18%	5787.113	5169.285	-11%
3	7168.942	8565.494	19%	6125.350	5649.305	-8%
4	7957.103	9253.635	16%	6551.746	6203.979	-5%
5	8582.797	9700.622	13%	7221.653	6573.292	-9%

Table 44: Procedure and Weight Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-2 P35 FTT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-2 AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	282.795	20%	232.659	200.119	-14%
2	246.776	306.367	24%	245.762	220.050	-10%
3	261.668	329.930	26%	260.150	240.488	-8%
4	291.929	356.342	22%	278.414	264.105	-5%
5	315.017	373.506	19%	306.898	279.830	-9%

Step 7

For step 7, NADP procedures defined in step 5 were used along with the thrust being reduced by 15% for takeoff and 10% for climb thrust. Aircraft weight was set to AEDT weight and the takeoff flaps setting was set to the lowest possible. This was defined as shown in Table 11. For B737-800, the noise results are shown in Figure 34 and the calculated noise metric are shows in Table 45 to Table 47. Reducing the takeoff and climb thrust lead to longer ground roll and shallower climb as depicted in Figure 33. Shallower climb resulted an increase in contour length for SEL 70 dB. However, for SEL 80 and 90 dB contour length decreases, because SEL 80 and 90 dB are more sensitive to thrust rather than the position of the vehicle. There is little to no changes in contour width and area for SEL 70 dB for all stage length. However, for SEL 80 and 90 dB there is significant decrease in overall contour width and area for all stage length. Changes in procedure and thrust, resulted in a decreased of NOx and increased in fuel burn below 3000 ft as shows in Table 48 and Table 49 for all stage length.

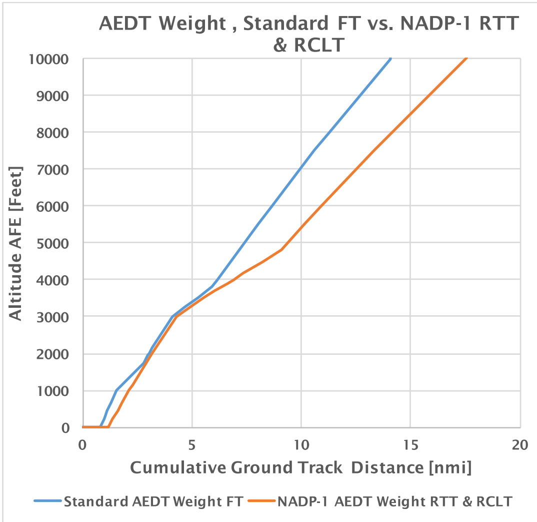

Figure 33: AEDT Weight, STANDARD FT vs NADP-1 RTT & RCLT

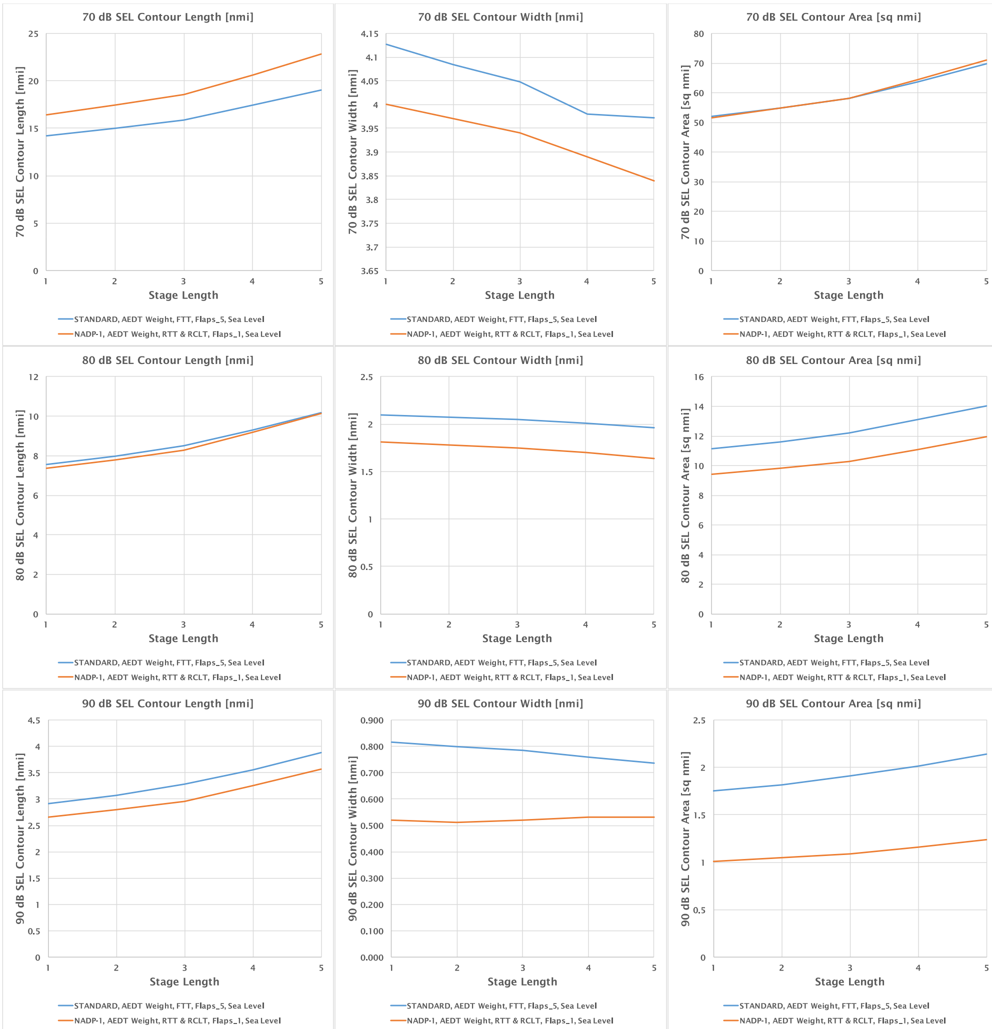

Figure 34: Procedure and Thrust Sensitivity Noise Results

Table 45: Procedure and Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	16.400	15%	4.128	4.000	-3%	52.013	51.630	-1%
2	14.998	17.410	16%	4.085	3.970	-3%	54.833	54.700	0%
3	15.888	18.530	17%	4.049	3.940	-3%	58.125	58.100	0%
4	17.421	20.630	18%	3.980	3.890	-2%	63.722	64.480	1%
5	19.050	22.840	20%	3.973	3.840	-3%	69.663	71.140	2%

Table 46: Procedure and Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.360	-3%	2.095	1.810	-14%	11.117	9.400	-15%
2	7.985	7.800	-2%	2.070	1.780	-14%	11.601	9.820	-15%
3	8.492	8.280	-3%	2.047	1.750	-15%	12.219	10.270	-16%
4	9.313	9.180	-1%	2.007	1.700	-15%	13.100	11.100	-15%
5	10.196	10.140	-1%	1.962	1.640	-16%	14.046	11.960	-15%

Table 47: Procedure and Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.650	-9%	0.816	0.520	-36%	1.753	1.010	-42%
2	3.068	2.800	-9%	0.800	0.510	-36%	1.818	1.050	-42%
3	3.285	2.950	-10%	0.786	0.520	-34%	1.912	1.090	-43%
4	3.550	3.250	-8%	0.760	0.530	-30%	2.013	1.160	-42%
5	3.874	3.570	-8%	0.738	0.530	-28%	2.136	1.240	-42%

Table 48: Procedure and Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-1 AEDT RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-1 AEDT RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	5545.383	-14%	5479.081	5918.405	8%
2	6761.583	5861.286	-13%	5787.113	6238.139	8%
3	7168.942	6207.151	-13%	6125.350	6592.422	8%
4	7957.103	6841.195	-14%	6551.746	7261.559	11%
5	8582.797	7491.16	-13%	7221.653	7959.436	10%

Table 49: Procedure and Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-1 AEDT RTT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-1 AEDT RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	247.908	5%	232.659	281.523	21%
2	246.776	261.992	6%	245.762	296.788	21%
3	261.668	277.417	6%	260.150	313.706	21%
4	291.929	305.704	5%	278.414	345.663	24%
5	315.017	334.743	6%	306.898	379.004	23%

Changes in procedure from STANDARD to NADP-2 and reducing takeoff and climb thrust resulted in longer ground roll and shallower climb as depicted in Figure 35. Shallower climb resulted in longer contour length for SEL 70 dB and decreased in contour width as shows in Figure 36. Reducing thrust resulted in decrease in contour length, width, and area for SEL 80 and 90 dB as shown in Figure 36. Looking at the calculated noise metric values in Table 50 and Table 52, there is little change in contour length for SEL 80 and 90 dB. However, there is a significant decrease in contour width and area. There is little to no change in contour area for SEL 70 dB, but significant increase in contour length and decrease in contour width. Changing from STANDARD procedure to NADP-2 and reducing the takeoff and climb thrust, results in decreased in NOx, but increase in fuel burn as shown in Table 53 and Table 54.

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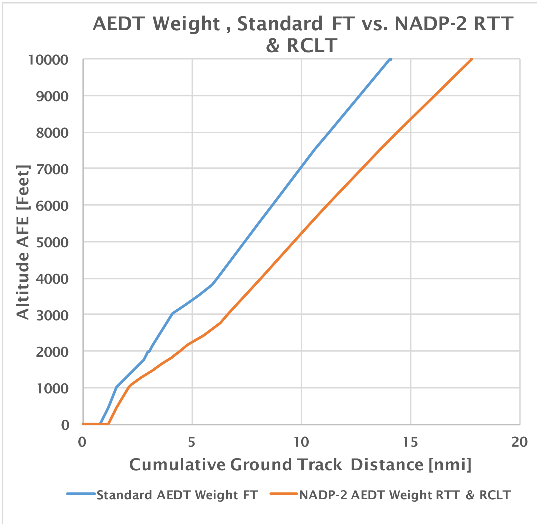


Figure 35: AEDT Weight, STANDARD FT vs NADP-2 RTT & RCLT

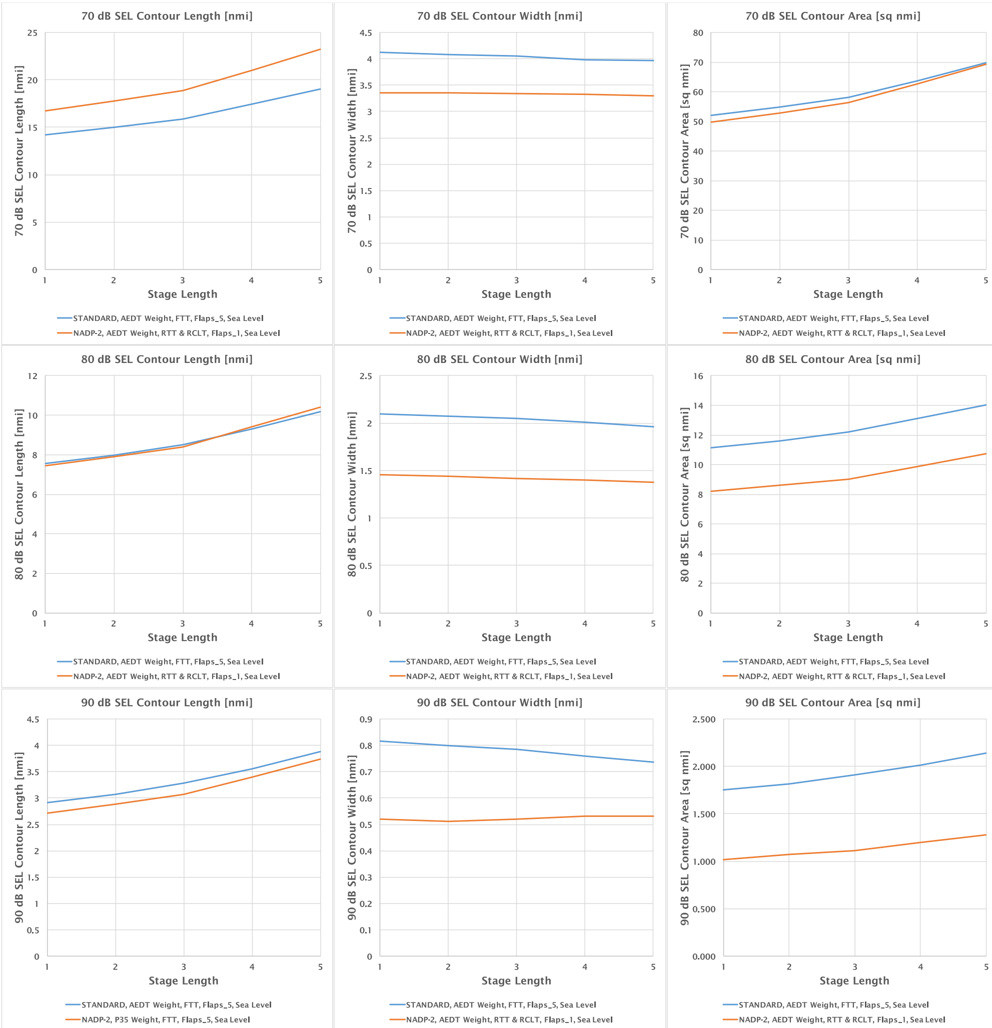


Figure 36: Procedure and Thrust Sensitivity Noise Results

Table 50: Procedure and Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	16.730	18%	4.128	3.360	-19%	52.013	49.850	-4%
2	14.998	17.750	18%	4.085	3.350	-18%	54.833	52.890	-4%
3	15.888	18.890	19%	4.049	3.340	-18%	58.125	56.260	-3%
4	17.421	21.020	21%	3.980	3.320	-17%	63.722	62.600	-2%
5	19.050	23.240	22%	3.973	3.300	-17%	69.663	69.170	-1%

Table 51: Procedure and Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.440	-2%	2.095	1.460	-30%	11.117	8.190	-26%
2	7.985	7.890	-1%	2.070	1.440	-30%	11.601	8.590	-26%
3	8.492	8.400	-1%	2.047	1.420	-31%	12.219	9.030	-26%
4	9.313	9.410	1%	2.007	1.400	-30%	13.100	9.880	-25%
5	10.196	10.390	2%	1.962	1.380	-30%	14.046	10.730	-24%

Table 52: Procedure and Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.720	-6%	0.816	0.520	-36%	1.753	1.020	-42%
2	3.068	2.890	-6%	0.800	0.510	-36%	1.818	1.070	-41%
3	3.285	3.070	-7%	0.786	0.520	-34%	1.912	1.110	-42%
4	3.550	3.400	-4%	0.760	0.530	-30%	2.013	1.200	-40%
5	3.874	3.740	-3%	0.738	0.530	-28%	2.136	1.280	-40%

Table 53: Procedure and Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-2 AEDT RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-2 AEDT RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	6009.781	-7%	5479.081	5024.006	-8%
2	6761.583	6335.084	-6%	5787.113	5335.536	-8%
3	7168.942	6690.593	-7%	6125.350	5681.548	-7%
4	7957.103	7152.028	-10%	6551.746	6010.581	-8%
5	8582.797	8229.982	-4%	7221.653	6801.334	-6%

Table 54: Procedure and Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-2 AEDT RTT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-2 AEDT RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	270.323	15%	232.659	239.352	3%
2	246.776	284.913	15%	245.762	254.226	3%
3	261.668	300.863	15%	260.150	270.748	4%
4	291.929	316.977	9%	278.414	286.433	3%
5	315.017	370.604	18%	306.898	324.231	6%

Step 8

For step 8, the NADP procedures defined in step 5 were used. The aircraft weights were changed from AEDT weights to Project 35 weights and the takeoff and climb thrust were reduced. The takeoff flaps were set to the lowest possible takeoff flap setting. This resulted in longer ground roll and shallower climb as depicted in Figure 37. Shallower climb resulted in longer contour length for SEL 70 as showed in Table 55. Because of the increase in aircraft weight and reduction of takeoff and climb thrust, the contour length of SEL 80 and 90 dB increased as showed in Figure 38 and Table 56 and Table 57. This different can be seen when comparing the noise results for step 8 and step 7. Reduction in thrust reduced the noise contour for all SEL level and all stage lengths. Reduction of thrust resulted in decreases in NOx for below 3000 ft, however increasing in the aircraft weight resulted increasing of fuel burn. The significant changes in NOx and fuel change due to changes in weight can be seen when comparing the fuel burn and NOx results from Table 58 and Table 59 to Table 53 and Table 54.

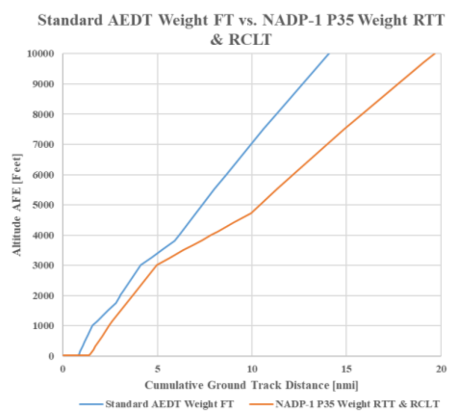


Figure 37: STANDARD AEDT Weight FT vs NADP-1 P35 Weight RTT & RCLT

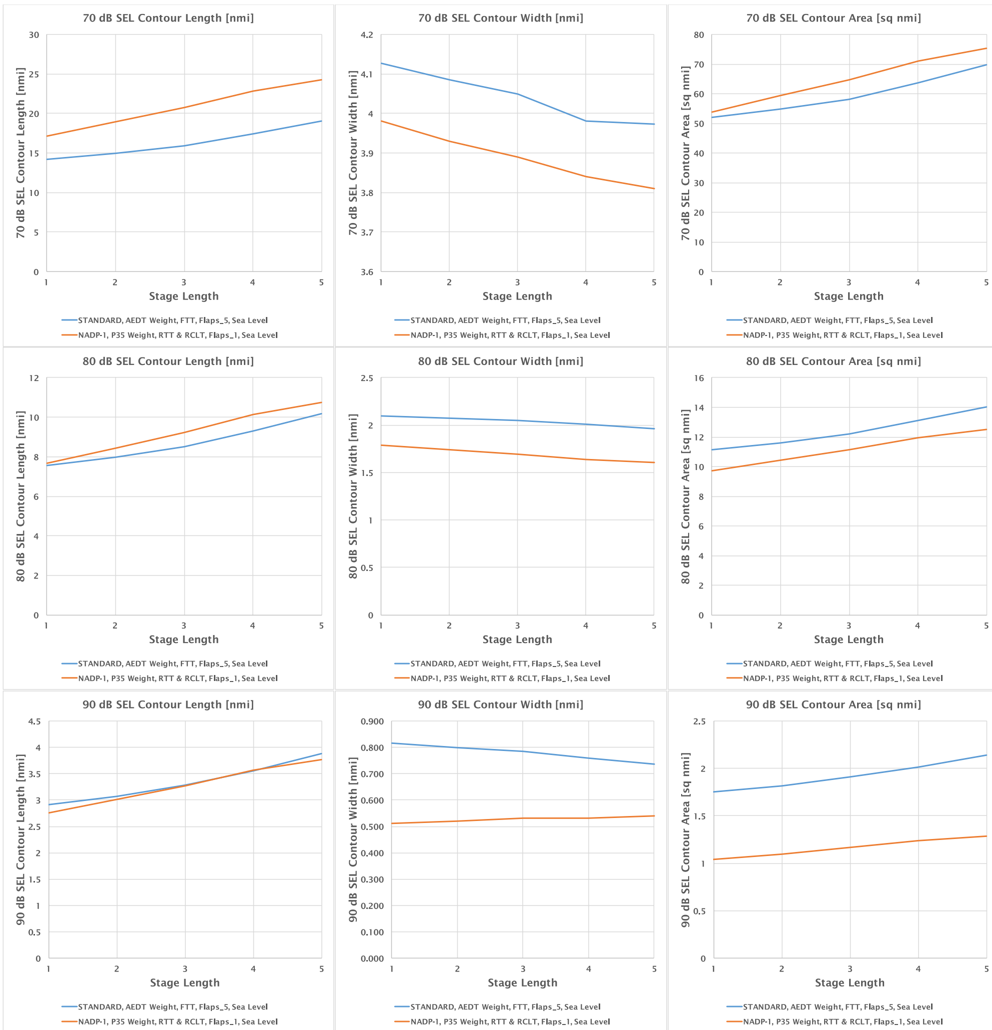


Figure 38: Procedure, Weight and Thrust Sensitivity Noise Results

Table 55: Procedure, Weight and Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	17.150	21%	4.128	3.980	-4%	52.013	53.920	4%
2	14.998	18.910	26%	4.085	3.930	-4%	54.833	59.260	8%
3	15.888	20.730	30%	4.049	3.890	-4%	58.125	64.760	11%
4	17.421	22.840	31%	3.980	3.840	-4%	63.722	71.140	12%
5	19.050	24.270	27%	3.973	3.810	-4%	69.663	75.400	8%

Table 56: Procedure, Weight and Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.690	2%	2.095	1.790	-15%	11.117	9.710	-13%
2	7.985	8.440	6%	2.070	1.740	-16%	11.601	10.420	-10%
3	8.492	9.220	9%	2.047	1.690	-17%	12.219	11.140	-9%
4	9.313	10.140	9%	2.007	1.640	-18%	13.100	11.960	-9%
5	10.196	10.740	5%	1.962	1.610	-18%	14.046	12.500	-11%

Table 57: Procedure, Weight and Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-1 P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-1 P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-1 P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.760	-5%	0.816	0.510	-37%	1.753	1.040	-41%
2	3.068	3.010	-2%	0.800	0.520	-35%	1.818	1.100	-39%
3	3.285	3.270	0%	0.786	0.530	-33%	1.912	1.170	-39%
4	3.550	3.570	1%	0.760	0.530	-30%	2.013	1.240	-38%
5	3.874	3.770	-3%	0.738	0.540	-27%	2.136	1.290	-40%

Table 58: Procedure, Weight and Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-1 P35 RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-1 P35 RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	5781.331	-10%	5479.081	6157.417	12%
2	6761.583	6322.117	-6%	5787.113	6714.687	16%
3	7168.942	6868.223	-4%	6125.350	7290.366	19%
4	7957.103	7491.16	-6%	6551.746	7959.436	21%
5	8582.797	7902.235	-8%	7221.653	8406.608	16%

Table 59: Procedure, Weight and Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-1 P35 RTT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-1 P35 RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	258.426	10%	232.659	292.934	26%
2	246.776	282.541	14%	245.762	319.544	30%
3	261.668	306.910	17%	260.150	347.039	33%
4	291.929	334.743	15%	278.414	379.004	36%
5	315.017	353.132	12%	306.898	400.372	30%

The STANDARD procedure was changed to NADP-2 procedure and takeoff and climb thrust was reduced by 15% and 10%. The takeoff weight were changed from AEDT to Project 35 weight and takeoff flaps was set to the lowest possible takeoff flaps setting. This resulted in longer ground roll and shallower climb as shown in Figure 39. Shallower climb resulted in increased contour length for all SEL levels as shows in Figure 40. Reduction of the thrust resulted in decreased of contour width for all SEL levels. Overall there is slight increases in contour area for SEL 70 dB, and significant decrease in contour area for SEL 80 and 90 dB as showed Table 60 and Table 62. The STANDARD procedure was changed to NADP-2 procedure and takeoff and climb thrust was reduced by 15% and 10%. The takeoff weight was changed from AEDT to Project 35 weight and takeoff flaps was set to the lowest possible takeoff flaps setting. There is little to no change in NOx as listed in Table 63, however significant changes in fuels burn as listed in Table 64.

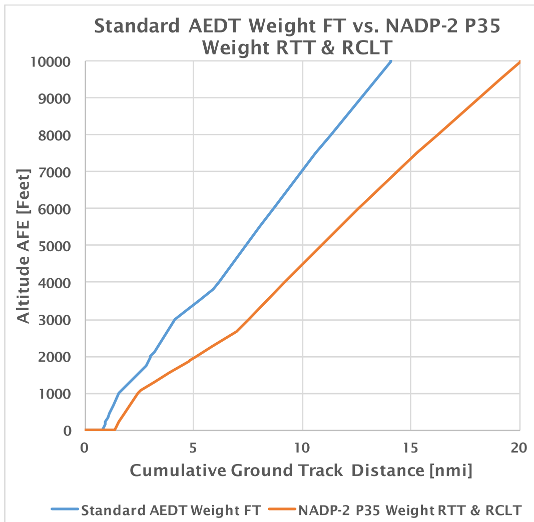


Figure 39: STANDARD AEDT Weight FT vs NADP-2 P35 Weight RTT & RCLT

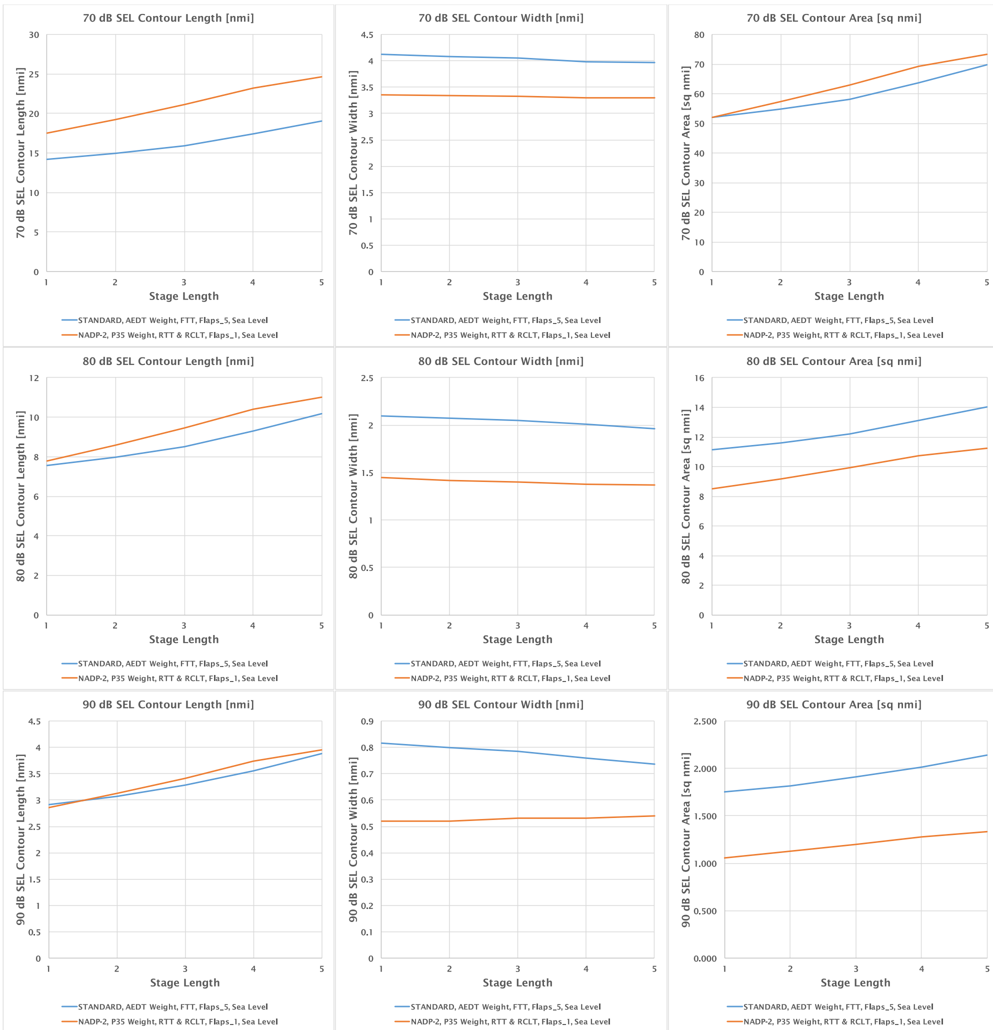


Figure 40: Procedure, Weight and Thrust Sensitivity Noise Results

Table 60: Procedure, Weight and Thrust Sensitivity SEL 70 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	14.228	17.500	23%	4.128	3.350	-19%	52.013	52.120	0%
2	14.998	19.270	28%	4.085	3.340	-18%	54.833	57.400	5%
3	15.888	21.110	33%	4.049	3.320	-18%	58.125	62.870	8%
4	17.421	23.240	33%	3.980	3.300	-17%	63.722	69.170	9%
5	19.050	24.680	30%	3.973	3.290	-17%	69.663	73.370	5%

Table 61: Procedure, Weight and Thrust Sensitivity SEL 80 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 P35 RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 P35 RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 P35 RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	7.559	7.780	3%	2.095	1.450	-31%	11.117	8.490	-24%
2	7.985	8.570	7%	2.070	1.420	-31%	11.601	9.180	-21%
3	8.492	9.450	11%	2.047	1.400	-32%	12.219	9.910	-19%
4	9.313	10.390	12%	2.007	1.380	-31%	13.100	10.730	-18%
5	10.196	11.010	8%	1.962	1.370	-30%	14.046	11.250	-20%

Table 62: Procedure, Weight and Thrust Sensitivity SEL 90 dB Metric

Stage Length	STANDARD AEDT FTT Contour Length [nmi]	NADP-2 AEDT RTT & RCLT Contour Length [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Width [nmi]	NADP-2 AEDT RTT & RCLT Contour Width [nmi]	Percentage Difference	STANDARD AEDT FTT Contour Area [sq. nmi]	NADP-2 AEDT RTT & RCLT Contour Area [sq. nmi]	Percentage Difference
1	2.909	2.850	-2%	0.816	0.520	-36%	1.753	1.060	-40%
2	3.068	3.130	2%	0.800	0.520	-35%	1.818	1.130	-38%
3	3.285	3.410	4%	0.786	0.530	-33%	1.912	1.200	-37%
4	3.550	3.740	5%	0.760	0.530	-30%	2.013	1.280	-36%
5	3.874	3.950	2%	0.738	0.540	-27%	2.136	1.330	-38%

Table 63: Procedure, Weight and Thrust Sensitivity NOx Metric

Stage Length	STANDARD AEDT FTT NOx below 3,000 ft [g]	NADP-2 P35 RTT & RCLT NOx below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT NOx 3,000 ft to 10,000 ft [g]	NADP-2 P35 RTT & RCLT NOx 3,000 ft to 10,000 ft [g]	Percentage Difference
1	6441.377	6253.094	-3%	5479.081	5243.264	-4%
2	6761.583	6810.3	1%	5787.113	5800.045	0%
3	7168.942	7589.803	6%	6125.350	6146.187	0%
4	7957.103	8229.982	3%	6551.746	6801.334	4%
5	8582.797	8647.649	1%	7221.653	7243.456	0%

Table 64: Procedure, Weight and Thrust Sensitivity Fuel Burn Metric

Stage Length	STANDARD AEDT FTT Fuel Burn below 3,000 ft [g]	NADP-2 P35 RTT & RCLT Fuel Burn below 3,000 ft [g]	Percentage Difference	STANDARD AEDT FTT Fuel Burn 3,000 ft to 10,000 ft [g]	NADP-2 P35 RTT & RCLT Fuel Burn 3,000 ft to 10,000 ft [g]	Percentage Difference
1	235.012	281.236	20%	232.659	249.858	7%
2	246.776	306.234	24%	245.762	276.406	12%
3	261.668	341.833	31%	260.150	292.945	13%
4	291.929	370.604	27%	278.414	324.231	16%
5	315.017	389.383	24%	306.898	345.346	13%

Task #3: Develop Aircraft State Estimator and APM Enhancement Recommendations

Georgia Institute of Technology

Objective(s)

Once the AEDT APM limitations were understood in Task 1 and the reduced flight dataset from Task 2, work could begin to develop a state estimator for vehicle weight, takeoff thrust, and payload factor as a function of ambient conditions and measured profile. AEDT will be tuned using the developed state estimator to predict the state variables. Keeping in mind that simplicity is desired, a methodology will be developed that is capable of tuning AEDT APM aircraft takeoff weight, takeoff thrust, and climb thrust both with and without detailed trajectory data. The methodology will be focused on AEDT APM, however, EDS models will also be tuned to understand how differences in the EDS and AEDT aircraft performance models impact the tuned state estimates.

Each of the prior tasks will culminate into a set of recommendations for enhancing the performance of AEDT in this research report.

Research Approach

Ideally, a simple, straight-forward implementation scheme will be developed that would not rely on Original Equipment Manufacturers (OEMs) to provide new Fleet DB coefficient definitions for BADA3 and BADA4 currently in AEDT2b. As the results of each task are acquired, insight to the most appropriate implementation scheme will evolve and be reviewed with the FAA Project Manager. Georgia Tech anticipates the following will be generated as a result of this research:

- Report detailing physics and modeling gaps in current AEDT APM algorithms with suggestions for enhancements
- Analysis of flight data and development of statistical correlation between flight data and aircraft state where possible
- Methodology to automatically calibrate aircraft state (thrust, weight) to available data
- Methodology to implement different departure procedures

The annual report summarizes the preliminary findings and recommendations. Since the project is on-going, the recommendations will be updated as more data become available. Table 65 is a high level summary of the findings based on the results from previous tasks and the potential methods to improve the APM, which will be discussed in more detail in this section. For the three areas of takeoff Gross Weight (GW), thrust, and departure procedures, the first two columns of the table describe the gaps between the AEDT assumptions and the reality and the impact of the modeling gaps to the environmental metric calculations. The next two columns list the methods to improve AEDT and the potential sources of data that are needed to implement the methods.

It is envisioned that improving AEDT's current APM assumptions will be achieved in two steps as illustrated in Figure 41. The end goal of this project is to support a successful implementation of new GW, thrust, and departure procedure to the next generation of AEDT, designated as AEDT 3, which is planned to be released in September 2018. Understanding this objective and the timeline, it is extremely important to provide a practical and feasible solution that can be implemented and tested in a timely manner. The first step in the method development is identification and collection of the real world data to come up with improved APM assumptions. While the data collected in the previous projects reviewed in Task 1 have been very useful for understanding the issues with GW, thrust, and departure procedures, the data used for those projects were limited to a handful of aircraft types from a couple of airlines. In order to update the APM assumptions in AEDT 3 for the majority of key aircraft types at minimum, it is necessary to conduct a more comprehensive data collection effort. As such, the research team has identified potential sources of data for each of the APM parameters and has been coordinating with the FAA and other entities to gather more data in parallel to methods development. The report discusses the current status and the next steps of these efforts.

Table 65. Summary of the Findings and Recommendations

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

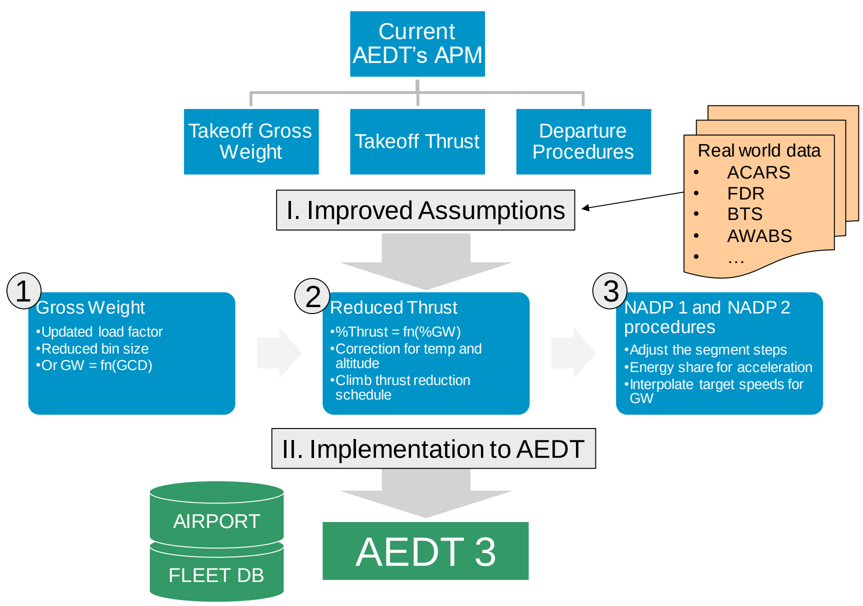


Figure 41. A Two-Step Approach to Improve AEDT's Modeling Accuracy

Development of a Thrust Prediction Model

Factors that Impact the Takeoff Thrust Setting

In order to better reflect the actual takeoff and climb thrust usage in day-to-day operations, it is important to understand how the actual thrust levels for each takeoff is determined. There are four categories of factors that lead to the selection of thrust setting for each departure as listed in Figure 42: thrust available, thrust required, a regulatory limit, and pilot choice. Thrust available is basically the maximum thrust that the engines on the aircraft can produce given atmospheric condition. Thrust required is determined by two aircraft performance constraints: takeoff field length and second segment climb gradient. The thrust required is the minimum thrust level that can be used to safely depart at an aircraft for given weight, runway condition, weather, etc. When the required thrust is less than the available thrust, an opportunity to use reduced thrust takeoff thrust arises. For example, if the available thrust is 100,000 lbs and the require thrust is 70,000 lbs, it is technically safe to use any thrust setting between 70,000 to 100,000 lbs to takeoff. However, the regulation limits the use of reduced thrust takeoff up to 25% of maximum thrust using assumed temperature method. Therefore, the pilot should actually choose a thrust level greater than 75,000 lbs. The pilot in command has final authority to choose any thrust level between 75,000 lbs to 100,000 lbs that he/she thinks most appropriate. Typically, pilots choose a thrust setting greater than the minimum thrust level offered to them. This process sounds quite complicated, but the process is very well established and being performed every time an aircraft departs. Airlines have a team of engineers perform the analysis for the pilots. There are FAA certified commercial software available on mobile devices like iPads that perform this runway analysis.

For the purpose of predicting the average takeoff thrust usage, performing full-blown runway analysis is not feasible nor necessary. Instead, the objective of this research is to develop a simple, general model that works for majority of the aircraft types in AEDT. In addition, AEDT can provide an option for the users to input the takeoff thrust settings they would like to model with their own thrust data for specific flights.

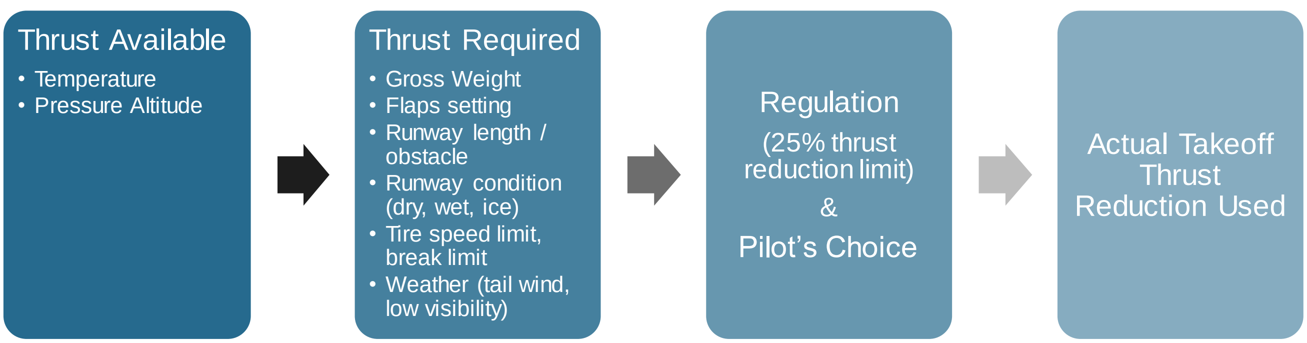


Figure 42. Four Factors of Takeoff Thrust Determination

Review of Takeoff Thrust Data Sources

The first step to develop a method that predicts takeoff thrust was to identify the potential sources of takeoff thrust data. The team considered the following five different types of flight data that might be able to provide takeoff thrust information. Among them, the ACARS data from ASCENT project 35 and AWABS data are most appropriate for the purpose of the project. Following sections provide preliminary analysis results using the dataset.

- Flight Planning
  - Includes actual GW, but no thrust
  - May include the specification of the thrust parameters that pilots are recommended to use
- Aircraft Communications Addressing and Reporting System (ACARS)
  - Includes actual GW and %Reduced Thrust data
  - No runway, no pressure alt, temperature may not be as accurate as AWABS
- AWABS (Dispatch data)
  - Accurate GW, runway, pressure alt, temperature, <u>thrust setting</u> data
  - No thrust, no info on actual pilot choice

- FDR / Flight Operations Quality Assurance (FOQA)
  - Need to estimate thrust based on fuel flow or other engine parameters
  - Best for departure procedures
- Radar Data
  - ACRP Project 02-41 attempted to use radar data, hi-fi weather, and BADA performance data to obtain engine thrust → very hard to obtain reliable thrust data

As mentioned earlier, the objective of ACRP 02-41 was to produce guidance to include the effects of reduced takeoff thrust in their emissions inventory calculations and to develop a Takeoff Thrust-Setting Estimator Tool (TTREAT) based on statistical analyses of extensive takeoff thrust data supplied by airlines. Specifically, ACRP 02-41 used flight planning and FDR data to either collect or drive takeoff thrust. In fact, none of the above five data types directly gives the thrust values. Rather, they provide some engine and aircraft performance parameters and atmospheric conditions that can be used to derive thrust. Figure 43 below is based on a plot from the ACRP 02-41 Technical Report. ACRP 02-41 used 747-400 FDR data to estimate takeoff thrust level used (% of max thrust available) based on fuel flow and other atmospheric conditions (temperature and pressure). Each point on the plot represents a combination of takeoff thrust and weight for an individual 747-400 takeoff. While the % thrust values are not completely accurate, the plot shows a very strong correlation between %Thrust and takeoff weight. It also shows that the thrust values didn't go below 75% even at very low weight. Another observation is that some takeoffs used the maximum thrust regardless of the weights. Finally, for a given weight, most takeoff thrusts could vary by about 10%. Based on the observations made here, a four step method that estimates takeoff thrust as a function of aircraft weight is proposed in the next section

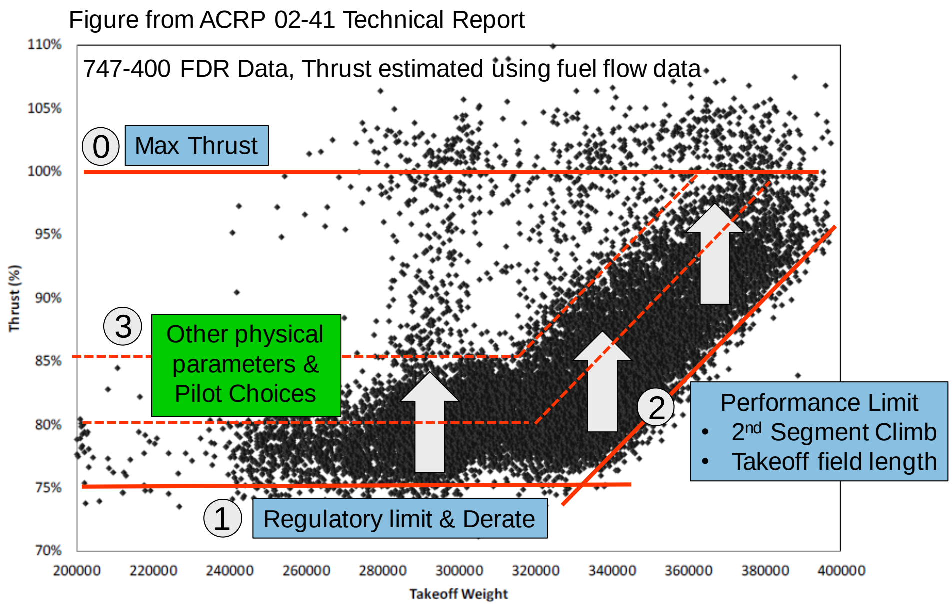


Figure 43. Schematic Diagram of the Takeoff Thrust Model

Proposed Takeoff Thrust Estimation Method:
The method proposed here is based on the observations made with limited aircraft takeoff thrust data. The assumption is that the flight physics, regulations, airline policy on reduced thrust takeoff, and pilot's practice are more or less consistent across aircraft types, regulatory authorities, airlines, and pilots. The method will be refined as more data become available and new trends are observed. The method prescribes the relationship between $\%Thrust_{adj}$ at the standard sea level condition and %GW. The %thrust is the ratio of actual thrust level used for the takeoff to the maximum thrust level available at the given atmospheric condition. $\%Thrust_{adj}$ is the ratio of actual thrust level used for the takeoff to maximum thrust level available at the sea level standard day condition. The %GW is defined as the ratio of the actual takeoff gross weight to the certified maximum takeoff gross weight (MTOW).

1. Maximum Thrust
   - Use the current AEDT's 100% thrust as an option
2. Regulatory Limit & Derates:
   - Set the lower thrust limit by regulation
     - For a 25% thrust reduction limit, the lower bound for %thrust is set at 75%
   - Some aircraft have derate (e.g. TO, TO1, TO2) options
     - Further thrust reduction is done by assumed temperature method up to 25%
     - TO2 with the highest assumed temp can give 40% thrust reduction
     - Set the lower limit at 60% of the max thrust in this case
3. Performance Limit:
   - Define a line (intercept and slope) to represent the thrust limit determined by aircraft performance constraints.
4. Add Margins to the limit sets in Step 2 and 3
   - The lower thrust limits set in Step 2 and 3 can be directly used for the aggressive thrust reduction option
   - Since the pilots typically are offered three takeoff thrust settings including the lower limits, shift the lines from 2) and 3) up by a certain percent (e.g. 5% and 10%) to create moderate and conservative thrust reduction options

A reduced thrust takeoff is typically followed by a reduced thrust in the initial climb segment. Although the pilot can choose to use full climb thrust after a reduced thrust in the takeoff segment, the FMS automatically selects a reduced climb schedule based on the takeoff thrust setting. Otherwise, it is possible to experience an increase in the thrust level at thrust cut-back. The research team recommends the follow climb thrust reduction schedule as shown in Table 66.

Table 66. Recommended Climb Thrust Reduction Schedule[10, 11, 12, 13]

Takeoff Thrust	Climb Thrust
Takeoff Derate < 5%	Use Max Climb Thrust
Takeoff Derate between 5-15%	Derate climb by 20% up to 10,000 feet
Takeoff Derate > 15%	Derate climb by 20% up to 10,000 feet

Application of the Thrust Correction Model in AEDT

The current version of AEDT calculates the engine thrust for a departure operation using the SAE-AIR-1845 method. The thrust coefficients in the ANP database are populated to calculate the thrust for the ANP aircraft ID and for the thrust type (either takeoff or climb) defined in the departure procedure. The SAE-AIR-1845 method calculates the thrust based on the sea level static thrust and corrects it for speed, pressure altitude, and temperature. The current plan of implanting thrust correction to model reduced thrust takeoff is to correct the sea level static thrust (defined by COEFF_E) using a multiplying factor (MF). The formula to calculate MF is provided in Table 67.

[10] GE, "Economic Impact of Derated Climb on Large Commercial Engines"
[11] RR, "Derated Climb Performance In Large Civil Aircraft"
[12] Boeing, "737 Flight Manual"
[13] Interview with Delta Chief Flight Instructor on xx-xx-2017

Table 67. Multiplying Factor for Thrust Correction

Thrust Correction for Reduced Thrust Takeoff COEFF_E_new = COEFF_E *MF **Multiplying Factor (MF)** If Temp <=30 degC, MF = %Thrust_adj(%GW) / alpha If Temp > 30 degC, MF = %Thust_adj(%GW) /alpha * beta where, beta = [1 – COEEF_H/COEFF_E*(TC -30)] alpha = thrust lapse rate with altitude beta = thrust reduction rate at high temp %Thrust_adj(%GW) = a + b*%GW alpha and beta are calculated using AEDT coefficients

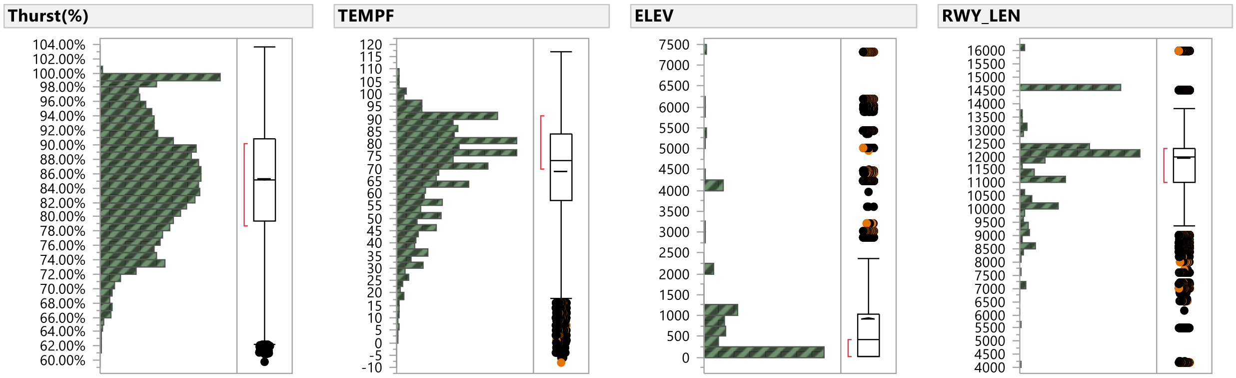
Preliminary Takeoff Thrust Model of Boeing 737-800

The takeoff thrust prediction method proposed in the previous section is applied here to Boeing 737-800. In order to successfully build and test a model for the aircraft types in AEDT, a large number of actual flight data including the following parameters are needed:

- Actual takeoff weight
- Actual takeoff used or %takeoff thrust used
- Airport temperature and pressure altitude

The research team has not yet identified any dataset that includes all these parameters. Among the different types of flight data examined, the ACARS data and AWABS data from ASCENT Project 35 found to be the closest to meet the data requirements. The ACARS data from Project 35 includes the actual takeoff weight and %Thrust reduction (FNRED). It also includes airport temperature, but it does not provide pressure altitude. Instead, it provides the airport elevation, which was used in the following analysis. AWABS data provides all above except the actual thrust or %Thrust used. Instead, it gives a set of assumed temperatures that can be used for each of the gross weights.

A preliminary version of the thrust model for Boeing 737-800 was developed using the ACARS data from Project 35. The dataset included the first ACARS report from 62,981 flights. A statistical analysis was performed to understand the distributions of the key performance parameters. Figure 44 shows histograms and summary statics of %Thrust, airport temperature, airport elevation, and the longest runway length. The %Thrust varied from 59.8% to 103.6% with the mean value of 85%. The temperature varied from -8 to 117 degrees Fahrenheit. About 25% of flights occurred when the temperature was higher than 84 degrees Fahrenheit. The airport elevation varied from 4 ft to 7316 ft, while 75% of the departure occurred from airports below 1026 ft. About 97.5% of departures took place from airports with the longest runways longer than 8400 ft.



Quantiles

Quantile		Thurst(%)	TEMPF	ELEV	RWY_LEN
100.0%	maximum	103.60%	117	7316	16000
99.5%		99.80%	104	7316	16000
97.5%		99.40%	95	5016	14512
90.0%		97.10%	90	4226	14511
75.0%	quartile	90.80%	84	1026	12300
50.0%	median	85.20%	73	433	12003
25.0%	quartile	79.40%	57	17	11002
10.0%		74.30%	39	13	9669
2.5%		69.90%	27	8	8385
0.5%		66.20%	12	4	7003
0.0%	minimum	59.80%	-8	4	4193

Summary Statistics

	Thurst(%)	TEMPF	ELEV	RWY_LEN
Mean	0.8523926	68.873931	918.81632	11931.315
Std Dev	0.0808464	19.301722	1456.6906	1805.6395
Std Err Mean	0.0003224	0.0769598	5.8081136	7.1994418
Upper 95% Mean	0.8530244	69.024772	930.20023	11945.426
Lower 95% Mean	0.8517608	68.72309	907.4324	11917.204
N	62902	62902	62902	62902

Figure 44. Statistics from the B737-800 ACARS Data

As the first step %GW was calculated by normalizing the takeoff gross weight with the MTOW. Here the MTOW of 174,000 was assumed. %Thrust values were calculated by subtracting the FNRED from 100. Then $\%Thrust_{adj}$ was calculated by: $\%Thrust_{adj} = \%Thrust/alpha$, where, alpha = thrust lapse rate with pressure altitude.

Due to the lack of pressure altitude information in the ACARS dataset, the airport elevation was used instead. The relationship between $\%Thrust_{adj}$ and %GW for B737-800 is shown in Figure 45. With the adjusted thrust and GW, a simplified takeoff thrust model, $\%Thrust_{adj}(\%GW) = a + b*\%GW$, was developed by applying the method proposed in the previous sections. The thrust model is illustrated on the figure and summarized in Table 68.

Table 68. Summary of the Findings and Recommendations

Thrust Types	Options	a (intercept)	b (slope)
Maximum Thrust	None	1	0
Regulatory Limit & Derate For %GW < 0.7	Low	0.6	0
	Medium	0.67	0
	High	0.74	0
Performance Constraints For %GW ≥ 0.7	Low	0.07	0.94
	Medium	0	0.94
	High	-0.07	0.94

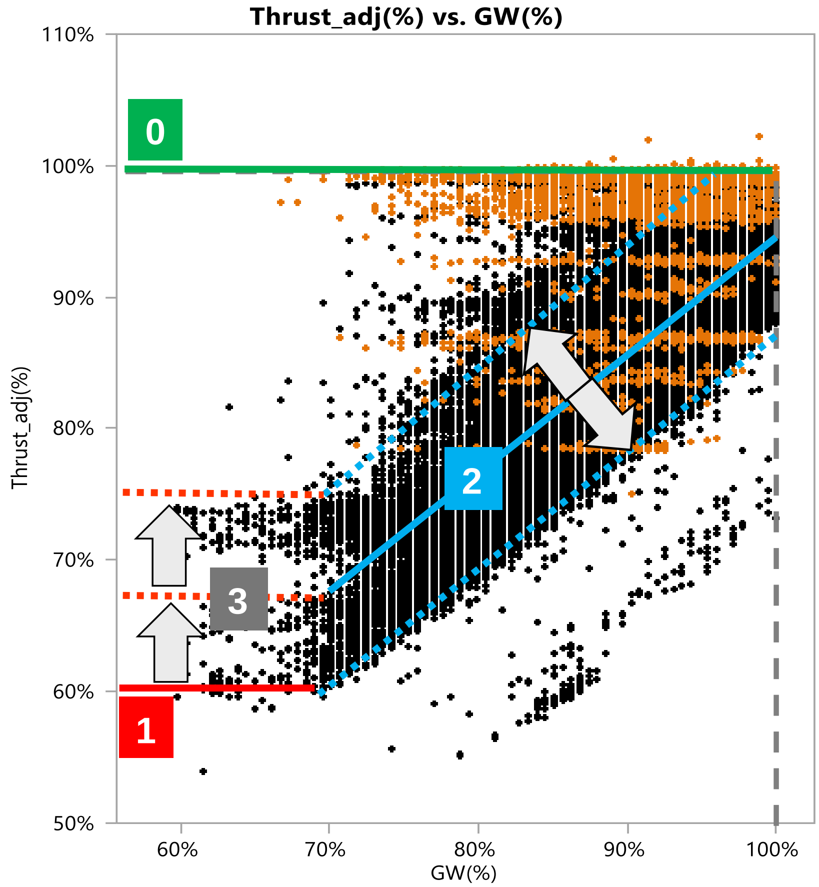


Figure 45. %$Thrust_{adj}$ vs %GW for B737-800

Development of a Takeoff Weight Prediction Method

Previous studies summarized in the literature review section showed the gap between the takeoff weight assumptions in AEDT and the reality. General observation was that AEDT tends to underestimate the weight by about 5%. Takeoff gross weight of an aircraft is comprised of three weight components: Operating Empty Weight (OEW), payload weight, and fuel weight. It is possible that the differences in all these three weight categories contribute to the differences in the gross weight between AEDT and the reality. Coming up with new weight assumptions requires collection of such weight data for majority of aircraft types flown by majority of airlines for an extended period of time. The goal of this research is to develop a new weight assumption that better represents an *average* takeoff weight for each of the aircraft types in AEDT in order to improve calculation of environmental impacts. The success of such a task largely relies on the accessibility of reliable and extensive takeoff weight data. The team has reviewed potential sources of such data including flight planning, ACARS, the BTS T-100, and AWABS. The team currently has some flight planning and ACARS data from one airline for a couple of aircraft types. The dataset includes the takeoff weight information for each flight. While the dataset is extremely valuable providing insights and a means to validate the method later on, it is not possible to use a dataset of an aircraft type for estimating the takeoff weight of other aircraft types. Therefore, the team is coordinating with the FAA to obtain the average payload data that ICAO has been collecting. Alternatively, the team can use the BTS T-100 data. Both the ICAO and T-100 data only provide average payload values. The ICAO data is supposed to be global, but the T-100 data is limited to US operations. Since those datasets only give average payload values, the OEW and fuel weight should be obtained separately to calculate the gross weight. Otherwise, only the payload portion of the gross weight can be updated in AEDT and keeping the current OEW and fuel weights. Though it is easier, the latter approach can lead to underestimation of the gross weight.

Once the gross weight (or just the payload or load factor) data is gathered, the data needs to be processed to be able to update the AEDT's weight assumptions. A handful of different options can be devised depending on the desired level of data aggregation. Currently, AEDT aggregates the takeoff weight of all departure operations for an aircraft type within a stage length. Therefore, one option to improve AEDT's accuracy is to update that representative weight by calculating the average of all the gross weights for each stage length for each aircraft type. This option will ensure that the new AEDT weights match the average weight of all departures for a stage length bin. AEDT currently uses the stage length bins with either 500 nm or 1000 nm width. Due to the wide ranges of flight distances represented by a stage length bin, even the updated assumption won't be able to model the average takeoff weights for a particular OD pair. The gap between the AEDT's weight assumption and the reality can be further reduced by increasing the level of granularity. Five different options below cover the spectrum of solutions that maintains the current level of aggregation (Option 1) to the option of modeling each weight for each flight (Option 5).

Option 1: Maintain the current stage length approach, updating the GW assumptions for each stage length and aircraft type
Option 2: Calculate average GW for finer stage length bins (e.g. 250 nm width)
Option 3: Use different GW assumptions for each SL and Departure Airport
Option 4: Model GW as a continuous function(s) of GCD
Option 5: Model GW for each flight (the users should provide the schedule data including the GW for each flight)

Generally speaking, the modeling accuracy, data requirements, and computational expense increase with the option number. Table 69 provides the initial qualitative assessments of the five weight prediction options with respect to the evaluation criteria. As the next step, the five options could be implemented to model an average day of departures at the ATL airport to provide a quantitative assessment depending on the level of resources available.

Table 69. Options for Takeoff Weight Assumptions, Expected Accuracy, Data Requirement, and Implementation Feasibility

Potential NEW GW Solutions	Computational Burden	Accuracy	Data Req.	Potential Data source/Current Status / Feasibility
AEDT	Baseline One run for each SL and Origin (74 runs*)	Off by 6% on Average*	Baseline (65% LF assumption for all SL and aircraft types	ANP DB includes GW info for 127 commercial aircraft types
Option 1-b: Update LF for each aircraft type	Same as the baseline	May not capture average GW at certain SL bins (high std. dev)	Avg LF or GW for all SL for each aircraft	BTS T-100 can be used for this option for aircraft types used in the US / NONE at the moment / highly feasible in a couple of months
Option 1-c: Different LF assumptions for different SLs	Same as the baseline	Match average GW of all flights in the SL bin (high std. dev) Accounts for MTOW and fuel limits	Avg LF or GW for each SL and aircraft	BTS T-100 can be used for this option for aircraft types used in the US / NONE at the moment / highly feasible in a couple of months
Option 2: Different LF assumptions for sub-SL Bins	Baseline x number of sub-SL bins	Match average GW of all flights in the sub-SL bin (med std. dev) Accounts for MTOW and fuel limits	Avg LF or GW for each sub-SL and aircraft	BTS T-100 can be used for this option for aircraft types used in the US / NONE at the moment / highly feasible in a couple of months
Option 3: Different LF sub-SL bins and Departure Airport	Baseline x number of sub-SL bins	Match average GW of flights in a stage length for the airport (low std. dev) Accounts for MTOW and fuel limits Accounts for runway length and elevation impact to GW	Avg LF or GW for each sub-SL, airport, and aircraft	BTS T-100 has all this info for US flights / NONE at the moment / may not be feasible getting airport level data for international and small US airports
Option 4: Continuous Function(s) of GCD	2.4 times the baseline* One run for each OD pair	Lines with kinks can account for MTOW and fuel limits Does not model airport to airport GW variation	Raw or avg. GW and GCD data GW vs GCD models for each aircraft	BTS T-100 can be used for this option + MTOW and fuel capacity data / regression models of 737-800, 767-300ER, 767-400ER, and 757-200 from P35 / not sure yet
Option 5: GW of each flight	280 times the baseline*	Match both average and individual GW	GW data for all the flights a study is modeling	Users should use their own data for a real study / Entire 737-800 and 767-300ER flight from year 2015? by an airline for test purposes

Qualitative Evaluation Score	
1	Worst
2	Not desirable
3	Okay
4	Good
5	Best

Development of a Process to Implement New Weight, Thrust, and Departure Procedures in AEDT

The final aspect of the research is to determine how to implement the modified weight, thrust, and departure procedure into the AEDT procedural definitions based on the data analysis and methods. Per the AEDT Technical Manual guidance for the departure procedure, it appears the flexibility exists to define any type of procedure. GT has developed a process with which a new aircraft with different weight, thrust, and procedure assumptions can easily be inserted into AEDT. The process illustrated in Figure 46 provides a step-by-step instruction on 1) to extract the current APM assumptions of the aircraft of interest, 2) to change the assumptions in an Excel or an XML file, 3) to update the AEDT's Fleet DB by running SQL scripts, 4) to select the new aircraft in the AEDT GUI, and 5) to run a metric result using the new aircraft. A word document that details all these steps has already been draft. The document will be refined as the team progresses to a larger scale test and will be provided to the FAA.

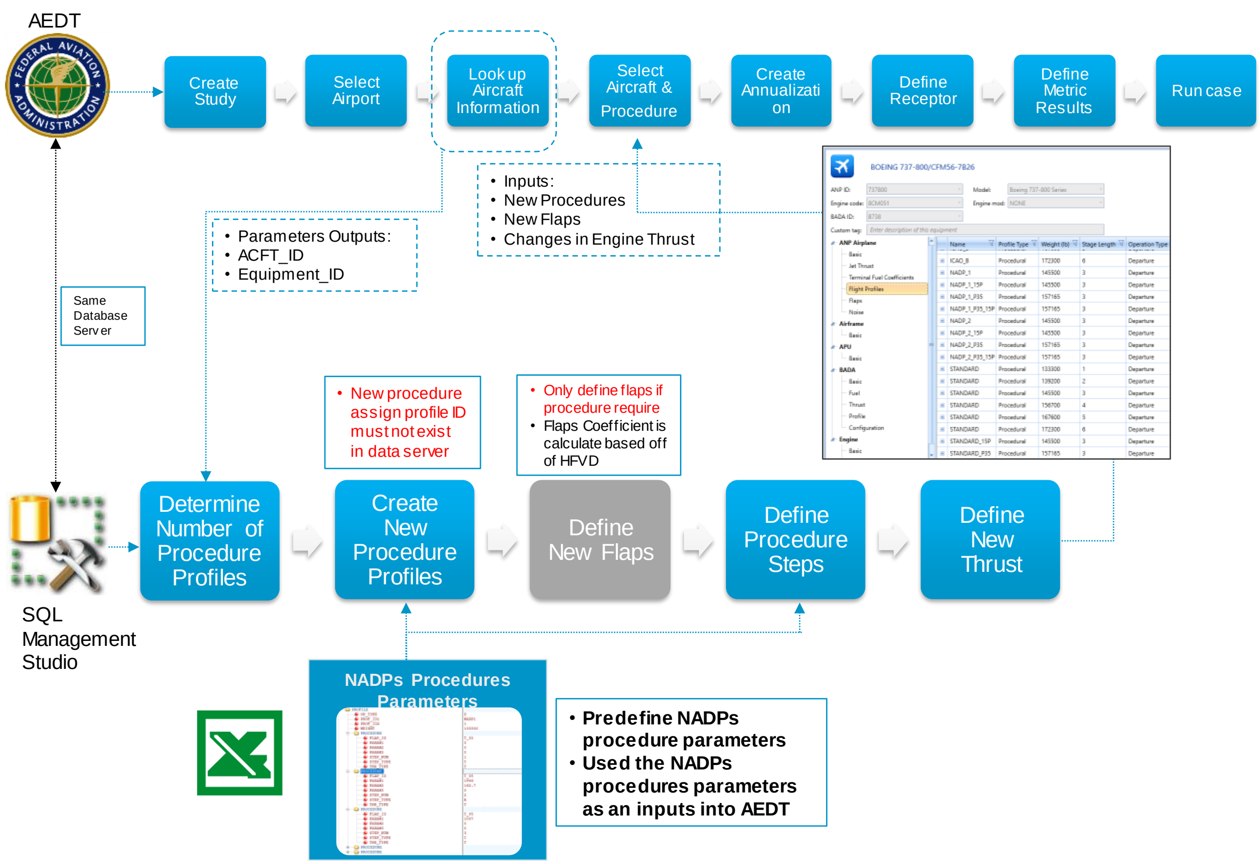


Figure 46. Process of Adding NEW GW, Thrust, and Procedures to AEDT

Milestone(s)
No specific milestones are associated with this project. However, significant progress is being made towards understanding the implications of the APM assumptions for departure.

Major Accomplishments
Significant insight to the impact of the APM assumptions have been obtained through the partial derivative sensitivity approach.

Identification of various implementation options to the APM and the Fleet dB

Publications
None

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

Awards
None

Student Involvement
Vu Ngo and Ameya Behere - Graduate Research Assistant, Georgia Institute of Technology

Plans for Next Period
The primary focus for the next period will be:
- Implementation of each sensitivity assumption to AEDT
- Assessment of new assumptions at the airport level

Appendix

B737-800

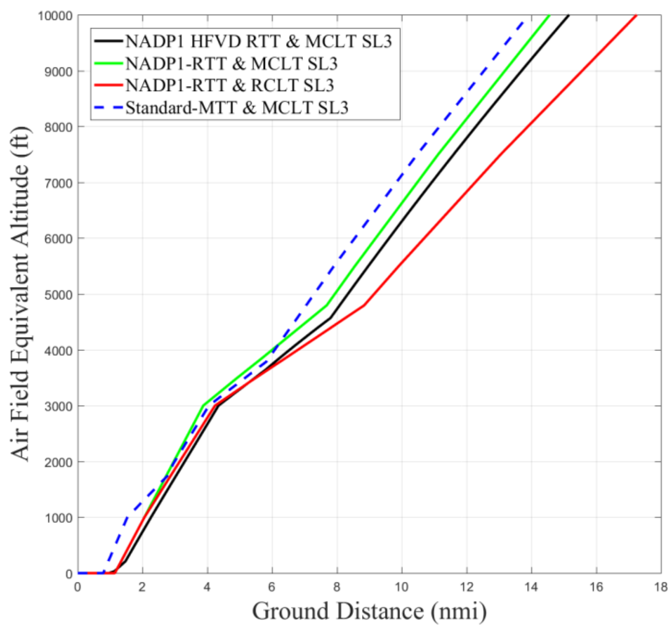


Figure 47: Altitude vs Ground Distance for B737-800 Trajectory Comparison for Stage Length 3 NADP1

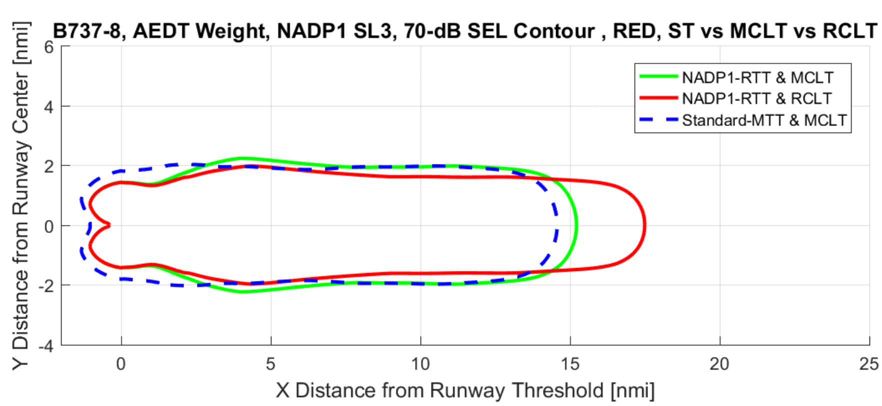


Figure 48: B737-800 Noise Contour Comparison at SEL 70dB for Stage Length 3 NADP1

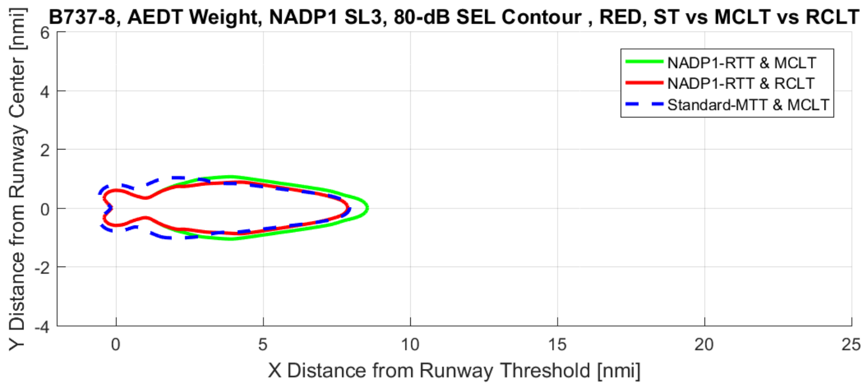


Figure 49: B737-800 Noise Contour Comparison at SEL 80dB for Stage Length 3 NADP1

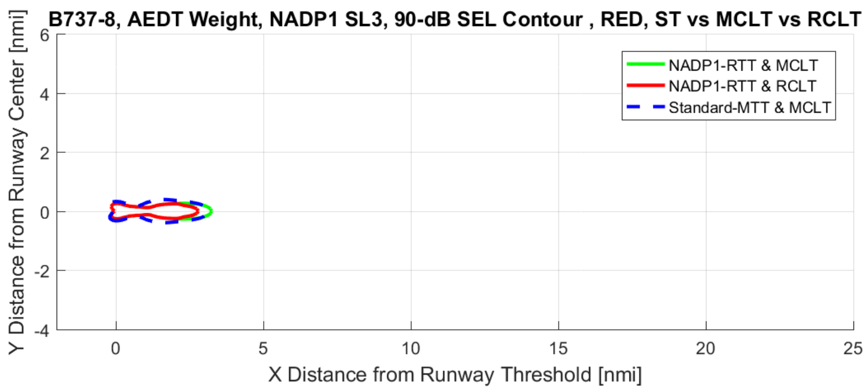


Figure 50: B737-800 Noise Contour Comparison at SEL 90dB for Stage Length 3 NADP1

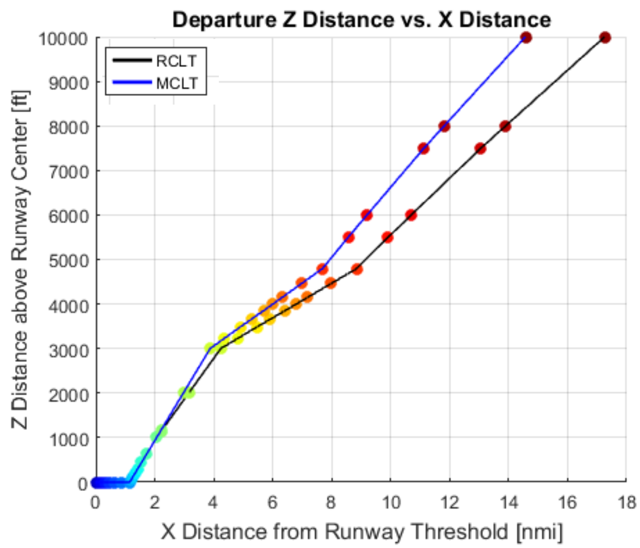


Figure 51: Detailed Altitude vs Ground Distance for B737-800 Stage Length 3 NADP-1

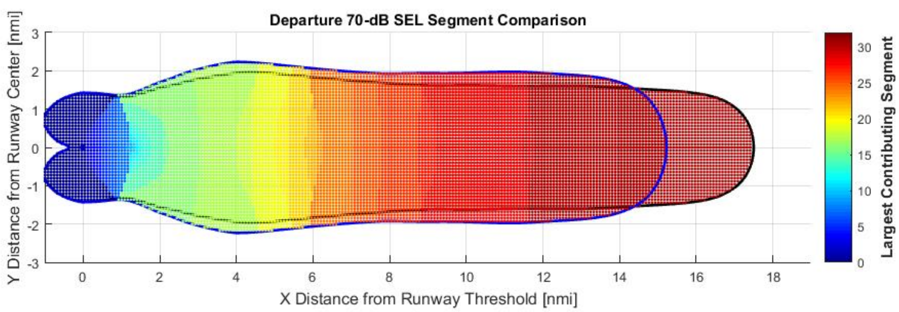


Figure 52: Detailed B737-800 Noise Contour Comparison at SEL 70dB at Stage Length 3 NADP-1

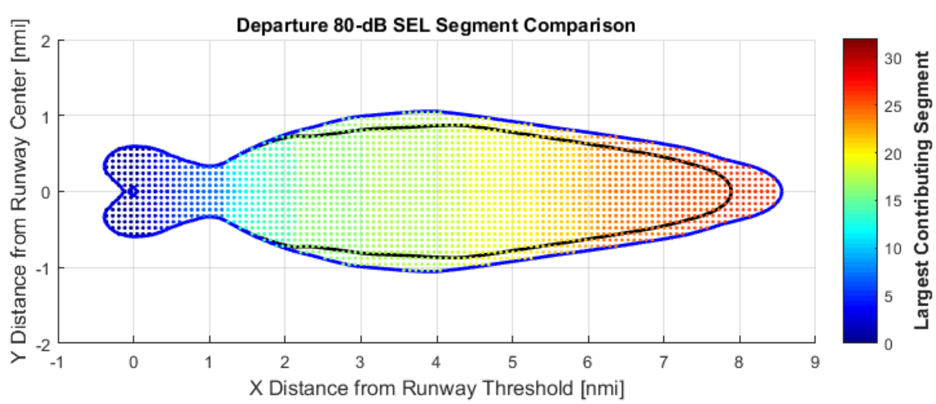


Figure 53: Detailed B737-800 Noise Contour Comparison at SEL 80dB at Stage Length 3 NADP-1

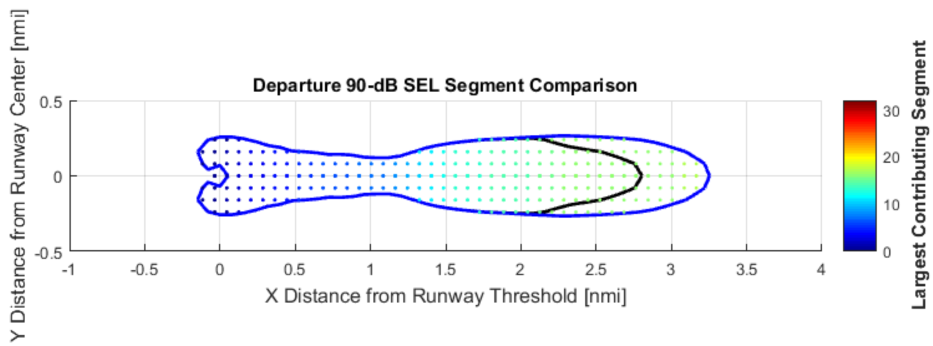


Figure 54: Detailed B737-800 Noise Contour Comparison at SEL 90dB at Stage Length 3 NADP-1

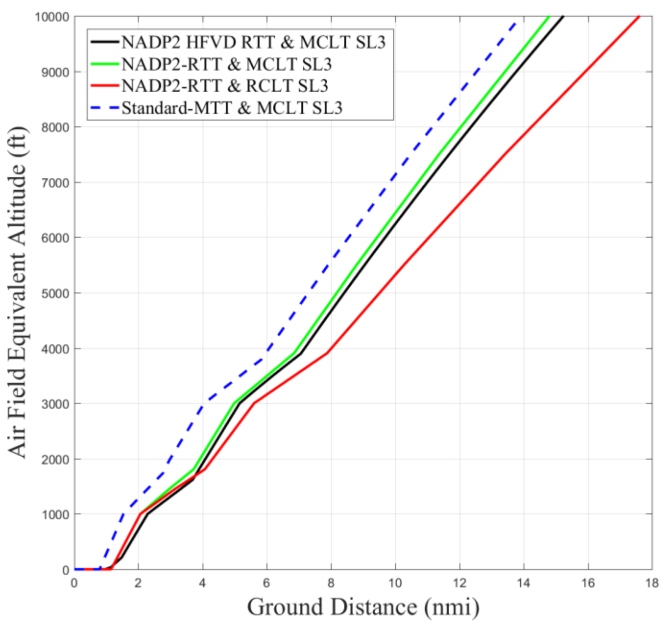


Figure 55: Altitude vs Ground Distance for B737-800 Trajectory Comparison for Stage Length 3 NADP2

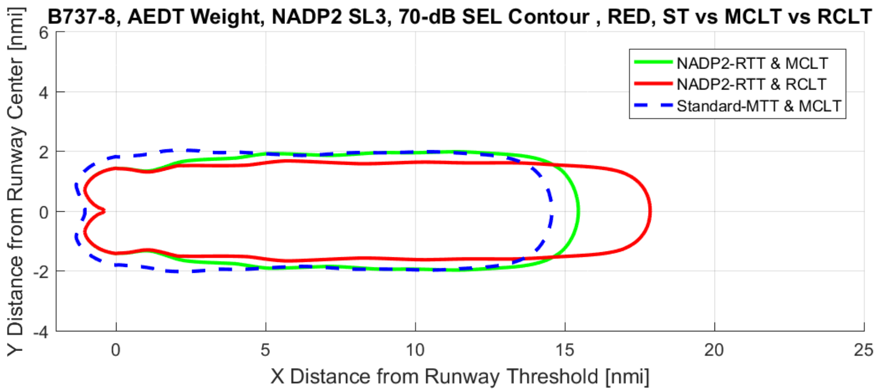


Figure 56: B737-800 Noise Contour Comparison at SEL 70dB for Stage Length 3 NADP2

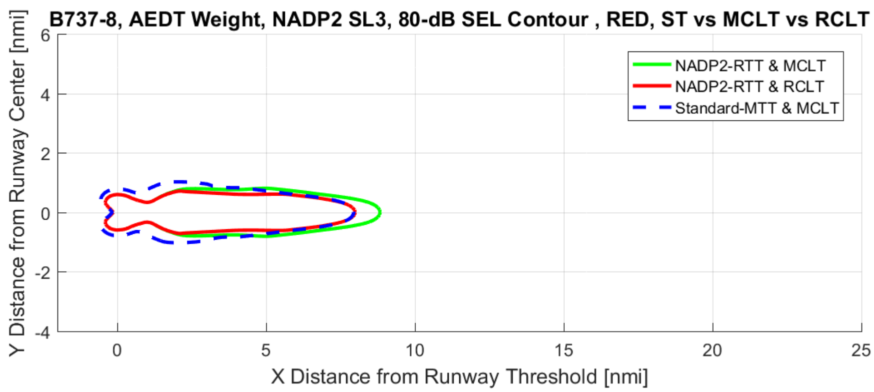


Figure 57: B737-800 Noise Contour Comparison at SEL 80dB for Stage Length 3 NADP2

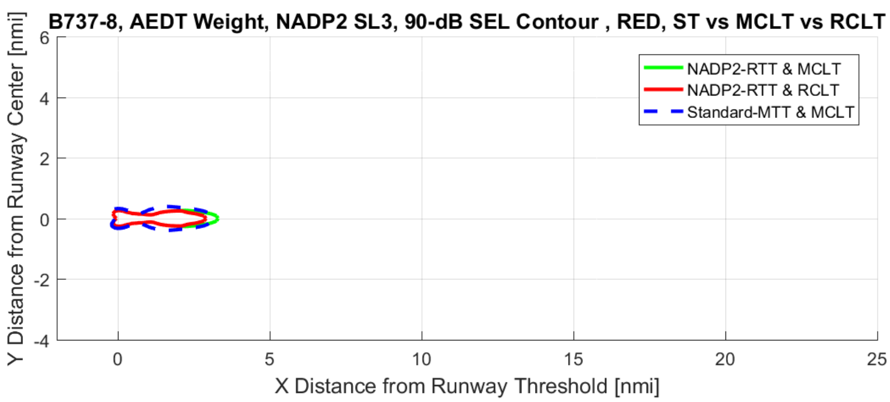


Figure 58: B737-800 Noise Contour Comparison at SEL 90dB for Stage Length 3 NADP2

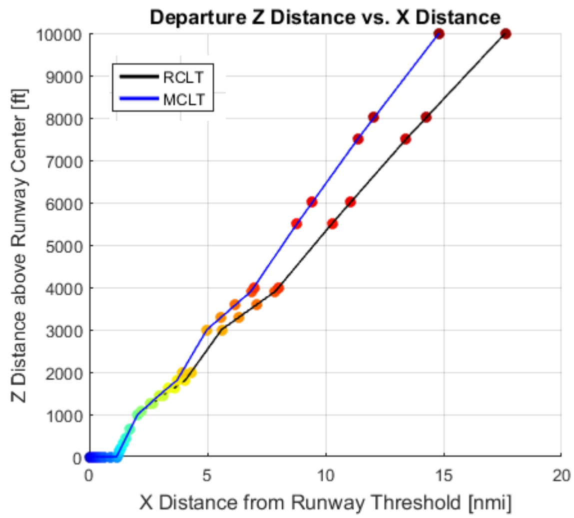


Figure 59: Detailed Altitude vs Ground Distance for B737-800 Stage Length 3 NADP-2

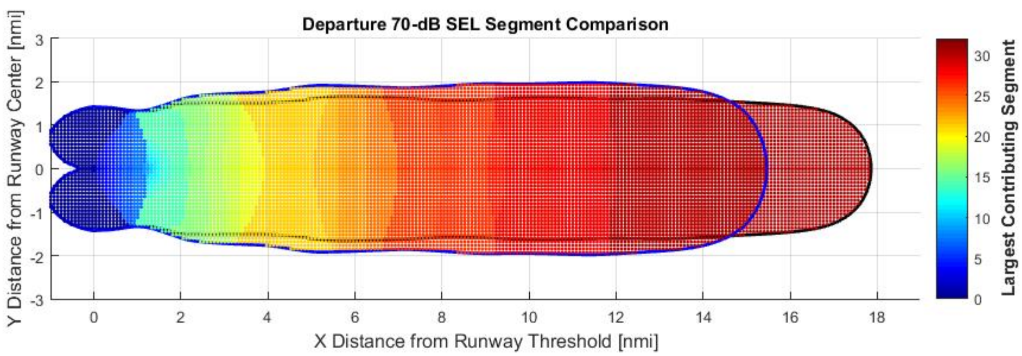


Figure 60: Detailed B737-800 Noise Contour Comparison at SEL 70dB at Stage Length 3 NADP-2

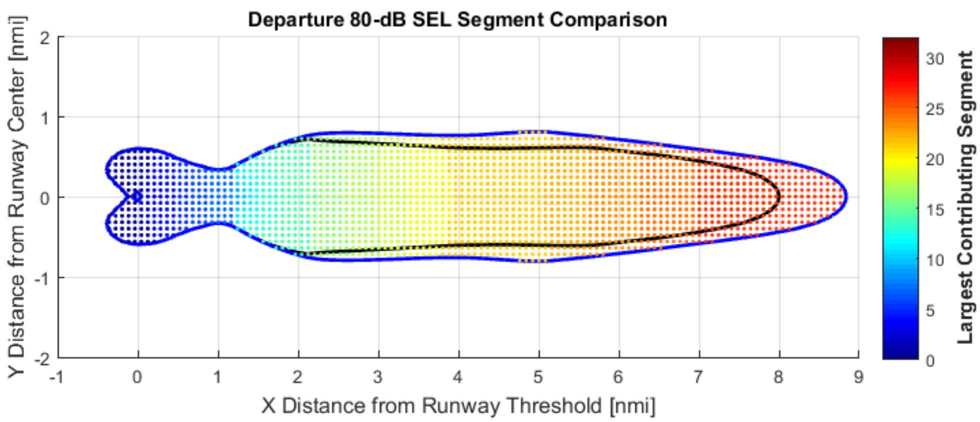


Figure 61: Detailed B737-800 Noise Contour Comparison at SEL 80dB at Stage Length 3 NADP-2

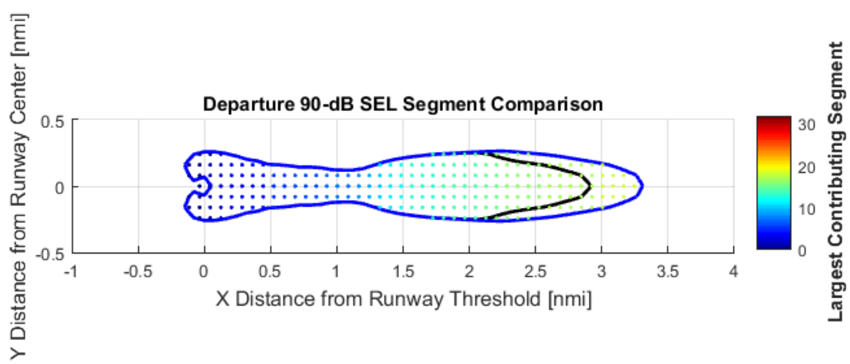


Figure 62: Detailed B737-800 Noise Contour Comparison at SEL 90dB at Stage Length 3 NADP-1

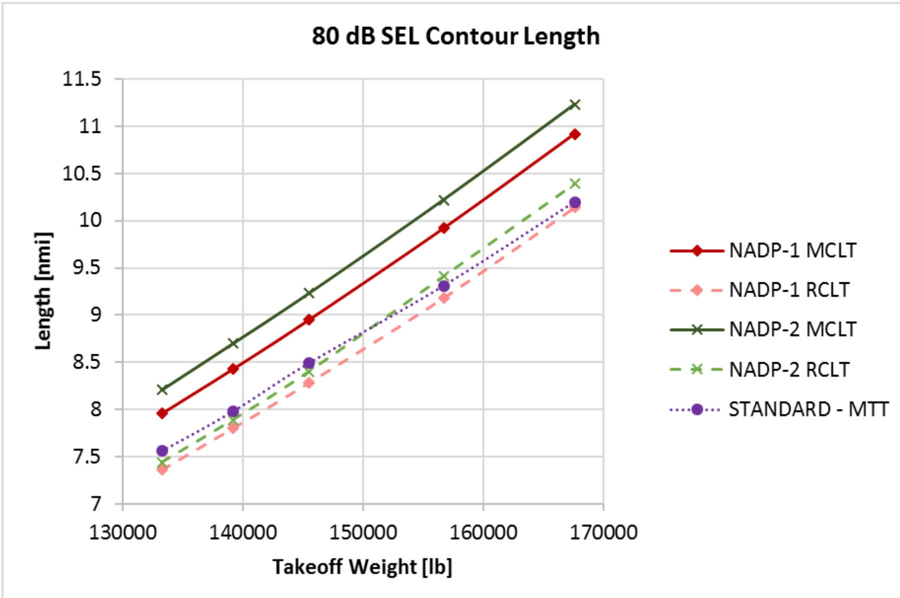


Figure 63: B737-800 Contour Length Comparison for SEL 80dB

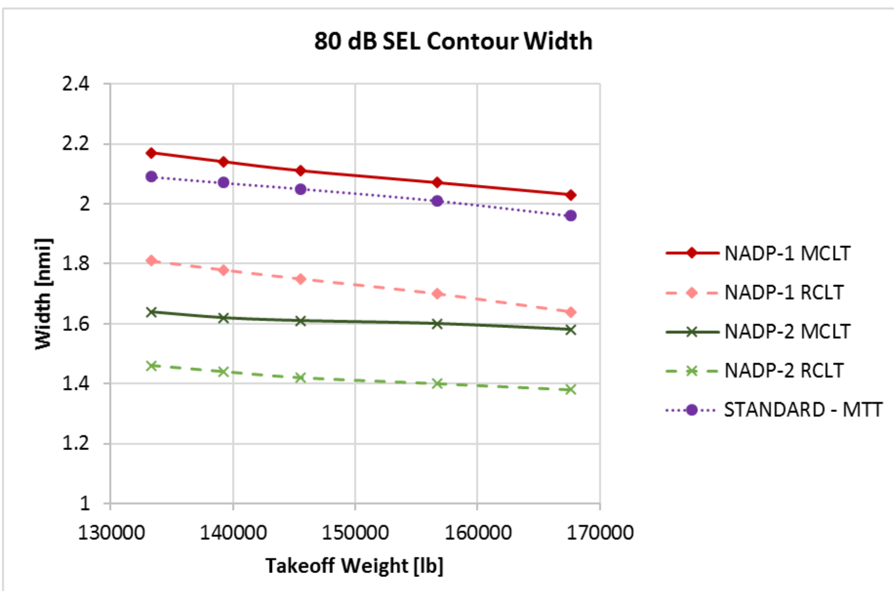


Figure 64: B737-800 Contour Width Comparison for SEL 80dB

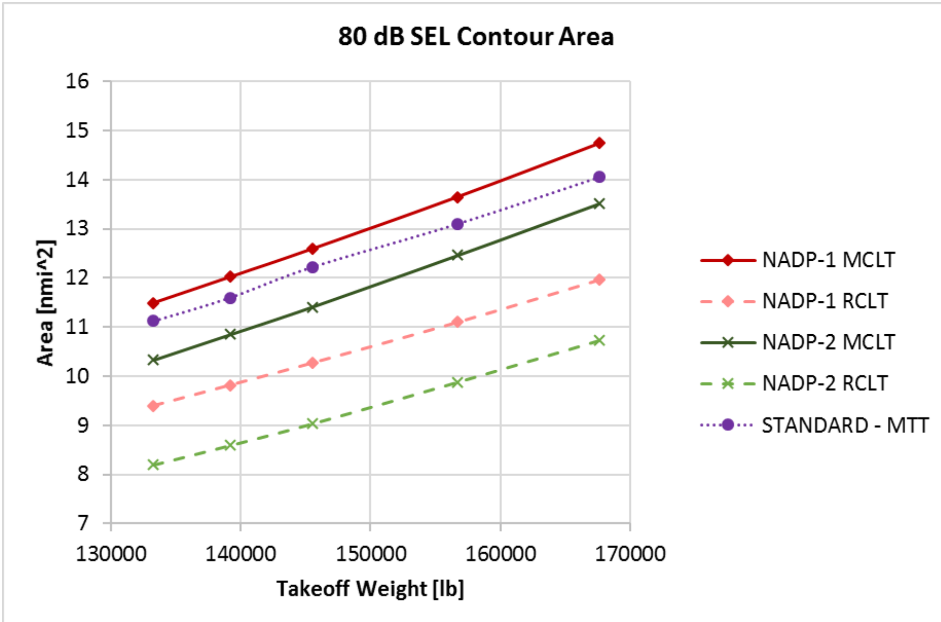


Figure 65: B737-800 Contour Area Comparison for SEL 80dB