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. 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

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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 in order 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

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 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. 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 was similar to the results of ASCENT Project 35.

The objective 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.

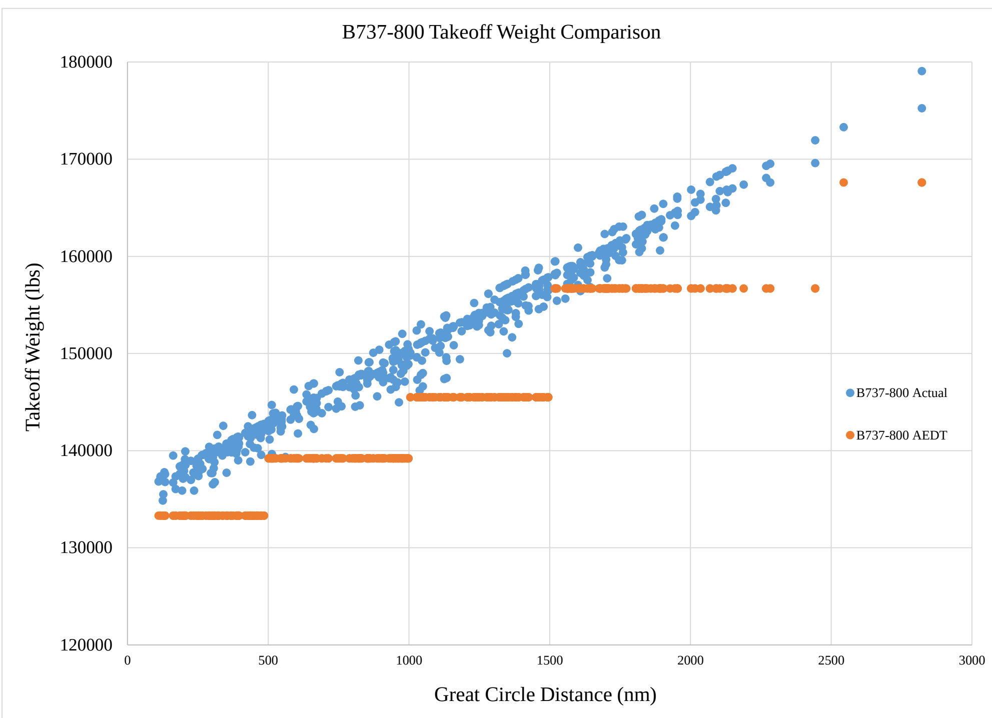

Figure 1. Takeoff Weight Variation with Great Circle Distance

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.

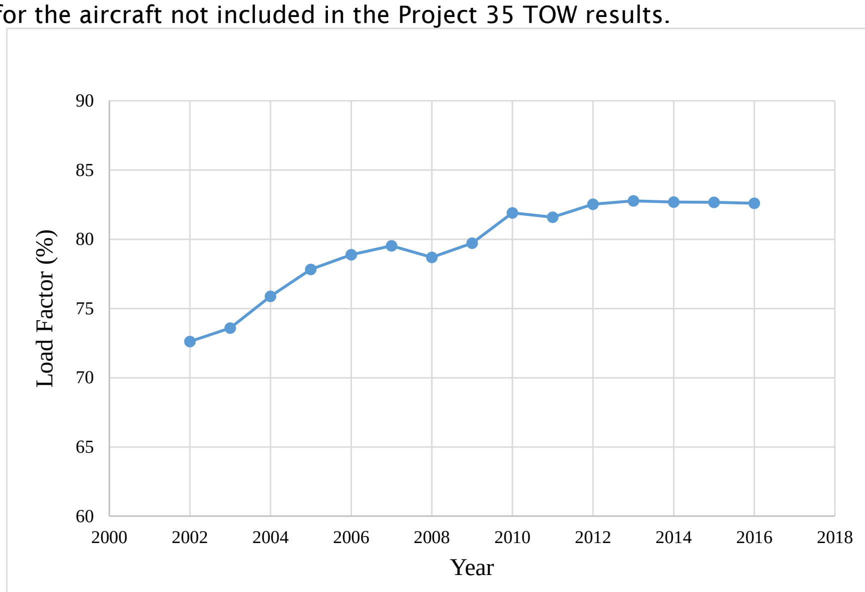

Figure 3. BTS Historical Load Factor

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

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

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 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

A four step approach was developed to quantify the impact of changing departure assumptions within AEDT and include:

- Conduct a sensitivity study of the APM assumptions with different takeoff weights, thrust, and procedures using EDS generated vehicles and also in AEDT
- Compare both results to high fidelity operational data, when available
- Compare environmental results with existing APM fixed assumptions
- Generate surrogate models of weight, thrust, GCD and procedure variations

The first step was to identify a series of Environmental Design Space (EDS) vehicles to serve as the basis of the sensitivity study. EDS is the key aspect to quantifying the environmental impacts and interdependencies of changing the departure modeling assumptions since the GT researchers can model the physics of the problem directly in a controlled simulation environment. Additionally, EDS has the capability to generate the required AEDT Fleet dB coefficients such that the environmental results may be calculated within the AEDT algorithms. The results of which will form the basis of the suggested APM modeling implementation in Task 3 and 4. GT suggested to the FAA project Manager the following engine/airframe models to use within EDS and AEDT for the parametric sensitivity study, in priority order:

- B737-800 with CFM56-7B27 engines, with winglets
- B767-300ER with CF6-80C2B7F engines
- B777-300ER with GE90-115b
- CRJ-900 with CF34-8C5 engines
- B747-400 with PW4056 engines with reduced emissions combustor or A380-800 with GP7270

Each of the EDS models would be compared to high fidelity performance data, when available, to ensure that the EDS model represents the actual aircraft performance within the fleet. As an example of the comparison to real world data, the aerodynamics for the B737-800 for cruise and low speed are depicted in Figure 6. As evident, the EDS model is a reasonable approximation to the actual B737-800 and can serve as the foundation of the sensitivity study.

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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.

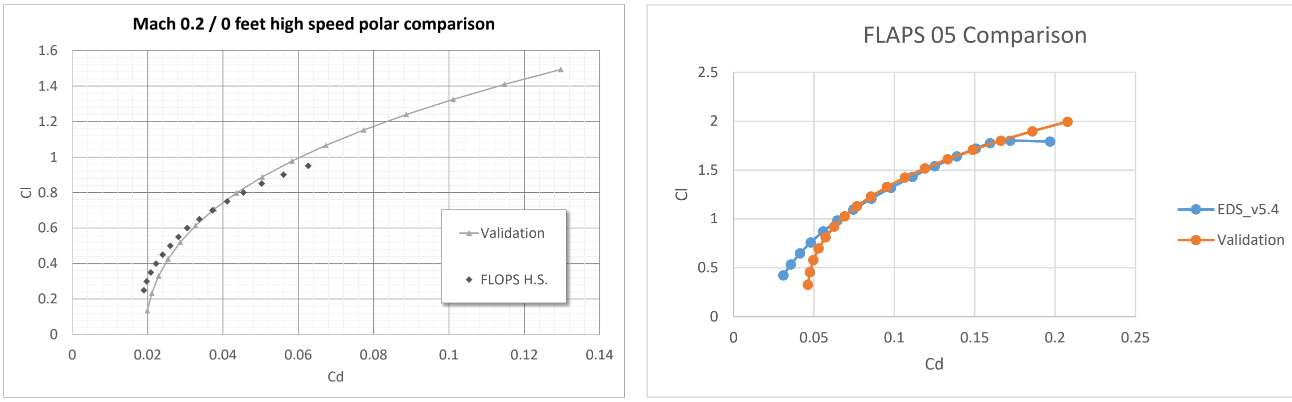

Figure 6. EDS Aerodynamic Comparison to Validation Data

At present, the research team is coordinating with various airlines to obtain actual flight performance data to compare to the EDS representation. From an analytical perspective, a high fidelity performance tool is also being utilized to compare the EDS model results of the sensitivity study. Only preliminary results exist at this time and will be described in future reports. However, the status of the modeling of the NAPD 1 and 2 are described in Task 3.

From an AEDT perspective, GT conducted a simple assessment of the impact of changing the takeoff weight and thrust to gain insight to the environmental impact of the modeling assumptions. The B737-800 model within AEDT was initially investigated with a 5% weight reduction and a15% reduced thrust takeoff (RTT) and to understand the sensitivity to the terminal area performance and noise contour areas. To change the takeoff weight within AEDT, the FLT_ANP_AIRPLANE_PROFILES Table must be modified and a user defined aircraft must be created. The aircraft was flown for a stage length 6 distance for the STANDARD, or Default, and the ICAO A departure procedures and the performance compared. For the 5% TOW reduction, the aircraft could get to a 10,000 ft. (AFE) altitude in a shorter ground track distance for both departure procedures, as depicted in Figure 7. The cutback altitude difference between the two procedures can also be visualized, where the STANDARD procedure cuts back at 1,000 ft. (AFE)and the ICAO A at 1,500 ft. Based on the procedures defined in Figure 4, the flap retraction and the acceleration to a constant speed occur at different altitude resulting in a slightly longer ground track distance for the STANDARD procedure as depicted in the speed and thrust variation in Figure 8 and Figure 9 respectively. The fuel burn is less with the reduced weight, and reduces linearly with flight distance.

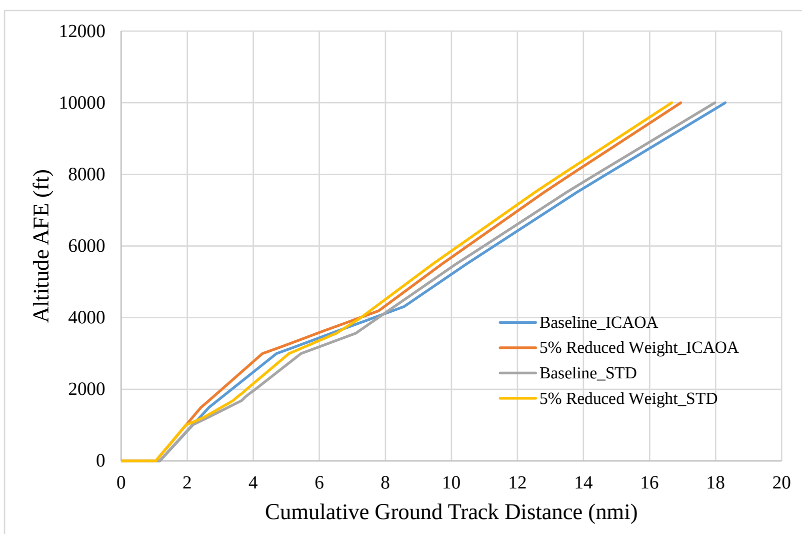

Figure 7. AEDT B737-800 Altitude and Ground Track Variation with -5% TOW Change

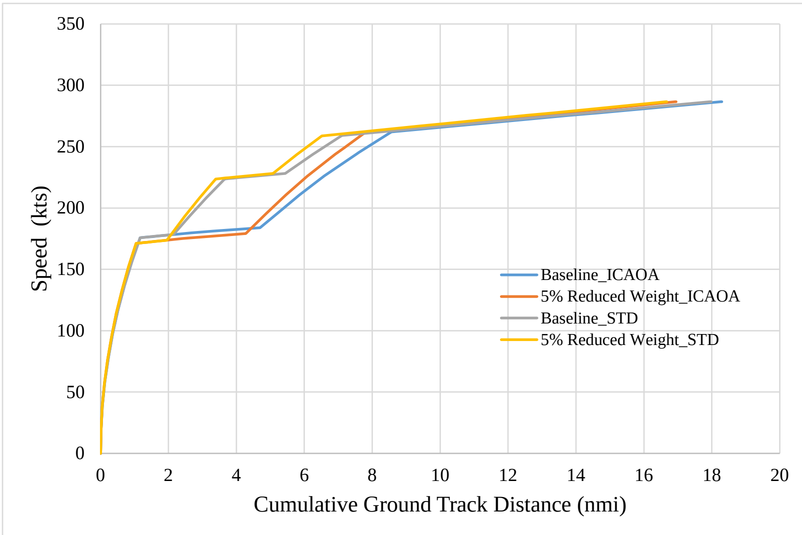

Figure 8. AEDT B737-800 Speed and Ground Track Variation with -5% TOW Change

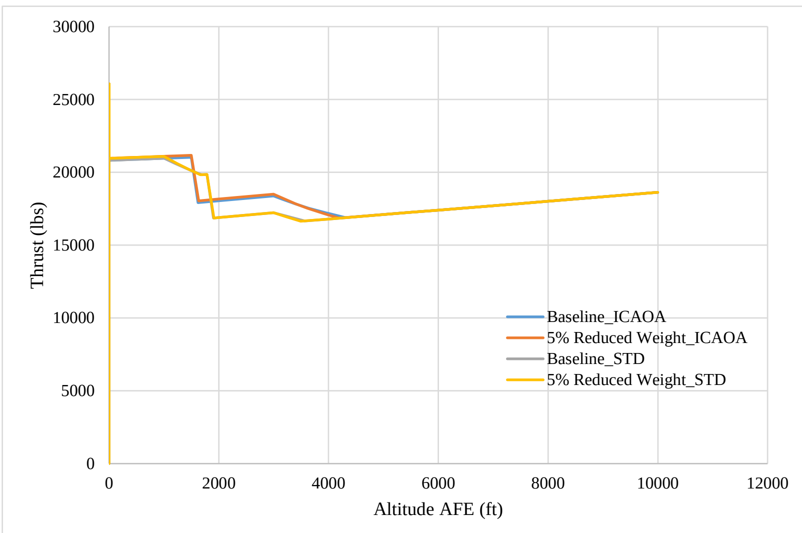

Figure 9. AEDT B737-800 Thrust and Altitude Variation with -5% TOW Change

As expected, the noise contour area is also impacted, as depicted in Figure 10, and for the STANDARD takeoff procedure. The reduced weight contours are highlighted in blue outline. The reduced weight results in a smaller contour length and also total area of approximately a 5% change at different Sound Exposure Levels (SEL) as listed in Table I.

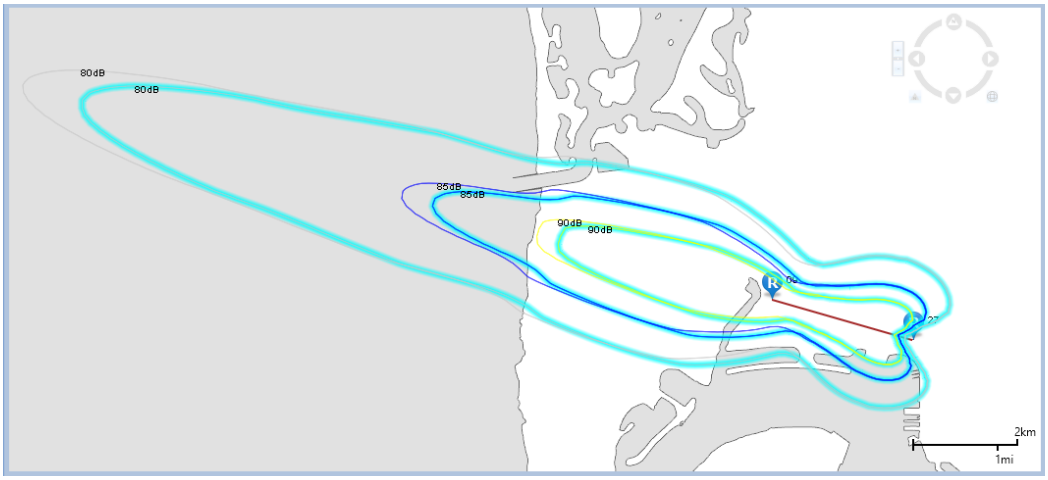

Figure 10. AEDT B737-800 Noise Contour Variation with -5% TOW Change

Table I: SEL Contour Area Changes with 5% TOW Reduction (SEL Metric)

SEL Contour (dB)	Shape Length (m)			Shape Area (nm²)		
	737-800	5% Reduced TOW	Difference	737-800	5% Reduced TOW	Difference
80	41,300	38,787	-6.1%	13.08	12.33	-5.8%
85	23,599	22,303	-5.5%	4.70	4.47	-4.8%
90	16,847	15,951	-5.3%	2.13	2.04	-4.3%

Next, the takeoff thrust impact was investigated. Based on the outcomes of the literature review, a 15% takeoff thrust was assumed. To adjust the takeoff thrust, the ANP coefficients must be modified within the Fleet dB for each of the departure procedure segments. The definition of the existing B737-800 as defined in AEDT is depicted in Figure 11. AEDT calculates jet aircraft corrected net thrust per engine by using a modified version of SAE-AIR-1845 equation:

$$F_n/\delta = E + F^*v + G_A{}^*h + G_B{}^*h^2 + H^*T_C$$

where

F_n/δ Corrected net thrust per engine (lbf);

v Equivalent/calibrated airspeed (kt);

h Pressure altitude (ft) MSL;

T_C Temperature (˚C) at the aircraft; and

E, F, G_A, G_B, H Regression coefficients that depend on power state (max-takeoff or max-climb power) and temperature state (below or above engine breakpoint temperature) (lbf, lbf/kt, lbf/ft, lbf/ft2, lbf/˚C, respectively). Thus, to control the thrust utilized for takeoff, the E coefficient was modified by 15% for both takeoff and climb.

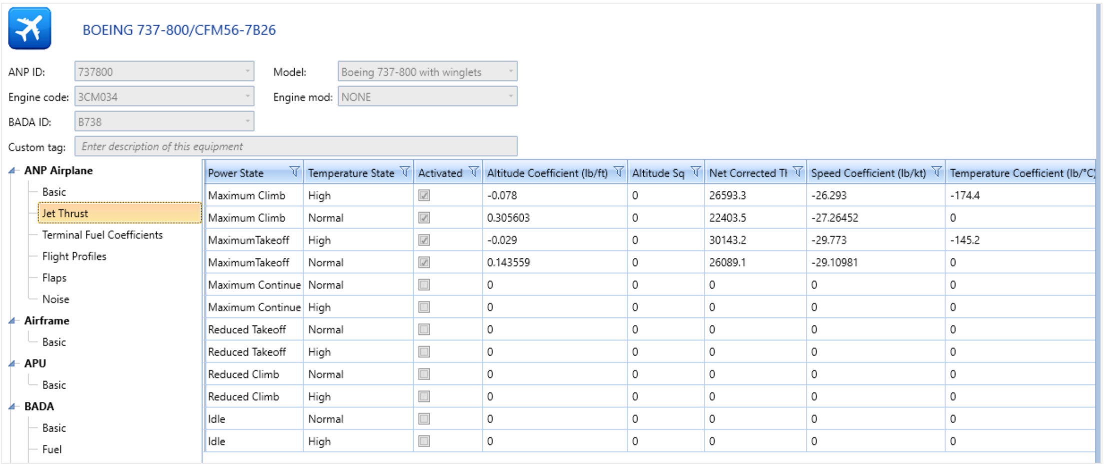

Figure 11. AEDT B737-800 ANP Thrust Coefficients

Only the STANDARD departure procedure was considered for this initial investigation. Similar to the takeoff weight sensitivity, the speed, altitude, and thrust variations were compared based on the maximum takeoff weight for a stage length of 6. For the reduced thrust takeoff, the cumulative ground track distance to reach a 10,000 ft altitude is increased approximately 8 nmi as depicted in Figure 12 and the cutback altitude and the acceleration segment after cut back also requires addition flight time to get to the constant speed climb as shown in Figure 13 and Figure 14, respectively.

From a noise perspective, the reduced thrust takeoff had a much more significant impact on the noise contours as shown in Figure 15. The contour shape and area were significantly reduced except for the 85 dB SEL, which is corresponding to the acceleration stage being delayed in the climb out. Unlike the reduced weight takeoff contours, the change in length and area was not consistent as listed in Table II. The length wasn't changed as much as the width. Thus, the reduced thrust takeoff will lower the lateral propagation.

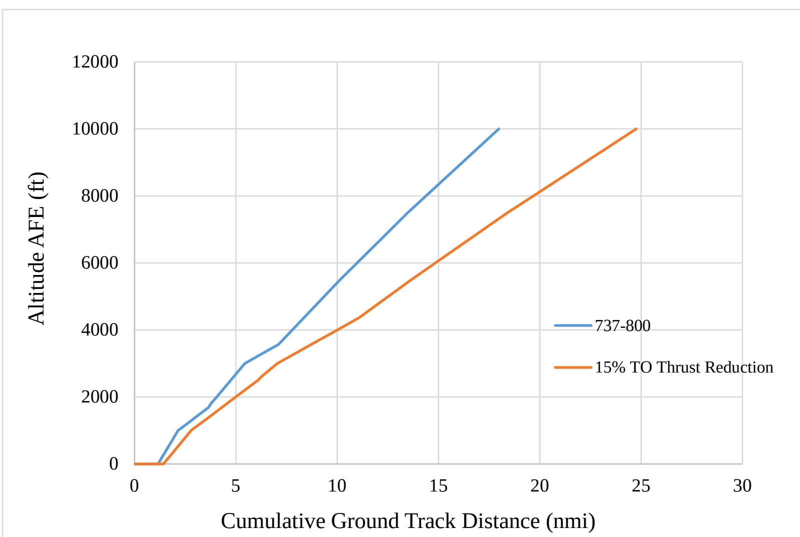

Figure 12. AEDT B737-800 Altitude and Ground Track Variation with 15% Reduced TO Thrust

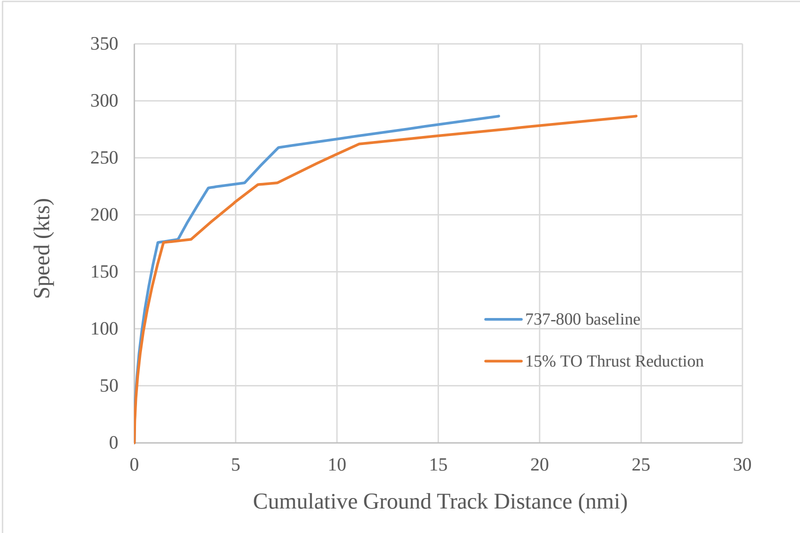

Figure 13. AEDT B737-800 Speed and Ground Track Variation with 15% Reduced TO Thrust

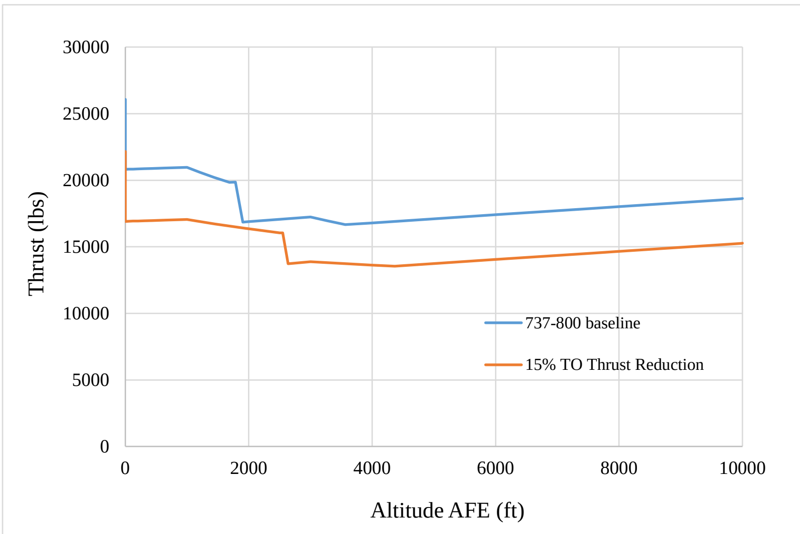

Figure 14. AEDT B737-800 Thrust and Altitude Variation with 15% Reduced TO Thrust

While the notional example procedure shows a 15% reduction in thrust from takeoff all the way up to 10000-ft air field equivalent altitude, these results are only intended as preliminary. In reality, thrust reduction between maximum takeoff thrust and maximum climb thrust are related but not necessarily identical. Based on past experience and prior data analysis, Georgia Tech established the following logic for modeling climb thrust derate relative to takeoff thrust derate:

- If takeoff thrust derate is less than 5%, use maximum climb thrust
- If takeoff derate is between 5% and 15%, derate climb thrust by 10% up to 10000-ft air field equivalent altitude
- If takeoff derate is greater than 15%, derate climb thrust by 20% up to 10000-ft air field equivalent altitude

This logic shall be used in future Georgia Tech modeling of reduced thrust takeoff procedures.

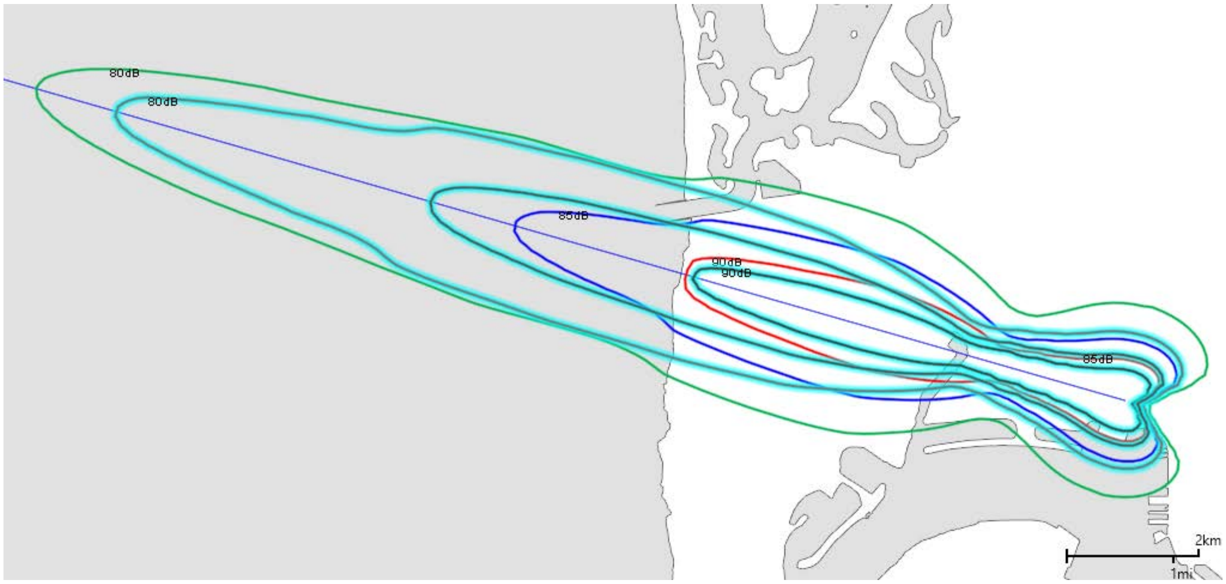

Figure 15. AEDT B737-800 Noise Contour Variation with 15% Reduced TO Thrust

Table II: SEL Contour Area Changes with 15% Reduced TO Thrust

SEL Contour (dB)	Shape Length (m)			Shape Area (nm^2)		
	737-800	5% Reduced TOW	Difference	737-800	5% Reduced TOW	Difference
80	41,301	36,837	-10.8%	13.08	9.23	-29.4%
85	23,599	25,193	6.8%	4.70	3.86	-17.8%
90	16,847	15,769	-6.4%	2.13	1.30	-39.2%

In summary, the initial sensitivity to takeoff weight and thrust has provided valuable insight to the impact of the APM assumptions. Although no definitive conclusions can be drawn, the environmental footprint due to more realistic departure procedures will be significant, especially when coupled together. As the research progresses, the impact to the environmental foot print will be quantified independently and also collectively. However, initial insight from this sensitivity study indicates that thrust will be the larger driver when considering the change in noise area.

From a departure procedure perspective, Georgia Tech (GT) began this task by modeling the Noise Abatement Departure Procedures (NADP) described in CAEP/7-WP/25 by directly changing procedure coefficients in AEDT. The aircraft coefficients and STANDARD procedures for a B737-800 vehicle were extracted from the AEDT Database. No changes were made to weight or thrust assumptions. The primary difference between the STANDARD procedures and the NADP procedures is the thrust cutback altitude. The STANDARD procedure for this vehicle did not cutback thrust from maximum takeoff thrust to maximum climb thrust until the acceleration and flap retraction steps were complete. This procedure specified a cutback altitude of 2040-ft. The NADP procedures feature cutback altitudes as low as 800-ft and no higher than 1500-ft, with cutback thrust always occurring before acceleration/flap retraction steps. For NADP1, the procedures closely align with ICAO-A procedures, with acceleration/flap retraction delayed until the aircraft reaches an altitude of 3000-ft. For NADP2, these acceleration/flap retraction steps begin immediately after flap retraction and the vehicle achieves a clean configuration before reaching an altitude of 3000-ft. NADP2 is similar to ICAO-B procedures, except the latter doesn't cutback thrust until after flap retraction (similar to the STANDARD procedure for this aircraft).

Some preliminary Sound Exposure Level (SEL) contours are shown in Figure 16 for the different noise abatement departure procedures. It should be noted, however, that these procedures only represent estimates from engineering judgment. The contour comparison is a useful guide to expectations of contour shapes, but the procedures must be dynamically generated to capture impacts of various weight and reduced thrust assumptions. This is primarily a concern for acceleration step, where AEDT specifies climb-rate and a calibrated airspeed where acceleration segments end, each of which varies as thrust or weight is varied. For the contour plots showed in Figure 16 these parameters were only estimated, and an example of these estimates for an accelerated climb step is shown in Figure 17.

Recent modeling efforts have been focused on modifying FLOPS runs in EDS to parametrically generate these parameters for different mission lengths, takeoff weights, and reduced takeoff thrust. Eventually, GT would like to validate these procedures against real FOQA data, but currently this data is unavailable. Instead, GT is validating the FLOPS models against a higher fidelity modeling tool. A subset of mission ranges and departure airport altitudes were chosen to be modeled, as listed in Table III. The "Estimated Weight" column in this table uses departure takeoff weights calculated from ASCENT Project 35 results. It should be noted that all of these weight estimates are higher than the AEDT assumed weight, even when the mission range is shorter than the AEDT representative mission range. SFO and BOS airports were chosen because these airports have altitudes close to sea-level. The stage-length 2 mission was repeated in the opposite direction to see the impact of a higher altitude airport (ATL has an altitude of approximately 1000-ft). DEN airport was also chosen to represent a high altitude airport (DEN has an altitude of approximately 5000-ft). Stage-length 5 and 6 missions are very rare for this vehicle and thus were omitted from this validation study.

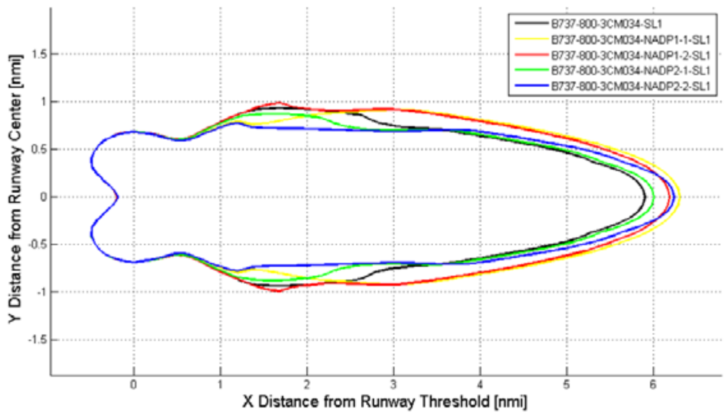

Figure 16. Notional SEL 80dB Contour Comparison for NADP Procedures

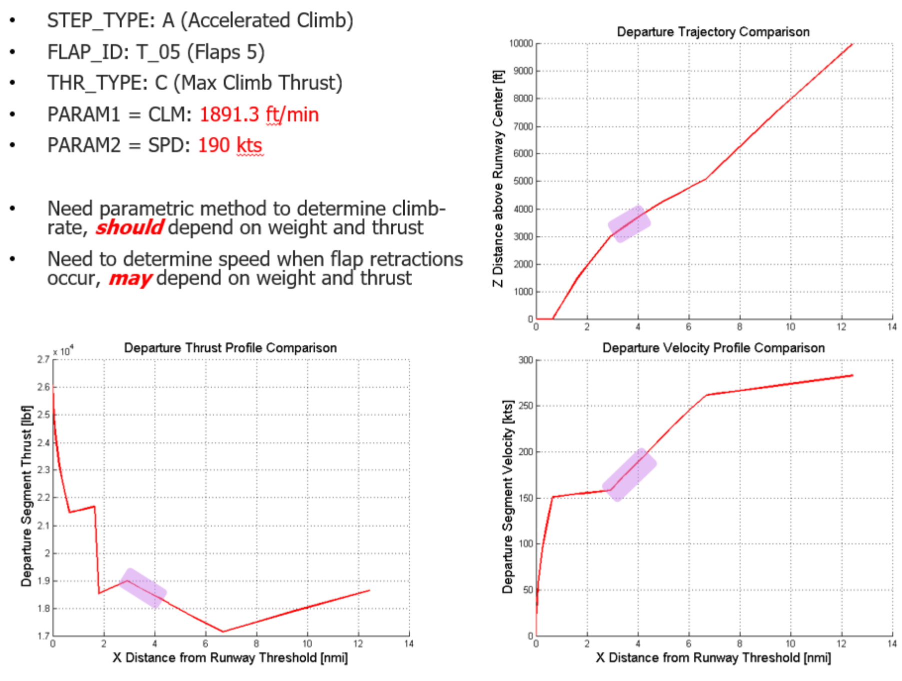

Figure 17. Example of Engineering Estimate for Accelerated Climb Step in AEDT for NADP1 Procedure

Table III: Mission Ranges and Weights to be Modelled for B737-800 Departures

Stage Length	AEDT Representative Mission Range [nm]	AEDT Assumed Weight [lb]	Origin	Destination	Mission Range [nm]	Estimated Weight [lb]
1	350	133300	SFO	SAN	388	141198
2	850	139200	BOS	ATL	822	146539
2	850	139200	ATL	BOS	822	147830
3	1350	145500	DEN	JFK	1413	158522
4	2200	156700	BOS	LAX	2269	168070
5	3200	167600				
6	4200	172300				

After a few iterations comparing FLOPS procedures versus the high-fidelity tool, it was suggested that GT modify FLOPS for the acceleration/flap retraction steps. Previously, GT specified flight path angle which needed to be varied as a function of aircraft weight and thrust, but without much data to determine this relationship. After discussing with Prof. JP Clarke and Jim Brooks, GT instead chose to specify pitch angle (flight path angle plus angle of attack). This approach more closely reflects the manner in which pilots actually fly the procedures, as they typically try to maintain a pitch angle between 10-12 degrees to ensure safe climb rates regardless of aircraft weight. This allows FLOPS to parametrically determine flight path angles and climb rates based on the performance of the aircraft, which makes the method more robust to changing takeoff weight and reduced thrust.

GT changed the method used for modeling reduced thrust. In actual procedures, reduced thrust takeoff is implemented via the Assumed Temperature Method, where the pilot tricks the flight management system into thinking the Outside Ambient Temperature (OAT) is higher than actual OAT. Thus, the engine to operate at lower thrust to protect internal components from excessively high temperatures, as notionally shown in Figure 18. AEDT contains both standard day thrust coefficients to represent the flat-rated curve and high-temperature coefficients for the sloped curve.

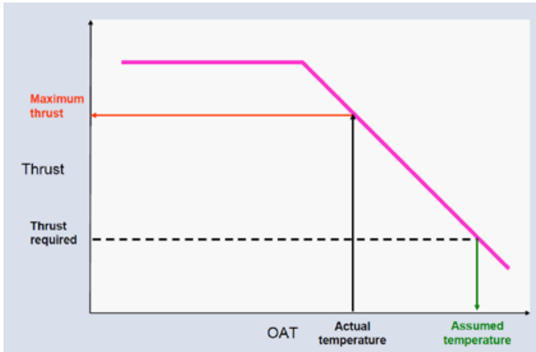

Figure 18. Notional Assumed Temperature Method for Reduced Thrust

FLOPS requires inputting an entire engine deck to calculate thrust levels and fuel flow at different combinations of velocity and altitude. To accomplish the reduced thrust, the engine decks are modified to remove power codes associated with full-rated takeoff thrust. Thrust cutback is accomplished by further removing power codes at cutback altitudes, and thus unique decks are generated for 800-ft, 1000-ft and 1500-ft cutback altitudes, respectively.

Validation efforts for the FLOPS procedures are currently ongoing. Once these procedures are validated, GT will enhance EDS codes to generate these NADP procedures in an automated manner. These procedures will be converted to AEDT procedures, which must also be validated against the high-fidelity tool (and FOQA data if it eventually becomes available). Once these AEDT procedures are validated, SEL contours will be generated with the AAM to quantify the impacts of the increased weight, reduced thrust, and noise abatement departure procedures. GT will look at sensitivities for each of these factors independently as well as the coupled impact of all factors simultaneously.

In summary, initial investigations to the takeoff procedure assumptions have been accomplished and provided initial insights to the environmental impact. GT will continue to investigate various surrogate and/or reduced order modeling techniques to develop mathematical models of takeoff weight and thrust as a function of the key terminal area performance metrics and also the takeoff procedure. For takeoff weight and thrust, GT will provide multiple models that will span the current fleet, which will provide the users different options depending on the data availability. For example, a surrogate model of takeoff weight as a function of great circle distance (GCD) only can be developed for each of the seat classes. Or a model can take much more input parameters including adjustments for each of the aircraft types. For each of the models, associated uncertainty bands will also be analyzed. This research will also quantify the impact to fuel burn, NO_x, and noise at the vehicle and also the fleet level for a TBD fleet scenario.

Task 3: Develop Aircraft State Estimator

Objective(s)

Once GT understands AEDT APM limitations in Task 1 and has a reduced flight dataset resulting from Task 2, work can begin to develop a state estimator for vehicle weight, takeoff thrust, and load factor as a function of ambient conditions and measured profile. Both EDS and 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 weights, 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.

Research Approach

The challenge of the aircraft state estimator development will be the extension of the focused investigations of a subset of aircraft in Task 2 and how those observations can be extended to the entirety of the aircraft/engine combinations within the AEDT Fleet dB. However, GT has identified that the takeoff weight assumption can be easily adjusted within AEDT based on the results of Project 35 for those 4 aircraft types and also the BAH fuel efficiency metrics investigations, when available. In instances when aircraft in the AEDT database are not covered by one of these studies, BTS data could be used to approximate takeoff weight assumptions for the remainder of the fleet. It should be noted, a high possibility exists that data may not exist to approximate all aircraft takeoff weights. In this instance, GT will investigate an option of classifying aircraft types and utilizing a broad takeoff weight assumption.

From the thrust perspective, multiple research endeavors have shown that a 15% takeoff thrust reduction is reasonable. However, that assumption should only be applied at takeoff and not at the cutback altitude. A methodology will be developed on how to implement the modification in AEDT based on a subset of the fleet.

The final aspect will be to determine how to implement the modified departure procedure based on an EDS implementation and a comparison to the AEDT procedural definitions. Per the AEDT Technical Manual guidance for the departure procedure defined in Figure 4, it appears the flexibility exists to define any type of procedure, but this must be investigated.

Task 4: Develop APM Enhancement Recommendations

Objective(s)
Each of the prior tasks will culminate into a set of recommendations for enhancements to AEDT in a 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. GT 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 enhancement
- 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

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 initial sensitivity studies conducted.

SQL scripts written to automate extraction of existing aircraft definitions and modifications to weight and thrust.

Matlab scripts written to automate the departure procedure modeling and visualization of performance.

Identification of sources of data that might provide justification of takeoff weight assumptions with the APM.

Publications
None

Outreach Efforts
Bi-weekly calls with the Project Managers.

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 Tasks 2 through 4. Task 2 will focus on the implementation of the NAPD procedures within EDS and FLOPS and how that modeling could be extended to the APM. As mentioned previously, validation efforts for the FLOPS NADP procedures are ongoing. Once these procedures are validated, the EDS code will be edited to automatically run these FLOPS NADP procedures and convert them into equivalent AEDT procedures. These procedures will be used in AEDT in conjunction with the acoustics module in order to determine the impacts of weight, thrust, and procedures on SEL noise contours. Currently Georgia Tech is focused on the B737-800, but validation efforts shall be repeated for other vehicles that EDS models. Once this validation is complete, the more detailed sensitivity study of the assumptions will be conducted, which will include one at a time, and also partial derivatives with respect to environmental metrics.