Extending Aircraft Performance Modeling Capabilities in the Aviation Environmental Design Tool (AEDT)

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***Abstract*— To support improved analysis of the environmental impacts of proposed global aircraft operational changes, the United States Federal Aviation Administration recently worked with European academic partners to update the airport terminal area fuel consumption methods used in the Aviation Environmental Design Tool. These updates are based on fitting data from a commercial third party aircraft performance program to previously developed empirical equations. These algorithm updates have adequate fidelity in the terminal area to assist air transportation policy makers in weighing the costs and benefits of competing environmental and economic demands. Comparison with Flight Data Recorder information for in-service airline operations shows that the combination of new aircraft data with the methods in the environmental model can accurately capture the fuel consumption consequences of different terminal departure and arrival procedures within a reasonable level of uncertainty.**

Keywords- fuel consumption; emissions; environmental impacts; modeling

I. Introduction

Fuel costs are the airline industry's largest direct expense [1]. Emission costs have also become an issue for airlines. The European Union (EU) includes aviation in its Emission Trading System (ETS) and, starting in 2012, all European domestic and international flights – to or from anywhere in the world – that arrive at or depart from an EU airport will be covered by the ETS [2]. From the costs of the fuel itself, to the costs of the resulting emissions, airlines are faced with the need to become as fuel efficient as possible. To support this need for increased efficiency, both the United States' Federal Aviation Administration (FAA) and the EU's EUROCONTROL have begun efforts to improve their respective Air Traffic Managements systems. The FAA has started implementing Next Generation Air Transportation System (NextGen) [3]; EUROCONTROL has undertaken the Single European Sky (SES) initiative [4].

As part of a continual effort to improve the ability to quantify flight efficiencies, the FAA has supported the development of aviation environmental models which enable fuel consumption and emission calculations for different modes of flight. To this goal, the FAA is in the process of developing a new single integrated aviation environmental tool. The Aviation Environmental Design Tool (AEDT) is a next generation suite of integrated aviation environmental analytical capabilities [7][8]. AEDT provides users with the ability to assess the interdependencies between aviation-produced noise, fuel consumption and emissions on any scale ranging from a single operation to the full set of global operations.

For fuel consumption analyses (upon which emission analyses depend), development versions of AEDT have relied on data from EUROCONTROL's Base of Aircraft Data (BADA) [9]. The BADA fuel consumption model uses an energy-balance thrust model and Thrust Specific Fuel Consumption (TSFC) modeled as a function of airspeed. BADA information on airplane performance and fuel consumption exists for a large part of the civil fleet: BADA 3.8 contains data for 111 directly supported aircraft, from single piston engine general aviation aircraft to the Airbus A380. The BADA fuel consumption model has been shown to have differences from airline reported fuel consumption of about 3% [10][11]. However, comparisons of BADA-predicted and actual airline fuel consumption - reported via their Flight Data Recorder (FDR) system - revealed that BADA does not perform as accurately in the terminal area - below 3048 m (10,000 feet) Above Field Elevation (AFE) and less than 250 knots - when compared with the cruise phase of flight [12].

To support a higher level of modeling fidelity in the terminal area, required for determining the benefits of NextGen and SES initiatives such as Optimized Profile Descents, Tailored Arrivals, RNAV/RNP procedures, and reduced-powered takeoffs, the FAA initiated a program to work with the Boeing Company and Airbus to use their performance tools to improve fuel consumption modeling in the terminal area. As a result of this effort, the Boeing Company provided their Boeing Climb-Out Performance (BCOP) low speed aircraft performance model to the FAA; this model was used to improve the terminal area for the Boeing aircraft in the fleet [12].

To provide information on other manufacturers' aircraft, the FAA purchased the Project Interactive Analysis and Optimisation (PIANO) aircraft performance analysis tool developed by Lissys [13] in England. PIANO contains aerodynamic and performance data for a large number of transport aircraft in the global civil fleet. For those aircraft where manufacturers have already provided aerodynamic data for the FAA's legacy tools, PIANO was used to determine the TSFC data. Note that these aerodynamic data are in the form described in [14] and enhanced in [15]. Those aircraft without any data in the legacy tools had both aerodynamic and TSFC data generated using PIANO. For all aircraft, the data were developed specifically for the terminal area. At altitudes above the terminal area, AEDT will continue to use BADA data and methods.

This paper provides background information on the fuel consumption methods in the FAA's aviation environmental model, discusses how both fuel consumption and aerodynamic data are derived and used in this model, and presents validation of these methods and data against FDR data. The paper concludes with an example of improvements in fuel consumption modeling for state-of-the-art operations enabled by NextGen. Note that this project is a continuation of work presented at the prior ATM seminar.

II. BACKGROUND

Differences between the BADA-modeled and the FDR fuel consumption data illustrated the need for an improved terminal area fuel consumption method in the AEDT model. This new fuel consumption method needed to be 1) more accurate than existing methods, 2) easy for manufacturers to supply requisite data while protecting their proprietary interests, 3) compatible with existing environmental models, 4) capable of capturing the effects of operational changes, and 5) sufficiently accurate to enable decision-makers to have confidence in modeled results. Examination of the fuel consumption characteristics of turbofan engines led to the conclusion that a single method would not suffice to cover the requirements of both departures and arrivals. Instead, two TSFC equations, one each for departure and arrival operations in the terminal area, were developed. The departure TSFC equation (1) is given below and is based on the form of the thrust model found in AEDT.

$$TSFC/\sqrt{\theta} = K_1 + K_2 M + K_3 h_{MSL} + K_4 F/\delta \qquad (1)$$

The arrival TSFC equation below (2) is based on work by Hill [17] with modifications by Yoder [18].

$$TSFC/\sqrt{\theta} = \alpha + \beta_1 M + \beta_2 e^{-\beta_3\left(F/\delta / F_0\right)} \qquad (2)$$

In the equations above, θ is the ratio of the temperature at the aircraft's altitude to the standard temperature at sea level, M is the aircraft Mach number, h_{MSL} is the height of the aircraft above mean sea level (MSL), F is the thrust of the engine, δ is the ratio of the atmospheric pressure at the aircraft's altitude to the standard pressure at sea level, and F_0 is the maximum thrust at sea level static conditions. In both equations, the individual coefficients (K_i, α, and β_i) for each airplane/engine combination are found by generating airplane performance data for a wide range of operational conditions, collecting those data into a common structure, and then statistically analyzing those data, as discussed briefly below.

III. PIANO USAGE WITH THE AEDT TERMINAL AREA FUEL CONSUMPTION MODEL

The fundamental methods of developing fuel consumption data are similar to methods previously developed for extracting fuel consumption data from other aircraft performance software (e.g. Boeing's BCOP model). Data from the software tool are generated for aircraft performance conditions (e.g. Thrust, Altitude, and Mach) which match the expected flight regime for the aircraft being modeled. An example of the expected flight regions for a departure is given below in Figure 1.

In Figure 1 below, the horizontal axis represents airspeed in units of Mach number and the vertical axis represents feet of altitude above Mean Sea Level (MSL). There are four regions of interest shown in the figure. The first region, primarily where take-off power is used, lies between Sea Level and 762 m (2500 feet) for airspeeds below Mach 0.35. Another region, representing airports at higher elevations, lays between 762 and 2134 m (2500 and 7000 feet) MSL and speeds below Mach 0.46. For the climb-out, another region is represented by altitudes between 2134 and 3048 m (7,000 and 10,000 feet) and Mach 0.25 and 0.46 – note that this upper limit roughly corresponds to the 250 knot airspeed restriction below 3048 m (10,000 feet) MSL. The final region is also for climb power modeling from higher elevation airports; this region is represented by altitudes from 3048 to 4876 m (10,000 to 16,000 feet) MSL and airspeeds between Mach 0.4 and 0.6.

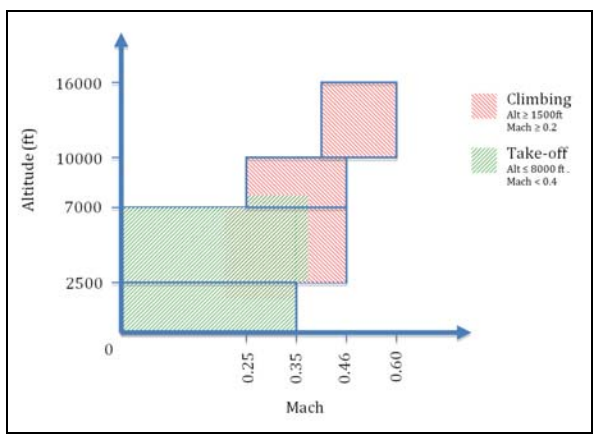

Figure 1. Typical departure data collection region

In Figure 1, the area of green, lower-left to upper-right cross-hatching show the expected flight region for take-off power settings; take-off power is assumed to be limited to use below 8000 feet MSL and Mach 0.40. The red lower-right to upper-left cross-hatching area shows the expected flight region for the climb-power settings; climb power is assumed to be limited to use above 457 m (1500 feet) MSL and Mach 0.2. Note that take-off and climb power do have areas of overlap. Similar limits are used for the arrival data, but in this case, the input limits are three dimensional – Mach, Altitude, and Thrust.

Statistical analysis was used to determine the TSFC and the engine thrust coefficients from the collected flight database. For this work, the coefficients were generated using linear (for the departure TSFC and the thrust equations) or non-linear (for the arrival TSFC equation) analysis tools, based on minimizing the least-squared error between the values calculated from PIANO and the TSFC (or thrust) equation with its associated coefficients.

IV. PIANO usage with the AEDT Terminal Area Performance Model

The prior section discussed the development of fuel consumption data with the implicit assumption that aerodynamic data were available for the aircraft under consideration. These aerodynamic data are available for the majority of large civil transport aircraft (i.e. all the in-production Airbus and Boeing wide-body aircraft, and the majority of their in-production single aisle aircraft), but not for a number of important regional transports (e.g. the Embraer 170/190 family). For these aircraft, PIANO was used to develop both the fuel consumption data (as discussed above) and the aerodynamic data in the format specified in [14] and [15].

The aerodynamic data are comprised of separate equations for both departures and arrivals. The departure equations include those necessary to determine takeoff ground roll distance, initial climb airspeed, and climb gradient. The arrival equations include those necessary to calculate the final approach speed and the thrust required for a given descent angle. These equations depend on aircraft weight, aerodynamic characteristics, and net thrust. The weight is a function of the distance flown and assumptions on load factors and reserve fuel requirements. The aerodynamic characteristics are a function of the flap, slat, and gear settings, which in turn depend on airspeed. The net thrust during departure is a function of mode (i.e. take-off or climb-out), airspeed, and altitude; net thrust during arrival is calculated from a force balance from a known (or assumed) landing weight, aerodynamic configuration, and descent angle.

PIANO provides the user with the ability to model in-flight maneuvers; these can be used to determine the associated aerodynamic coefficients. These coefficients are found for the aircraft in a stable, unaccelerated state. For example, an aircraft can be modeled for a departure in a known configuration, while climbing at a constant calibrated airspeed; for this particular configuration and airspeed, the lift over drag ratio and the climb gradient can be found from the PIANO output.

V. Validation Of The AEDT Coefficients With FDR Information

Validation of the new fuel consumption data was conducted by comparing in-service airline fuel consumption data to the fuel consumption predicted with these new methods. The airline fuel consumption data are part of FDR data sets collected from a number of airlines.

A. Departure Operations

FDR information - available for a number of Airbus aircraft - was used to validate the usage of PIANO for developing the AEDT TSFC coefficients. FDR information was available to validate the departure model for the Airbus A319-100, A320-200, A321-200, A330-200, A340-300 and A340-500.

The AEDT software was used to simulate different departure procedures; these simulations were used to generate the required values for Mach, altitude and thrust. Instead of comparing the fuel flow at a certain point in time for a particular flight, the total amount of fuel consumed was calculated for different departure procedures until 10,000 feet Above Field Elevation (AFE). For these departures, the AEDT Takeoff Weight (TOW) associated with different aircraft ranges was used, so that a relationship could be developed showing the amount of fuel consumed versus the TOW for both the FDR data and AEDT-modeled departures. These TOWs are provided by the manufacturer. This has the advantage of showing the nominal as-modeled fuel consumption for a standard AEDT operation compared to actual fuel consumption for that modeled aircraft. An example plot of this method can be found below in Figure 2.

This figure shows the fuel consumption per engine up to 10,000 feet for departures by Airbus A340-500 aircraft. The fuel consumption is given as a function of takeoff weight. The individual points in the figure represent the fuel consumption measured by the FDR system onboard the aircraft – each point is the fuel consumption for a single departure. The upper, solid line represents the fuel consumption predicted by the new AEDT method; the lower, dashed line represents the fuel consumption predicted by the prior BADA 3.8 method. The AEDT method passes through the cluster of FDR points, indicating relatively good agreement. The BADA method passes below the majority of the FDR cluster, indicating a general under-prediction of fuel consumption for this particular aircraft. Note that both the modeled lines were created by using the weights associated with various stage length weights for this aircraft type; the fuel consumption is based on a standard departure procedure. Similar curves were generated for each of the aircraft with FDR data listed at the beginning of this section.

Table I below provides a summary of the differences between the measured and modeled fuel consumption for those aircraft with FDR data. The modeled fuel consumption is within about 5% of the FDR measurements. The authors believe this level of agreement indicates that the methods and data in AEDT are sufficiently accurate to be used for determining the fuel consumption impacts of flight operations.

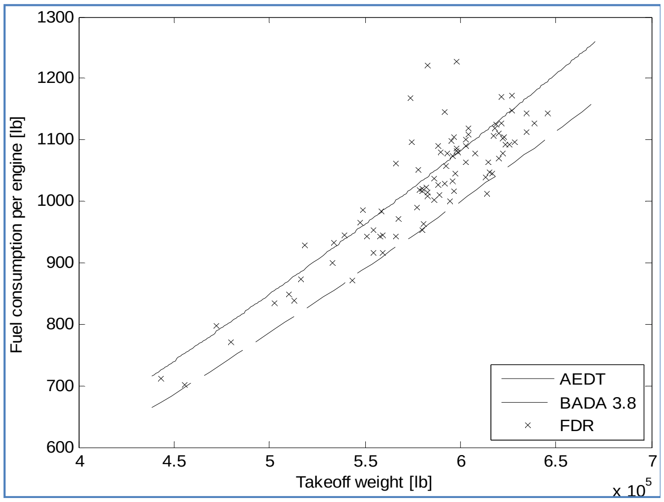

Figure 2. A340-500 Fuel consumption to 10,000 feet

TABLE I. DIFFERENCES IN AEDT-MODELED FUEL CONSUMPTION RELATIVE TO FDR MEASURED DEPARTURE DATA

Aircraft	AEDT
A319-100	+0.9%
A320-200	+0.2%
A321-200	-5.2%
A330-200	-3.9%
A340-300	+0.2%
A340-500	+1.6%
Average Absolute Error	2.0%

The departure TSFC coefficients were developed with an expectation that 10,000 AFE would be the limit of their applicability; above this altitude, we expect this method to lose accuracy.

B. *Arrival Operations*

Arrival operations cannot be modeled accurately assuming a standard procedure, as was done for the departures – fuel consumption during arrivals is significantly influenced by the actual conditions of the individual flight. These influencing conditions include the weather, arrival routes and descent profiles, and the amount of concurrent air traffic at the particular airport. The arrival coefficients therefore need to be validated on an individual flight basis. In order to do this, the fuel flow was calculated using the Mach, altitude, and thrust values from a sample of simulated FDR flights, and then these calculated fuel flows were compared to the measured fuel flow from the aircraft's FDR system. This type of validation was done for a sample of A319-100 and A320-200 arrivals. For these aircraft, the aerodynamic parameters used are from AEDT (and hence from the manufacturer, Airbus), not from PIANO. The thrust values are not those from the FDR, but rather are values calculated by AEDT to match the FDR aircraft state.

For each of the two aircraft types, three random flights were selected for modeling. This modeling involves matching the altitudes, airspeeds, and flap and landing gear settings of the aircraft from 10,000 feet down to the runway. Figure 3 below shows an example of the fuel consumption for one of these flights and the modeled results from the AEDT. The horizontal, independent axis represents the time from the start of the arrival analysis at 10,000 feet AFE, to the end time when the aircraft arrives on the runway; in this instance, about 750 seconds after the start of the analysis. The vertical, dependent axis represents the cumulative fuel consumed (in pounds) during this part of the arrival. The upper, solid line represents the measured fuel consumption, as recorded by the FDR system. The lower, dashed line represents the modeled fuel consumption, as calculated by AEDT. The two vertical lines represent the times when the aircraft reaches the runway and when the analysis stops; with the solid line again representing the FDR data and the dashed line representing the AEDT calculation. In this case, AEDT under-predicts the measured FDR fuel consumption.

The results of the analysis for the six sample A319 and A320 arrivals are given in Table II below. The average error of the new method relative to FDR data is +4.7% compared with the average error of +8.9% using the prior method. As with the departures, the average fuel consumption of the new method is within about 5% of the FDR measured fuel consumption, though individual flights lie outside this range.

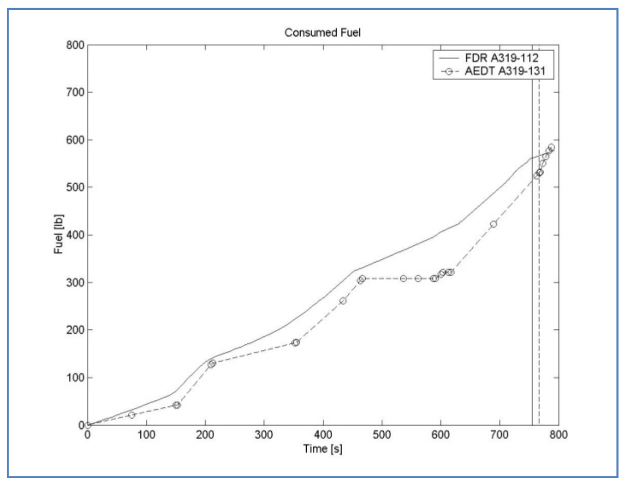

Figure 3. Example of A319-100 arrival cumulative fuel consumption from 10,000 ft.

TABLE II. DIFFERENCES IN AEDT-MODELED FUEL CONSUMPTION COMPARED WITH SAMPLE FLIGHT FDR ARRIVAL DATA

Aircraft	New method	Prior method
A319-100 flight 1	+4.7%	+21.9%
A319-100 flight 2	-5.5%	-1.0%
A319-100 flight 3	-1.7%	+2.8%
A320-200 flight 1	+5.3%	+4.8%
A320-200 flight 2	+0.2%	+19.0%
A320-200 flight 3	-12.4%	+5.7%
Average absolute error	5.0%	8.9%

VI. PRACTICAL USAGE EXAMPLE

As part of a study of the implementation of Automatic Dependent Surveillance – Broadcast (ADS-B) in the FAA's NextGen system, an A330 aircraft arrival into a major US airport was analyzed with the prior TSFC coefficients and with those generated as part of this study. As with the validation discussed earlier in this paper, FDR data from this arrival were available to the researchers. Figure 4 below shows the arrival altitude profile of this flight. The analysis begins at a level segment at 14,000 feet and ends at the runway after traveling approximately 100 nautical miles. This arrival contains numerous altitude holds, with prominent holds at 8000, 6000, and 4000 feet.

Below 10,000 feet MSL, where the new fuel consumption methods apply, the measured fuel consumption from the FDR system was 379 kg (836 lb). Using the prior methods of modeling, AEDT calculated a fuel consumption of 450 kg (993 lb), which is 71 kg (157 lb) or 19% more than the actual consumption. Using the new methods, AEDT calculated a fuel consumption of 416 kg (917 lb), which is 37 kg (82 lb); 10% more than the actual consumption. The new method is significantly closer to the actual fuel consumption than the prior method, with the difference reduced by about half.

Note that we expect these improvements in the absolute fuel consumption to translate to even smaller discrepancies when analyzing changes in fuel consumption between a standard operation and a modified operation. Although errors in the total fuel consumption for any particular operation may exist, the error in the difference between two modeled operations should be significantly smaller.

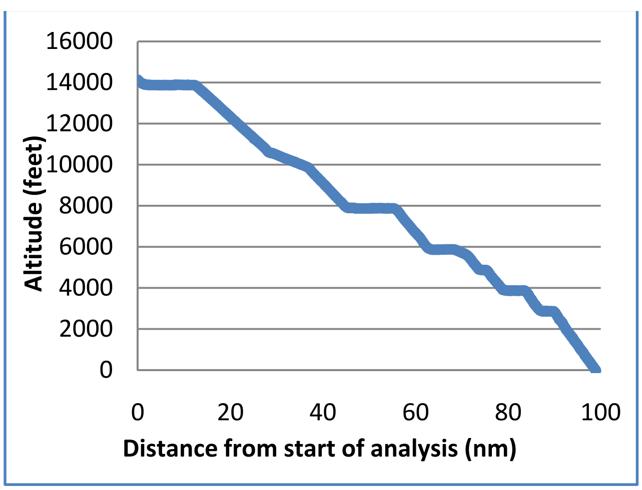

Figure 4. A330 arrival altitude profile using ADS-B

VII. CONCLUSIONS

This paper presents the results of using a new source of aircraft performance and fuel consumption data for computing low speed terminal area airplane fuel consumption. These new algorithms have been implemented in FAA's AEDT model. The authors believe the new data show sufficient fidelity to enable modelers to accurately capture the effects of operational changes on airplane fuel consumption. These operational changes could include Optimized Profile Descents, Tailored Arrivals, RNAV/RNP procedures, and reduced-powered takeoffs. This improvement in fuel consumption modeling will be important to airlines and other users of the global airspace system, as those responsible for the airspace system seek to improve the efficiency of the national and international airspace while considering the associated environmental impacts, an important objective of both the FAA's NextGen and of EUROCONTROL's Single European Sky initiative.

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